BIOMIMETIC RESTORATIVE DENTISTRY

Pascal Magne, PD, DR MED DENT
Urs Belser, PROF, DR MED DENT

VOLUME 1

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Fundamentals and Basic Clinical Procedures

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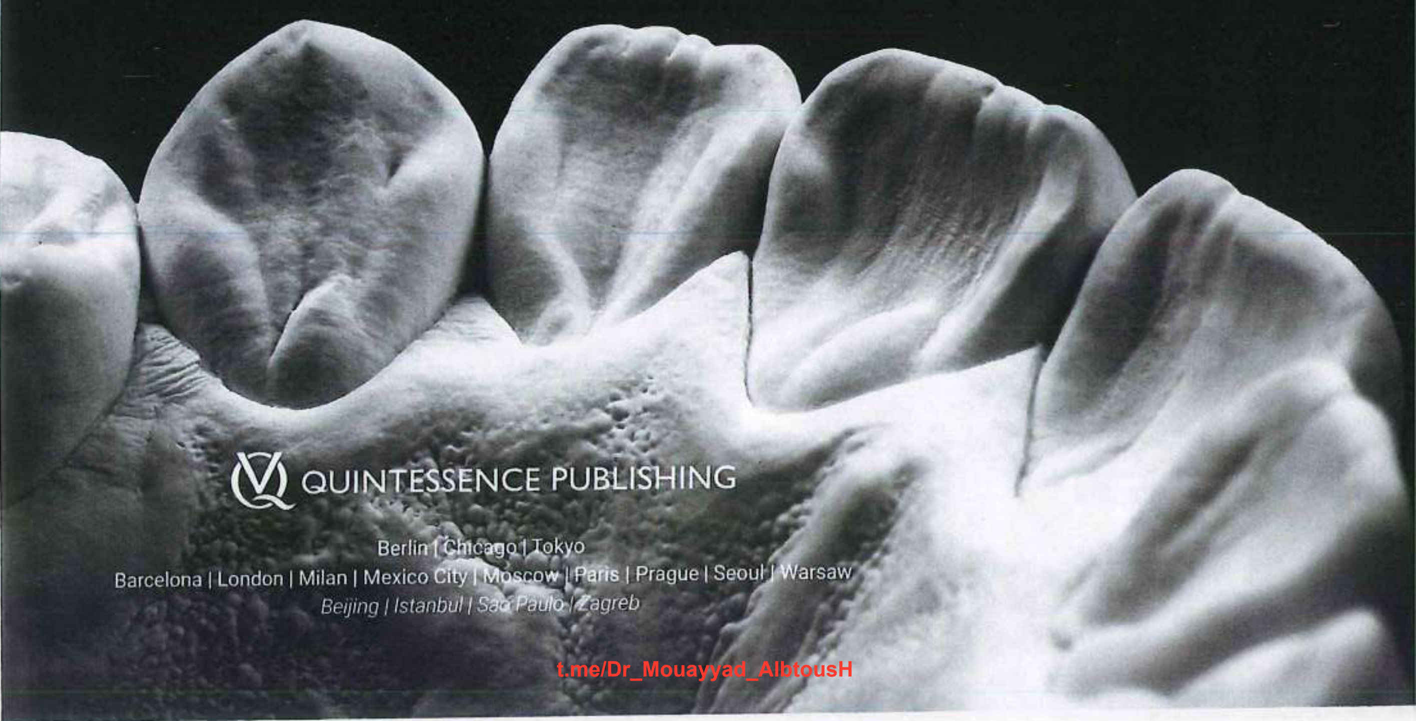

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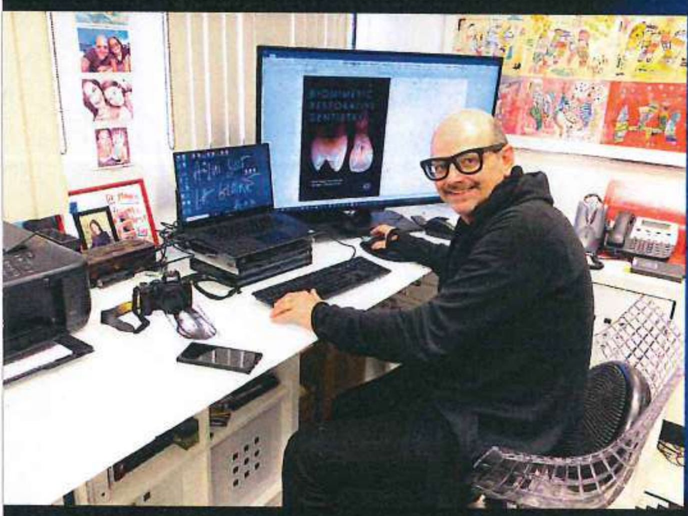
PASCAL MAGNE

Dr Pascal Magne is an Associate Professor with tenure and the Don and Sybil Harrington Foundation Professor of Esthetic Dentistry in the Division of Restorative Sciences at the University of Southern California Herman Ostrow School of Dentistry in Los Angeles. He graduated from the University of Geneva Dental School in Switzerland in 1989 with a Med Dent degree and later obtained his doctorate in 1992 and his Privat Docent degree in 2002. Dr Magne received postgraduate training in fixed prosthodontics and occlusion, operative dentistry, and endodontics and was a lecturer at the same university beginning in 1989 until 1997. From 1997 to 1999, he was a Visiting Associate Professor at the Minnesota Dental Research Center for Biomaterials and Biomechanics at the University of Minnesota School of Dentistry. After concluding 2 years of research, Dr Magne returned to the University of Geneva Dental School and assumed the position of Senior Lecturer in the Division of Fixed Prosthodontics and Occlusion until he was recruited to the University of Southern California in February 2004. He is the recipient of multiple awards from the Swiss Science Foundation and the Swiss Foundation for Medical-Biological Grants and was honored with the 2002 Young Investigator Award from the International Association for Dental Research as well as the 2007, 2009, and 2018 Judson C. Hickey Scientific Writing Awards (for the best research/clinical report of the year published in the *Journal of Prosthetic Dentistry*). He was also the recipient of the Distinguished Lecturer Award of the Greater New York Academy of Prosthodontics in 2016. Dr Magne is the author of numerous clinical and research articles on esthetics and adhesive dentistry and is an internationally known mentor and lecturer on these topics. The first edition of this textbook has been translated into 12 languages and is considered one of the most outstanding books in the field of adhesive and esthetic dentistry. Dr Magne is a founding member of the Academy of Biomimetic Dentistry and a mentor of the Bio-Emulation think-tank group. In 2012, he launched a revolutionary approach to the teaching of dental morphology, function, and esthetics (the 2D/3D/4D approach) for freshman students at the Herman Ostrow School of Dentistry at USC.



QR codes like this are placed throughout the book and can be scanned to access exclusive video content demonstrating techniques or further explaining concepts. They will be updated as new material becomes available.

URS BELSER

Prof Urs Belser graduated from the Dental Institute at the University of Zurich in Switzerland. He received postgraduate specialty training in reconstructive dental medicine (board-certified specialist) at the University of Zurich and was an Assistant Professor and then Senior Lecturer in the Department of Fixed Prosthodontics and Dental Materials there (Prof Dr Peter Schärer, MS) from 1976 to 1980. He was also a Visiting Assistant Professor from 1980 to 1982 in the Departments of Oral Biology (Prof Dr A.G. Hannam) and Clinical Dental Sciences (Prof Dr W. A. Richter) in the Faculty of Dentistry at the University of British Columbia in Canada. Between 1983 and 2012, Prof Belser acted as the Professor and Head of the Department of Fixed Prosthodontics and Occlusion at the University of Geneva School of Dental Medicine, serving as the president of the Swiss Association of Reconstructive Dentistry from 1984 to 1988. He was the recipient of the Scientific Research Award of the Greater New York Academy of Prosthodontics in 2002, President of the European Association of Prosthodontics (EPA) from 2002 to 2003, and Visiting Professor at Harvard University in the Department of Restorative Dentistry and Biomaterials Sciences (Prof Dr H. P. Weber) in 2006. Since 2012 he has been Guest Professor in the Department of Oral Surgery (Prof Dr D. Buser) and Department of Reconstructive Dentistry (Prof Dr Urs Braegger) at the School of Dental Medicine at the University of Bern. In 2013 he became an Honorary Fellow of The International Team of Implantology (ITI). Between 2013 and 2017 he served as editor-in-chief of *Forum Implantologicum* (ITI), and in 2014 he became a lifetime honorary member of the American College of Prosthodontists (ACP) and received the Lecturer of the Year Award. In 2018 he was presented the Morton Amsterdam Interdisciplinary Teaching Award (together with Prof Dr D. Buser). Prof Belser's research is focused on implant dentistry, with special emphasis on esthetics and the latest developments in the field of CAD/CAM technology and high-performance dental ceramics, as well as on adhesive reconstructive dental medicine.

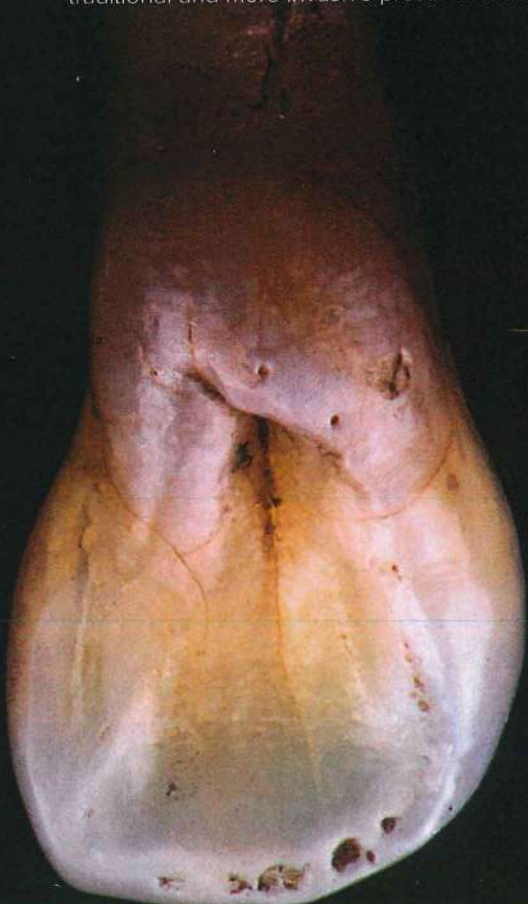
BIOLOGY – FUNCTION – MECHANICS – ESTHETICS

BRD

Biomimetic Restorative Dentistry

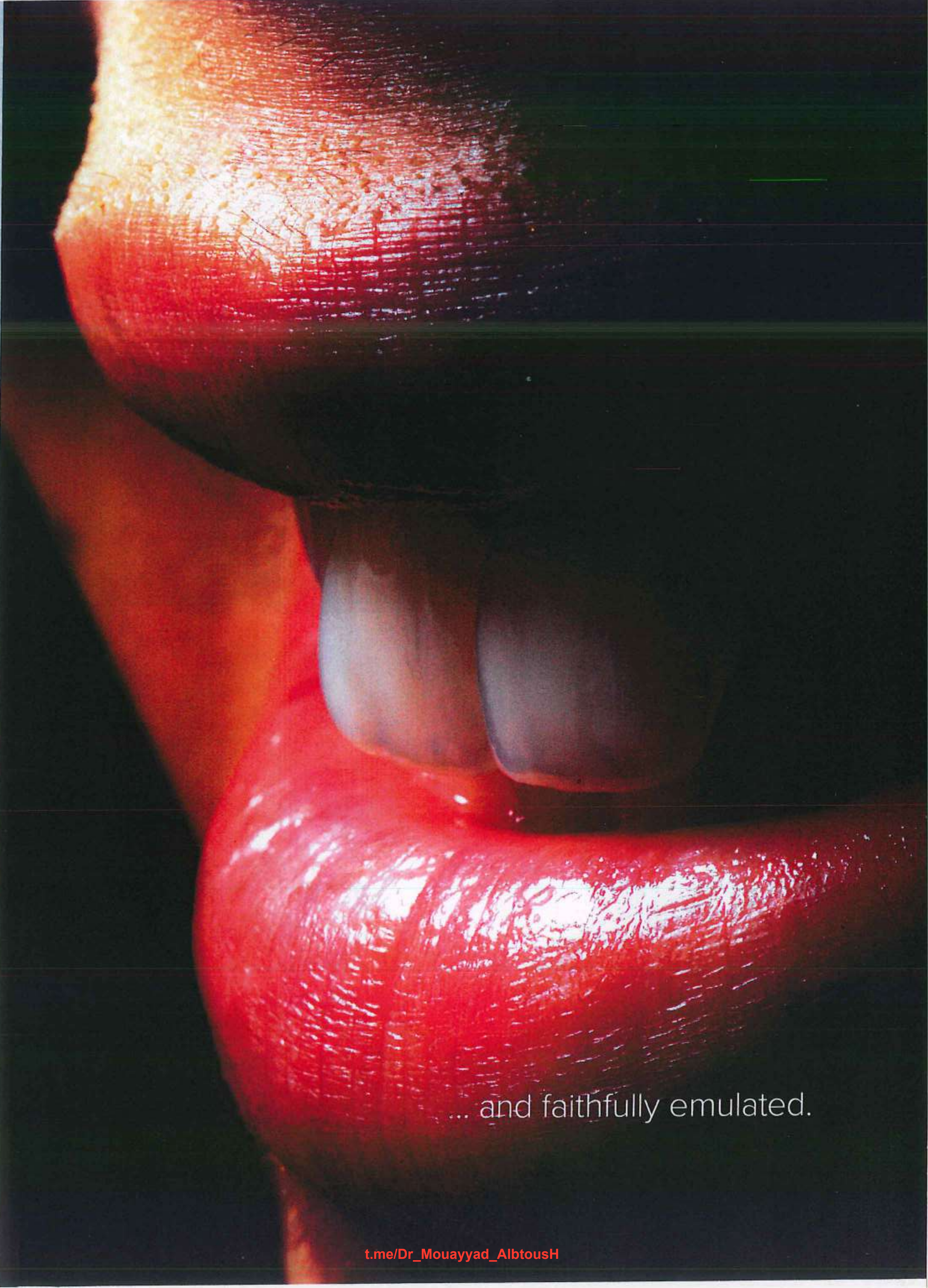
Emerging concepts in biomimetic restorative dentistry (BRD) provide the ability to restore the biomechanical, structural, and esthetic integrity of teeth with utmost respect for biologic structures (pulp and periodontal tissues). Adhesive techniques constitute the cornerstone of BRD, and novel restorative designs are striking elements of this nascent approach to tooth restoration. Indications for bonded restorations have expanded to include more advanced destructive conditions such as severely broken-down teeth, crown-fractured teeth, and nonvital teeth. As a result, considerable improvements have been made both medicobiologically and socioeconomically: More sound tissue is preserved, tooth vitality is maintained, and treatment is less expensive than traditional and more invasive prosthodontics.

BRD offers restorative solutions that balance the functional and esthetic needs of the anterior and posterior dentitions. A wide range of restorative techniques, from direct to semi-(in)direct and indirect approaches, are available to cover each patient's specific needs. Combining ceramics and composite resin optimal stiffness, their wear and surface characteristics, and the biomechanical strength achieved through high-performance bonding enable the crown of the tooth as a whole to support masticatory function. By the same token, the optical effects inherent in the tooth and the lifelike features of composite resins and ceramics make this restorative approach the ultimate in esthetic satisfaction for both the practitioner and the patient.



Watch nature...

Not manmade, not humanly inspired, but divinely designed ...


... and faithfully emulated.

DEDICATION

To my wife, Geibi, and my children, Erine and Santiago, the most precious gifts from God in my life. To my brother, Michel, whom I love dearly and who shared and brought to light his passion for God, for dentistry, and for dental technology. To my sister, Marina, her husband, and my nephews, who were always present and available despite the physical distance separating us. To my nieces, also distant but always present in my heart. In memory of my mother, Agnès, who was taken from us by cancer too early, and my father, Albin, who supported me and encouraged me in all situations.

—PM

In memory of my mother, Heidi, and my father, Theodor. To my wife, Christine, for her unfailing support and patience. To my children, Marc and Michèle, and grandchildren.

—UB

Geneva, 2018

As iron sharpens iron, so one person sharpens another. —Proverbs 27:17

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FOREWORD

It is with considerable pleasure that I write the foreword to Dr Magne and Prof Belser's book, which takes the science of esthetic dental reconstruction to a new level both clinically and academically. Dr Magne spent 2 years as a Visiting Associate Professor in the Minnesota Dental Research Center for Biomaterials and Biomechanics at the University of Minnesota, where many of the ideas promulgated in this book were hotly debated, refined, and tested in a modeling and experimental environment. In this book, the clinician will find all that he or she could wish for in terms of indications and the classic clinical steps for tooth preparation, laboratory as well as CAD/CAM procedures, adhesive luting procedures, and maintenance protocols. Those who have heard Dr Magne lecture will not be disappointed. In fact, they will find much more that is practically and intellectually satisfying.

The central philosophy of the book is the biomimetic principle—that is, the idea that the intact tooth in its ideal hues and shades, and perhaps more importantly in its intracoronal anatomy and location in the arch, is the guide to reconstruction and the determinant of success. The approach is basically conservative and biologically sound. This is in sharp contrast to the porcelain-fused-to-metal technique, in which the metal casting with its high elastic modulus makes the underlying dentin hypofunctional. The goal of the authors' approach is to return all of the prepared dental tissues to full function by the creation of a hard tissue bond that allows functional stress to pass through the tooth, drawing the entire crown into the final esthetic result.

I hope that this new edition of the book will receive a wide readership and that its principles will be carefully studied and become fully established in teaching and research, as well as de rigueur in the practice of restorative dentistry.

William H. Douglas, BDS, MS, PhD
Former Director, Minnesota Dental Research Center for Biomaterials and Biomechanics
Former Chair, Department of Oral Science, University of Minnesota
Professor Emeritus, School of Dentistry, University of Minnesota
Minneapolis, Minnesota

Minneapolis, 1998

FOREWORD

In today's 24/7 media culture, everyone strives to become an expert, but not everyone realizes what it actually takes in order to reach the level of a master. True mastery requires enormous amounts of work, persistence, and perseverance. It requires time and discipline. It requires fortitude and effort. It requires setbacks and failures.

From 2005 to 2007 while teaching alongside Michel Magne and Dr Pascal Magne at the USC Herman Ostrow School of Dentistry, I witnessed mastery personified in their pursuit of excellence. Nothing was left to chance, from the specialized equipment utilized in order to test his null hypotheses to the research and development carried out by his talented postdoctoral students, to continually optimize protocols enabling the dental community to achieve the highest quality of work for their patients.

From the start and over the years Pascal has become a revered mentor and cherished friend, and he ever remains a distinguished colleague of mine. The authenticity in his didactic approach paired with his common-sense clinical methodologies have inspired a new generation of adhesively driven restorative dentists to further explore the science and art of dentistry in order to faithfully bioemulate nature.

A polymath in every sense, Dr Pascal Magne has the disposition of a perioral architect simultaneously operating like an intraoral engineer. To marvel, wonder, and attempt to decode the divine design of our Creator has become his passion, his vocation, his calling.

Yet the simplicity and profundity of his message is to observe and preserve the harmony of the dental structures and, only when absolutely necessary, to intervene with the utmost respect and care to the natural dental substrates, utilizing biomimetic principles and analogous restorative biomaterials in such a modality as to ultimately conserve and reinforce the remaining sound tissue structures.

First do no harm; then try to prevent it at all costs.

Panaghiotis K. Bazos, DDS, MClinDent Orthodontics, MOrth RCS (Edin.)
Founder and CEO, Bio-Emulation
Private Practice in Restorative Dentistry and Orthodontics
Aigio, Greece

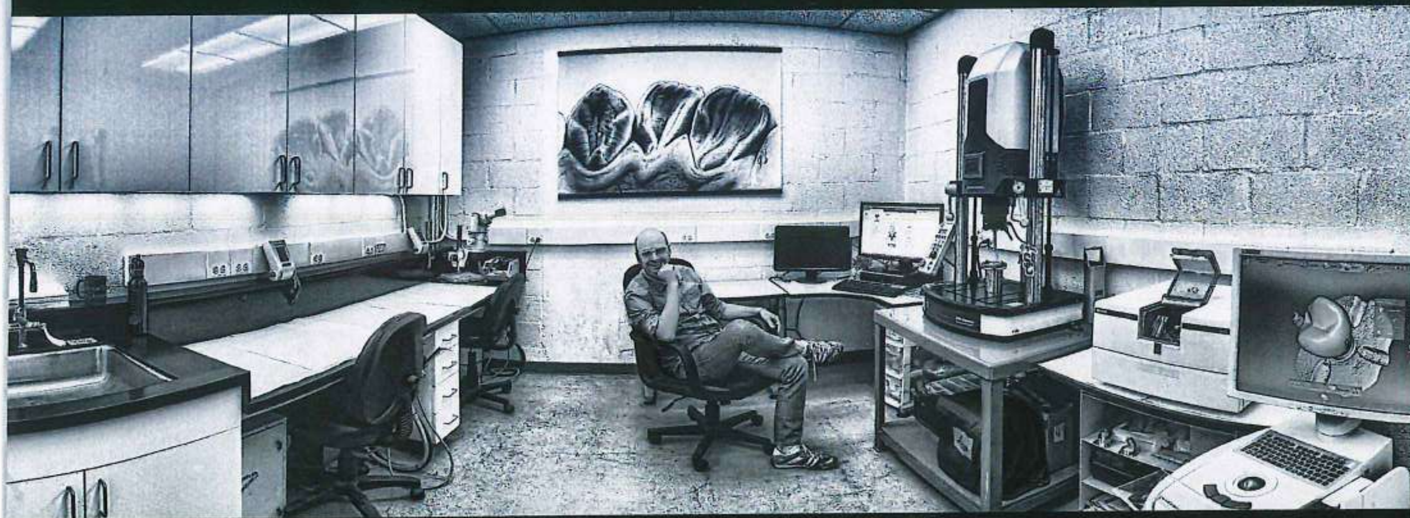
Los Angeles, 2007

BIOLOGY – FUNCTION – MECHANICS – ESTHETICS

Biomimetic Restorative Dentistry

BRD gave rise to a new generation of multitalented dentists and dental technicians, intently enthusiastic for advancing the concept further by diving deeper into understanding the archetype of the natural tooth. The Bio-Emulation movement has become a beautiful fruit of this laborious endeavour. If there is a single word that makes creative people different from others, it is the word *simplicity*. Many minds that are interconnected by one universal mindset that allows for sharing their collective experience and tacit knowledge, by freely exchanging ideas and conceptualizations. Special appreciation and gratitude for my fellow Bio-Emulator, esteemed colleague and dear friend, Dr Javier Tapia-Guadix (Madrid, Spain), one of the most inspirational and instrumental members of the group. His amazing creativity and undeniable talent in CGI and mesmerizing animations are on full display in chapters 1 and 2.

PREFACE



The most exciting developments in dentistry have emerged within the past decade. Digitally guided implant dentistry, guided tissue regeneration, adhesive restorative dentistry, and CAD/CAM restorations are strategic growth areas both in research and in clinical practice. However, the many advances in dental materials and technology have generated a plethora of dental products in the marketplace. Clinicians and dental technicians are faced with difficult choices as the number of treatment modalities and technologic tools continues to grow. Further, changes in technology do not always simplify technique or decrease treatment costs. Prudence and wisdom need to be combined with knowledge and progress when it comes to improving our patients' welfare. In this perplexing context, no one will contest the need for less expensive, satisfactory, and rational substitutes for current treatments. The answer emerged from an interdisciplinary biomaterial science called *biomimetics*.[1] This concept of medical research involves the investigation of the structure and physical function of biologic "composites" and the design of new and improved substitutes. Biomimetics in dental medicine has increasing relevance. The primary meaning for dentistry refers to processing material in a manner similar to that by the oral cavity, such as the calcification of a soft tissue precursor. The secondary meaning refers to the mimicking or recovery of the biomechanics of the original tooth by the restoration. This, of course, is the goal of restorative dentistry.

Several research disciplines in dental medicine have evolved with the purpose to mimic oral structures. However, this nascent principle is applied mostly at a molecular level, with the aim to enhance wound healing, repair, and regeneration of soft and hard tissues.[2,3] When extended to a macrostructural level, biomimetics can trigger innovative applications in restorative dentistry. Restoring or mimicking the biomechanical, structural, and esthetic integrity of teeth is the driving force of this process. Therefore, the objective of this book is to propose new criteria for esthetic restorative dentistry based on biomimetics.

Biomimetics in restorative dentistry starts with an understanding of hard tissue structure and related stress distribution within the intact tooth, which is the focus of the opening chapter of this book. It is immediately followed by a systematic review of parameters related to natural oral esthetics. Because the driving forces of restorative dentistry are maintenance of tooth vitality and maximum conservation of intact hard tissues, the next chapters describe the ultraconservative treatment options and armamentarium that can precede a more sophisticated treatment. The description of semi-(in)direct approaches concludes Volume 1 of the book; those techniques can be considered when direct techniques are challenging to apply (eg, large restorative volume with cervical margins in dentin) and when indirect technique costs are not justified or simply not affordable by the patient.

The core of Volume 2 of the book centers on the application of the biomimetic principle in the form of anterior indirect bonded porcelain restorations using composite resins and ceramics. The broad spectrum of indications of anterior indirect bonded porcelain restorations is described, preceded by detailed instruction on the treatment planning and diagnostic approach, which is the first step for every case. Proposed treatments are described step by step throughout both book volumes, including tooth preparation and impression, laboratory and CAD/CAM procedures related to the fabrication of composite resin and ceramic workpieces, and their final insertion through adhesive luting procedures. CAD/CAM techniques are also included as pertinent tools for the achievement of the biomimetic principle. Volume 2 ends with discussion of the follow-up, maintenance, and repair of bonded restorations.

Acknowledgments

We should always remember that a key element for successful and predictable restoration is teamwork, and an essential ingredient for teamwork is humility—to consider others better than oneself. We must try to serve each other rather than expect to be served. I would have been unable to achieve this work without the valued collaboration of other dentists, dental technicians, specialists, and researchers, all mentioned below.

In 2003, Dr Harold Slavkin, as a Dean, along with Dr Cherilyn Sheets, had a vision that included recruiting me to the University of Southern California (USC), thus initiating our amazing journey to the United States in 2004. The numerous visiting scholars in my research laboratory as well as all graduate dental students have been enlightening my daily academic activities. They have been a constant source of fresh air and the breath of my life at USC. Our research works have been possible thanks to the unconditional gifts of various colleagues, in particular Dr Parto Ghadimi. I also want to thank all the companies who provided their materials for research with no strings attached.

There are numerous ceramists and laboratories who have inspired me much and offered support in one way or another. Special thanks to Willi Geller, Klaus Müterthies, Claude Sieber, Enrico Steiger, Naoki Hayashi, Sascha Hein, August Bruguera, Giuseppe Romeo, Milos Miladinov, and Sam Alawie, among others.

Witnessing the birth of The Academy of Biomimetic Dentistry with Dr David Alleman as well as The Bio-Emulation group with Dr Panaghiotis Bazos, Javier Tapia Guadix, and Gianfranco Politano have been among the most memorable

moments of my journey. Their members have been instrumental in stimulating my mind and pushing the boundaries of my creativity.

I feel so blessed to have studied under Prof Urs Belser; his teaching and guidance have been invaluable to me and his support always unconditional. Life lessons have been learned thanks to him. He is my first mentor.

I extend my endless appreciation to my brother, Michel Magne, MDT, my second mentor, for his significant contributions to the chapter on laboratory procedures and for his skills in fabricating the ceramic restorations for most of the cases in this book. Our brotherly "BOND" is to be compared to a perfect resin-ceramic bond that has overcome the numerous storms of life. Our synergy is also that of a perfectly bonded porcelain restoration: "Michel, delicate and fragile like porcelain but strong once bonded. Pascal, more resilient like composite resin but made beautiful by Michel's skills."

Special thanks go to Dr William Douglas, my third mentor, but also Drs Ralph DeLong, Maria Pintado, Antheunis Versluis, and Thomas Korioth at the University of Minnesota for their help and friendship during my 2-year research scholarship there that led to my PhD. They expanded my vision and knowledge of scientific research in biomaterials and biomechanics.

I also acknowledge my precious students and patients, who directly contributed to the making of this book, and the private practitioners who donated extracted teeth for the studies and illustrations.

Special thanks to Mr William Hartman and the Quintessence Chicago team—Leah Huffman, Sue Zubek, and Sue Robinson—for pushing the envelope of my creativity and rendering this work in the most exquisite way. A particular thought goes to the late Mr Peter Sielaff from Quintessence Berlin who had been instrumental to the making of the first edition of the work.

Finally, I give honor and glory to my Lord and Savior, Jesus Christ, my mentor above all mentors, who has made all of my projects possible through his gracious love. He also provided my soul mate, Geibi, and two additional gifts, our children Erine and Santiago. None of this work would have been possible without them.

I hope that you will enjoy reading this work and applying its content for the good of your patients and the joy of practicing biomimetic restorative dentistry.

God bless you!

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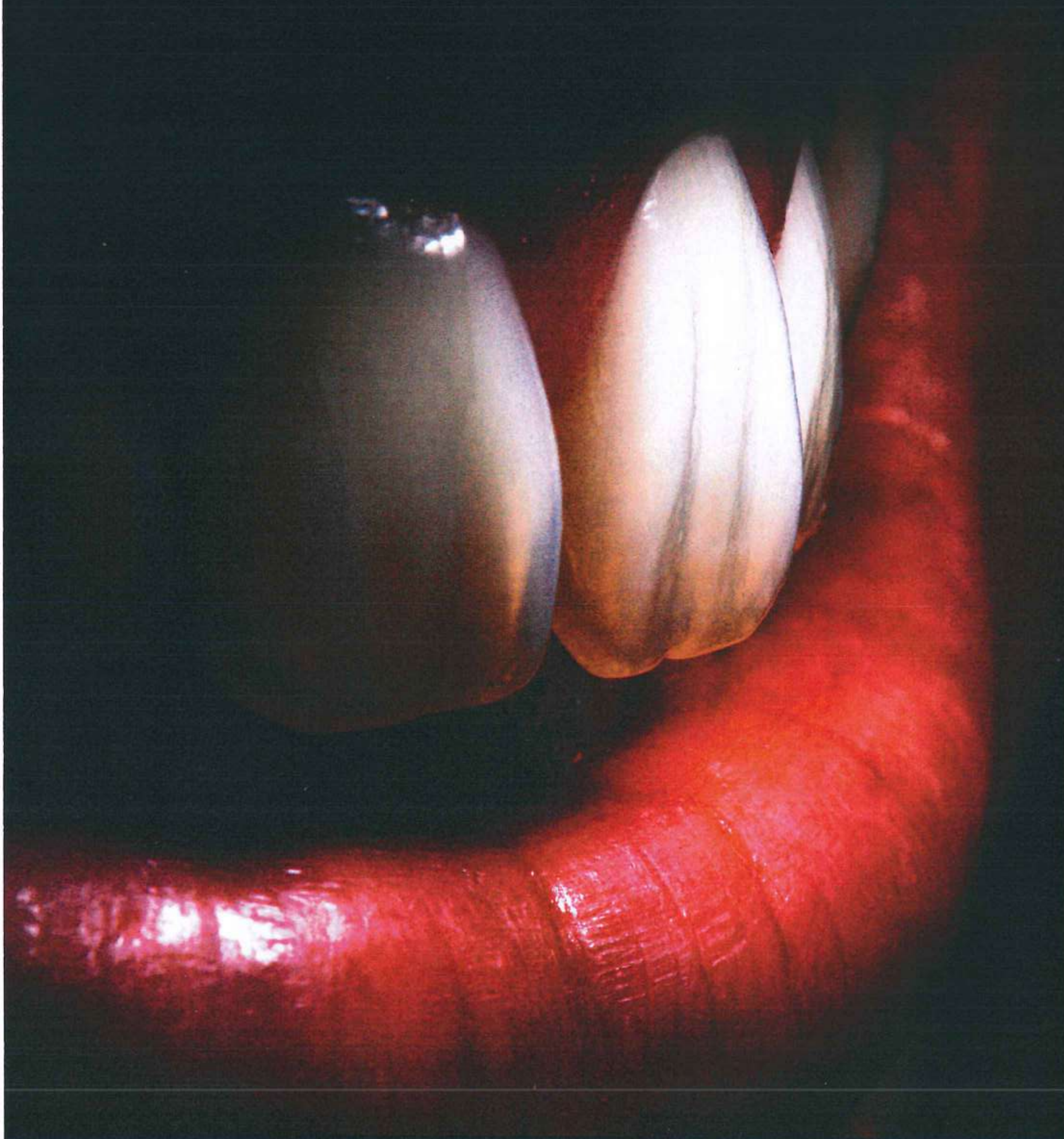
Pascal Magne

The Four Elements...



1. SCIENCE. *Science comes from the work of men.*

Hence, science can be flawed. Humans make mistakes, and during the many steps in the making of a scientific work, imperfections can be cumulated. Scientific interpretation adds to the widening of the prediction values. While science is undeniably necessary to the growth of knowledge, it may become much less valuable if not paired with common sense.

2. EXPERIENCE. *Experience is YOUR story.*

It is made of the practical knowledge, skill, or elements that you accumulated from direct observation or participation in events or in a particular activity. Experience may be considered as part of science but is not accepted per se as scientific, which is a contradiction because experience is truly priceless.

3. COMMON SENSE. *Common sense is placed by God in your heart.*

Common sense is the ability to make a good decision. It is based on wisdom (knowing what to do) and discretion (knowing when and where to do it). Common sense triggers further investigation of scientific facts that do not add up. Common sense allows you to look at situations the way God does.

Proverbs 3:21–22
Dear friend, guard clear thinking and common sense with your life; don't for a minute lose sight of them. They'll keep your soul alive and well, they'll keep you fit and attractive.

4. THE PATIENT!

Science, common sense, and experience may lead to a specific therapeutic approach. The patient, however, through informed consent, must be the major decision maker. Timing, affordability, culture, and history might preclude the chosen therapy and call for a different approach. The patient's constraints and preferences must always be respected.

Albert Einstein confides, "I want to know God's thoughts ... the rest are details."

Science, experience, common sense, and the patient

It is undeniably true that we live in very intense times in the history of humanity. The times to come do not promise to be easy, so it is more important than ever to remain in the faith. A faith that will prove that this fragile mosaic that we form (each of us as a piece of broken glass) has the power to transform itself into an eternal work of art. In this context, which challenges our beliefs, we also try to be high-level professionals. And it must be admitted: In dentistry the plethora of materials and techniques at our disposal is not without challenges for our "dental faith." As a practitioner trying to find one's way through an avalanche of new dental products, new technologies, conflicting scientific publications, etc, it is more important than ever to examine one's beliefs, values, and the foundations that will enable one to make the most appropriate choices. There are four synergistic components involved in the decision for the optimal treatment plan:

1. Science: The scientific method is a priori a fundamental basis according to which a hypothesis is tested with various levels of evidence (expert opinion, in vitro test, clinical case presentations, case series, cohort and randomized controlled trials, systematic reviews, and meta-analyses). The scientific approach is unfortunately not without flaws. The conditions of study do not always represent the daily clinical reality. Due to medical ethics, it is not possible to standardize all clinical conditions. A multitude of confounding variables, such as the operator, the nature of the clinical situation, the habits of the patient, etc, "adulterate" the results. Therefore, it is not uncommon for the null hypothesis to be confirmed (no difference between the method or material tested and the control method), particularly with clinical studies, which by default have a majority of confounding variables. As such, the combined studies of numerical simulation and in vitro tests represent considerably advantageous research tools because of the extreme possibilities of standardization.[1,2] Unfortunately, however, the latter are not part of the official hierarchy of evidence-based medicine.

2. Experience: It has been shown that one of the significant variables of clinical practice is represented by the clinician themself and their ability to master a particular approach. In medicine, for example, a study of carotid stenting has clearly shown that patients of experienced operators have less risk of complications.[3] Similar data exist with respect to dental bonding performance both in vitro and in vivo.[4,5] Clinicians who participate in many training courses and develop these skills will therefore tend to produce more reliable results.[6]

3. Common sense: It is established that many acts of daily practice lack high-level scientific evidence. The scientific community itself recognizes the existence of a "talking pig."[7] It is a parable explaining that common sense must be recognized even in the scientific method. According to this parable, a researcher trained a pig to speak. "Is it madness?" you say to yourself. But we bring this pig to speak in front of you and the pig says, "Good evening," and proceeds to a summary of the news of the day for you. We hope you would be surprised by this phenomenon and would not be necessarily interested in a random selection of 100 pigs to verify this. The fact that any pig can talk is what is important. By the same principle, it is possible to ask whether a randomized study is necessary to prove that the use of a parachute can prevent death in the event of an airplane disaster.[8] These examples of "talking pigs" demonstrate that common sense must be used in every situation. It is not uncommon for conflicting scientific data to be produced, which then requires a decision based on experience and common sense.

4. The patient: Finally, it is quite possible that science, experience, and common sense all point to the same therapeutic solution. However, the patient may find it impossible to choose this solution, for example for economic reasons or availability. A segmentation of the treatment or a "low cost" alternative must then be explored, which does not necessarily correspond to the ideal solution proposed by the health care team. Each patient presented in this book has been treated with the FOUR elements in mind.

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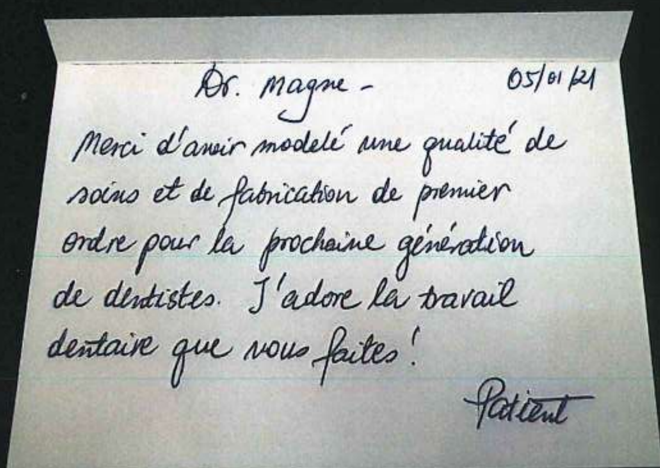
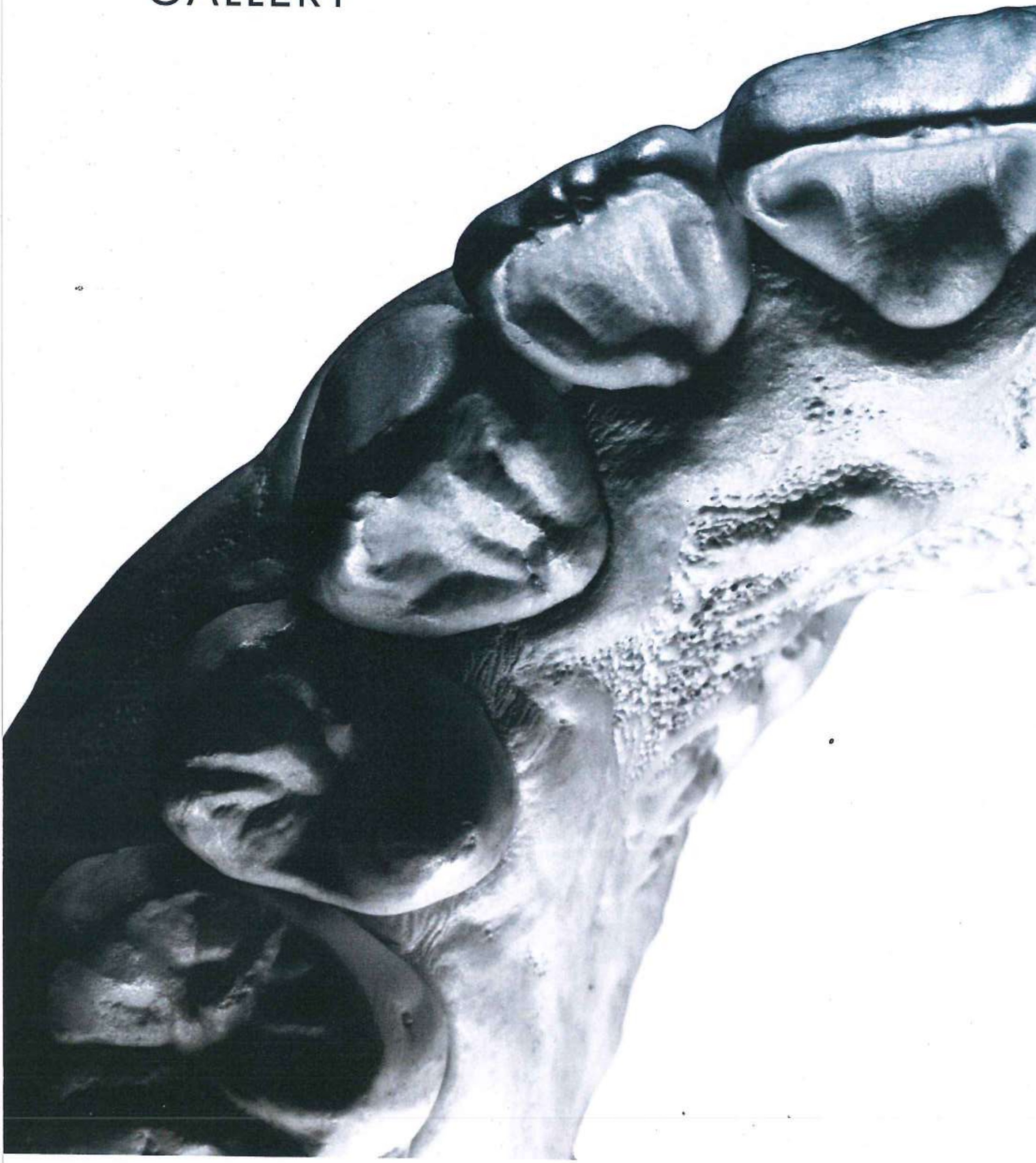
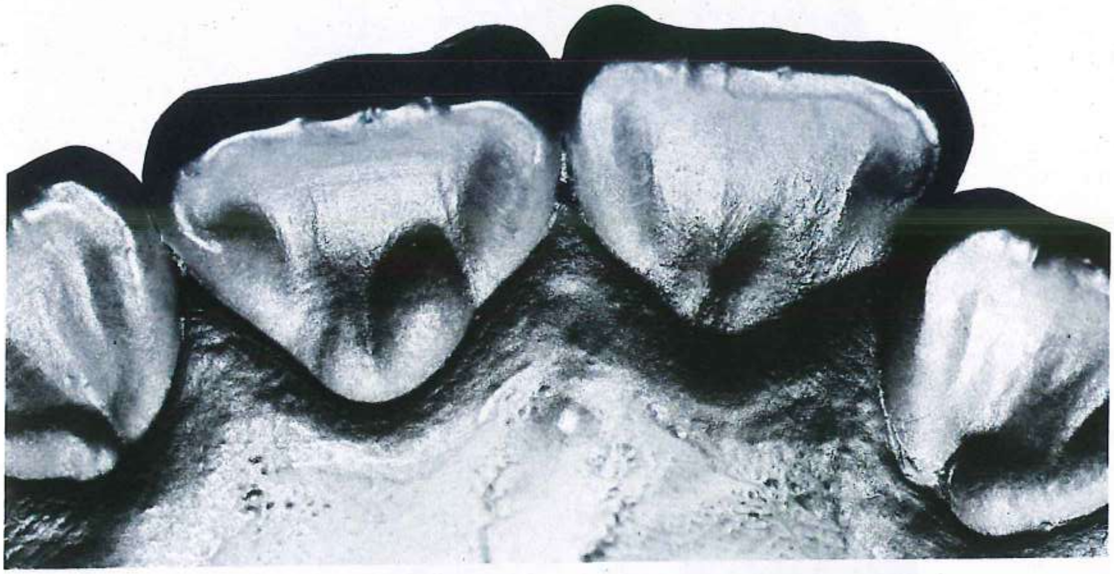
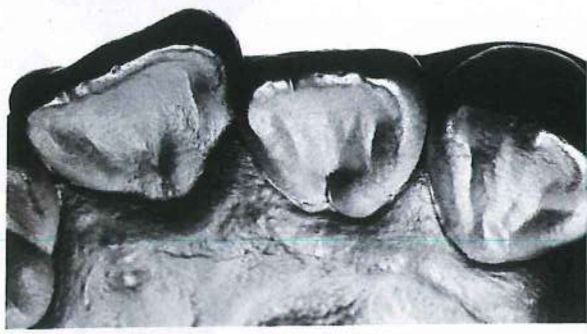


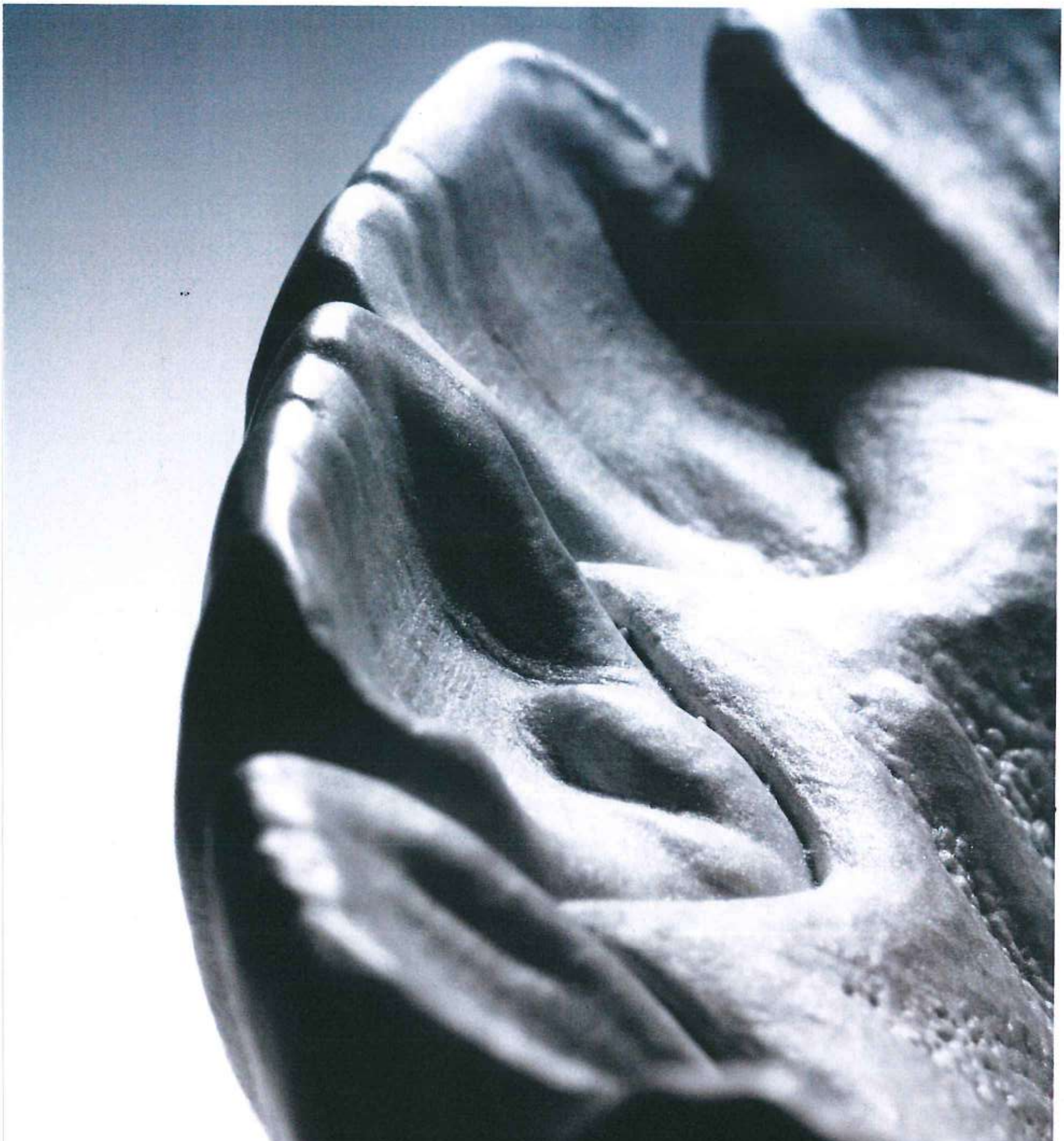
Dr. Magne, thank you for providing top-notch quality of care and workmanship for the next generation of dentists. I love the work you do. Patient

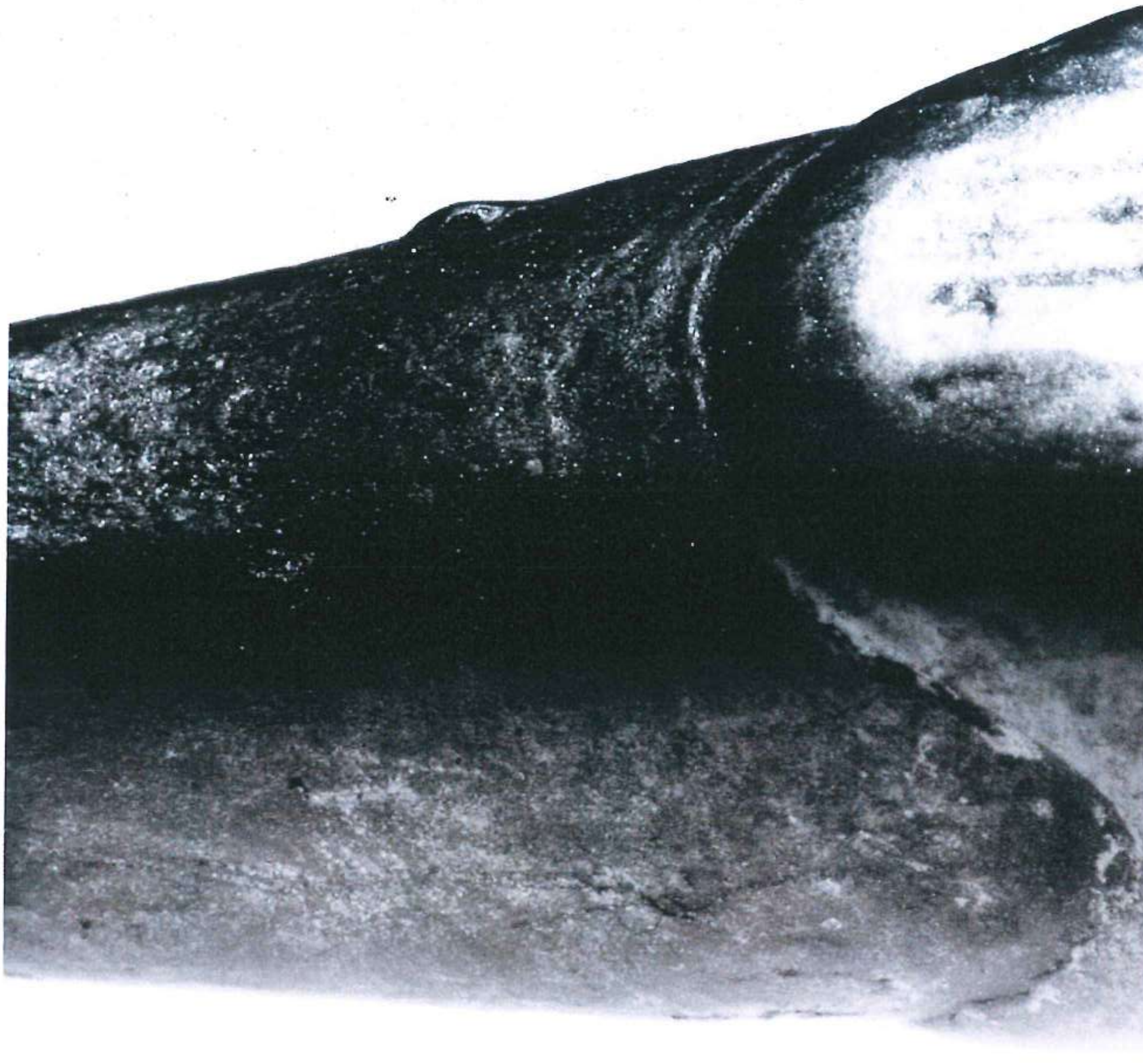
GALLERY

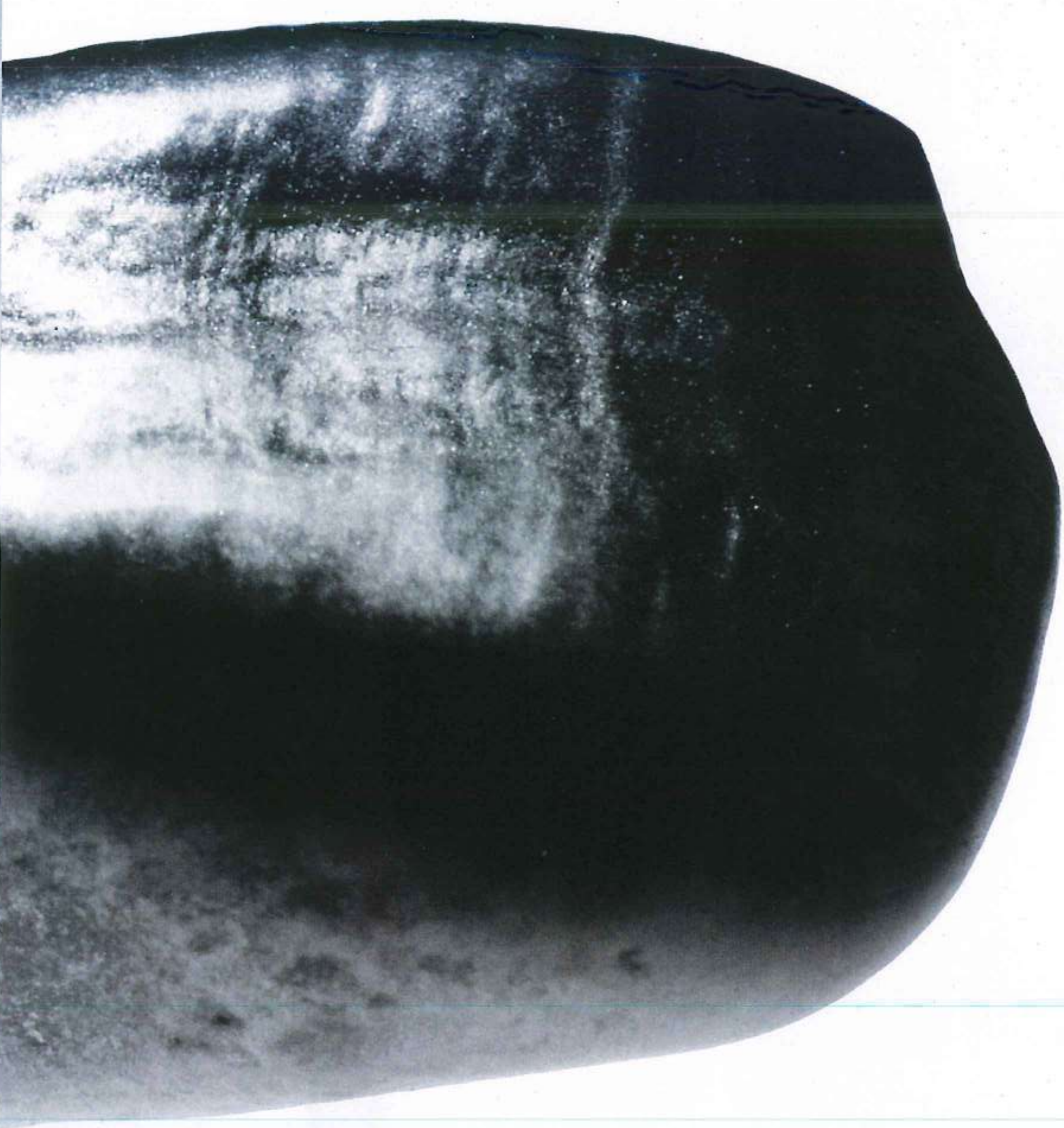












1

UNDERSTANDING THE INTACT TOOTH AND THE BIOMIMETIC PRINCIPLE

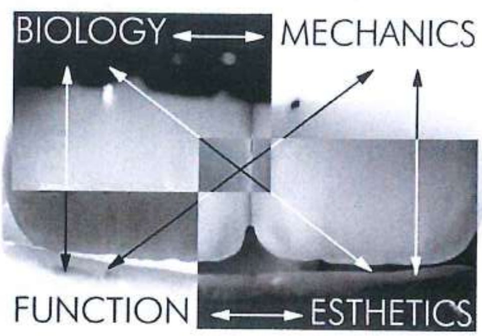
Mimicry in the field of science involves reproducing or copying a model—a reference. Dental professionals who want to replace what has been lost need to agree on what is the correct reference. The accepted frame of reference must be the same for the entire profession, and it should be timeless and unchanging. Once this is established, appropriate research designs, valid concepts, and rational dental treatment plans can be constructed, devised, and created. For the restorative dentist, the unquestionable reference should be the intact natural tooth. Remains of Inca civilization in South America as well as mummies in Egypt[1] or even so-called "Stone Age" specimens[2] demonstrate this age-old principle: The original number, dimensions, and structure of teeth have not changed. While the pattern of oral diseases (infections, wear, parafunctions) has been influenced by the ever-changing human lifestyle, the original structure of enamel and dentin appears to be the same today as it was 5,000 or 6,000 years ago. In this context, it seems commendable to study and understand the marvelous design of natural teeth before considering any further concepts in restorative dentistry.

1.1 BIOLOGY, MECHANICS, FUNCTION, AND ESTHETICS

Physiologic performance of intact teeth is the result of an intimate and balanced relationship between biologic, mechanical, and functional parameters (Fig 1-1a). Esthetics should not be the driving force of treatment but only the result of this relationship—"the cherry on top." ***Biology is undoubtedly the dominating element in this equation, and all efforts should go to the preservation of tooth vitality.*** Endodontically treated teeth, no matter how they are restored, will always present a compromised prognosis (ie, a higher risk of fracture) compared to vital teeth.[3]

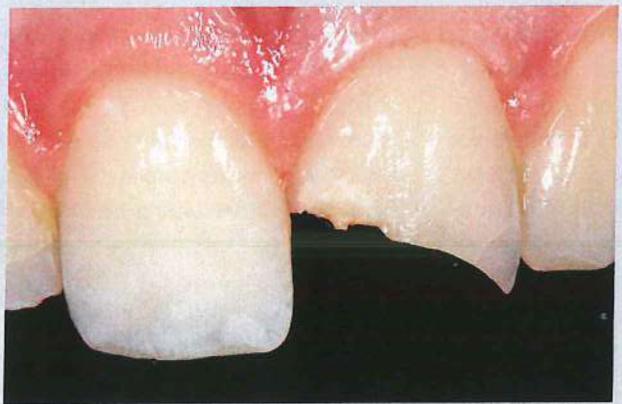
The most educational situations supporting the complex interactions between biology, function/mechanics, and esthetics are found in cases of traumatic injuries like that illustrated in Fig 1-1. The price of an injury can be paid in the form of either a mechanical failure (hard tissue involvement) or a biologic failure (pulpal involvement). In both cases, the influence on the esthetic and functional parameters is observable. Fortunately for the patient in Fig 1-1, simple and economical treatment strategies could be used[4] (ie, fragment reattachment on the left central incisor and root canal therapy and internal bleaching on the other), which are covered extensively in chapter 3. Yet a critical question can be raised: What would have been the outcome if, instead of being intact, these central incisors had been previously restored by two rigid and extremely resistant full crowns (eg, porcelain-fused-to-metal [PFM] or reinforced ceramics)? We know from impact experiments that a more profound fracture (root involvement), which would be problematic to restore, is encountered when stiff and unyielding crowns are used.[5] This contrasts with the behavior of the more fragile cemented jacket crowns, which often shatter, leaving the remaining tooth substance intact. A partial crown fracture might be preferable if one considers that the energy dissipated during fracture can prevent further biologic damage or root injury.

In consideration of the above-mentioned parameters, it is of primary importance to ask ourselves: ***Is it better to pursue the development of strong and stiff restorations or to find treatment modalities that reproduce the biomechanical behavior of the intact tooth? Stronger and stiffer might not always be better.***



1-1a

FIG 1-1 Physiologic performance of teeth. *(a)* Performance of teeth is the result of an intricate physiologic puzzle including biology, mechanics, function, and esthetics. *(b to h)* Illustrative case: The maxillary left central incisor fractured following trauma that involved both maxillary central incisors *(b)*. The tooth fragment was recovered *(c)*. The situation was potentially compromised by pulpal exposure *(d)*. After direct capping under rubber dam, the tooth fragment was rebonded to the remaining tooth substance (see Fig 3-24). A 1-week postoperative view reveals the favorable situation *(e)*. One month later, the unfractured right central incisor showed signs of pulpal damage *(f)*. The severe organic discoloration was completely removed by internal bleaching ("walking bleach technique," see Figs 3-17 to 3-19) after root canal treatment was accomplished. (The root canal therapy was indicated only by the presence of symptoms and radiographic evidence.) The tooth was slightly overbleached to anticipate the initial color relapse *(g)*. The 5-year postoperative view shows stable results *(h)*. (Parts *b* to *g* reprinted with permission from Magne and Magne.[4])



1-1b

1-1c

1-1d

1-1e

1-1f

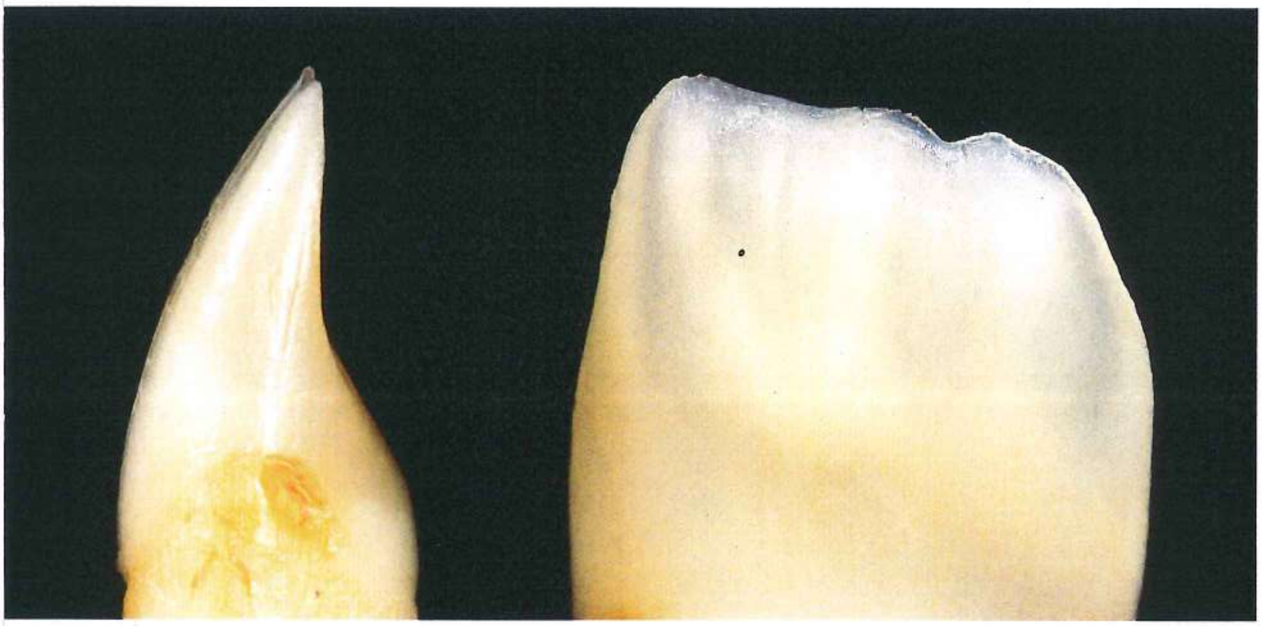
1-1g

1-1h

1.2 OPTIMAL COMPLIANCE AND FLEXIBILITY

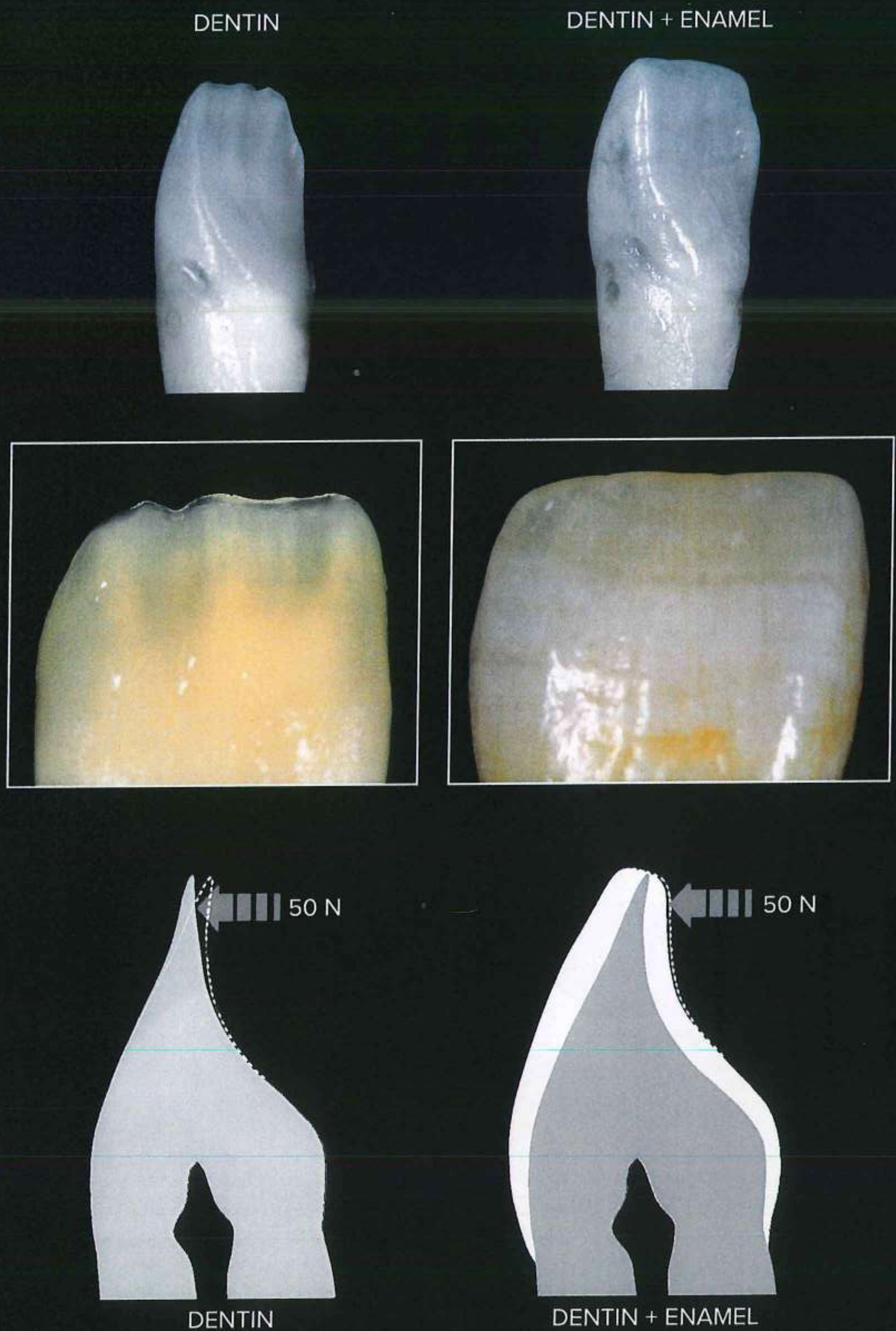
The previous section calls for a strong and natural protection concept present in natural teeth called *compliance* or *flexibility*. This is an essential quality[6] that enables a structure to absorb the energy of a force. In other words, a compliant structure will cushion a sudden impact by bending elastically under a given load. Up to a certain point, the more compliant or resilient a structure is, the better. This ability to store energy without undergoing permanent damage is inherent to intact teeth and can be considered a reference. Dentin is the key element in this capability. Figures 1-2a and 1-2b show the exact shape and structure of this essential "resilient" component. It was demonstrated by Stokes and Hood[5] that during impact, an anterior intact tooth is able to absorb the highest energy of fracture when compared to teeth restored with different types of crowns. Although resilience promotes protection against impact through energy absorption, excessive elasticity might also render a structure too "floppy" for its purpose (Fig 1-2b, *left*). The dentin core alone would be functionally inadequate without its rigid outer shell of enamel (Fig 1-2b, *right*).

In this respect, natural teeth, through the optimal combination of enamel and dentin, demonstrate the perfect and unmatched compromise between stiffness, strength, and resilience. Restorative procedures and alterations in the structural integrity of teeth can easily violate this subtle balance.



1-2a

FIG 1-2 Resilient component of teeth. An extracted tooth was specially acid treated to eliminate the enamel shell *(a)* and expose the dentin core (*left*, proximal view; *right*, palatal view). The lost enamel volume is evident in part *b*. The dentin core alone is weak, and bending under 5 kg can be perceived with the naked eye (*b, bottom left*; incisal edge displacement about 0.5 mm). The enamel shell provides the tooth crown with sufficient resistance to bending (*b, bottom right*; incisal edge displacement about 0.1 mm). (The bottom diagrams in *b* were produced with the finite element method; see also Figs 1-5 to 1-9.)



1-2b

1.3 RATIONALIZED ANTERIOR TOOTH SHAPE

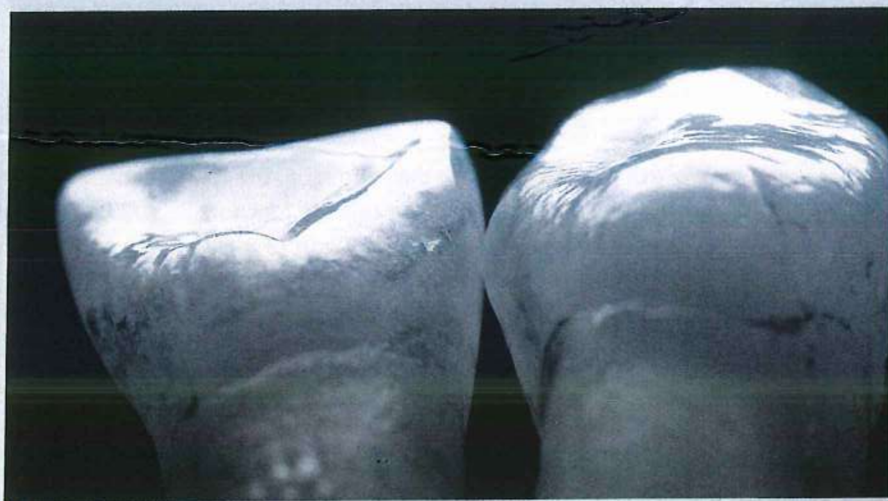
Starting in the posterior segment and moving in the anterior direction within the dental arch, the process of "incisivization" takes place (Fig 1-3a), whereby the occlusal table is gradually replaced by an incisal edge that has the obvious function of cutting.

Anatomically, incisors show a distinct contrast between facial and palatal surface morphology. The labial aspect of the crown features smooth and mainly convex contours, whereas the palatal surface displays a deep concavity extending axially from the dental cingulum to the incisal edge and laterally between the two pronounced proximal ridges (Fig 1-3b). With this shape, the incisal edge is designed like a blade, which undoubtedly plays a major role in the cutting efficiency of the tooth. In some instances, vertical lobes rising from the cingulum interrupt the palatal concavity. The portion of the crown featuring the thinnest enamel layer, namely the cervical third, is also the area of maximum thickness of dentin. Inversely, the thick incisal enamel is supported by a thin dentin wall.

Canines display a different morphology. The cingulum is large and the marginal ridges are strongly developed. All of these convex elements are confluent, and there is no major palatal fossa (Figs 1-3b to 1-3d). The peculiarity of such architecture will be explained later in view of the specific functional requirements of this strategic tooth.

Detailed aspects of anterior tooth shape are also presented in chapter 2 (section 2.2, criterion 8, Figs 2-5 and 2-6).

1-3a



1-3b

1-3c

1-3d

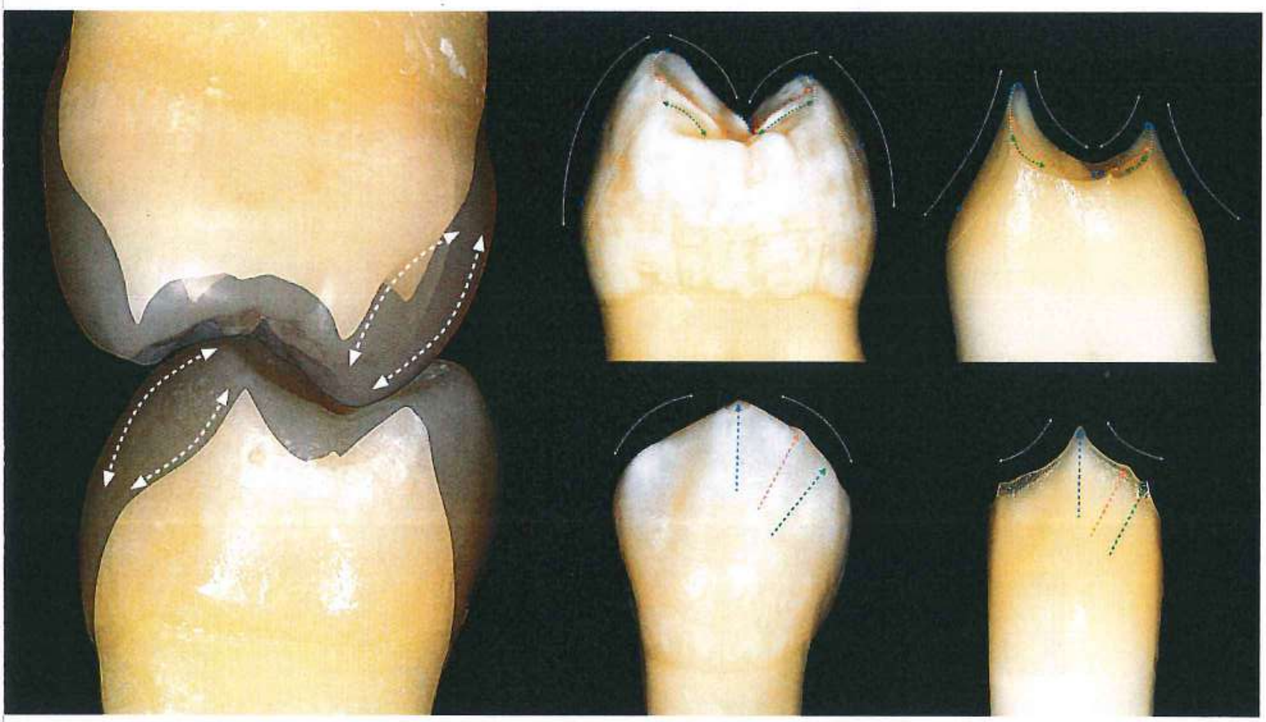
FIG 1-3 Basic anatomy of the anterior dentition. Comparative views showing functional surfaces of extracted teeth. Palatal surfaces of canines *(a, center; b, right; c and d)* display soft and convex curvatures compared to the concavities of incisors *(b, left)*.

1.4 RATIONALIZED POSTERIOR TOOTH SHAPE

While the anterior teeth play a major role in shearing and cutting food, the primary function of posterior teeth is the comminution of food into small swallowable and digestible fragments.

The process of mastication is made possible through interdigitating cusps (Fig 1-4a). The robust macrostructure of each cusp is given by the contours of the enamel surfaces, rounded and clearly convex, both at the outer surface and at the interface with the dentinoenamel junction (DEJ).[7] The contours of dentin, on the other hand, are concave and sharp-edged. While the enamel surface is marked with deep developmental grooves and fissures, the surface of dentin at the DEJ is rather smooth (Figs 1-4b to 1-4d).

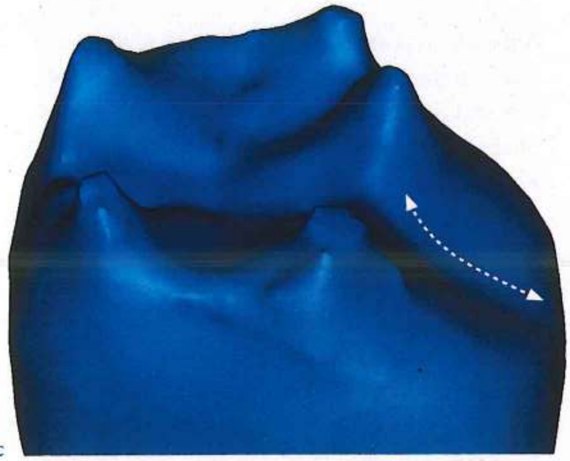
Detailed aspects of posterior tooth shape are also presented in chapter 2 (section 2.4, Figs 2-21 to 2-28).



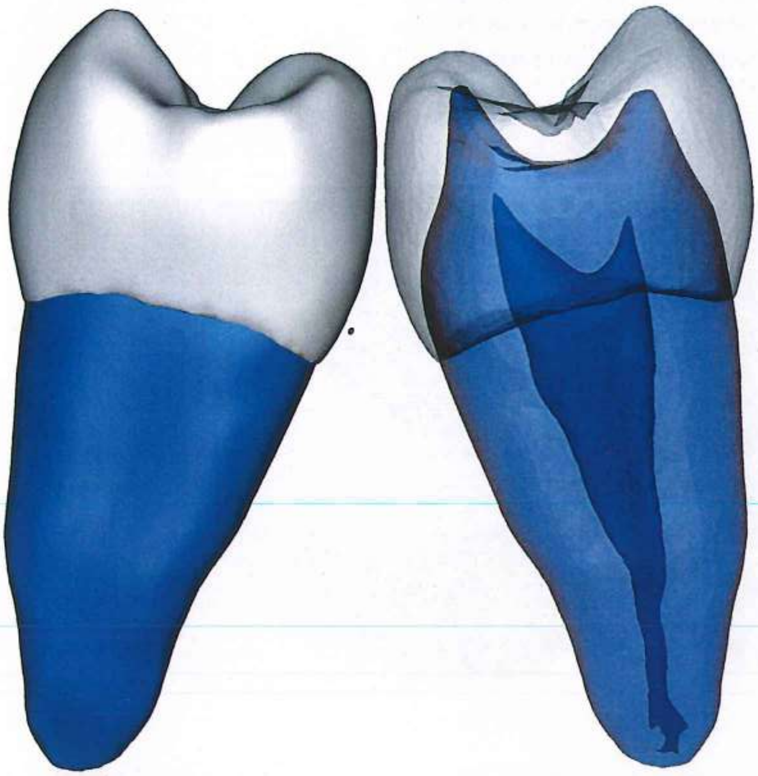
1-4a

FIG 1-4 Basic anatomy of the posterior dentition. *(a, left)* Antagonistic posterior teeth in maximum intercuspal position. Note the thicker biconvex enamel at the level of the supporting cusps *(dotted arrows)*, both maxillary and mandibular, as well as the sharp edges of the underlying dentin at the cusp tips. *(a, right)* Maxillary premolar: Interdental *(top)* and buccal *(bottom)* views with and without enamel. *(b and c)* Mandibular molar obtained from 3D reconstruction based on microCT data. Note the wide base of the supporting cusps and concave cusp slopes of the dentin. *(d)* Maxillary premolar obtained from 3D reconstruction based on microCT data. (Figures in part *a* reprinted with permission from Bazos and Magne.[7])

1-4b



1-4c



1-4d

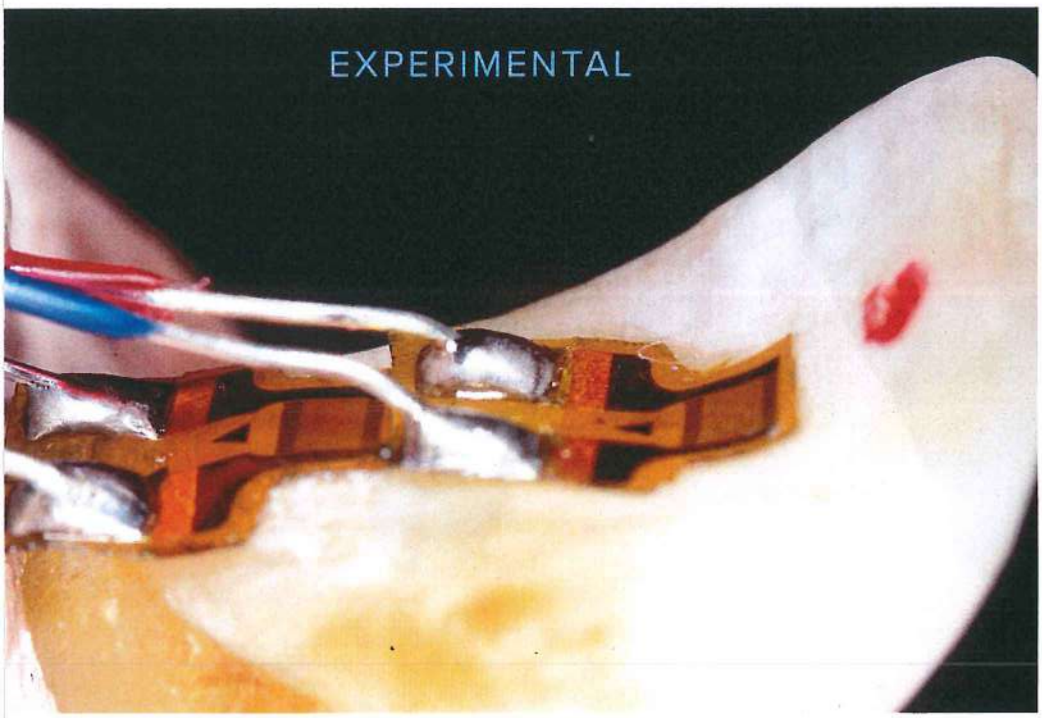
1.5 MECHANICS AND GEOMETRY DURING FUNCTION

A thorough understanding of stress and related strain allows restorative techniques to be optimized. Load-to-failure tests have been popular among the wide range of mechanical testing approaches. However, these "conventional" strength studies, no matter how accurately conducted, are not always sufficient to guarantee structural integrity under operational conditions. Failure under load conditions well below the yield stress often occurs in structures with small cracks or cracklike flaws, such as teeth and some dental materials. Therefore, modern testing approaches must include nondestructive methods. For instance, the effect of functional loading can be quantitatively determined by the crown flexure, which can be measured under simulated conditions by bonded strain gauges (Fig 1-5a) and numeric methods, such as the finite element method (FEM; see Figs 1-5b to 1-8).[8–12]

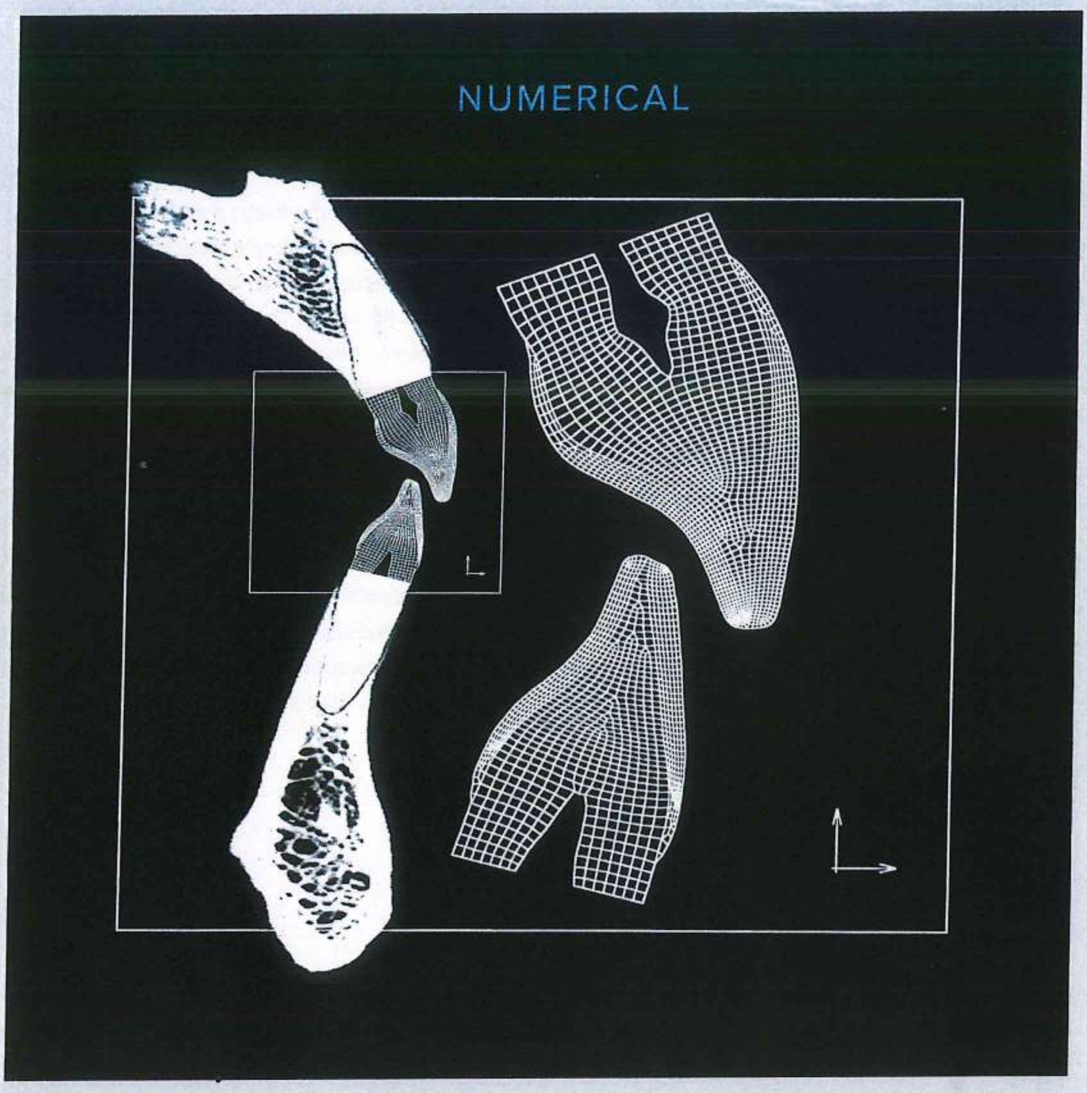
Anterior tooth mechanics/function

The aforementioned investigation instruments must reproduce the loading configuration of anterior teeth, which has been clearly established and can be characterized as follows:

- ***Because of the arrangement and position of the anterior dentition, mechanical loads act primarily in the buccolingual plane of each tooth. Proximal contact areas restrain mesiodistal loads (Fig 1-5b).***
- ***The horizontal component of realistic biting loads induces bending, which is the major challenge for the incisor.***



1-5a



1-5b

FIG 1-5 Nondestructive experimental methods in mechanical testing. *(a)* Experimental specimen (intact central incisor) mounted with gauges for comparison of strains at the fossa and cingulum; strain gauges were oriented along the long axis of the tooth. *(b)* Numeric modeling of anterior teeth can be achieved using buccolingual cross sections and 2D finite element methods.* (Part *a* reprinted with permission from Magne et al.[12])

*In an FEM, a large structure is divided into a number of small simple-shaped elements *(b)*, for which individual deformation (strain and stress) can be more easily calculated than for the entire undivided structure. By determining the deformation of each small element simultaneously, the deformation of the entire structure can be reconstructed. The FEM has become an accepted modeling tool, and new trends in research tend to combine both the experimental strain gauge approach and FEM evaluation in the same investigation.

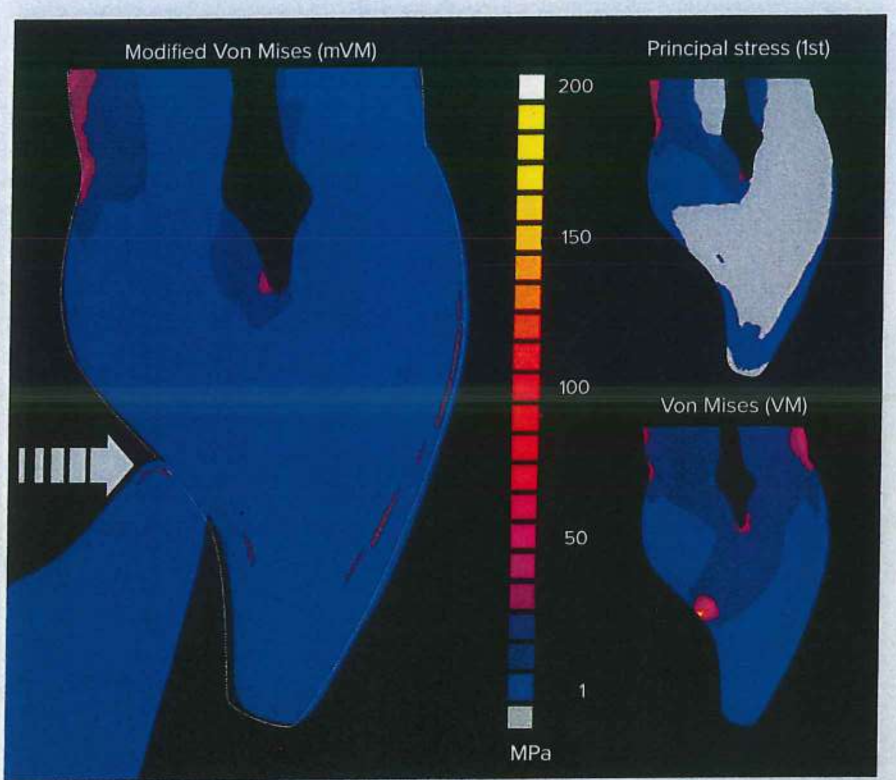
It is important to be aware of the yield criteria used for failure prediction in numeric analyses. The Von Mises criterion (VM) is commonly used. It works well with materials for which the yield stresses measured in uniaxial tension and compression are equal. However, ***both enamel and dentin are brittle materials that present a higher strength in compression than in tension.***

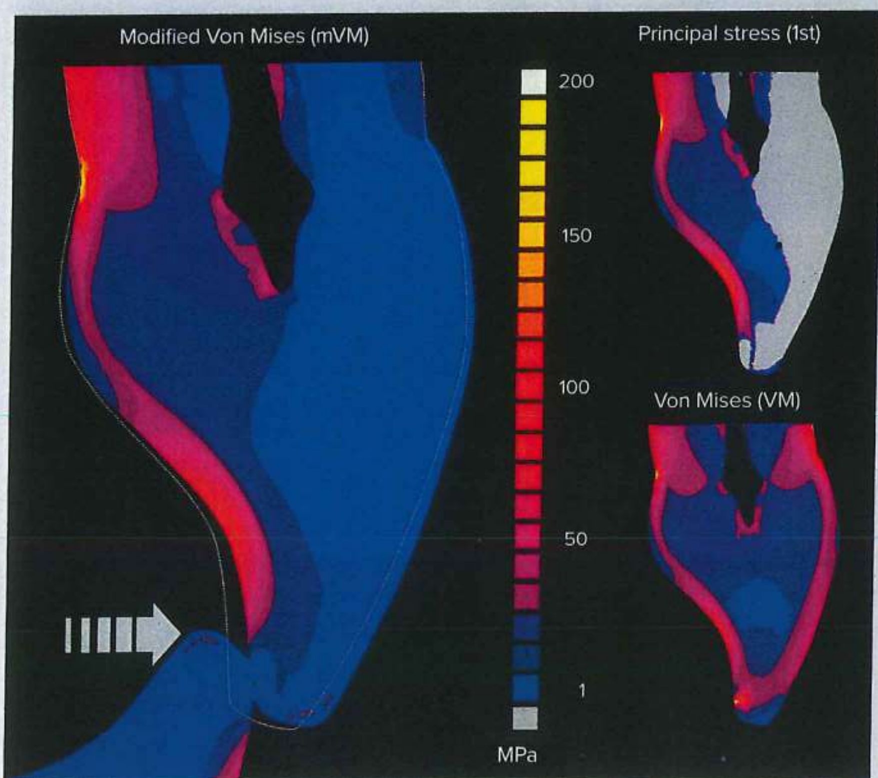
The ratio between compressive strength and tensile strength has been incorporated in an adapted failure criterion for brittle materials: the modified Von Mises criterion (mVM).[13] Figures 1-6a and 1-6b illustrate the stress distribution (using the mVM criterion) throughout the central incisor during protrusive movements.

Initial guidance starting at the intercuspal position (Fig 1-6a) does not cause significant stresses, as determined by mVM. In this position, most of the tooth crown is subjected to compressive forces, and bending is minimal. ***Moving toward an edge-to-edge position (Fig 1-6b), significant tensile stress concentrations are detected in the palatal fossa.*** Even in that challenging position, which induces maximum bending moments, the facial half of the tooth and the cingulum area still do not display detrimental stresses.

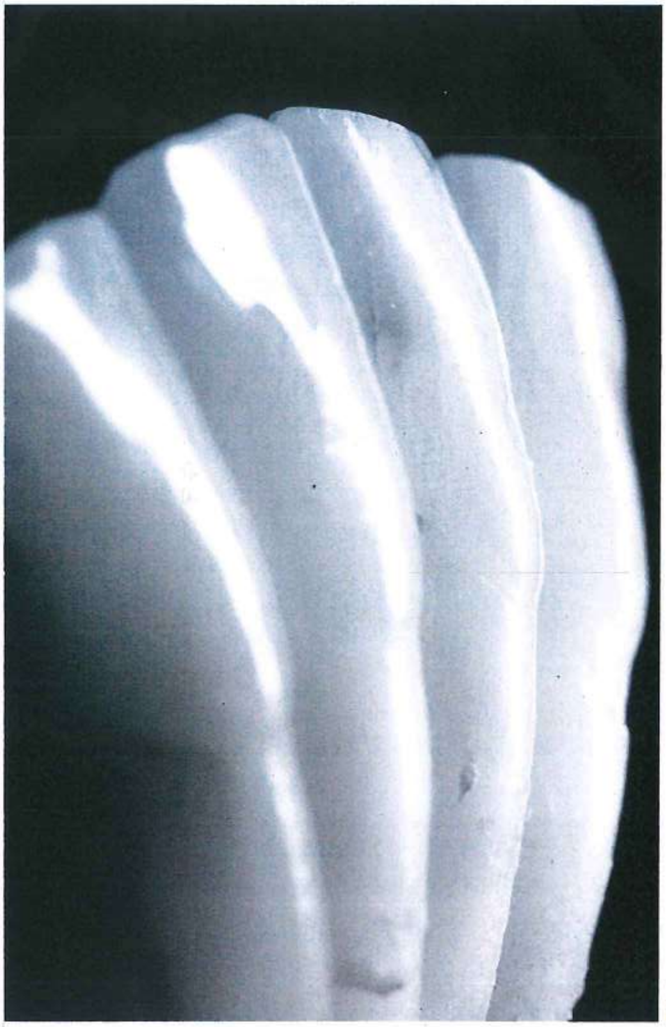
It is appropriate to analyze stresses in a direction for which the *x* and *y* components of stresses will display their maximum values. The resulting analysis (upper right of Figs 1-6a and 1-6b) outlines the principal stresses in the form of areas of compression and tension. The original maxillary incisor is separated into two distinct areas when subjected to maximum bending: The palatal half of the tooth exhibits positive values, namely tensile stresses, whereas the facial half of the tooth displays compressive stresses. Note again the quiescent area of the cingulum regarding tensile stresses.

FIG 1-6 Stress distribution on a natural maxillary central incisor during function. Nonlinear finite element contact analysis. The mandibular incisor is sliding in protrusion starting at the intercuspal position *(a)* and moving toward an edge-to-edge position *(b)*. Real tooth deformation is magnified 5× to emphasize the bending mode of the crown. In *a*, most of the cross-sectional area is subjected to compression (*gray area* in the principal stress) or negligible tensile stresses. In *b*, the tooth behaves like a cantilever beam with a compressive side (facial half) and a tensile side (palatal half) separated by a neutral axis. Maximum tensile forces are found at the level of the fossa. The external force created by the mandibular incisor is about 50 N, and real horizontal deformation at the maxillary incisal edge is about 100 µm *(b, distance from dotted line)*. The tooth is fixed (zero displacement) at the cut plane of the root.


Modified Von Mises (mVM)
Principal stress (1st)
200
150
100
50
1
MPa
Von Mises (VM)
1-6a

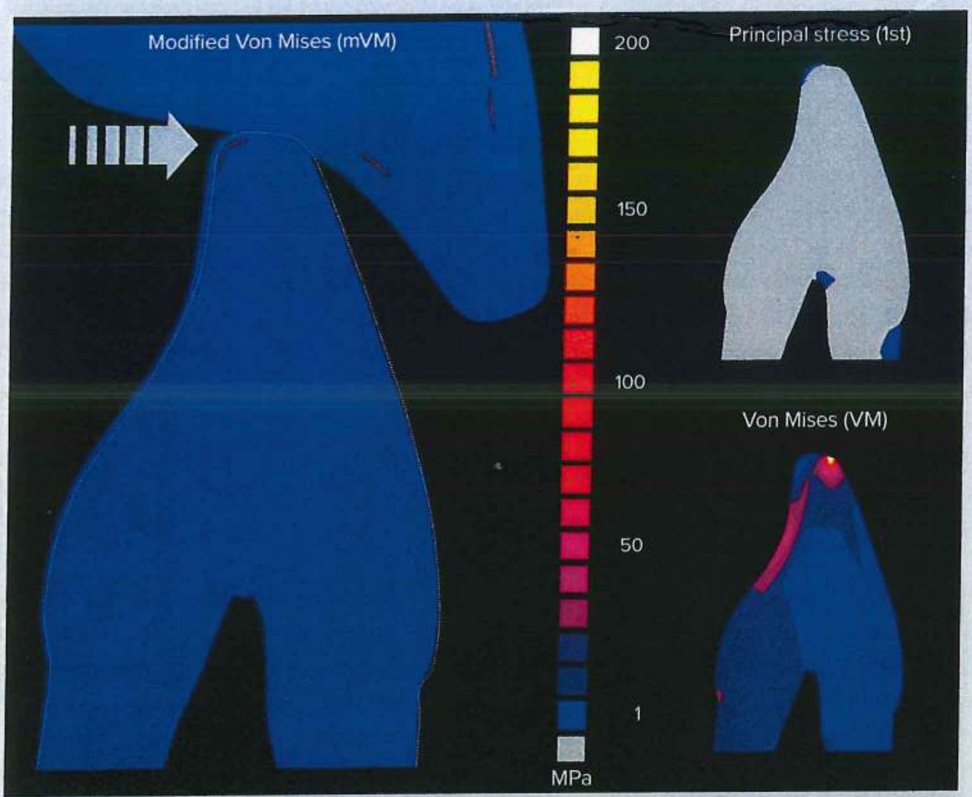

Modified Von Mises (mVM)
Principal stress (1st)
200
150
100
50
1
MPa
Von Mises (VM)
1-6b

Mandibular incisors, when subjected to similar loading conditions (Fig 1-7a), present inverted stress patterns. As with maxillary incisors, initial guidance starting at the intercuspal position does not produce significant mVM stresses. In this position, the mandibular crown is subjected only to compressive forces (Fig 1-7b). Moving toward an edge-to-edge position, tensile stresses begin to develop at the facial surface (Fig 1-7c). This stress pattern is exactly the opposite of that of the antagonistic tooth. Because of the favorable facial geometry of mandibular incisors, which displays flat or convex contours (Fig 1-7a), the level of facial tensile stresses remains moderate and less detrimental compared to those found at the antagonistic fossa (Figs 1-6b and 1-7c).



1-7a

FIG 1-7 Stress distribution on a natural mandibular incisor during function. Nonlinear finite element contact analysis. The facial aspect of a mandibular incisor exhibits extremely simple morphology with mostly flat or slightly convex surfaces *(a)*. As in Fig 1-5, the mandibular incisor is sliding in protrusion starting at the intercuspal position *(b)* and moving toward an edge-to-edge position *(c)*. Real tooth deformation is magnified 5×. In *b*, most of the cross-sectional area is subjected to compression (*gray area* in the principal stress). In c, the tooth behaves like a cantilever beam with a compressive side (lingual half) and a tensile side (facial half) separated by a neutral axis. Maximum tensile forces are found at the facial middle third of the crown but are minor compared to the stresses of the antagonistic tooth at the palatal fossa. The external force created by the contact is about 50 N, and real horizontal deformation at the mandibular incisal edge is about 60 µm *(c, distance from dotted line)*. The tooth is fixed (zero displacement) at the cut plane of the root.


Modified Von Mises (mVM)
200
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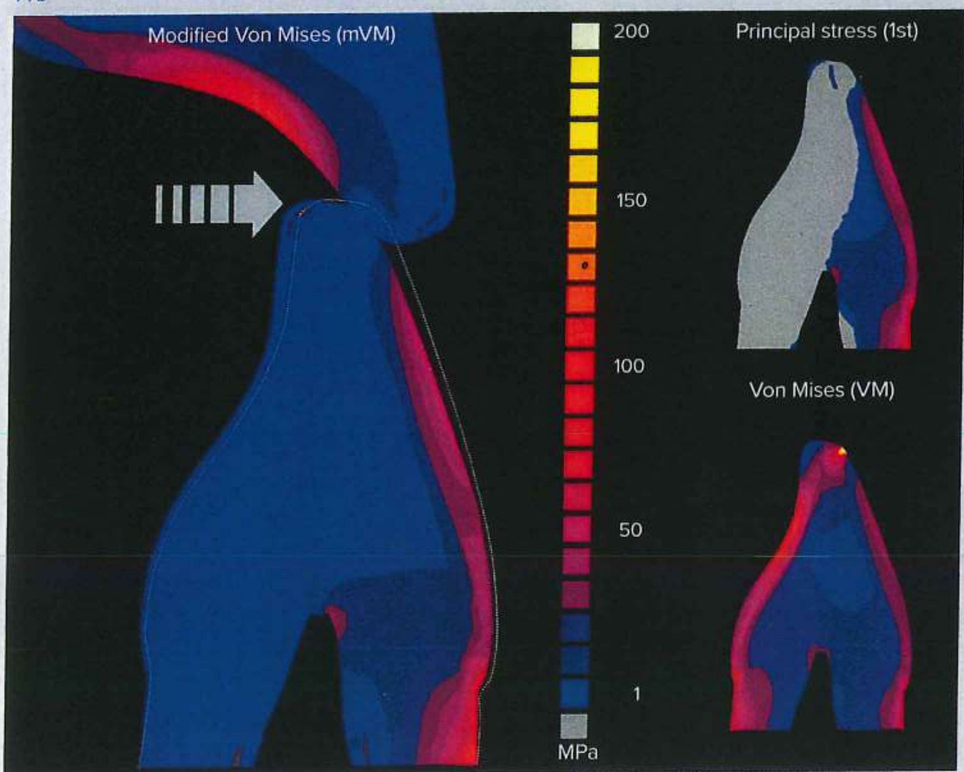
MPa
Principal stress (1st)
Von Mises (VM)

1-7b


Modified Von Mises (mVM)
200
150
100
50
1
MPa
Principal stress (1st)
Von Mises (VM)

1-7c

As previously outlined, form (ie, geometry) and function are essential determinants of stress distribution.

It is important to remember that low stress levels are found in surfaces of maximum convex curvature, ie, the cingulum and the cervical part of the facial surface. Therefore, it is concluded that ***convex surfaces with thick enamel experience fewer stress concentrations than do concave areas, which tend to accumulate them.***[12]

This statement is clearly supported by Fig 1-8a, which shows the influence of enamel geometry and thickness after modification of the palatal surface contour of a maxillary incisor. The resulting contour might be assumed as the proximal aspect of an incisor (Fig 1-8b) or as vertical lobes extending from the cingulum. The addition of enamel discloses a seemingly better balance and stress distribution. In this regard, it can be presumed that moderate stress concentrations would occur on the totally convex palatal surfaces, such as that found on canines. Canines have very curvilinear facial surfaces that may better withstand compressive forces. A canine with its accentuated biconvex contour (buccolingual section) displays an almost perfect convex design, which leads to a favorable mechanical configuration.

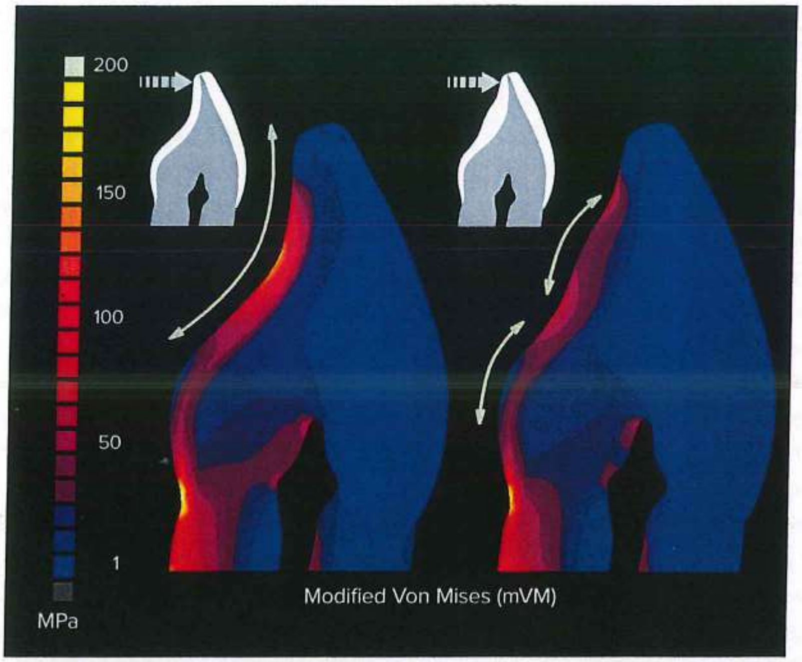
An irregular surface anatomy, ie, the palatal surface anatomy of an incisor (Fig 1-8b), logically yields to a different stress pattern. Stress concentration in the palatal fossa contrasts with the low stresses observed on smooth and convex areas (ie, the cervical half of the crown for both palatal and facial surfaces). Accordingly, the following conclusions can be made[12]:

- ***The palatal concavity provides the incisor with its sharp incisal edge and cutting ability but is shown to be an area of stress concentration.***
- ***Specific areas featuring thick enamel, such as the cingulum and the marginal ridges, can compensate for this shortcoming and act as stress redistributors.***

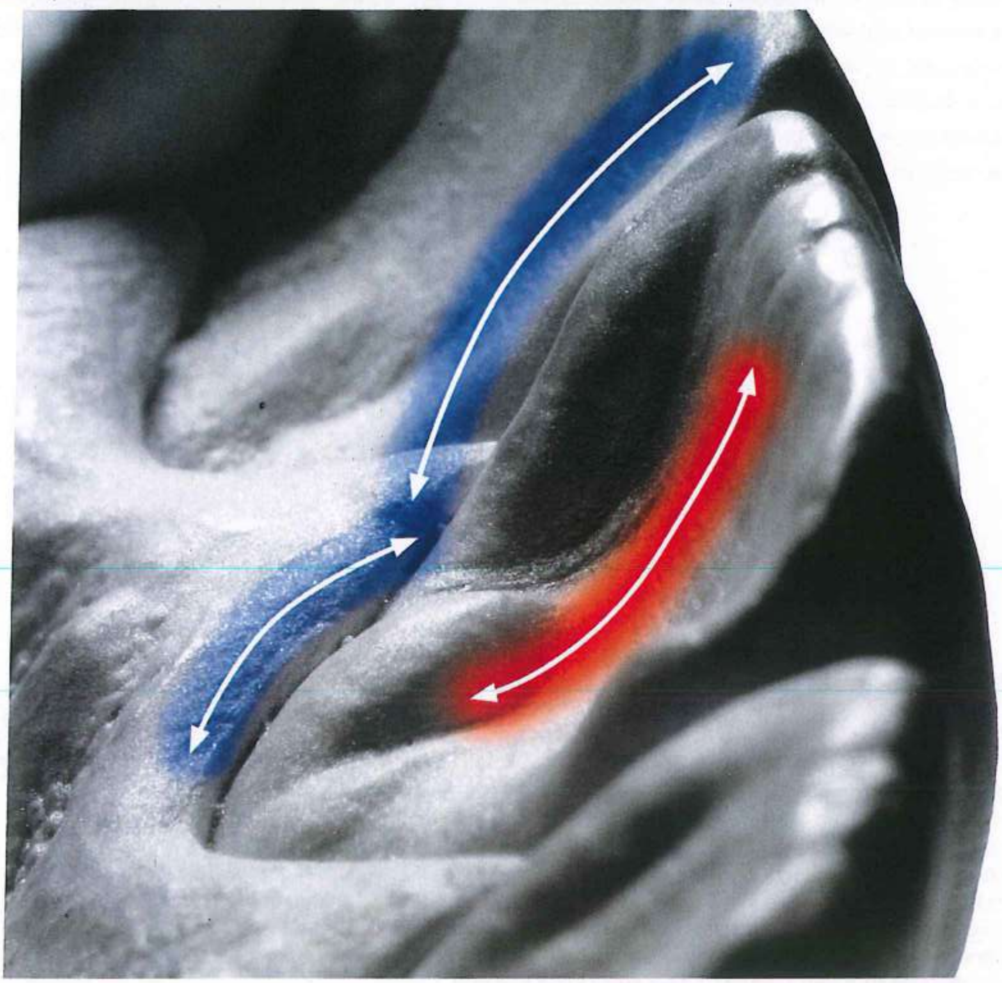
Cingula and marginal crests also represent essential palatal stops that allow for maintenance of the vertical dimension of occlusion (VDO) in the anterior segment.

FIG 1-8 Stress distributions with varying enamel thickness and geometry. *(a)* An original buccopalatal cross section *(left)* is compared to a modified incisor with thickened, convex palatal enamel *(right)*. The modified tooth displays the lowest palatal surface stresses. Two small stress peaks still subsist in the palatal surface and correspond to concave areas delimiting the thickened enamel.* *(b)* The modified finite element model reproduces the prominent distal crest of the tooth. This typical incisal feature helps to improve stress distribution along the palatal surface.

*Although the loading condition (50 N palatal load) was chosen to reflect a realistic situation, it should be emphasized that the conclusions are based on only this one loading condition. However, the conclusions about the effect of shape (convex versus concave) and composition (enamel-dentin distribution) are universal and do not depend on the exact load direction or magnitude.



1-8a



1-8b

Posterior tooth mechanics/function

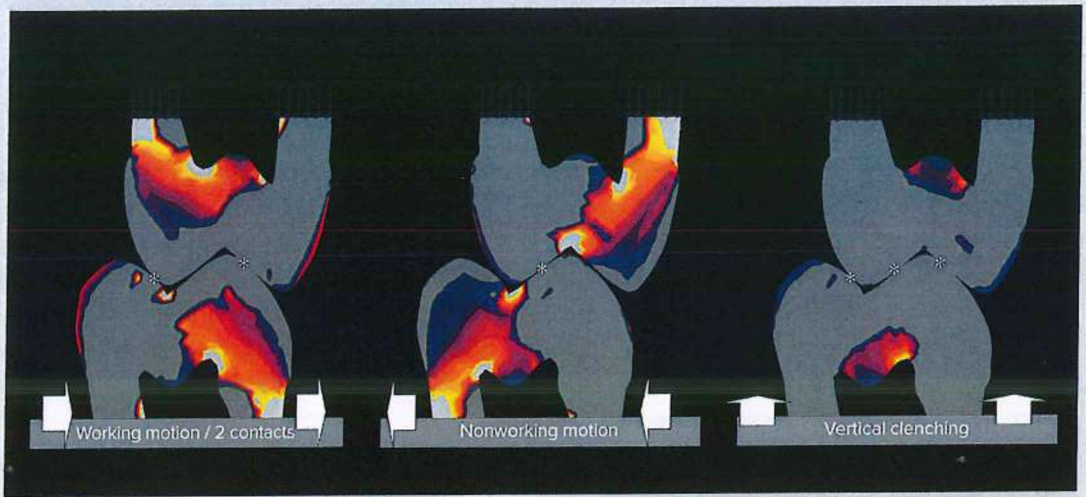
Inversely to anterior teeth, cusps do not deform under load as simple cantilever beams.[14] The deformation mode is complicated by the numerous possibilities in the application of loads (working, nonworking, closure). General assumptions claiming the harmful effect (crack propensity) of lateral loading have been confirmed both experimentally[14,15] and clinically.[16] Vertical loading of the tooth (clenching in the direction of its main axis) does not generate harmful concentrations of stress. More challenging situations are encountered during working and nonworking micromotions, both generating inverted stress patterns (2D finite element analysis; Figs 1-9a to 1-9c). Supporting cusps are generally well protected during both working and nonworking load cases (mostly subjected to compressive stresses), but the area of the central groove can be extremely challenged, especially during nonworking excursions. In this case, enamel bridges and crests proved to be essential mechanisms to protect the natural crown biomechanics (Fig 1-9d).

Accordingly, the following conclusions can be made:

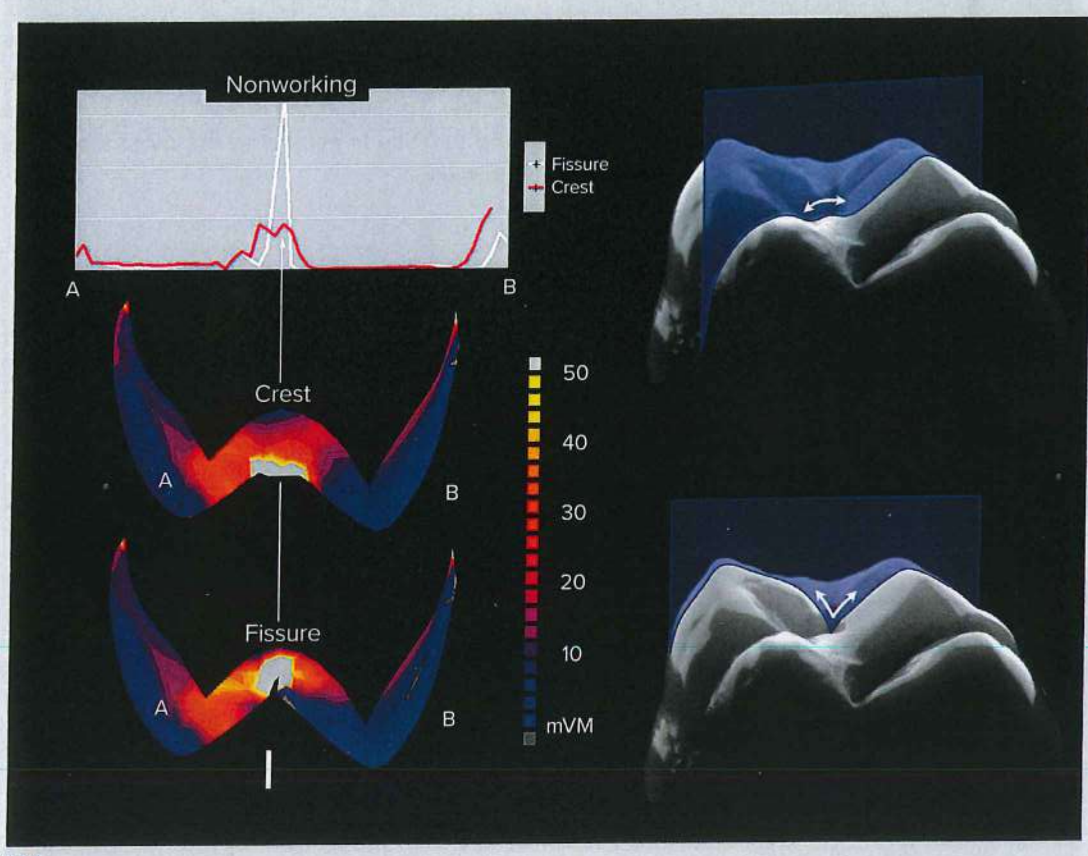
- ***Prominent supporting cusps provide the premolars and molars with their crushing/grinding ability but are shown to be involved in nonworking interferences.***
- ***Specific areas featuring thick enamel, such as the oblique and marginal ridges, can compensate for this shortcoming and act as protectors.***
- ***Oblique and marginal ridges also represent essential occlusal stops that allow for positional stability of posterior teeth and maintenance of the VDO in the posterior segment (see chapter 2, Fig 2-29).***

The DEJ constitutes another crucial element that must be mentioned among the natural protective mechanisms of the tooth (see next section). One must also keep in mind that that occlusal wear does not necessarily lead to loss of VDO (growth of the alveolar process may compensate wear without loss of VDO).

FIG 1-9 Stresses within molar cross sections. *(a to c)* Negative values of first principal stress appear in gray and delineate the areas of compressive stresses. Color shadings indicate the different levels of tensile stresses. In each load case, the sum of external forces on the contact nodes is ~200 N. * = area of contact. Note the reversed stress patterns of nonworking vs working micromotions. The nonworking micromotion is causing the largest stresses (maximum separation of the cusps), while the vertical clenching appears to generate mostly compressive stresses. *(d)* mVM stresses during nonworking micromotions. The path plot proceeds along the enamel surface from the lingual/palatal cementoenamel junction (CEJ; A) to the buccal side (B). Note the marked reduction of the stress peak at the central groove in the presence of the crest *(red curve)* compared to the fissure *(white curve)*. The same tooth can display extreme morphologic types within the occlusal table, either with an enamel bridge or crest *(top right)* or a deep fissure *(bottom right)* according to the cross-sectional area. (Reproduced with permission from Magne and Belser.[14])



1-9a 1-9b 1-9c



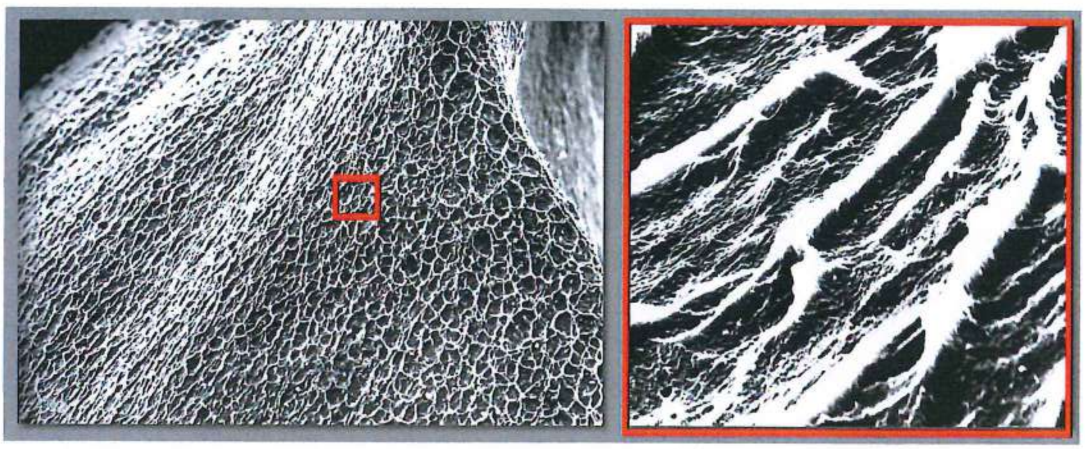
1-9d

1.6 PHYSIOLOGIC ENAMEL CRACKING AND THE DEJ

The assembly of two tissues with distinctly different elastic moduli requires a complex fusion for long-term functional success. Stress transfer in simple bilaminate structures with divergent properties usually induces increased focal stresses at the interface.[17] If enamel and dentin at the functional surfaces of a tooth comprised such a simply bonded bilaminate, then enamel-initiated cracks would easily cross the DEJ and propagate into dentin. In reality, the situation seems to be quite different. Although multiple enamel cracks are typically encountered in aged teeth, they seldom affect the structural integrity of the enamel-dentin complex. The explanation lies in the most fascinating feature inherent to the natural tooth—a complex fusion at the DEJ (Figs 1-10a to 1-10d), which can be regarded as a fibril-reinforced bond.[18]

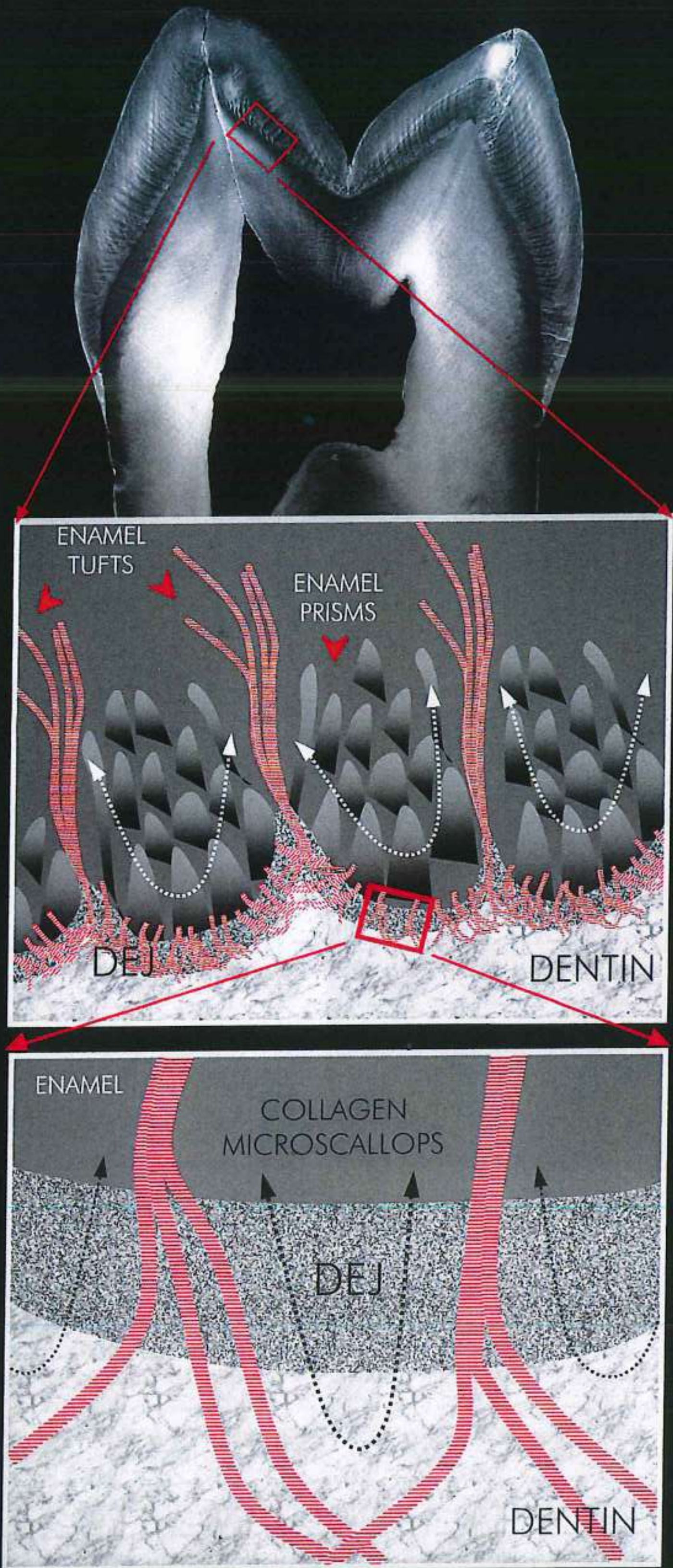
The DEJ is a moderately mineralized interface between two highly mineralized tissues (enamel and dentin). Parallel, coarse collagen bundles (probably the von Korff fibers of the mantle dentin) form massive consolidations that can divert and blunt enamel cracks through considerable plastic deformation.

Scanning electron microscopy fractographs of DEJ specimens have demonstrated crack deflection to another fracture plane when forced through the DEJ.[19] The structure of the DEJ shows two levels of scalloping (Figs 1-10a and 1-10b), which increase the effective interfacial area and strengthen the bond between enamel and dentin. The scalloping is most prominent where the junction is subject to the most functional stresses.[20]



1-10a

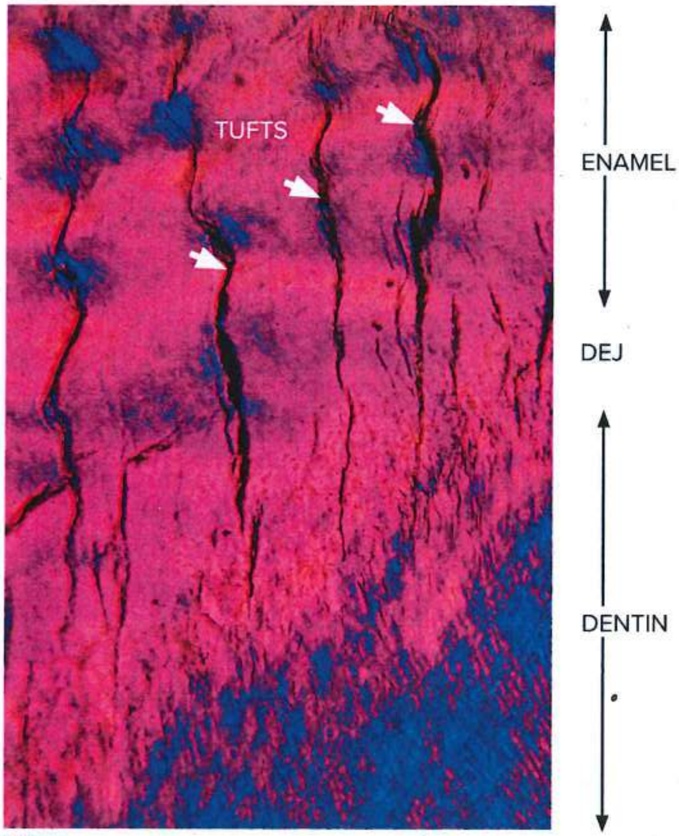
FIG 1-10 Spatial DEJ architecture and formation. *(a)* Dentin surface morphology at the DEJ looks scalloped like a honeycomb structure, which contributes to increase the contact surface with enamel. *(b)* Schematic representation of the spatial relationship of collagen fibrils. Thick bundles and tufts reinforce the fusion of enamel and dentin *(middle, corresponding to the ridges visible in a, right)*. Coarse collagen bundles form "microscallops" *(bottom, black dotted arrows)* within the major scallops of the DEJ outline *(middle, white dotted arrows)*. These bundles merge with other fibrils before or after entering the enamel matrix *(bottom)*. (Part *a* reproduced with permission from Doukoudakis et al[20]; top figure in part *b* reprinted with permission from Bazos and Magne[7]; middle and bottom figures in part *b* modified with permission from Lin et al.[18])


ENAMEL
TUFTS
ENAMEL
PRISMS
DEJ
DENTIN
ENAMEL
COLLAGEN
MICROSCALLOPS
DEJ
DENTIN

1-10b

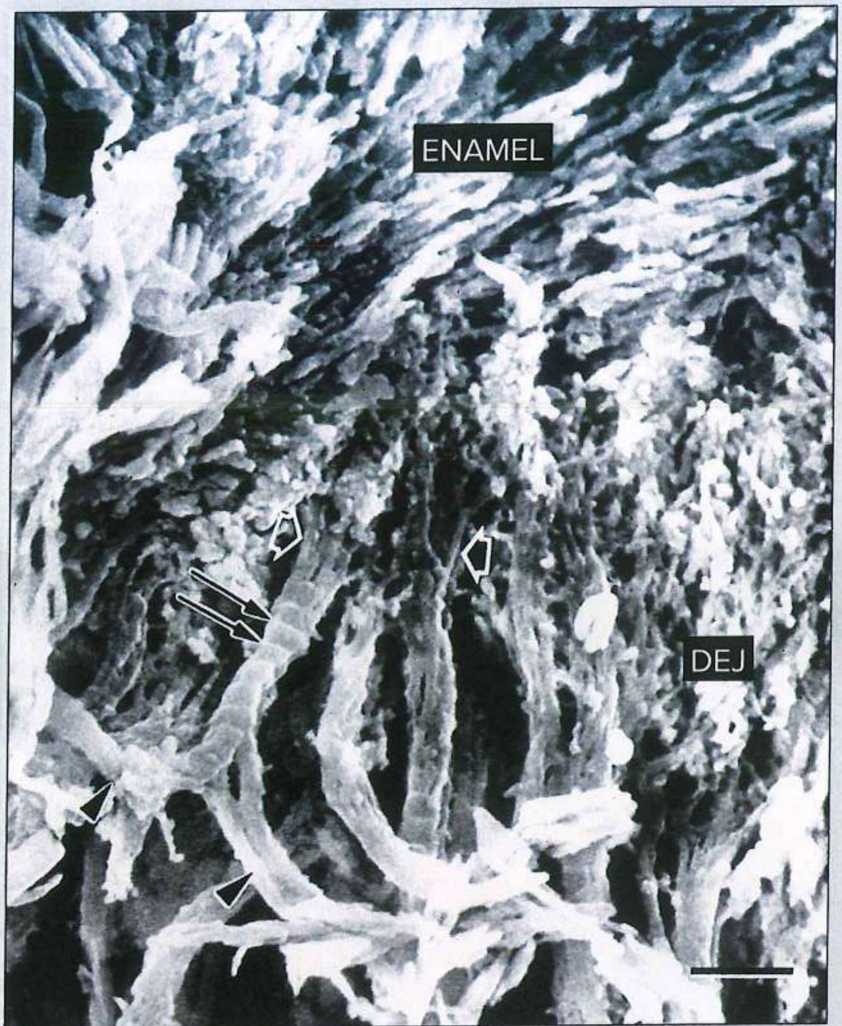
Interestingly, the DEJ is formed in the earliest developmental stage of the tooth crown, at the time of incipient mineralization and much earlier than an identifiable pulp (Fig 1-10e). This chronology is not coincidental, and another sequence would not allow the creation of such a complex dentinoenamel fusion. It is probably more correct to regard the crown of the tooth as growing out bidirectionally from the DEJ rather than from the pulp.

In other words, the DEJ is the "center" of the tooth, not the pulp.

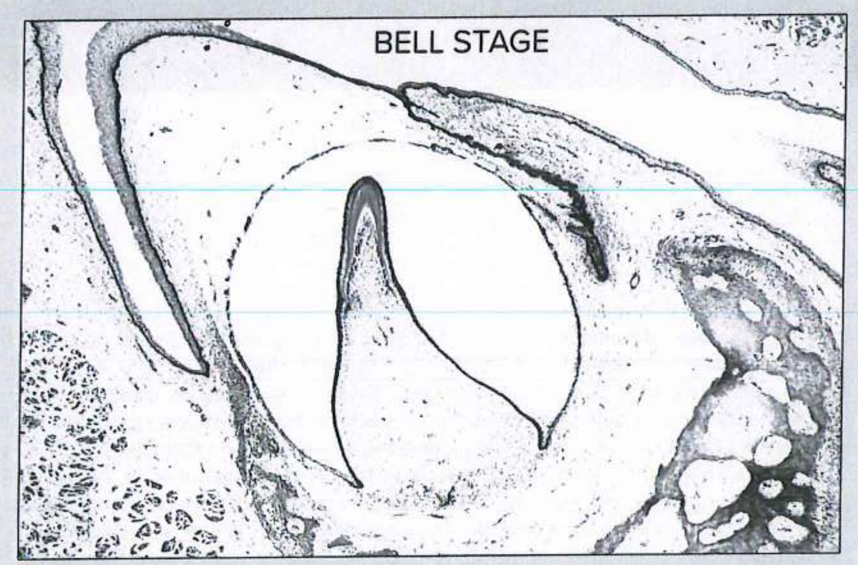


1-10c

FIG 1-10 *(cont) (c)* Thin tooth section under polarized light showing the collagen tufts in the enamel (original magnification ×250; courtesy of N. Allenspach, University of Geneva). *(d)* Low-voltage field-emission scanning electron microphotograph of the DEJ decalcified with neutral ethylenediaminetetraacetic acid; 80- to 120-nm-diameter collagen fibrils merge with dentin matrix fibrils *(arrowheads)* and splay out into the enamel matrix *(open arrows)*. Note the cross banding of the collagen fibrils every 600 Å (1^{-9}) *(black arrows)* (original magnification ×50,000). This deep penetration of collagen into the enamel, which is the sine qua non of the DEJ, could not take place with fully calcified enamel (99% mineral by weight). This points to the fact that the DEJ forms early in embryonic development and subsequently calcifies. *(e)* The DEJ of a primary tooth is being formed at the late bell stage (early crown stage) of tooth formation; dentin and enamel have begun to form at the crest of the folded internal dental epithelium. At this stage and in the continuing early growth, interpenetration of collagen into the contiguous enamel organ takes place. At maturity, this forms the fully functional DEJ, which should be considered an interphase rather than an interface. (Part *d* reprinted with permission from Lin et al[18]; part e courtesy of Dr W. H. Douglas, University of Minnesota.)



1-10d



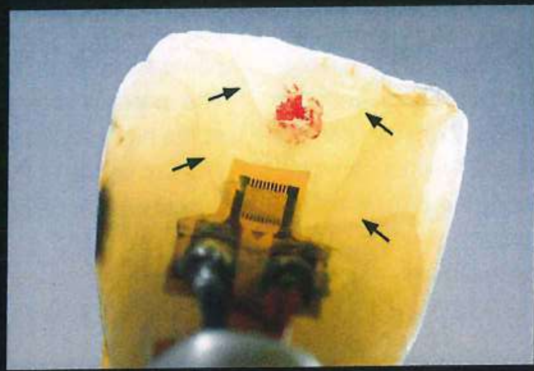
1-10e

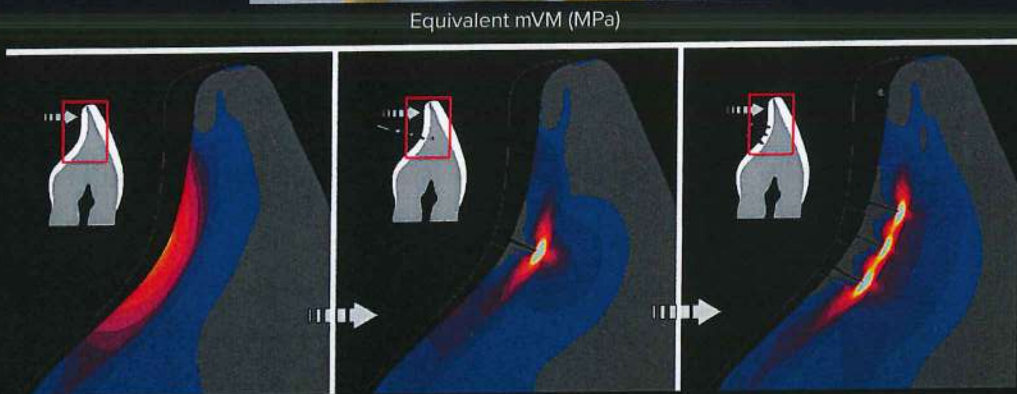
Due to the inherent brittleness of enamel and the collagenous consolidation of the DEJ, enamel cracking should be considered a normal aging process (Fig 1-10f). In addition, there are other effects of enamel cracks, which are visible in finite element models. Stress in the enamel is redistributed around the crack through the DEJ, which creates a stress concentration at the crack tip and leaves the tooth surface in the area of the crack relatively quiescent (Fig 1-10g).

Thus, enamel cracks can be considered an acceptable enamel attribute, and the DEJ plays a significant role in assisting stress transfer (as opposed to stress concentration) and in resisting enamel crack propagation (Fig 1-10h). The fascinating properties of the DEJ must serve as a reference for the development of new dentin bonding agents, which should allow for the recovery of the biomechanical integrity of the restored crown.

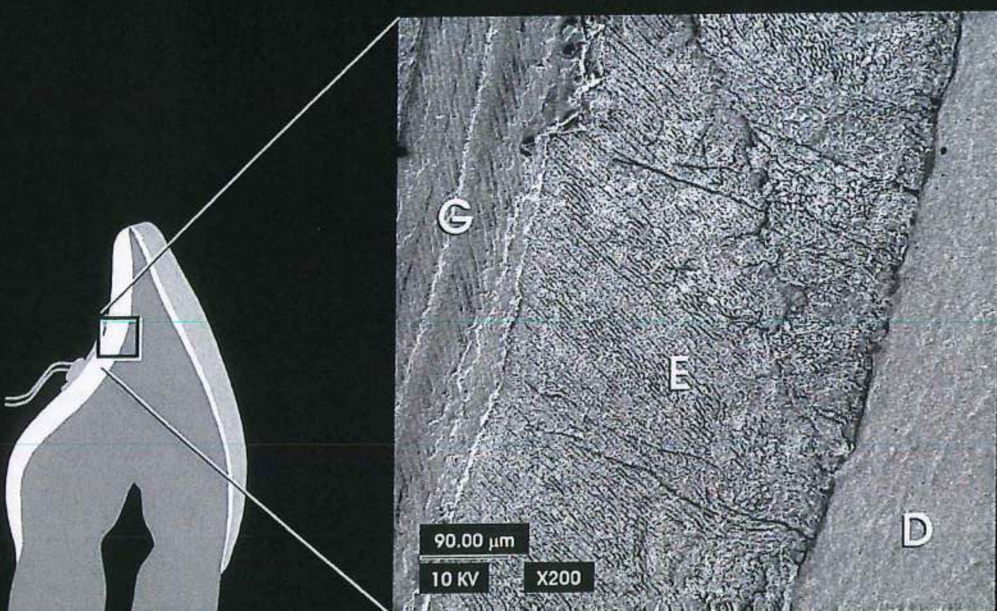
1-10f

FIG 1-10 *(cont) (f)* Clinical image of maxillary incisors' lingual surfaces displaying numerous cracks in enamel (see also Fig 1-17e). Note similar cracking of the bonded ceramic full-crown coverage on the right central incisor (the repair of this case by resin infiltration is illustrated in chapter 7, Fig 7-12). *(g)* A photomicrograph of a strain gauge study specimen displays multiple cracks on the palatal surface *(top)*. Similar experimental conditions including modeling of single and multiple cracks were simulated in FEM. Enamel surrounding the flaws appears to be totally quiescent with regard to tensile forces (*gray areas* correspond to mVM stresses between 0 and 1 MPa). Stresses at the crack tip are well above 200 MPa (*bottom*; teeth are loaded horizontally with 50 N on the incisal edge, 7× deformation factor). *(h)* Scanning electron micrographic view of palatal enamel cracks above a strain gauge (G). This appears to be the area of maximum tensile stresses in the numeric model. The full thickness of enamel (E) is cracked, but the flaws never propagate into dentin (D). (Part *g* reprinted with permission from Magne et al[12]; part *h* reprinted with permission from Magne and Douglas.[10])





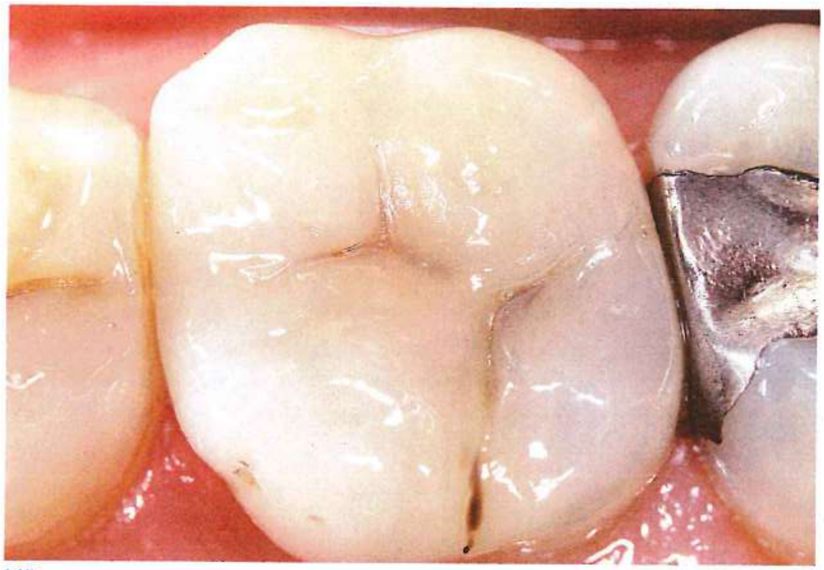
1-10g



1-10h

The data presented previously is a reminder that restorative designs must emulate the protective "biomechanisms" found in natural teeth (Fig 1-11). It also raises the question whether carious decay formed at the pits and fissures of natural posterior teeth is caused by the difficult access to cleaning or simply because it is a mechanically sensitive area. It could be hypothesized that the first incident is an enamel crack allowing direct penetration of the bacteria into the DEJ (Fig 1-12). The extreme similarity between the geometry of the highest tensile stresses found in fissures and the shape of fissure decay is startling and may reveal that biomechanics should never be underestimated.

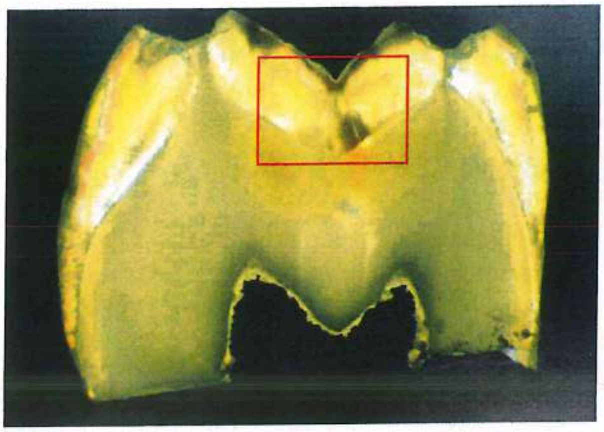
1-11a



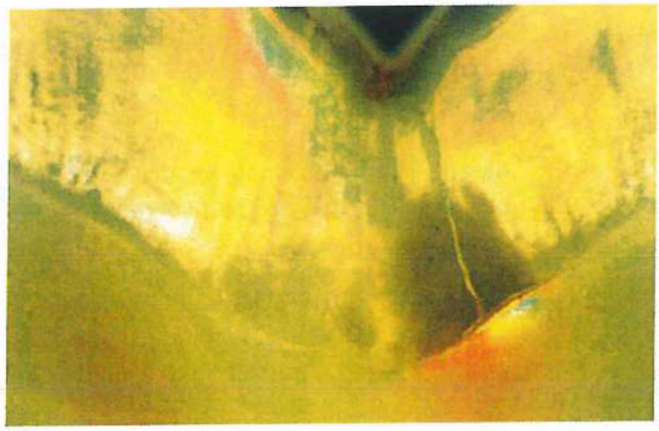
1-11b

FIG 1-11 Emulation of protective "biomechanisms" (marginal ridges and enamel bridge). *(a)* This patient suffered from cracked tooth syndrome because of a well-defined crack under an amalgam restoration (note crack at the base of the distopalatal cusp). *(b)* The restoration (mesio-occlusodistal [MOD] composite resin inlay with minimal coverage of the distopalatal cusp) features strong marginal ridges and a central enamel bridge.

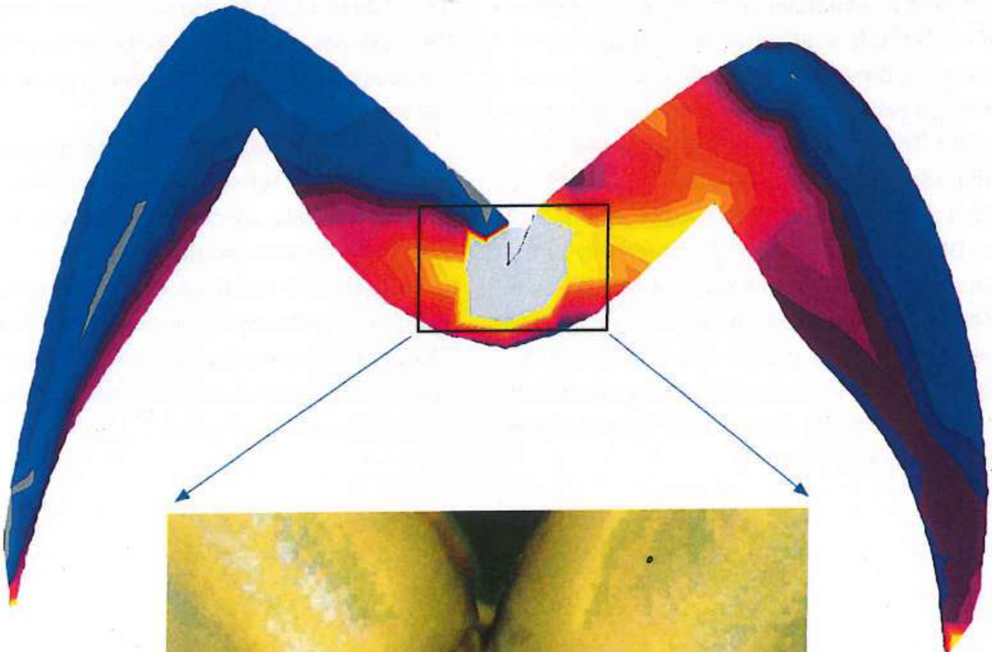
FIG 1-12 Pit and fissure decay initiated by a mechanical defect? *(a)* Tooth section in polarized light showing carious decay in the central groove. *(b)* Higher magnification reveals an enamel crack in the center of the lesion. Was the crack present before the demineralization started? *(c and d)* There is a startling similarity between the geometry of the maximum mVM stresses at the central groove *(light gray area in c)* and the area of enamel demineralization *(d)*. (Parts *a*, *b*, and *d* courtesy of N. Allenspach, University of Geneva.)



1-12a



1-12b



1-12c

1-12d

BIOLOGY OR MECHANICS?

1.7 NATURAL TOOTH AGING AND ENAMEL THINNING

As previously mentioned, enamel and dentin exhibit different physical properties.

Enamel can resist occlusal wear but is fragile and cracks easily. Dentin, on the other hand, is flexible and compliant but is not wear resistant and does not age favorably when directly exposed to the oral environment.

Because of their respective shortcomings, neither enamel nor dentin independently would be considered an effective restorative material. However, they form a "composite" structure, which provides a tooth with unique characteristics[21]: The hardness of enamel protects the soft underlying dentin, while the crack-arresting effect of dentin and the thick collagen fibers at the DEJ[19] compensate for the inherently brittle nature of enamel. This structural and physical interrelationship between an extremely hard tissue and a more pliable tissue provides the natural tooth with its original beauty but also its ability to withstand mastication, thermal loads, and wear during a lifetime.

Anterior tooth aging/wear

The original morphology and thickness of the enamel shell (Fig 1-13a) seem to have been designed to anticipate wear and function requirements[22]: Maximum wear areas are specifically those presenting higher bulks of enamel, ie, the incisal edge in the case of anterior teeth. This "preventive" architecture still allows physiologic wear to create dentin exposure in the incisal area (Fig 1-13b to 1-13d). By the same token, teeth in the posterior region, where masticatory forces are stronger, have thicker enamel than do anterior teeth.[23]

The dynamic wear pattern of the incisal edge must stand as a reference for the development of new materials, which should be able to age similarly to enamel and dentin.

Natural tooth aging also impacts the optical interaction between enamel and dentin (Figs 1-13e and 1-13f). Here again, the incisal edge area is the most affected by age-related alterations (see also chapter 2, Fig 2-8).

FIG 1-13 The seasons of tooth life. *(a)* Anterior teeth initially present typical mamelons and surface texture. These elements are progressively eliminated by wear. *(b to d)* Ongoing enamel cracking and dentin exposure are linked to obvious color changes. *(e and f)* Extreme wear allows for understanding the optical interaction between enamel and dentin, especially the crucial role of dentin in limiting light transmission in the incisal area. Optimized ceramic or composite resin stratification techniques are needed to reproduce the selective light transmission of enamel and dentin.


1-13a


1-13b


1-13c


1-13d


1-13e


1-13f

Age-related changes of the dentition are the main challenge of modern dentistry, which is faced with a population that is getting older and keeping more of its natural teeth.

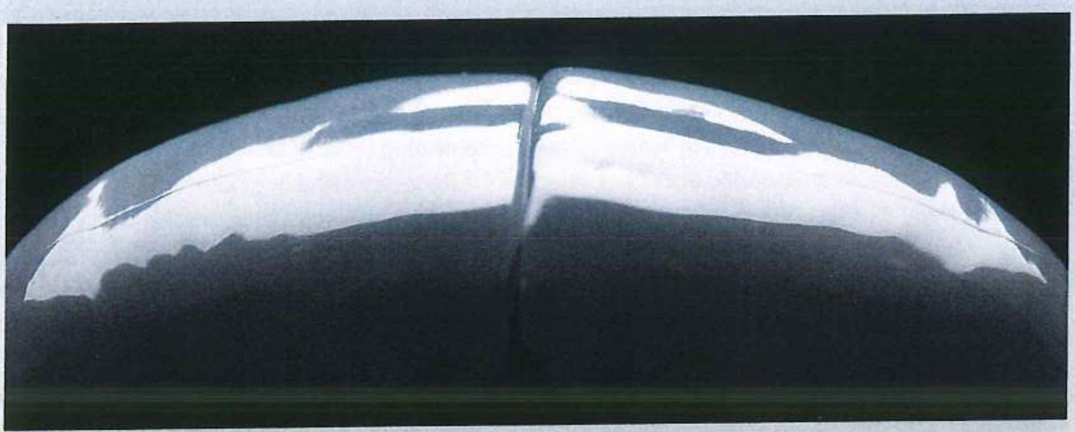
Smiles can show physical and esthetic signs of aging. Among these, excessive wear in the incisal area contributes to the loss of anterior tooth prominence and insufficient anterior guidance, thus generating new responsibilities for the restorative dentist. This degenerative phenomenon is overshadowed by color changes following dentin exposure, enamel cracking, and related extrinsic infiltration (Figs 1-14a and 1-14b). The widespread interest in vital bleaching has become the driving force of esthetic dentistry to rejuvenate tooth appearance at a limited cost. However, this ultraconservative chemical treatment addresses only the cosmetic component of a complex problem.

In the physiologic aging process, the original enamel thickness is progressively reduced (Figs 1-14c to 1-14e). Therefore, the color and cosmetic problems related to tooth aging should not be the only concern of the restorative dentist.[8] As mentioned previously, dentin plays a crucial role in providing the tooth with compliance and flexibility, whereas the enamel shell will ensure its rigidity and strength. The increased crown flexibility of worn teeth can be associated with functional and mechanical problems. ***A sufficient and uniform thickness of facial enamel is essential to the balance of functional stresses in the anterior dentition.***[12]

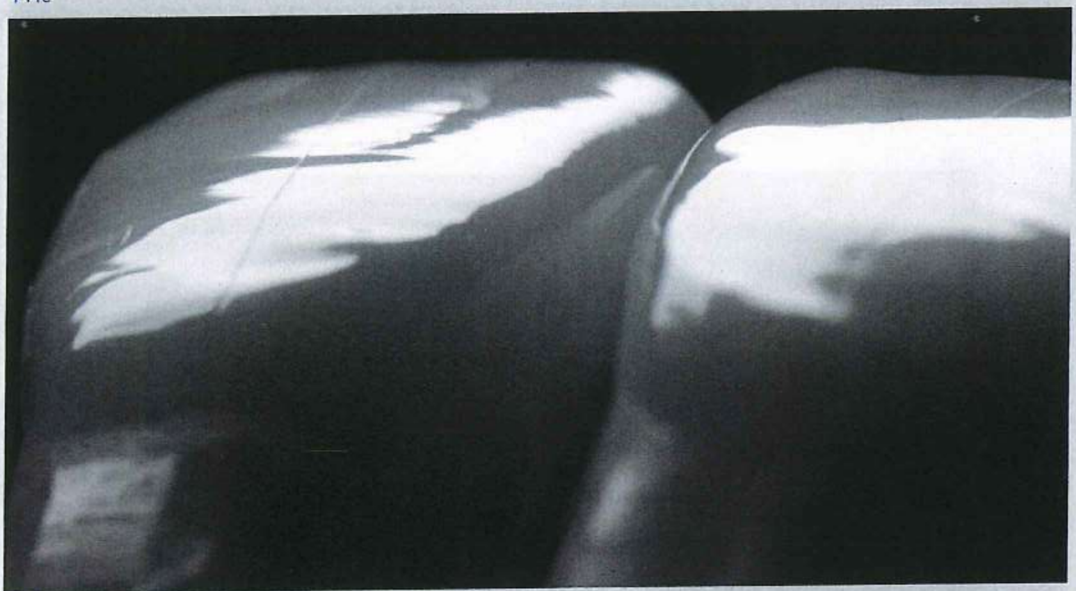
1-14a

1-14b

FIG 1-14 Enamel in the aging process. *(a and b)* Teeth of a 70-year-old patient with obvious age-related enamel wear, cracking, and extrinsic infiltration of both central incisors. Bleaching will not address the biomechanical issues, which require crown stiffness recovery through adequate restorative approaches (see treatment steps of this case in chapter 5, Fig 5-3, and chapter 6, Fig 6-45). *(c to e)* Detail views of extracted central incisors. Tangential light is used to reveal the loss of tooth form, surface architecture, and palatoincisal wear.



1-14c

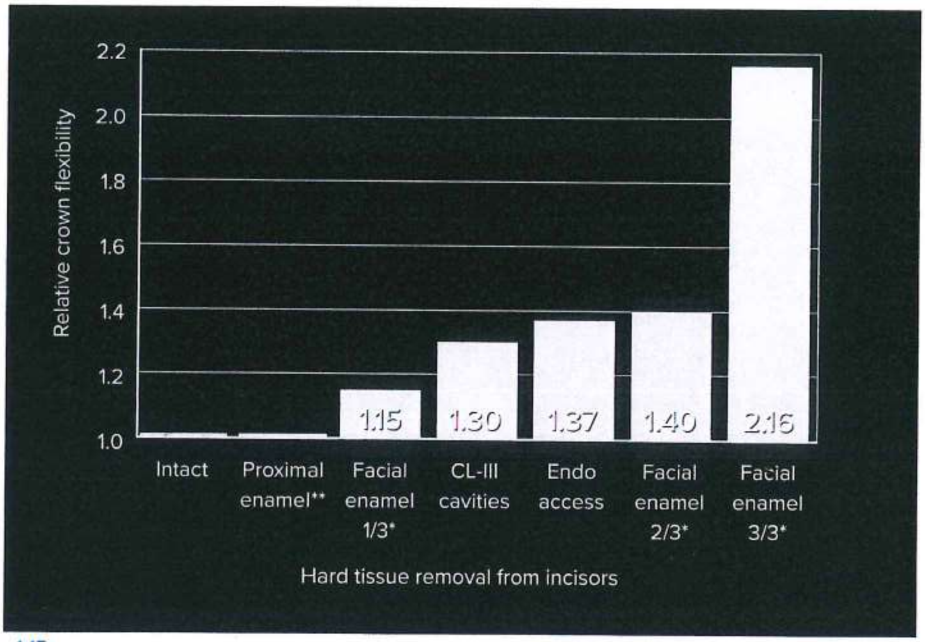


1-14d

1-14e

The combined results of different studies yield significant information about the effect of various tissue reductions on anterior crown flexure.[10–12] For example, the substantial loss of facial enamel or the presence of endodontic access cavities is more likely to affect crown rigidity than is the interdental reduction of enamel or large Class 3 preparations (Fig 1-15a). As a matter of fact, thin, aged facial enamel can lead to high stress concentrations during function. Surface cracks typically found on aged teeth account for this problem. The significant effect of the enamel shell on stress distribution was demonstrated using both strain gauge experiments and finite element models (Figs 1-15b and 1-15c).[10–12] The total loss of facial enamel negatively affects the behavior of remaining palatal enamel. Similarly, loss of palatal enamel will significantly affect remaining facial enamel.

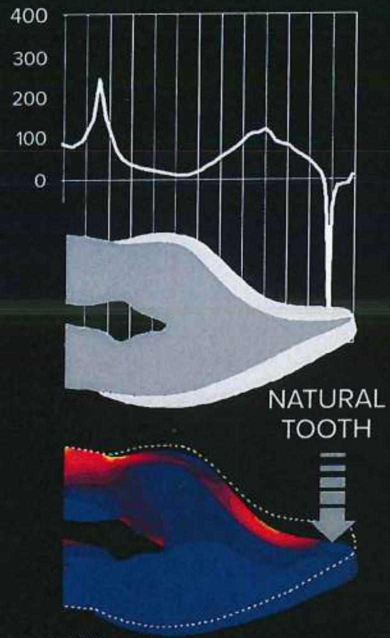
Recovery of the original enamel thickness and architecture is necessary for the biomechanical balance of the tooth crown. The choice of restorative material is critical in this matter (Figs 1-15d and 1-15e). ***Restitution of enamel thickness is therefore a combined esthetic and biomechanical endeavor. Bonding and adhesive ceramic restorative procedures have the potential to reverse the esthetic manifestations of aging in teeth (Figs 1-15b to 1-15e).***



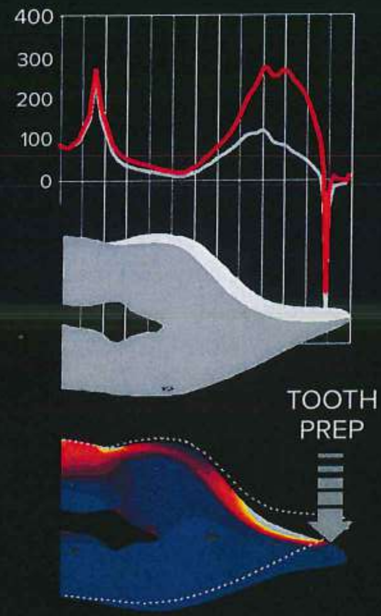
1-15a

FIG 1-15 Impact of enamel loss and enamel restitution. *(a)* Graphic representation of relative flexibility (changes in flexibility relative to the baseline) for natural incisors after removal of coronal tissues; total removal of proximal enamel (second column) does not affect crown rigidity, but total removal of facial enamel (last column) is most adverse; 1/3, 2/3, and 3/3 indicate the amount of facial enamel thickness removed. (*Results published by Magne et al.[12] **Results published by Magne and Douglas.[10] Other data published by Magne and Douglas.[11]) *(b to e)* Tooth preparation by total facial enamel removal was simulated in FEM; the plot of tangential stresses *(red line)* proceeds for each tooth along the palatal surface from cervical to incisal. *(b and c)* A dramatic increase in tensile stresses is found in the remaining enamel of the palatal fossa (tooth loaded palatally with 50 N onto incisal edge, deformation factor 10× on mVM stress mapping). *(d)* The original profile of tangential stress is completely recovered after bonding a feldspathic porcelain veneer. *(e)* The use of composite resin as the veneering material allows only partial recovery of stiffness. The original stress distribution of the natural tooth *(gray line)* is reported as a reference. (Parts *a* to c modified with permission from Magne and Douglas.[10])

Surface palatal tangential stress (MPa)

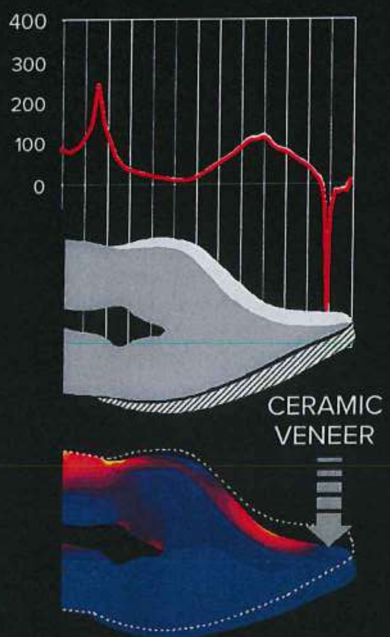


1-15b mVM

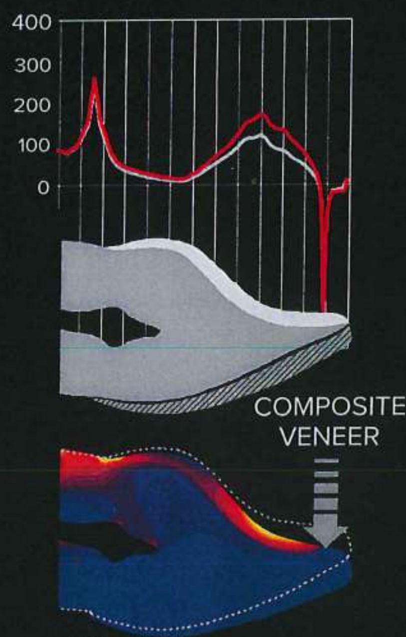


1-15c mVM

Surface palatal tangential stress (MPa)



1-15d mVM



1-15e mVM

Posterior tooth aging/wear

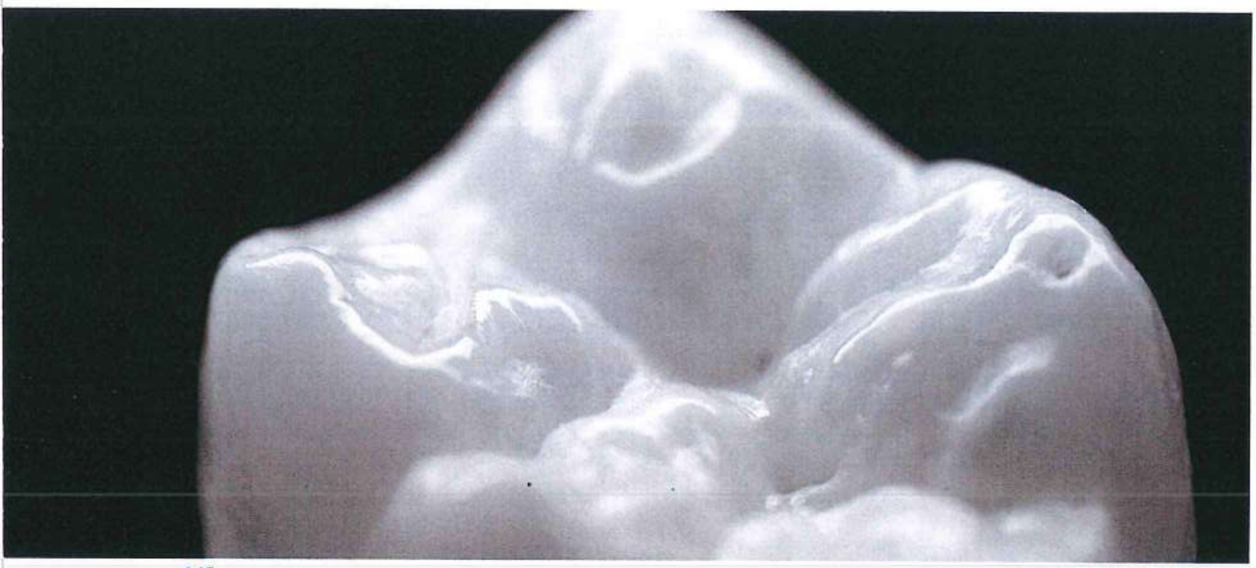
The natural history of posterior teeth is more complex than that of the anterior dentition. The mouth (and the occlusion) is the portal of entry to the alimentary canal and as such is a main component of the digestive system. The maxilla and the mandible meet only at the articular surfaces of the teeth, hence the significance of occlusion. In the digestive process, cusps are responsible for breaking food (Fig 1-16a).[22] Excursive movements generate a combined type of occlusal wear (Figs 1-16b and 1-16c). We can define *contact (articular) wear* and *contact-free (nonarticular) wear*. The latter is itself a composite type of wear including food abrasion in the spillways (developmental and supplemental grooves) and chemical degradation (corrosion). Abrasion can be difficult to distinguish from corrosive wear. During the crushing phase of the masticatory cycle, the food bolus is broken into smaller pieces until eccentric contacts are reached, initiating the gliding phase toward maximum cuspal interdigitation (Fig 1-16c). Even though most researchers measure a qualitative depth only, there are two expressions of occlusal wear (Fig 1-16d):

1. **Volumetric wear (V)** is a material property unrelated to the occlusion because a volume can assume any shape (area × depth).
2. **Depth of wear (d)** is an occlusal property because the wear is defined in one direction (usually related to facial height).

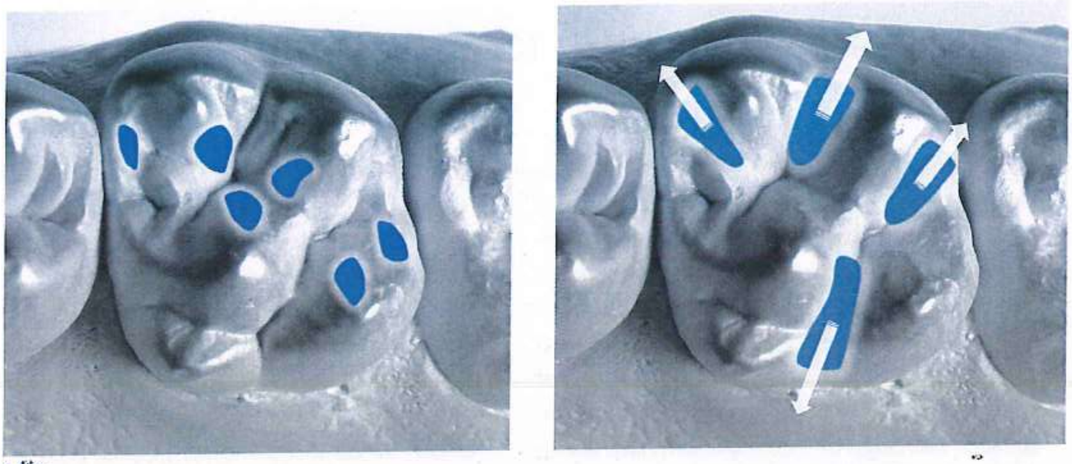
Hence, **the natural history of the occlusion** can be summarized as follows:

1. The price paid for occlusal or masticatory function is the volumetric wear of teeth.
2. A good occlusion (good morphology and interdigitation) will turn a high volumetric wear into an acceptable depth wear by increasing the area of contact. Facial height is preserved.
3. The price paid for increasing the area of contact is the loss of cuspal morphology leading to flat occlusion.
4. It can be projected that once flat occlusion is reached, depth wear catches up with volumetric wear, leading to a potential collapse of facial height.

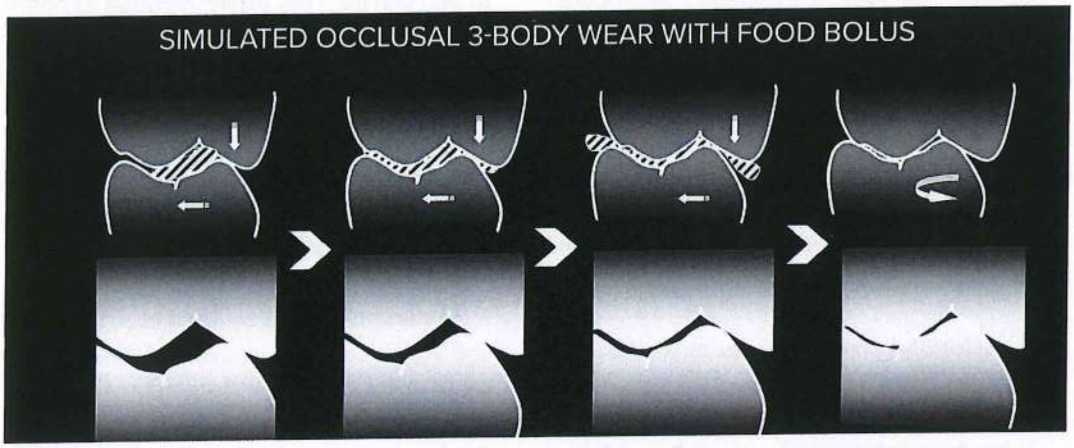
Ceramic and composite resin materials wear differently, which will be explained in chapter 4 (see Figs 4-7 and 4-9).



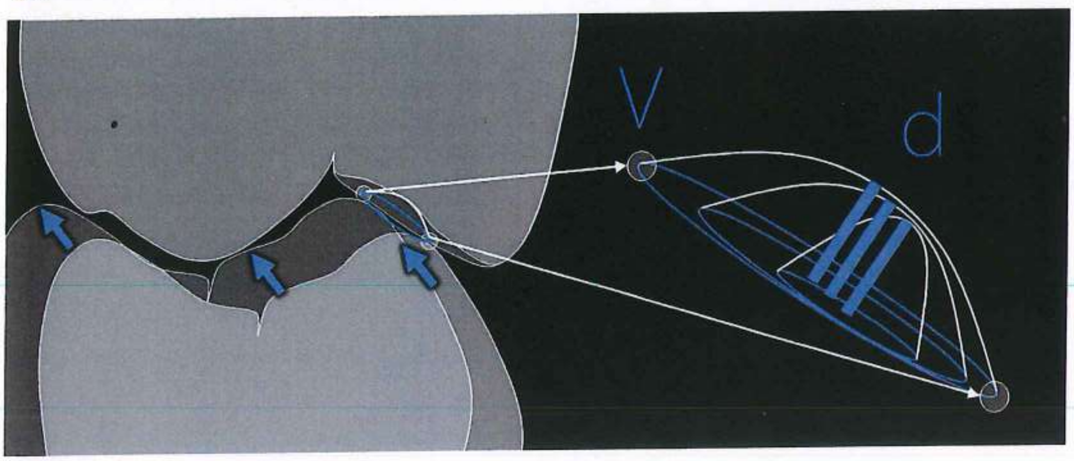
1-16a



1-16b



1-16c



1-16d

FIG 1-16 Natural history of the occlusion and occlusal wear. *(a)* Natural mandibular molar with intact cuspal features. *(b)* Contact wear usually appears as facets with sharp margins *(left)*. Nonarticular wear usually results from the pushing and sliding of food particles along the buccal and lingual developmental grooves and supplemental grooves *(right)*. *(c)* Comminution of food ends with the gliding phase. *(d)* Loss of contour by articular wear can be characterized by depth wear (d) and volumetric wear (V). Volume loss is a material property and does not necessarily correlate with depth wear due to the increased contact area.

1.8 BIOMIMETICS APPLIED TO MECHANICS

A natural tooth's unique ability to withstand masticatory and thermal loads during a lifetime is the result of the structural and physical interrelationship between an extremely hard tissue (enamel) and a more pliable tissue (dentin). The recognition of this relationship has led to a growing concern about the biomechanical response of intact hard tissue to restorative procedures. The situation has been particularly informative about posterior teeth (see Figs 1-25 and 1-26). A significant step was made when researchers focused their attention on the biomechanical side effects of amalgam restorations (ie, cuspal fractures and cracked tooth syndromes).[24–26]

In response, a number of studies[27–30] analyzing biophysical stress and strain have shown the following:

- ***Restorative procedures can make the tooth crown more deformable.***
- ***The tooth can be strengthened by increasing its resistance to crown deformation.***

Based on these principles, tooth reinforcement was obtained by some form of full or partial coverage (extracoronal strengthening) at the expense of the intact tooth substance.[31–33] Today, adhesive technology has proved its efficiency in simultaneously reestablishing crown stiffness and allowing maximum preservation of the remaining hard tissue (intracoronal strengthening).[34–36] These studies demonstrated that bonded composite resin restorations permit the recovery of tooth stiffness, which was not possible with amalgam fillings.

However, it should be remembered that the physical properties of composite resins are somewhat limited. One limitation is the elastic modulus, which for an average microhybrid material can be up to 80% lower (approximately 10 to 20 GPa) than the elastic modulus of enamel (approximately 80 GPa). As mentioned before, the enamel shell proves to be instrumental in the way stresses are distributed within the crown.

When a more flexible material replaces the enamel shell, only partial recovery of crown rigidity can be expected.

Studies conducted by Reeh et al[32] and Reeh and Ross[9] showed a recovery of 76% to 88% in crown stiffness after the placement of composite resin restorations and composite resin veneers. On the other hand, it was demonstrated that crown rigidity can be 100% recovered when feldspathic porcelain (elastic modulus approximately 70 GPa) is used as an enamel substitute, as with porcelain veneer restorations (see Fig 1-15d).[10] Teeth restored with dentin-bonded porcelain veneers also proved their absolute biomimetic behavior when subjected to cumulative restorative procedures[11] and catastrophic testing (Fig 1-17).

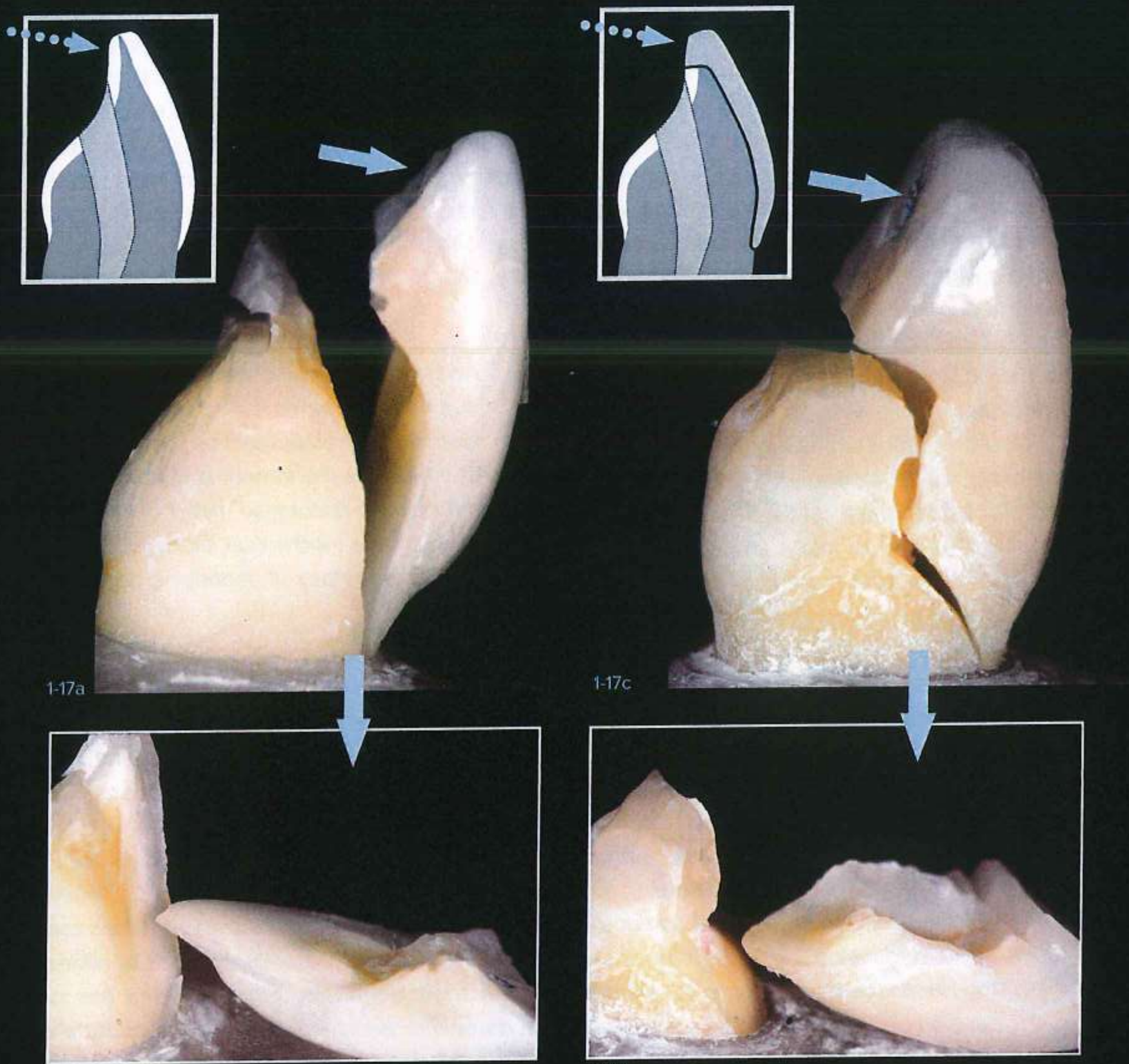


FIG 1-17 Catastrophic failure of intact incisors versus incisors restored with dentin-bonded porcelain veneers.* Natural *(a and b)* and veneered *(c and d)* incisors were subjected to cumulative restorative procedures (endodontic treatment followed by Class 3 restorations) followed by simulated aging (thermocycling 1000× at 5°C to 55°C) and impact testing (catastrophic palatal load at incisal edge, notched palatal surface). Note the similar fracture pattern. Both teeth behaved like cantilever beams. Due to the stress distribution within the tooth, cracks did not propagate horizontally but obliquely by respecting the facial compressive stress area (see Fig 1-5b). Crack propagation in the restored tooth *(c and d)*, however, followed a characteristic path that precisely avoids the dentin-bonded veneer. A significant amount of dentin cohesively failed *(d)*, leaving the restoration intact and uncracked. The restoration was made of feldspathic porcelain.

*The veneered specimen in Figs 1-17c and 1-17d was initially prepared by completely removing enamel from the buccal surface, reducing the incisal edge by 1.5 to 2 mm, and creating a moderate interdental wrapping (penetrating half of the proximal surface). A special dentin bonding procedure (immediate dentin sealing) was then used[10] (see also chapter 6, Fig 6-45). The extensive removal of enamel and dentin exposure is not a traditional approach for veneer preparation. This risky experimental design was chosen to create a maximum challenge for the tooth-restoration complex.

From Figs 1-15 and 1-17, it is easy to understand the impact of the biomimetic principle, which logically leads to analysis of which materials can best simulate the behavior of enamel and dentin. Part of this approach is represented in Table 1-1.[37–46] Simple feldspathic porcelain can be compared to enamel. ***It is important to note that the weakest dental ceramics (ie, feldspathic porcelain) have a higher ultimate tensile strength than natural enamel. High-strength materials such as PFM and reinforced ceramics do not seem to be required to comply with the biomimetic principle.***

Wear properties (abrasiveness) of feldspathic materials, however, remain a concern,[47] especially for full coverage of lateral segments of the dentition, as well as inlays and onlays. In this regard, new hybrid materials (eg, CAD/CAM resin-infused ceramics; see chapter 4, Fig 4-9) might bring significant improvements in the future. On the other hand, porcelain veneers might not subject opposing teeth to significant wear problems because of the conservative nature of the treatment; the palatal and functional side of the tooth often remains intact.

The closest substitute for dentin is represented by micro- and nanohybrid composite resins, due to their similar elastic modulus. Most composite resins, however, develop shrinkage stresses and exhibit high thermal expansion (up to 4× the thermal expansion of the natural tooth or porcelain). This might become problematic when combining thin layers of porcelain and luting composites, especially when thick die spacers (> 200 µm) are used during the fabrication of the restorations.[48]

The most challenging parameter is the simulation of the DEJ, the complexity of which seems to be out of reach.[18,19] Nevertheless, progress in adhesion has allowed improvement in the integrity of the tooth-restoration interface (see Figs 1-17c and 1-17d; see also next pages and chapter 4, Fig 4-17).

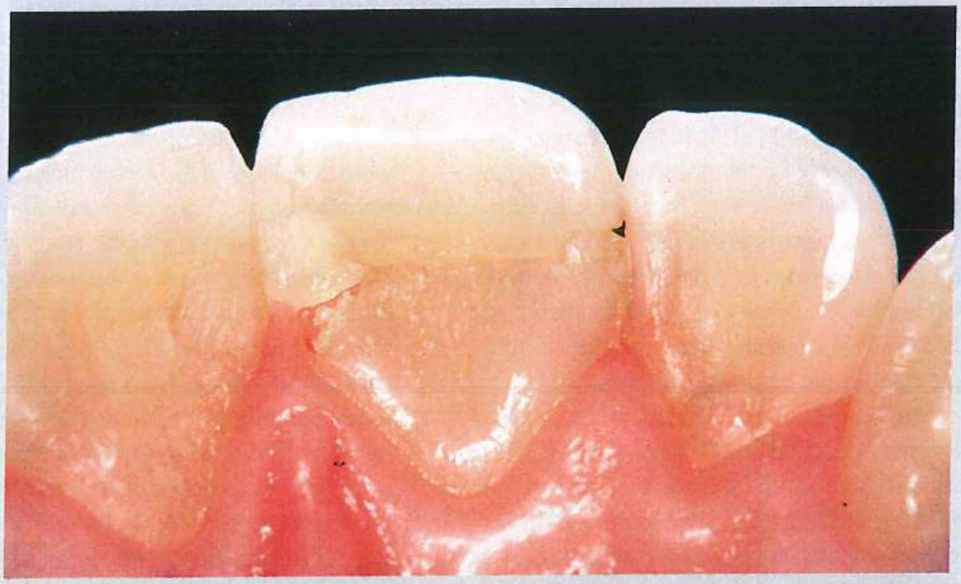
Applying the biomimetic principle, it seems reasonable to conclude that new restorative approaches should aim to create not the strongest restoration but rather a restoration that is compatible with the mechanical, biologic, and optical properties of underlying dental tissues.

While the combination of ceramics and composite resins seems to represent the finest biomimetic pair, it may not always be the most cost-effective choice. For some patients with limited finances, the sole use of composite resins can help resolve a number of problems "semi-biomimetically." These approaches are extensively covered in chapters 3 and 4. ***When considering a single material, composite resins, with their dentinlike elasticity and almost enamellike wear (see Fig 4-7), constitute a prime choice.***

TABLE 1-1 Physical properties of dental hard tissues and corresponding biomaterials

	Elastic modulus (GPa)	Thermal expansion coefficient (×10⁻⁶/°C)	Ultimate tensile strength (MPa)		Corresponding material	Elastic modulus	Thermal expansion coefficient	Ultimate tensile strength
Enamel	~80[37]	~17[38]	~10[39]	→	Feldspathic porcelain	~60–70[40]	~13–16[41]	~25–40[42]
Dentin	~14[43]	~11[38]	~105[43]	→	Hybrid composite resins	~10–20[44]	~20–40[45]	~40–60[46]
DEJ	–	–	–	→	Dentin adhesives	–	–	–

All values are approximations. A detailed presentation of composite resins is provided in chapter 3, Figs 3-32 and Table 3-3.



1-17e

1-17f

FIG 1-17 *(cont) (e and f)* The in vitro simulation in parts *a* to *d* appears to be clinically relevant, as illustrated by this case of fracture; a crack started in the palatal concavity and propagated obliquely toward the facial aspect of the root. (Courtesy of Dr L. N. Baratieri et al, Federal University of Santa Catarina.) The similarity between parts *a* and *f* is striking. Such a clinical situation is not anecdotal, as demonstrated by Baratieri et al.[49]

The "trinity" of resin bonding

A good understanding of Table 1-1 can lead to the successful application of the biomimetic principle only if the union of enamel and dentin through the DEJ can be mimicked. This biologic adhesion (DEJ) has been quantified by standard tests used to assess resin bonding, the microtensile bond test (MTBS), and has been estimated at 51.5 MPa.[50] The same study concluded that contemporary resin bonding systems can reproduce this bond strength. The DEJ is the cornerstone of the functioning of the natural tooth.[19] By the same token, dentin and enamel bonding can potentially eradicate the principles of retention and resistance form (including dentin pins and endodontic posts) and enable the principle of absolute preservation of healthy tissue even in the most desperate situations on anterior and posterior teeth.[51–54]

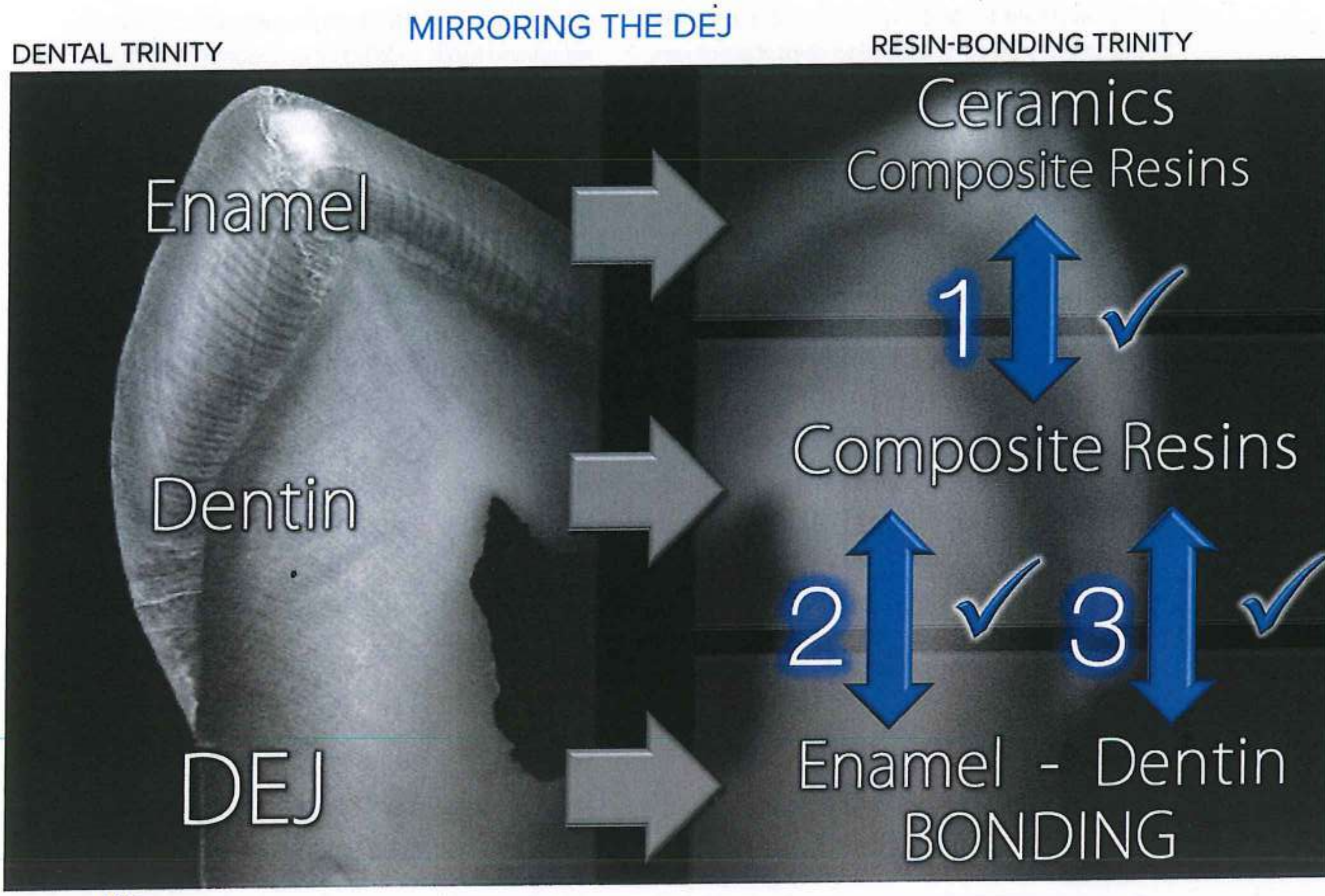
The application of the biomimetic principle requires a deep knowledge of the principles of adhesion to tooth structure in order to replicate the structural continuity between the enamel and the dentin. Composite resins are the centerpiece of this "Trinitarian" adhesion, because they allow the union between the restorative material and the tooth. Three adhesive interphases must be considered (Fig 1-17g, *blue numbers and arrows*):

1. **Resin bonding to the restorative material** (either ceramic or composite resin) can be predictably mastered by a methodical approach comprising micromechanical retention and chemical coupling (explained in chapter 4, Figs 4-20 to 4-23). Each type of material requires specific conditioning methods to achieve those goals (see chapter 4, Table 4-5). Unfortunately, there is much confusion created by the brand name of some products (eg, use of the word "nanoceramics" or "hybrid ceramics" to designate composite resin materials).
2. **Resin bonding to enamel** by acid etching and wetting through low-viscosity resin is recognized as being stable and reliable. It is important to know that enamel, once etched, remains fragile. Gentle care and handling of the microbrush is required in order not to damage the brittle prisms of hydroxyapatite while conditioning the dentin or even during the application of the adhesive on the enamel itself (explained in chapter 3, Fig 3-28a). It is also important to bevel margins to obtain cross-sectioned hydroxyapatite prisms for optimal bonding, particularly in the interdental area (see chapter 3, Fig 3-51a).
3. **Resin bonding to dentin** remains a controversial subject. The reason is that there is an overwhelming number of adhesive systems on the world market and many of these systems lack proven and established clinical follow-ups. Adhesive systems are the perfect example of the commercial plethora and a dental market guided by the competition between different brands and not clinical performance. Thus, some dentin adhesives are developed and promoted for the sole purpose to target the market of a competing brand. The tenets of dentin bonding are explained in chapter 3 (see Fig 3-28b). Some of the greatest advances of recent decades have been the use of the immediate dentin sealing (IDS) technique (chapter 4, Fig 4-17) and the understanding of the detrimental effect of oxygen inhibition (including bleaching agents) on the polymerization of thin resin layers. Isolation techniques are also fundamental, as well as always bonding to a clean and freshly cut dentin surface.

Intricate mimicking of the DEJ implies that the surface of the freshly cut dentin must be as rough as possible (see DEJ roughness in Fig 1-10a) to increase the bonding surface. It implies cutting with a rough diamond at low speed immediately followed by acid etching to remove the smear layer and allow the complete infusion of the demineralized collagen layer by the primer to form a homogenous dentin-resin hybrid layer.

While MTBS values of some dentin bonding systems (three-step etch-and-rinse; see chapter 3, Fig 3-29a) can easily match and even exceed that of the DEJ, it is the stability of that bond that is in question, especially with the more recent generations of products. This prompted the use of chlorhexidine (after etching) to inhibit the enzymes (matrix metalloproteinases) responsible for the degradation of the collagen.

In the biomimetic approach, the following equation can be written: The more predictable the resin-bonding trinity, the less the need for strong materials; inversely, the less efficient the bonding strategy, the more the need for strong materials along with retention and resistance form of the preparations. In most cases, the operator is the main variable in this equation.



1-17g

FIG 1-17 *(cont) (g)* **Enamel and dentin form a continuous entity through the DEJ.** The essence of the biomimetic principle is to mimic this continuity. Three interfaces must be considered, all of which depend on adequate resin bonding. Hence, the centerpieces of this bonding "trinity" are the composite resins (either used as direct restoratives or as luting agents for semidirect and indirect techniques), which must be predictably adhered to ceramic/composite resin workpieces (1), to enamel (2), and to dentin (3).

Limitations of alloy restorations—Amalgam ban

Patients' requests and clinicians' interest in esthetic restorations are not limited to anterior teeth. As a result, posterior "tooth-colored" adhesive restorative techniques have become a standard in recent decades. Clinical studies,[55] common sense, and clinical experience have validated the use of bonded tooth-colored restorations, and the "post-amalgam era"[56] started along with the new millennium, proving that the modern goals of restorative dentistry could not be achieved with traditional materials and techniques (Table 1-2 and Figs 1-18 to 1-24). ***A ban on the use of mercury, including dental amalgam, was announced in 2008 by Norway, Sweden, and Denmark. In Norway, the reason for the ban was the risk that mercury from products may constitute for the environment. Because satisfactory alternatives to mercury in products were available, the ban was deemed appropriate.*** Curricular changes in the dental schools at the University of Zurich and University of Geneva (Switzerland, where the first author graduated in 1989) had started almost 30 years ago. By the new millennium, most European schools started to abandon the teaching of amalgam.[57,58] Even young patients displayed a preference for tooth-colored alternatives.[59] Hence, pediatric dentistry was not excluded from this phenomenon.[60]

From an academic perspective, shifting from amalgam to tooth-colored materials in teaching the restoration of posterior teeth was a complete change in treatment philosophy[58] and was found to have a considerable enriching effect on the dental curriculum.[57] The principal reasons for the shift from dental amalgam to adhesive dentistry with composite resins at Nijmegen Dental School (the Netherlands) were the reduced need for preparation and the strengthening effect on the remaining tooth. In 2010, Niek Opdam et al, from the same school, published a long-term clinical survival study of large amalgam and composite resin restorations,[61] proving that even large composite resin restorations (up to three and four surfaces) showed a higher survival in the combined population (high and low caries risk) and in the low caries risk group. Most interestingly, the study revealed the significant problems of fracture of the tooth and the restoration as well as the cracking of the tooth associated with amalgam (Table 1-2).

TABLE 1-2 Results of a 12-year survival study of large composite resin vs amalgam restorations

	Amalgam						Composite					
	All risks		High caries risk		Low caries risk		All risks		High caries risk		Low caries risk	
	%	n	%	n	%	n	%	n	%	n	%	n
Clinically acceptable	75.6	909	62.8	157	79.0	752	84.7	633	66.8	137	91.5	496
Secondary caries	5.7	69	14.0	35	3.6	34	6.6	49	19.0	39	1.8	10
Primary caries	1.1	13	3.2	8	0.5	5	1.6	12	3.9	8	0.7	4
Fractured tooth	5.9	71	5.2	13	6.1	58	1.3	10	2.4	5	0.9	5
Fractured restoration	0.9	11	1.2	[illegible]	3.8	8	0.9	7	1.[illegible]	[illegible]	0.7	4
Cracked tooth	4.5	54	1.6	4	5.3	50	0.1	1	0.0	0	0.2	1
Endo/pain	2.5	30	4.8	12	1.9	18	3.5	26	3.9	8	3.3	18
Other	2.2	27	4.0	10	1.8	17	0.9	7	2.4	5	0.4	2
Unknown	1.5	18	3.2	8	1.1	10	0.3	2	0.0	0	0.4	2
Total	100.0	1202	100.0	250	100.0	952	100.0	747	100.0	205	100.0	542

Note that besides the outstanding survival of composite resin restorations, the fracture and cracking of the tooth amounts to a total of 10.4% for amalgam restorations vs 1.4% for composite resin ones. (Reproduced with permission from Opdam et al.[61])

1-18a

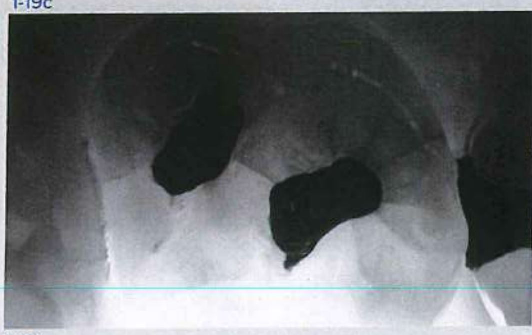
1-18b

1-19a

1-19b

1-19c

1-19d



1-19e

FIG 1-18 The hidden face of amalgam revealed. *(a and b)* Natural history of an amalgam-restored tooth: Despite the fact that only a limited amount of the occlusal surface has been opened, this maxillary first molar presents with significantly undermined cusps and cracks at the cusp base, jeopardizing the stability of this tooth.

FIG 1-19 Cracked tooth syndrome. *(a)* This patient presented with significant pain to hot/cold air or fluids and biting localized on the maxillary first molar. *(b and c)* Absence of cusp stabilization by the amalgam restoration has resulted in cracking at the base of both buccal and lingual cusps. (Reproduced with permission from Magne.[56]) *(d)* Another example of multiple cracks clearly originating and radiating from small amalgam restorations; the cracks radiate ("star-like" crack) from the center of each occlusal restoration, as evidenced in the transillumination *(e)*.

Pediatric dentistry during community service to underserved populations can be challenging, and amalgam is sometimes considered most adequate because of its simplicity of use. When it comes to primary molars, however, adhesive tooth-colored materials keep the same promises of more conservative preparations, maintaining more tooth structure.[62,63] Another approach is the use of glass-ionomer cements and in particular the resin-modified types. Their properties make them almost ideal for pediatric dentistry. Both composite resin and resin-modified glass ionomer serve well in pediatric dentistry.[64] By the turn of the millennium, patients' parents in Switzerland, Belgium, Denmark, Netherlands, Norway, Germany, and Sweden usually either asked or insisted that materials other than amalgam be used in their children.[65] Already in 2004,[66] composite resin and resin-modified glass ionomer were considered the materials of choice by 40% of California pediatric dentists.

At the other end of the spectrum of indications for tooth-colored restorations is the replacement of gold inlays and onlays (Figs 1-20 and 1-21). The conservative nature of gold alloy restorations calls for a conservative alternative. Recent data is showing that thin composite resin restorations may substitute for thin gold onlays without further sacrifice of intact tooth substance (Fig 1-21).[67,68]

1-20a

1-20b

FIG 1-20 Fractured cusp under a gold inlay. *(a and b)* The lack of cusp stabilization is also found in gold restorations. Because of the nonretentive design of preparations for gold inlays, a wider cusp base is maintained (compared to the undermined cusps left by amalgam preparations), which may explain why such failures are less common with this type of restoration.

FIG 1-21 Ultraconservative replacement of a gold onlay. *(a and b)* This gold onlay lost retention perhaps due to remaining decay at the level of dentin *(c)*. The preparation could be cleaned out extremely conservatively (no further enamel prepared), and the exposed dentin was sealed (IDS, see chapter 4, section 4.4) followed by the application of a localized composite resin base *(d)*. An indirect composite resin overlay was produced *(e)* and adhesively placed *(f*, postoperative view). *(g and h)* Postoperative views during the third year of clinical service.

1-21a

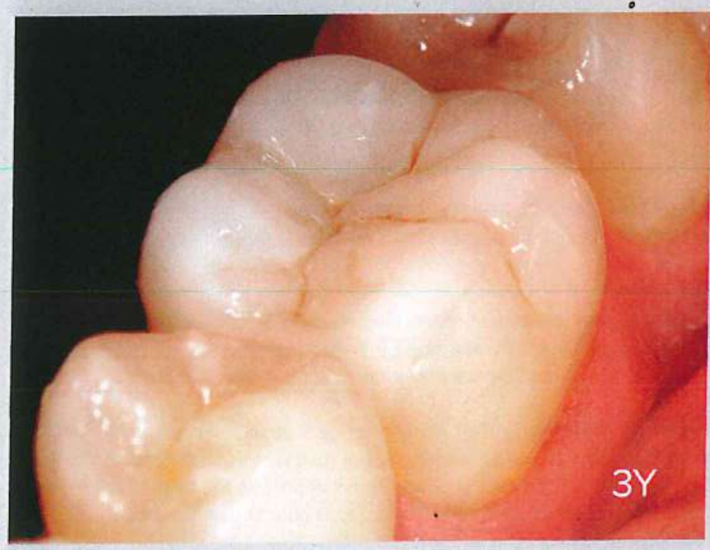
1-21b

1-21c

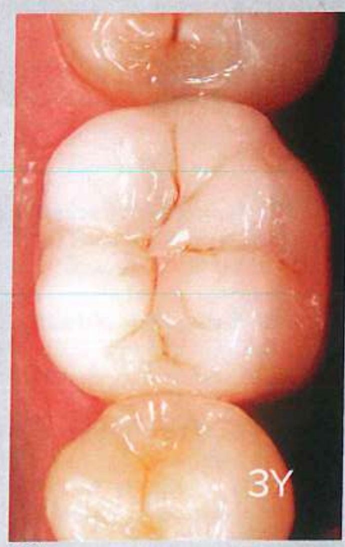
1-21d

1-21e

1-21f



1-21g



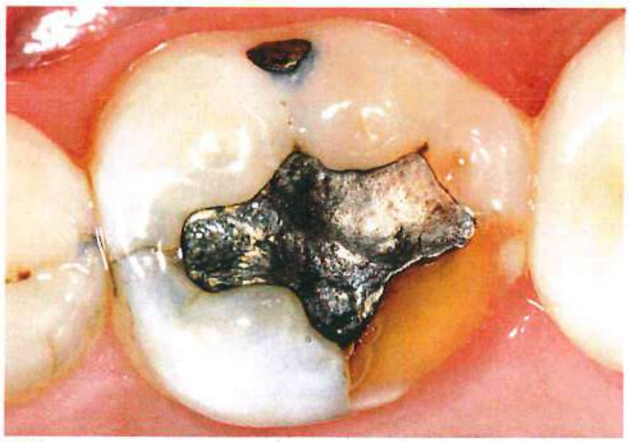
1-21h

Tooth's circle of death

Extending the interdental preparation to the facial and lingual and allowing for "self-cleansing" margins was G. V. Black's concept of "extension for prevention." Extending preparations through fissures and grooves and obtaining margins beyond fissured enamel was also part of Black's 1891 idea. This concept is no longer acceptable today even for amalgam restorations.[69] The so-called "molar life cycle,"[70] also called *tooth's circle of death* (Fig 1-22), corresponds to a series of unfortunate events starting with a small proximal lesion treated with Black's concept and a proximo-occlusal amalgam restoration (Fig 1-23, stages A and B). The next stage is the fatigue failure of weakened cusps (Fig 1-23, stage C).[71] Because this approach is characterized by the lack of belief in adhesion, it leads to the increased need for extracoronal resistance form (Fig 1-23, stage D) and root canal therapy in order to obtain intraradicular retention and a stiff preprosthetic buildup (Fig 1-23, stages E and F). The circle logically reaches its most dramatic stage when serious interferences occur with periodontal health (Fig 1-23, stages G and H) due to the necessity to hide the crown margins and provide sufficient preparation height. The circle is complete when the tooth is replaced with a dental implant (Fig 1-23, stage I).

Fortunately, early placement of adhesive restorations with or without cuspal coverage has been demonstrated to be able to stop this dramatic circle at stage C and provide successful treatment for painful cracked teeth (Fig 1-24).[72]

1-22a

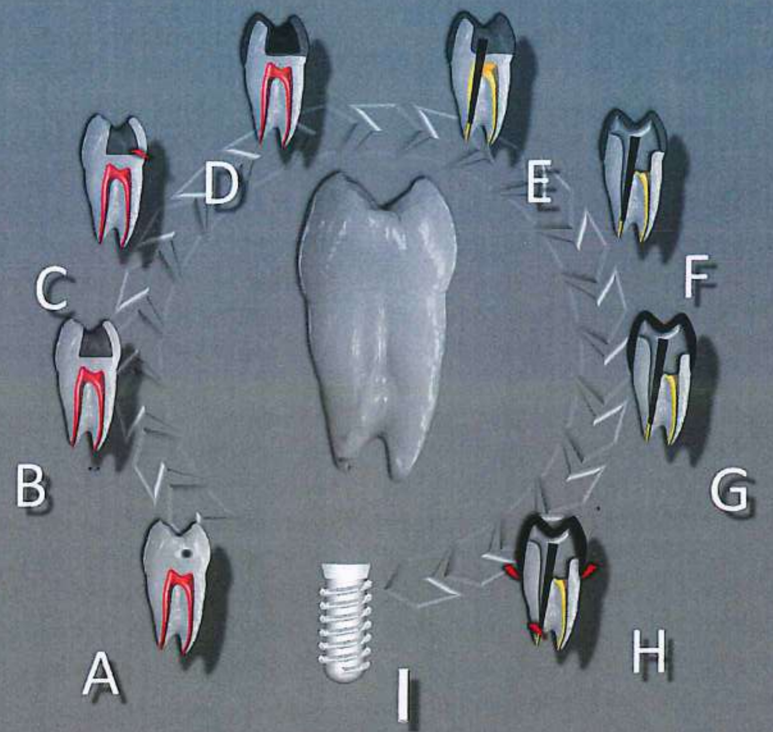


1-22b

FIG 1-22 Typical tooth fracture under amalgam. This patient presents with multiple amalgam restorations *(a)* and is consulting on a regular basis because of recurring cusp fractures *(b)*. When handled inappropriately, this may initiate the so-called "molar life cycle."[70]

FIG 1-23 Tooth's circle of death. A, interdental caries. B, mechanically retained amalgam. C, cusp cracking. D, cuspal coverage lacking mechanical retention. E and F, mechanical retention by endodontic therapy and post-and-core buildup. G, extracoronal strengthening. H, periodontal interference and root cracking. I, dental implant.

FIG 1-24 Long-term success of adhesive restorations. *(a)* This minute occlusal amalgam generated significant cracks at both mesial and distal marginal ridges, followed by secondary decay. *(b)* It was treated successfully with a direct MOD composite resin restoration (clinical view at 7th year of clinical service) despite the high functional loads (note the wear facets). (Reproduced with permission from Magne.[56]) *(c)* Restorations after 14 years (occlusal, first molar) and 20 years (OD, second premolar) of successful service. The layering of the first molar is detailed in chapter 3, Figs 3-59a to 3-59f.



1-23


1-24a

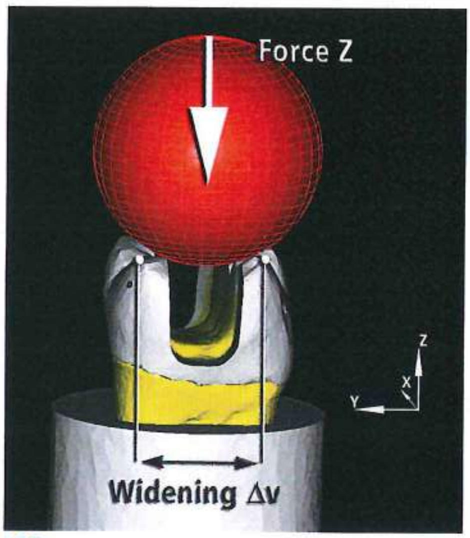
1-24b

1-24c

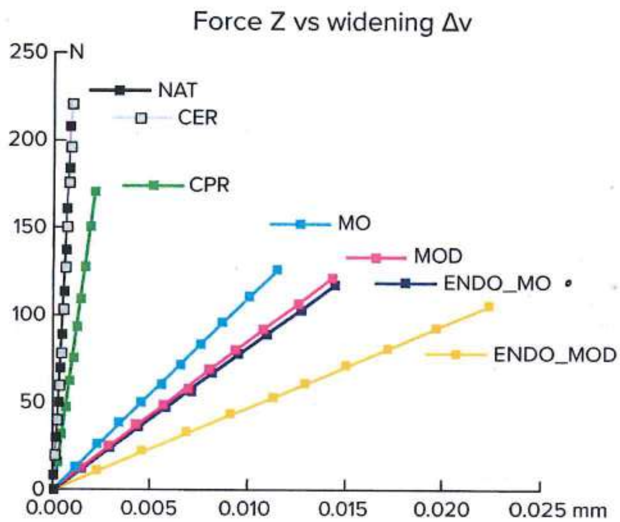
Cusp reinforcement by the acid-etch technique

As previously mentioned, ***on the one hand the tooth crown is made more deformable by certain restorative procedures, and on the other hand cusps can be strengthened by increasing their resistance to crown deformation*** (Figs 1-25 and 1-26). The above statement is the conclusion of numerous studies about the biophysical stress analysis in the posterior dentition.[27–30,73] The study and understanding of cuspal flexure and plastic yielding is paramount to explain the performance of the tooth-restorative complex. Morin et al can be credited first for their classic work, "Cusp reinforcement by the acid-etch technique," in 1984.[34] They demonstrated the existence of subclinical cuspal microdeformation below the threshold of chairside observation.[29,30] Intact posterior teeth demonstrate cuspal flexure due to their morphology and occlusion. Cuspal movement (under occlusal load) can be increased by restorative procedures (Tables 1-3 and 1-4),[74] resulting in altered strength, fatigue fracture, and cracked tooth syndromes.[24–26] The most typical example of cyclic fatigue crack growth is found under amalgam restorations (see Fig 1-22). Various forms of full or partial coverage[31,33] and conservative adhesive techniques (see Fig 1-24)[35,36] allowed considerable development of methods for improving fracture resistance of teeth.

Recently, modeling and virtual prototyping techniques (Figs 1-25 and 1-26)[75–77] have replicated the previous experiments.[78–82] As expected, it is concluded that the most conservative approach should be favored, two-surface preparations rather than MOD (Fig 1-26 and Table 1-3), allowing for the recovery of cuspal stiffness through the use of adhesive techniques.



1-25a



1-25b

FIG 1-25 Molar cuspal deformation and related stresses. (Reproduced with permission from Magne[75]; see also Table 1-2). *(a)* Contact analysis between a rigid load sphere (moving along the *z* axis against the tooth) and a deformable tooth at various restorative steps. *(b)* The widening of the cusps (in mm) is presented as a function of the load (N) applied to the sphere. There is a linear relationship, the slope of which indicates the cuspal stiffness. Note the severe alteration of cuspal stiffness of the various preparations (MO, MOD with and without endodontic access) and the very similar cuspal stiffness of the intact tooth (NAT) and MOD composite resin restoration (CPR) and MOD ceramic inlay (CER). *(c)* First principal stress distribution in four of the seven models studied. To allow for better comparison of the stress pattern, the MOD insert of enamel and dentin (model NAT) or the MOD ceramic restoration (model CER) were made invisible. *Colors* = tensile stresses; *gray* = compressive stresses. Note the similarity between NAT and CER.

TABLE 1-3 Molar cuspal deformation at 100 N according to various studies

Experimental condition	Widening Δv (microns) at 100 N load (force Z)			
	FEA[75]	Panitvisai and Messer 1995[78]	Jantarat et al	
			2001a[79]	2001b[80]
NAT (intact tooth)	0.4	< 1	< 2	–
MO (MO cavity)	9.1	6	–	–
MOD (MOD cavity)	11.8	10	6–10	–
ENDO_MO (MO cavity + endodontic access cavity)	12.3	14.4	–	–
ENDO_MOD (MOD cavity + endodontic access cavity)	21.3	28.8	24–32	17–18
CER (MOD ceramic inlay)	0.4	–	–	–
CPR (MOD composite inlay)	1.3	–	–	–

TABLE 1-4 Premolar cuspal deformation at 150 N according to various studies

Experimental condition	Widening Δv (microns) at 150 N load (force Z)		
	FEA[77]	Gonzáles-López et al	
		2006[81]	2007[82]
NAT (intact tooth)	2.7	2.6	2.9–3.7
MO (MO cavity)	5.0	7.2–8.0	–
MOD (MOD cavity)	179.4	114.4	–
SLOTS (M + D cavities)	5.4	–	–
MO_CPR (MO composite)	3.5	–	3.3
MOD_CPR (MOD composite)	6.9	–	8.5
SLOT_CPR (M + D composite)	3.8	–	–

1.9 COPYING VS SIMULATING NATURE

It is not always possible to biomimetically emulate nature. Significant alterations of the teeth and periodontium due to disease and aging can result in irreversible losses of structure and integrity. Those alterations can have complex interactions, affecting the balance between biology, mechanics, and esthetics. For instance, interdental bone loss, which starts as a biologic problem, will generate esthetic and morphologic alterations (ie, black triangles).

Hence, restorative dentate cases can be classified in at least two degrees of emulation:

1. When the periodontium is intact (original scalloped architecture) and the teeth are vital and in a reasonable position, it is possible to copy nature's morphology faithfully. In these cases, the biomimetic principle can be applied in full (Fig 1-27).
2. In situations with a history of periodontal disease (see chapter 6, Fig 6-7), in the presence of narrow roots or diastemas (Fig 1-28), or in the presence of an implant (Figs 1-29 to 1-31), the periodontium has lost its positive architecture and copying nature is no longer possible. In these cases, the irreversible biologic or structural loss must be compensated for by special effects included in the restorations. Those effects are not necessarily the result of the biomimetic principle. They can be in form of optical illusions, morphologic alterations[84] (eg, the miniwing concept to close interdental triangles; see chapter 6, Figs 6-6 and 6-7), or masking procedure (to prevent color changes in nonvital teeth; see chapter 6, Fig 6-16).

The two restorative situations in dentate patients are therefore:

1. **Copy-only situation:** vital teeth and periodontium intact; the biomimetic principle can be applied as a whole (no special effects needed, such as miniwings).
2. **Simulation situation:** nonvital teeth, periodontal architecture altered; the biomimetic principle is not entirely applicable and special effects must be used.

FIG 1-27 Copy-only biomimetic case. Maxillary anterior teeth before *(a)* and after *(b)* placement of six porcelain veneers to restore enamel volume and length. No morphologic alterations were applied because the periodontium is continuous with the teeth (no black triangles).

FIG 1-28 Special effect—miniwings. Case of diastema closure using a porcelain veneer that required a subgingival preparation (with a deflection cord) and the use of the miniwing concept both on the veneer itself and the neighboring teeth. Direct composite resin restorations were used to close small residual triangles with the canine and the central incisor. *(a)* Note the minuscule space at the cervical embrasure between the periodontal probe and the central incisor. *(b)* The composite resin miniwing closes that space and converts the interdental contact point into a contact line extending near the papilla, hence closing the gap with the bone crest to a range of about 5 mm that will ensure the stability of this papilla.[83] Note the alteration of the original morphology of the tooth with opaque and more saturated interdental additions. *(c to e)* Either composite resin or ceramic (in the case of veneers and crowns) can be used. Other views of this case are found in chapter 6 (Fig 6-6). A very similar case with implants and veneers is presented in Fig 1-31.

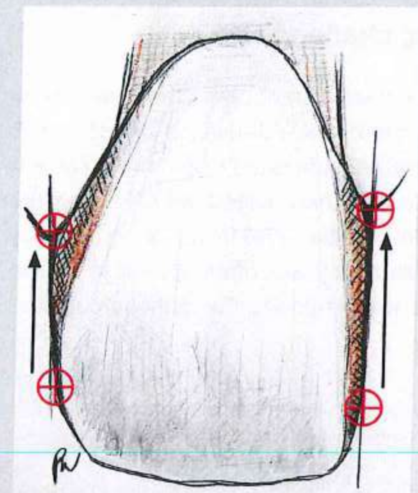

1-27a


1-27b


1-28a


1-28b


1-28c


1-28d

1-28e


1.10 BIOMIMETIC IMPLANT RESTORATIONS

Implant-supported restorations constitute a well-accepted treatment concept in fixed prosthodontics. While the topic of implant dentistry is beyond the scope of this work, it is worth considering some aspects of the biomimetic principle that could be used to restore dental implants in the future.

The primary biomimetic "effect" of dental implants lies in the fact that they allow intact teeth (next to the edentulous area) to be spared from being prepared for a fixed partial denture. Apart from this indirect biomimetic effect, dental implants may suffer esthetic and biomechanical challenges. Unfavorable bone architecture, the absence of periodontal ligament, and the lack of flexibility of the implant itself are the main tenets preventing the biomimetic integration.

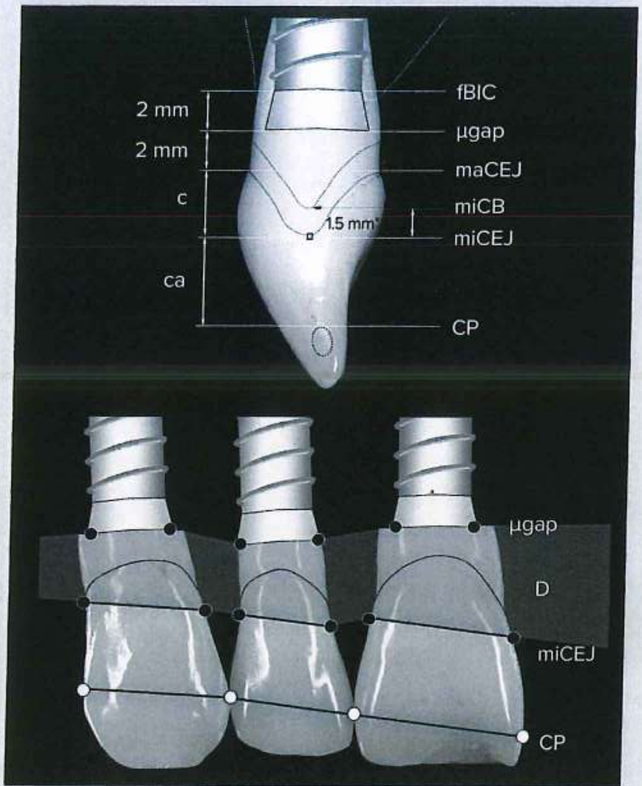
Esthetic challenges

From an esthetic standpoint, there are major challenges to be expected in the long-term with anterior implant-supported restorations. Zachrisson pointed out that implants are not always the best treatment alternative for replacing maxillary incisors, and clinicians often appear to be too optimistic with regard to the esthetic outcome from a long-term perspective.[85] A lifetime of maintenance and care has to be expected and potential problems over time include darkening labial gingivae, progressive infraocclusion (even in mature adults), and gingival recession with fixture exposure.

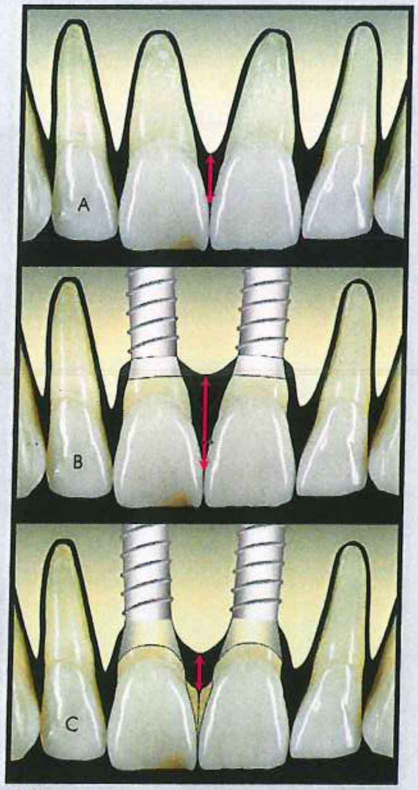
One of the main discrepancies between teeth and implants lies in the morphology and dimensions of the biologic width.[86] Most implant designs have a flat, rotation-symmetric shoulder that is in complete incongruity with the scalloped nature of the cementoenamel junction (CEJ; Fig 1-29).

As a result, immediate esthetic challenges include the management of interdental black triangles (Figs 1-30 and 1-31). Loss of interdental papilla can result in black triangles that need to be managed with an extreme consideration for the miniwing concept as explained in Fig 1-28 for "simulation" cases. Multiple adjacent implants are even more challenging in this regard and might call for the development of a scalloped platform to complement the effect of the miniwings (Fig 1-29b).

FIG 1-29 Tooth-implant CEJ incongruencies. *(a)* Simulation of traditional implant placement superimposed with a proximal view of a natural tooth *(top)*. fBIC, first bone-to-implant contact; µgap, microgap (implant-abutment junction); maCEJ, most apical point of the CEJ; miCB, most incisal point of the crestal bone level; miCEJ, most incisal point of the CEJ; CP, most apical point of the interproximal contact surface; c, ca: CP to miCEJ distance. *(bottom)* Schematic view of tooth-implant discrepancies (D, translucent surface). Implants are placed ~2 mm apical to the most apical point of the buccal CEJ contour. There is a constant distance between the most apical point of the contact surface (CP) and the most incisal point of the proximal CEJ within the same tooth (mesiodistal comparison). *(b)* Tooth/implant-to-bone relationships. *Red arrows* symbolize the distance to be filled by soft tissues (biologic width) between central incisors. A, schematic situation with natural teeth only. B, schematic situation with adjacent standard implants. Deeper placement is performed to allow for appropriate emergence profile and esthetics at the buccal surface but compromises the interimplant bone level. C, schematic situation with optimized esthetic implants. Both interimplant and buccal relationships are improved by the rootlike scallop-contoured transmucosal portion (abutment) and interdental miniwings (ceramic extension, *dashed areas*) at the proximal surface of coronal restorations, which also contribute to maintain a realistic biologic width. (Reproduced with permission from Gallucci et al.[86])

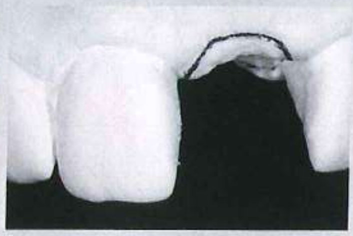


1-29a



1-29b

1-30a



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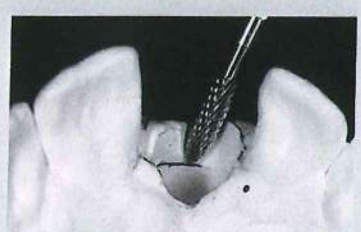

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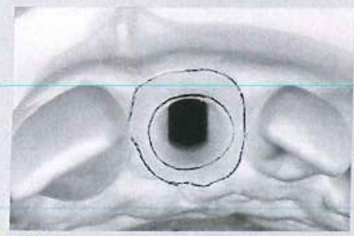

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FIG 1-30 Single implant restoration—miniwing dilemma. *(a)* The implant replacing the left central incisor has a scalloped platform. *(b to d)* The soft tissue was sculpted with a bur to provide a similar emergence profile as the contralateral natural tooth. Note the soft tissue cast with custom-made removable implant analog.[87] *(e and f)* A screw-retained provisional crown was designed to follow this shape and extend interdentally to form mesial and distal miniwings. Note that interdental closure is incomplete due to the lack of the miniwing structure on the intact adjacent tooth. The provisional restoration can be used as a guide to place a small composite resin addition in the form of a miniwing on the mesial surface of the right central incisor. (Images courtesy of Michel Magne, MDT.)

1-31a

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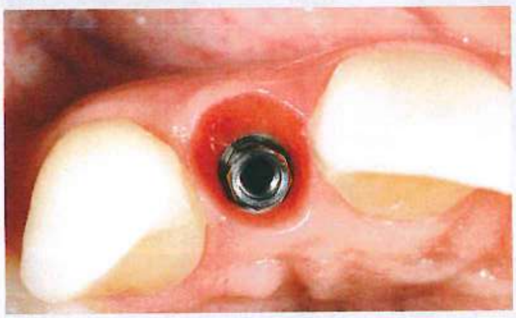
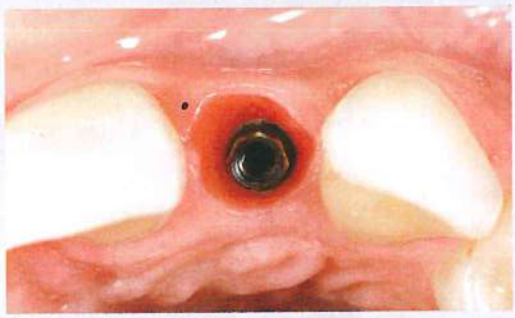
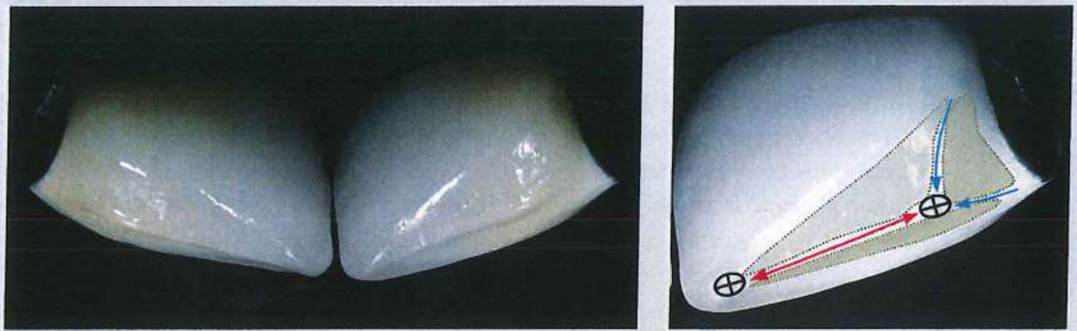


1-31g



1-31h

FIG 1-31 Multidisciplinary case—missing lateral incisors. *(a and b)* The patient is missing the maxillary lateral incisors, and the spaces are partially closed with old composite resin restorations. The treatment plan included reopening the spaces orthodontically (c, orthodontic setup), which was achieved successfully *(d)* and was followed by the implant placement guided by a wax-up and mock-up (not illustrated). *(e and f)* The central incisors and canines received first four porcelain veneers along with two screw-retained provisional crowns on the implants (modified soft tissue cast with removable custom-made implant analogs and removable dies for the veneers). The provisional crowns served both for tissue conditioning and interim restorations while the teeth with the veneers reached a stable shade (by rehydration and water sorption). *(g and h)* Note the beautiful conditioning of the peri-implant tissues and interdental contact lines →



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provided by the miniwings on the veneers. *(i)* The shade of the integrated veneer restorations was then used as a reference for the color of the final restorations on the implants. Note the substantial miniwing design to compensate for the missing papillary tissue. The miniwing is made of a more saturated and opaque porcelain (rootlike color) and presents the shape of a three-surface pyramid with the longest vertice representing the interdental contact line *(red arrow)*. *(j to l)* Final postoperative views (overlay image of preoperative situation for comparison) showing excellent integration and interdental closures. (Implant placement and surgery by Dr Jean-Pierre Ebner, Basel, Switzerland.)

Functional challenges

Schweiger et al[88] pointed at functional challenges and the problems of minor or major chipping of the veneering material on implant restorations because they are, in addition to other implant-related specificities, subjected to higher loads than those on natural abutment teeth. The general trend to prevent technical complications is the use of high-strength materials, but this does not resolve the problem of overloading. High forces transmitted to the implant components can potentially increase the risk of technical and biologic complications.

Possible biomechanical improvements

Can implant-supported restorations be more biomimetic? New trends have emerged with the use of replaceable veneers made from high-performance polymer material (HPP) on modified implant abutments.[88]

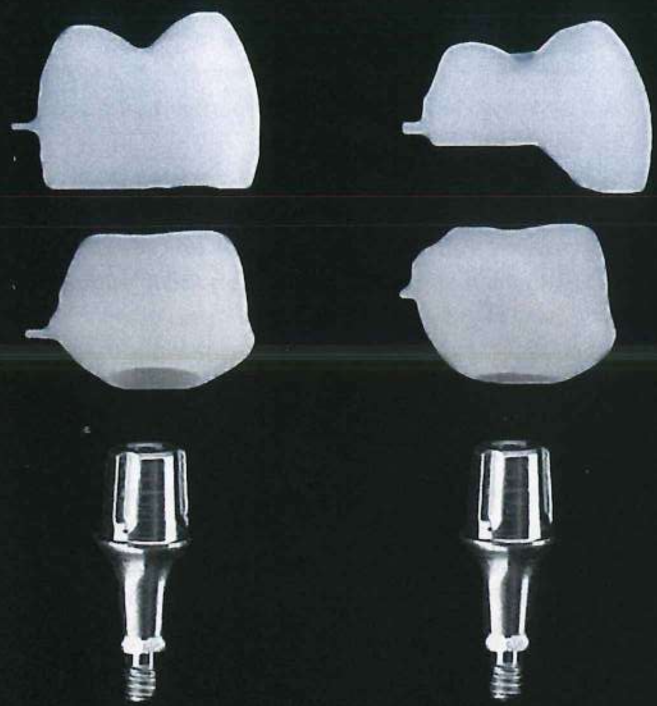
> In fact, it was demonstrated that including CAD/CAM HPP components in form of a veneer, onlay, or crown, and even as a mesostructure,[89,90] can substantially improve the dynamic response to loading (energy damping) to mimic the behavior of the natural tooth (Fig 1-32a).[91]

This strategy opened the door to bilaminar bonded assemblies through splitting files in the CAD/CAM approach (Fig 1-32b). Two different materials can be combined to follow the histo-anatomical structure of the tooth with a more compliant HPP core ("dentin") and a beautiful ceramic translucent veneer ("enamel").[92] ***The benefit of the bilaminar assembly is not only structural but also optical.*** Unlike zirconia, composite resin abutments can be easily prepared intraorally, allowing the immediate placement of an abutment in the form of a screw-retained CAD/CAM HPP dentinlike provisional restoration. Once the tissues are healed, the abutment can be directly prepared as needed (veneer, onlay, or crown) and restored with a bonded restoration. Because the abutment does not need to be removed or replaced, the mucosal barrier and the crestal bone are more likely to be preserved.[93] The possibility of using a nonretentive abutment design (such as a veneer or onlay) enables the treatment of cases with abnormal implant axis or location and allows resolution of situations with limited occlusal or interdental clearances (see chapter 6, Fig 6-13).[94]

Possible alternatives to implants

There are alternatives to single-tooth replacement in the anterior dentition with extremely successful long-term outcomes. Kern et al have pioneered the use of all-ceramic resin-bonded fixed dental prostheses (RBFDPs, Fig 1-33).[95–98] The original design included two-retainers; in a number of cases, unilaterally fractured connections were observed, but the prostheses kept functioning successfully. As a result, anterior single-retainer cantilever prostheses were used successfully by Kern et al since 1996. These results were confirmed in vitro with no difference found on the fracture strength between single- and two-retainer prostheses.[99]

FIG 1-32 Possible bilaminar adhesive designs for implant-supported restorations. *(a)* Titanium or zirconia bases can be used and assembled with various elements and designs. CAD/CAM files can be split for a crown or an onlay restoration with a composite resin mesostructure. *(b)* A histoanatomical design of the mesostructure[92] can be used to provide sophisticated optical effects of dentin mamelons and enamel opalescence by combining an opaque core with a translucent enamel veneer. (Part *a* reproduced with permission from Magne et al.[91])



1-32a

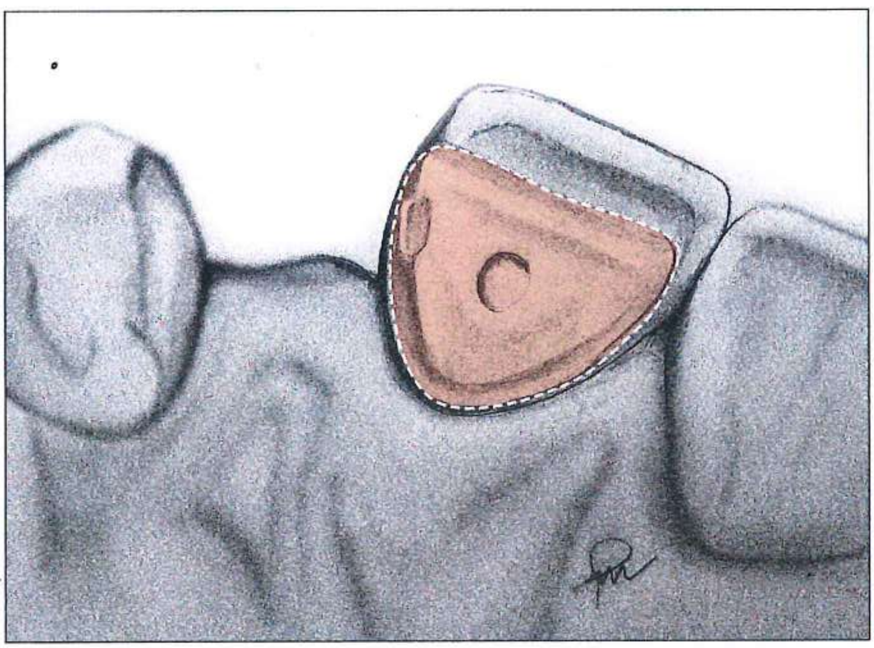
1-32b

Compared to the two-retainer prostheses, the single-retainer design makes it even more conservative, more rational, and easier to maintain (floss can be used normally on the open side), and it allows the immediate observation of retention loss. In addition, a diastema can be created in the case of excessive space for the pontic. The abutment tooth is prepared for a minimal lingual veneer, including the four following elements (Fig 1-33): *(1)* a shallow chamfer (0.2 mm) near the cingulum, *(2)* a shallow incisal chamfer/shoulder (0.2 mm), *(3)* a central lingual pinhole, and *(4)* a flat proximal box.

Densely sintered zirconia was originally preferred as a framework material for long-term success of RBFDPs. More recently, lithium disilicate glass-ceramic has demonstrated encouraging medium-term results (Fig 1-34),[100] but long-term studies are missing regarding RBFDPs. While zirconia will likely fail by debonding of the retainer wing, lithium-disilicate will rather fracture at the connector area due to its lower flexural strength (alike aluminum oxide) and high bond strength.[101–103] Only high-strength 3Y-TZP zirconia can be recommended; higher content of yttrium oxide to improve the optical properties (newer 4Y- and 5Y-TZP zirconia) reduces the mechanical properties after aging.[104]

The zirconia prosthesis is delivered under rubber dam. Enamel is air abraded and etched as for any bonding procedure. The retainer wing's fitting surface is also air abraded with 50-micron alumina particles and cleaned in an ultrasonic bath with 99% isopropanol. A phosphate monomer (MDP)–containing luting agent (eg, Panavia 21 TC, Kuraray) is applied to the ceramic surface, and the RBFPD is seated and held in position for 6 minutes (including excess removal and placement of an oxygen barrier).

If the principles of preparation, design, and adhesion are respected, even the replacement of canines and premolars appears to be predictable.[97] More posterior areas might require a double-retainer design depending on the connector surface and size of the missing tooth.[97,105]



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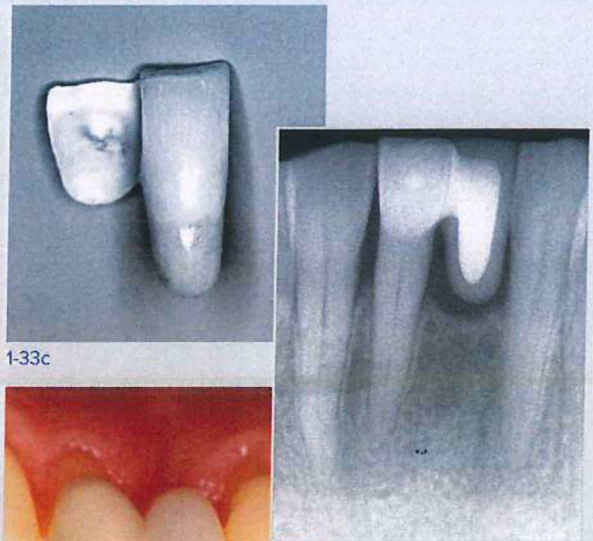

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FIG 1-33 Long-term result with resin-bonded fixed cantilever prostheses. *(a)* Lingual view (drawing) of single-retainer preparation including shallow chamfers, cingulum pinhole, and proximal box on the maxillary right central incisor. *(b)* Labial view of mandibular anterior teeth. The left central incisor cannot be preserved. The lingual surface of the right central incisor was prepared (shallow incisal shoulder, central pinhole, and slight mesial slice) followed by final impression taking. *(c)* After removal of the problematic tooth from the working model, the single-retainer cantilever prosthesis was fabricated with a 3-mm-deep ovate pontic design (dental technician Rainer Gläser, Freiburg, Germany), which was delivered under rubber dam isolation on the day of the extraction. *(d and e)* Postoperative views and radiograph *(overlay)* after healing of the tissues. *(f)* This prosthesis is still in function nearly 20 years later. (Images courtesy of Prof Matthias Kern, Kiel, Germany; reproduced with permission from Kern.[97])

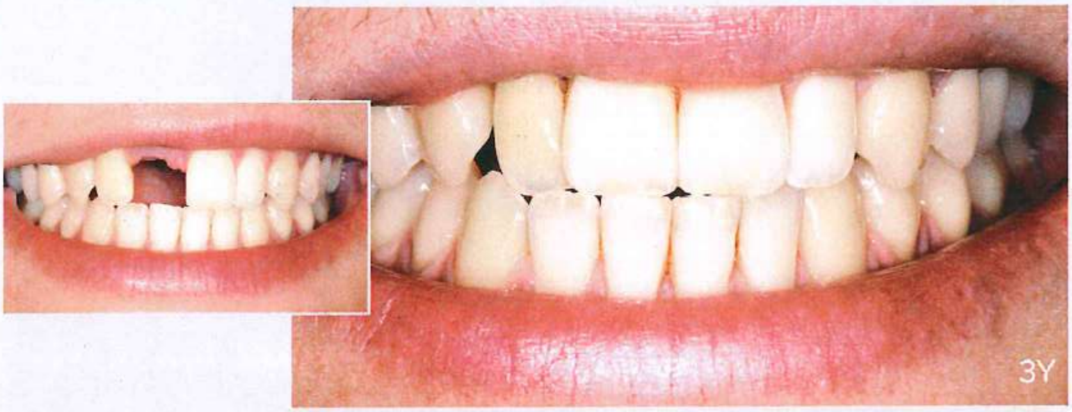

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FIG 1-34 Missing maxillary right central incisor replaced with a single-retainer cantilevered RBFDP. *(a)* Baseline and 3-year postoperative views of 25-year-old woman consulting for replacement of her missing maxillary right central incisor. *(b to d)* The comprehensive clinical and radiographic examination revealed substantial bone loss mesial of the maxillary right lateral incisor, as well as a marked deficiency of the alveolar bone crest profile on its facial aspect. Hence, implant therapy in the edentulous region would have required bone grafting and a staged surgical approach. *(e to g)* As this perspective was unacceptable for the patient, a single-retainer cantilevered RBFDP was chosen as an alternative treatment (laboratory work by Pascal Müller, Glattbrugg, Switzerland). The patient's minimal anterior overbite enabled a highly conservative approach in terms of abutment preparation and the use of lithium disilicate as the restorative material. Furthermore, it was possible to provide the cantilever pontic with an ovate design, facilitating daily use of Superfloss. Its incisal edge was deliberately slightly lengthened in comparison to the adjacent natural central incisor to comply with the more coronal incisal edge position of the right lateral incisor *(h)*. *(h to j)* Stable peri-restorative soft tissue conditions and favorable esthetic integration of the RBFDP can be observed at the 3-year follow-up examination. (Images courtesy of Prof Urs Belser, Geneva, Switzerland.)

Acknowledgments

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2 NATURAL ORAL DESIGN

Esthetic restorative procedures can be mastered consistently only if both clinician and ceramist are intimately familiar with the basic principles of natural oral design. The most significant criteria have been selected and are presented in this chapter in the form of a checklist for esthetic restorative success. This overview of esthetic principles is not limited to only tooth esthetics but includes gingival esthetics and the final esthetic integration into the frame of the smile, face, and, more generally, the individual. The goal of esthetic dentistry is not necessarily to objectively apply all esthetic criteria as presented in the checklist. As a matter of fact, a balanced smile seldom 100% fulfills this checklist but rather includes visual tensions that are carefully placed in a state of equilibrium. This subjective esthetic integration is also discussed and presented as an essential element of the balanced smile. The chapter concludes with a specific section dedicated to the detailed morphology of posterior teeth.

2.1 GENERAL CONSIDERATIONS

Fundamental esthetic criteria

A didactic presentation of oral esthetics should first include objective fundamental criteria related to soft and hard tissues, which can easily be controlled using an esthetic checklist[1] (Fig 2-1a). ***Both dental and gingival esthetics act together to provide a smile with harmony and balance. A defect in the surrounding tissues cannot be compensated by the quality of the dental restoration and vice versa.***

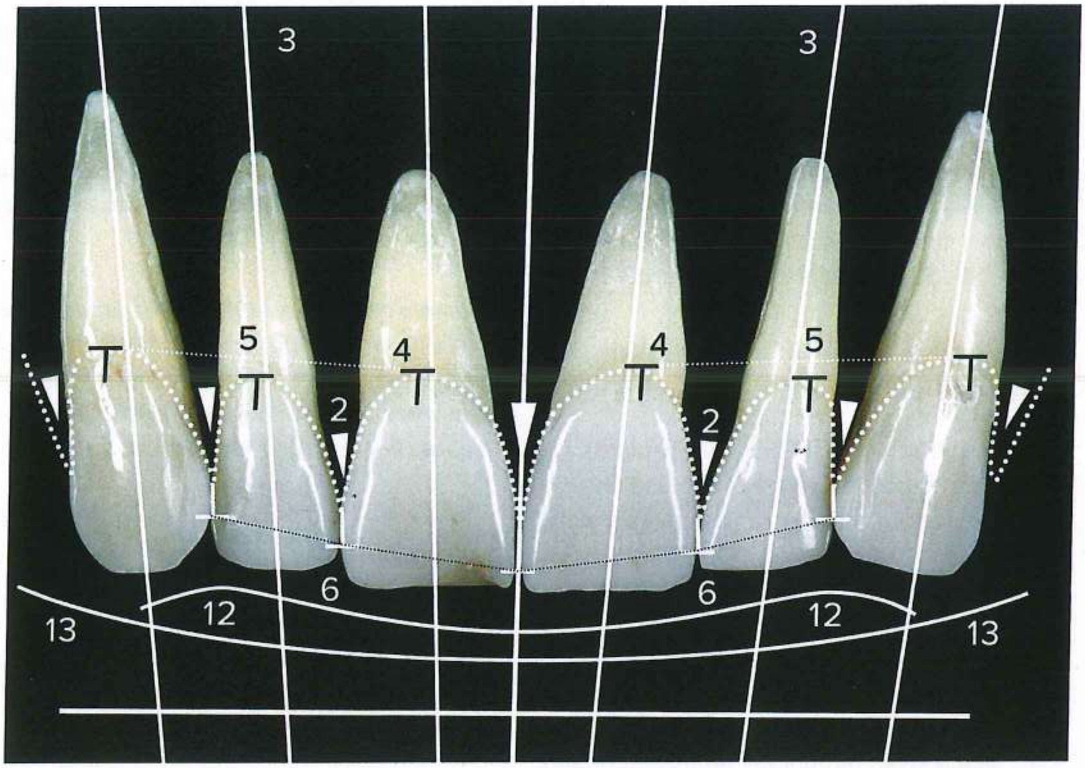
The fundamental criteria related to gingival esthetics are well established.[1–3] Both gingival health as well as gingival morphology have been included among the first parameters to be evaluated (criteria 1, 2, 4, and 5).

As far as characteristics of teeth are concerned, their relative importance among objective parameters has been prioritized as follows:

1. Form and dimension (criteria 7 and 8)
2. Characterization (criterion 9), especially opalescence, translucency, and transparency
3. Surface texture (criterion 10)
4. Color (criterion 11), especially fluorescence and brightness

Analytical observation of extracted teeth and natural teeth in vivo is essential to this didactic approach. Duplicating the specimens with dental stone can facilitate the appreciation of form and texture. The teeth themselves can be observed in transillumination to determine the effects of light reflection. Finally, selective grinding and sectioning have been used to create access to the internal structures of a tooth and to permit a better understanding of certain intense colorations inside the tissues, such as dentinal developmental lobes and zones of dentin infiltrations.[4]

Configuration of incisal edges as well as their relationship with the lower lip line and smile alignment are determinants for the age of the smile and are included among objective criteria (12 to 14).



2-1a

Fundamental objective criteria

1. Gingival health
2. Interdental closure
3. Tooth axis
4. Zenith of the gingival seam
5. Balance of the gingival levels
6. Level of the interdental contact
7. Relative tooth dimensions
8. Basic features of tooth form
9. Tooth characterization
10. Surface texture
11. Color
12. Incisal edge configuration
13. Lower lip line
14. Smile alignment

Subjective criteria (esthetic integration)

- Variations in tooth form
- Tooth arrangement and positioning
- Relative crown length
- Negative space

FIG 2-1a The esthetic checklist. (Modified with permission from Belser.[1])

It is important to understand, however, that the checklist is a subjective double-edged sword. On the one hand, it should help the dental team understand the goals of esthetic dentistry. On the other hand, if applied too strictly (symmetry and elimination of all imperfections), it can also lead to rather monotonous smiles lacking character—what patients often refer to as the "perfect" smile.

Subjective esthetic integration: Balance of the smile

Knowing that the esthetic result depends on the harmonious integration of the fundamental esthetic criteria with the smile and, ultimately, the character of an individual (see Fig 2-15),[5] it can be determined that ***there are at least two subjective ways of restoring a smile:*** **with *or* without *so-called "visual tensions*."**

Visual tensions can be defined as deviations from the original checklist. Classic examples are variations in tooth form, arrangement and positioning, and relative crown lengths, as well as fine-tuning of the so-called "negative space." While they can be regarded as "defects," they also provide charm and character when they are handled appropriately. These imperfections have different visual weight depending on where they are found.

Ultimate esthetics might lie in the balancing of the respective weight of residual imperfections (visual tensions) rather than aiming at perfect symmetry and eliminating all visual tensions (see section 2.3 and Figs 2-16 and 2-17).[6]

It is a fact that there will always be clinical situations in which symmetry cannot be obtained (eg, patient rejecting orthodontic treatment or corrective mucogingival surgeries). In those cases, knowing how to balance these residual nonconformities is the only way to a harmonious result (Figs 2-1b and 2-1c; see also Fig 2-2f).

2-1c

2-1d

FIG 2-1 *(cont)* **Balanced composition.** *(b)* The preoperative view of the patient revealed sequelae of periodontal disease (black triangles), asymmetric gingival contours, and tooth malpositions. Hence many criteria of the esthetic checklist were impossible to fulfill. The case was restored with a combination of large direct composite resin restorations (lingual and proximal, *c and d*) and indirect porcelain veneers *(e)*. No surgeries or orthodontics were used. Note the balanced result despite the residual discrepancies and severe asymmetries. The tenets of smile balance are explained in section 2.3.

2-1b

2-1e

2.2 FUNDAMENTAL CRITERIA

Criterion 1: Gingival health

Healthy soft tissues should display the following elements (Fig 2-2a)[7]:

- The free gingiva extends from the free gingival margin (coronal) to the gingival groove (apical) and has a coral pink, dull surface.
- The attached gingiva extends from the free gingival groove (coronal) to the mucogingival junction and has a coral pink color and firm texture (keratinized and attached to underlying alveolar bone), with an "orange peel" appearance present in 30% to 40% of adults.
- The alveolar mucosa is apical to the mucogingival junction, with a loose (mobile) and dark red aspect.

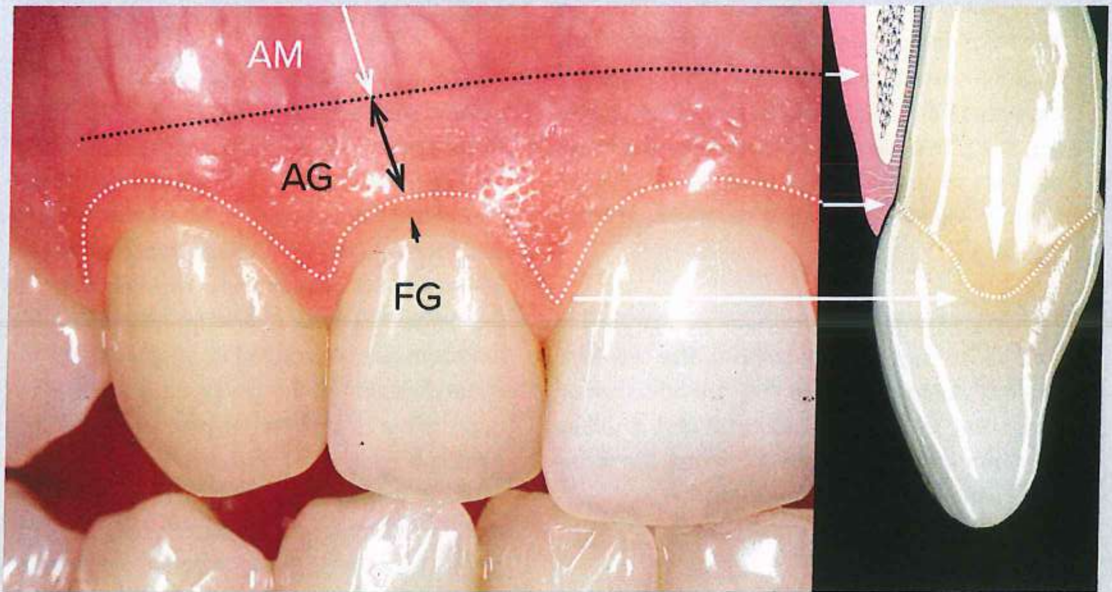
During aging, gingival health can be maintained by optimal oral hygiene[8] and periodontal therapy if necessary. To maintain gingival health, atraumatic clinical procedures should be used during tooth preparation and impression taking (see chapter 6, Figs 6-28 and 6-48), respecting the so-called "biologic width,"[9,10] and preparation margins should be precise and provisional restorations adequately adapted. Finally, the axial contours of the final restorations as well as the nature of the restorative material chosen will influence gingival health.[11–17]

Criterion 2: Interdental closure

In the juvenile healthy gingiva, interdental spaces are closed by the scalloping of the tissues forming the papillae (Fig 2-2b). Transient neglect of oral hygiene and periodontal disease, as well as diastemata and narrow root bases, can alter this gingival architecture (eg, loss/lack of interdental papillae; see Fig 2-1b). It may be possible to compensate for loss of attachment and open embrasures by restorative means alone (see Fig 2-1c as well as chapter 1, Figs 1-28 to 1-31, and chapter 6, Figs 6-7 and 6-43 to 6-45). The design of the interdental contact can be easily modified (using the "miniwing" concept) to ensure a limited distance (< 5 mm, depending on the biotype) between the bone crest and the most apical part of the contact.[18]

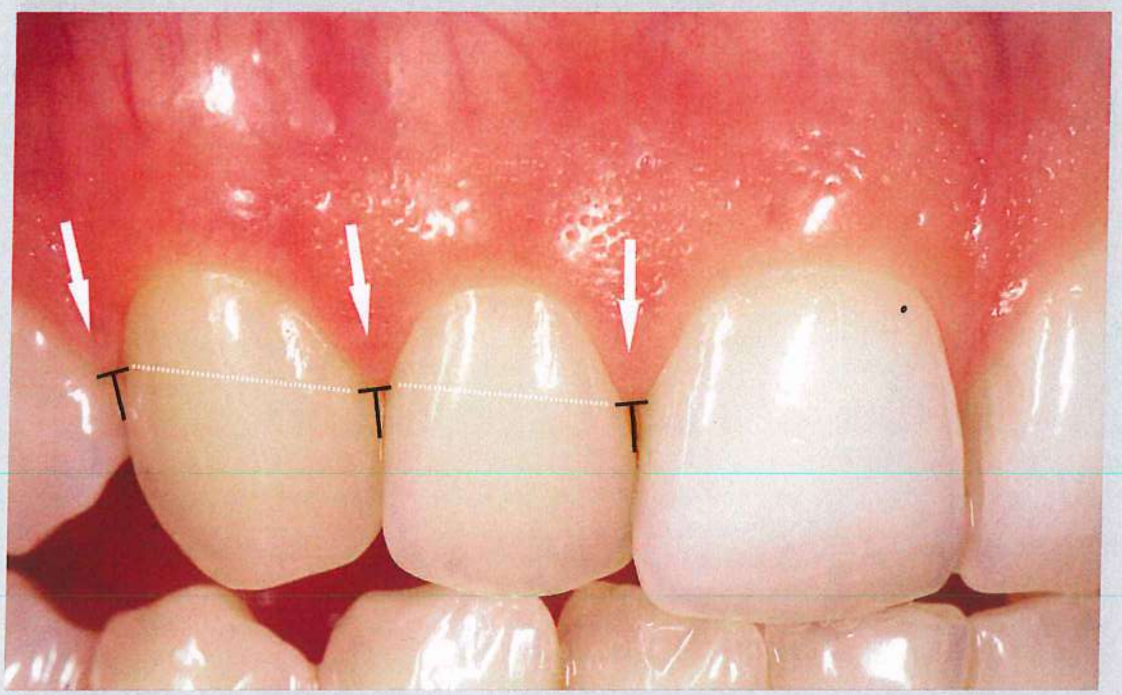
FIG 2-2 Gingival esthetics and tooth-gingiva relationships. *(a)* Basic components of healthy gingiva: free gingiva (FG), gingival groove *(white dotted line)*, attached gingiva (AG), mucogingival junction *(black dotted line)*, and alveolar mucosa (AM). *(b)* Due to the presence of the interdental papillae, the free gingival margin follows a scalloped course that closes the gingival embrasure *(arrows)*.

1. GINGIVAL HEALTH



2-2a

2. INTERDENTAL CLOSURE



2-2b

Criterion 3: Tooth axis

The main axis of the tooth inclines distally in the incisoapical direction. This inclination seemingly increases from the central incisors to the canines (Fig 2-2c). This criterion is mentioned at this stage because tooth position/morphology and gingival contour are interdependent, as shown in criterion 4.

Variations in tooth axis and midline are frequent and do not necessarily compromise the final esthetic outcome as long they are balanced or symmetric (see Figs 2-15c and 2-16e). Another common effect is to upright canines if a more masculine connotation is sought.[19]

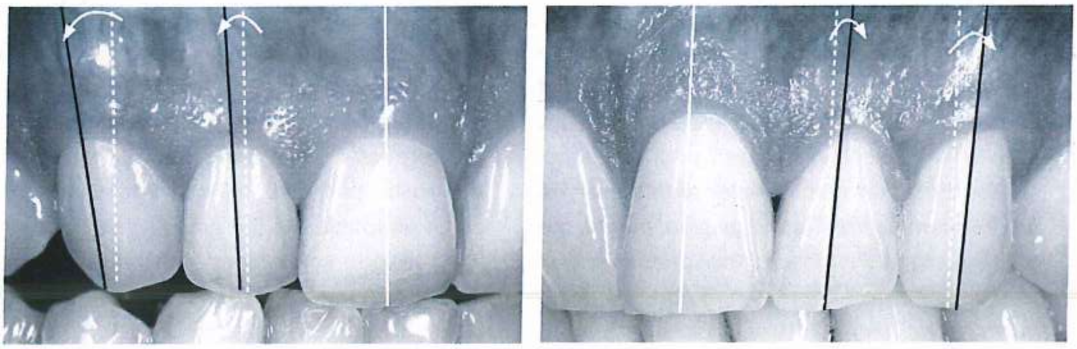
Criterion 4: Zenith of the gingival seam

The gingival zenith (the most apical point of the gingival outline) usually lies distal to the center of the tooth (Fig 2-2d), which results in an eccentric triangular tooth neck. This is particularly true concerning central incisors. According to Rufenacht,[2] this rule does not always apply to maxillary lateral incisors or mandibular incisors, for which the gingival zenith can also be centered along the tooth axis. According to another study, the distal deviation of the gingival zenith does not apply either to canines, for which it can be also centered.[20]

Tooth preparations for full-crown or veneer restorations must respect this basic shape of the gingiva (see * in Fig 6-26b). Adequate placement of the deflection cord, when indicated, is instrumental in that matter.

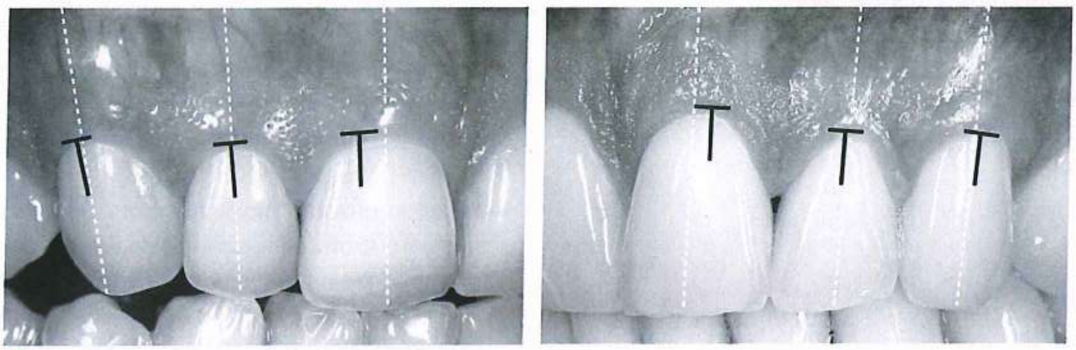
FIG 2-2 *(cont) (c)* Each criterion is demonstrated on the reference dentition *(left)* and on a worn dentition *(right)*. The central incisor axis *(white dotted lines)* is compared with the axis of the lateral incisor and canine *(black lines)*; the distoapical inclination tends to increase from the central incisors to the canines. *(d)* The zenith of the gingival margin lies distal in reference to the tooth axis.

3. TOOTH AXIS

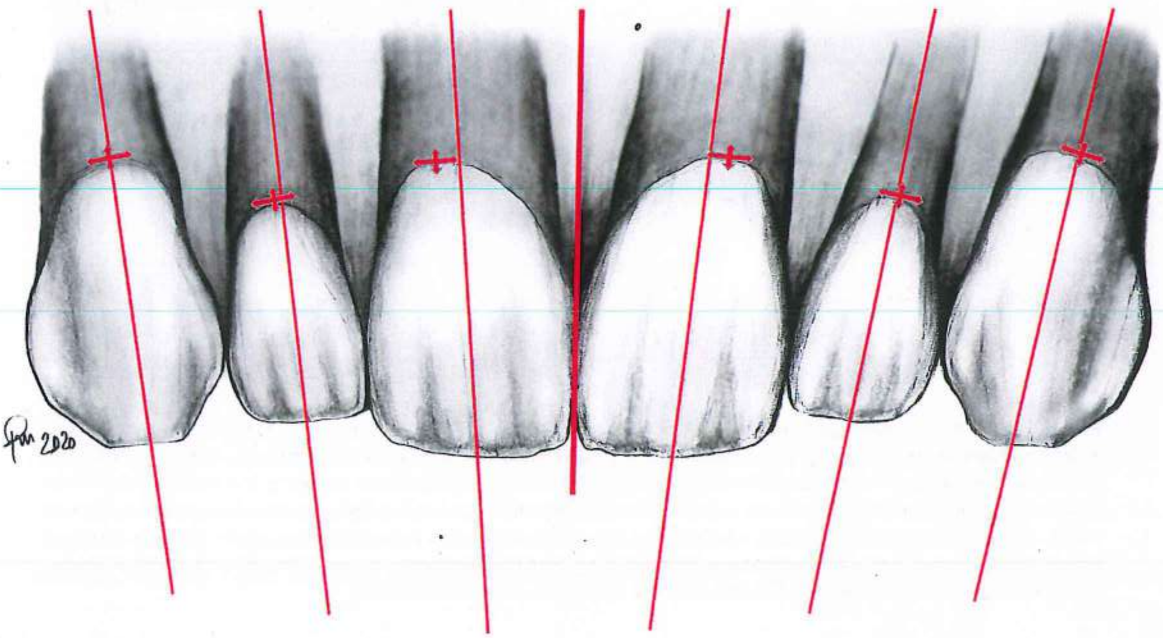


2-2c

4. ZENITH OF THE GINGIVAL SEAM



2-2d



Criterion 5: Balance of gingival levels

The gingival contour of lateral incisors should lie somewhat more coronal compared to that of central incisors and canines (Fig 2-2e). This ideal situation represents the Class 1 gingival height.[2]

Moderate variations related to this criterion are frequent. In the Class 2 gingival height, the gingival contour of lateral incisors lies apical to that of central incisors and canines; for a harmonious result, lateral incisors with more apical gingiva must feature a shorter incisal edge (Fig 2-2f). Concomitantly, such lateral incisors should slightly overlap the central incisors, providing a natural variety to dental composition (according to Rufenacht[2]).

In cases of severe deformity, plastic periodontal surgery must be used to optimize gingival contours for the restorative treatment.[21]

Criterion 6: Level of interdental contact

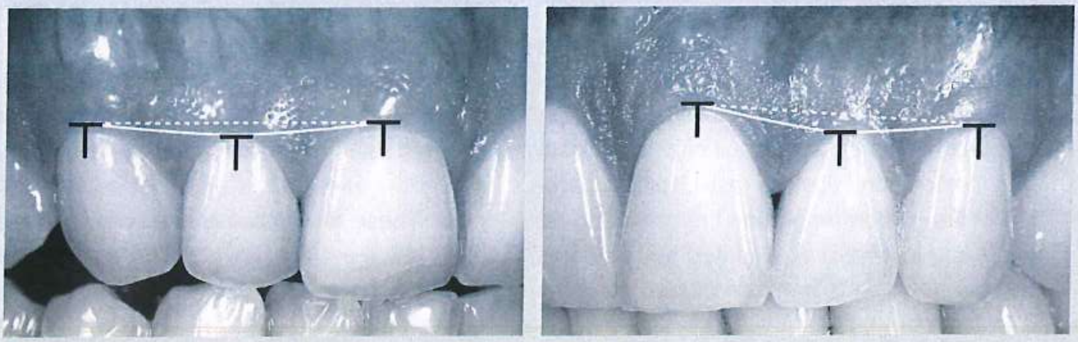
The position of interdental contact is related to tooth position and morphology. Whereas it is most coronal between central incisors, it tends to progress apically from the incisors toward the posterior dentition (Fig 2-2g), also maybe as an adaptation to the progressive flattening (decrease in scalloping) of the interproximal cementoenamel junction.[22] This criterion is closely related to criterion 12 (see Figs 2-12b and 2-12c).

Criterion 7: Relative tooth dimensions

Because they can be easily and physically controlled, the relative dimensions of teeth seem to be among the most objective dental criteria within the esthetic checklist. Due to individual variations and proximal/incisal tooth wear, it is difficult to provide "magic numbers" to define adequate tooth dimension. Relative proportionality of teeth has long been compared with classic elements of art and architecture. As a result, mathematic theorems such as the "golden proportion"[23,24] and the "golden percentage"[25] have been proposed in the determination of so-called ideal mesiodistal spaces (Fig 2-3).

FIG 2-2 *(cont) (e)* The average horizontal level of the gingiva is lower for lateral incisors compared to canines and central incisors, defining the Class 1 gingival height. *(f)* Variations in this criterion are common, as illustrated in this prosthetic case viewed before and after replacement of preexisting full ceramic crowns in the maxillary arch. The gingival contour around the right lateral incisor is normal (Class 1), but the high gingival contour around the left lateral incisor (gingival height Class 2) had to be balanced by a relatively shorter incisal edge compared to the preexisting crown. This visual tension is somewhat compensated also by the malpositions in quadrant III (canine and first premolar). *(g)* Interdental contacts progress cervically from the central incisors to the canines.

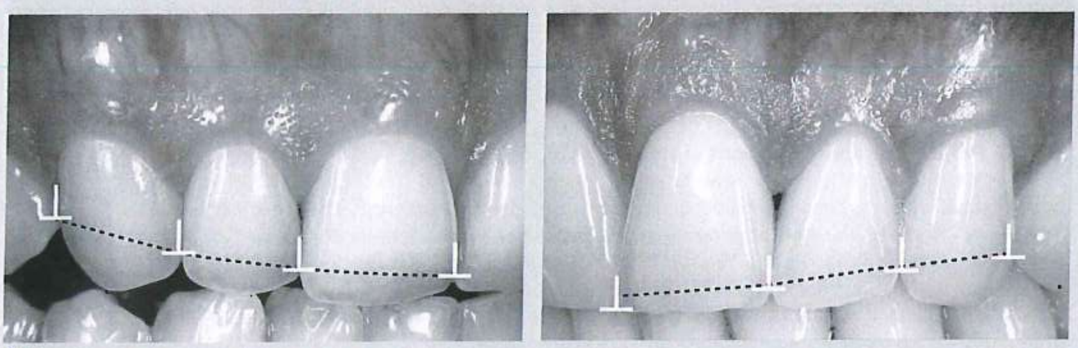
5. BALANCE OF THE GINGIVAL LEVELS



2-2e

2-2f

6. LEVEL OF THE INTERDENTAL CONTACT



2-2g

These rules were applied to the "apparent" size, as viewed directly from the anterior.

Perception of symmetry, dominance, and proportion, however, is also strongly related to tooth height, crown width/length ratios, transition line angles, and other "special effects" of tooth form (see criterion 8). As a result, strict application of the golden proportion has proved to be too strong in dentistry, as stated by Lombardi, who was the first to mention golden numbers for anterior teeth.[23]

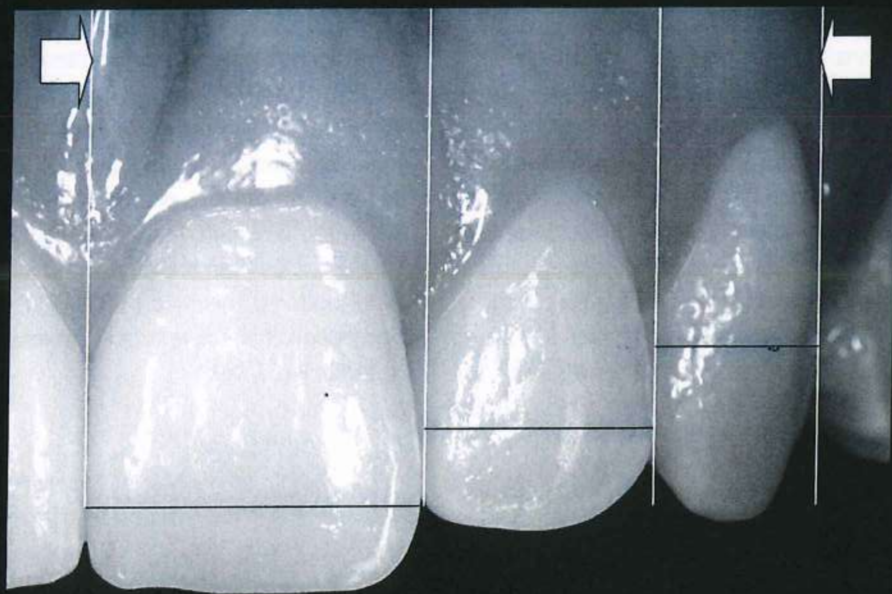
The unrealistic nature of the golden rule was confirmed in measurements by Preston.[26] Strict adherence to this original rule would result in excessive narrowness of the maxillary arch and "compression" of lateral segments, as illustrated in Fig 2-3b.

Again, it must be pointed out that the perceived width of a tooth is highly influenced by the shape and especially the interincisal angles.

Although it is rare to observe golden numbers in anterior teeth (Fig 2-3a), lateral incisors and canines feature open interincisal angles that naturally generate the perception of narrowness. These teeth appear narrower than they really are, therefore providing the illusion of the golden proportion, which is dominated by the central incisors.

As stated by Lombardi,[23] "Just as unity is the prime requisite of a good composition, dominance is the prime requisite to provide unity." The mouth is the dominant feature of the face by virtue of its size. By the same token, the central incisor is the dominant tooth of the smile. It goes without saying that dominance must be measured according to personality.

FIG 2-3 Proportions and dimensions of anterior teeth. Measurements have been made according to the apparent width of teeth, as viewed directly from the anterior. *(a)* The original, untouched view of the central incisor to canine does not conform to the golden proportion. *(b)* The same image was digitally modified to generate golden numbers. The proportion of the lateral incisor is now 1:1.618 with the central incisor (which is realistic for only 17% of individuals, according to Preston[26]) and 1:0.618 with the canine (this ratio was not found in any individual, according to Preston[26]). The size of the central incisor was maintained as in *a*. The golden proportion is unrealistic because it would result in an abnormally narrow maxillary arch (endognathic or micrognathic).



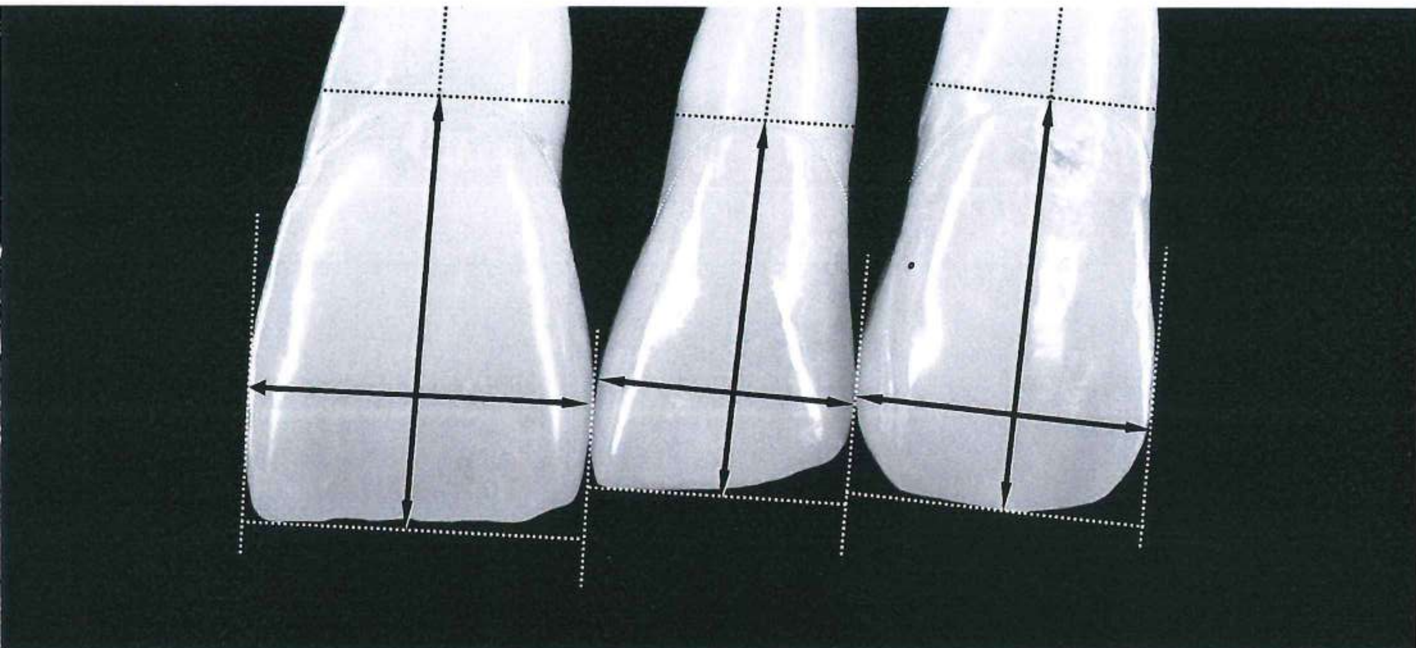
2-3a

2-3b

Some relevant aspects of dental esthetics, such as the crown width/length ratios (Fig 2-3c), have not been presented in tooth morphology sources until relatively recently. Inversely, dimensions of teeth have been available for a century. Average measurements made on normal subjects offer significant help in defining relative tooth dimensions.[27–30] The findings of Sterrett et al[27] can be used to determine a working approximation of final clinical crown width or length (Fig 2-3d, top). It appears that general tooth dimensions are not correlated to the subject stature (height). The same study revealed a greater maxillary anterior tooth width and length for males compared to females. The clinical crown width/height ratio proved to be the most stable reference because it shows minimal variations between gender or between teeth (Fig 2-3d, top).

Similar values were obtained in another study using anatomical crowns (extracted teeth instead of stone casts) of white subjects.[28] However, significant differences were found between worn and unworn teeth (Fig 2-3d, middle). The same effect of wear difference was present in Asian teeth, which also appear to have much smaller ratios than those of white subjects (Fig 2-3d, bottom). This ratio also is influential in the perception of absolute tooth dimensions as illustrated in Fig 2-3e.[23]

7. RELATIVE TOOTH DIMENSIONS



2-3c

FIG 2-3 *(cont) (c)* Anatomical crown measurements of width and length. (Reproduced with permission from Magne et al.[28])

2-3d

FIG 2-3 *(cont) (d)* Crown width/length. Clinical ratios are identical for incisors and canines within the same gender.[27] A comparison of the ratios between males and females found no differences, except for the canines *(top)*, which tend to be longer in males (see also Fig 2-3g). Anatomical measurements in white subjects[28] *(middle)* and Asians[29] *(bottom)* showing the significant effect of wear on the width/height ratios. The *dotted rectangles in d* link ratios without statistical significance.

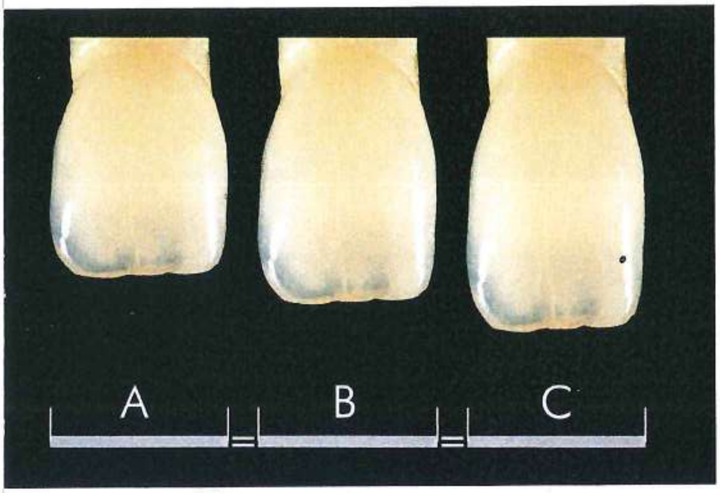
Another factor that can significantly affect the perception of dimensions and position in the frontal plane is the brightness of the object (Fig 2-3f; see also criterion 11).

Additional results from the same literature (Fig 2-3g)[27–31] lead to the following guidelines for maxillary anterior teeth:

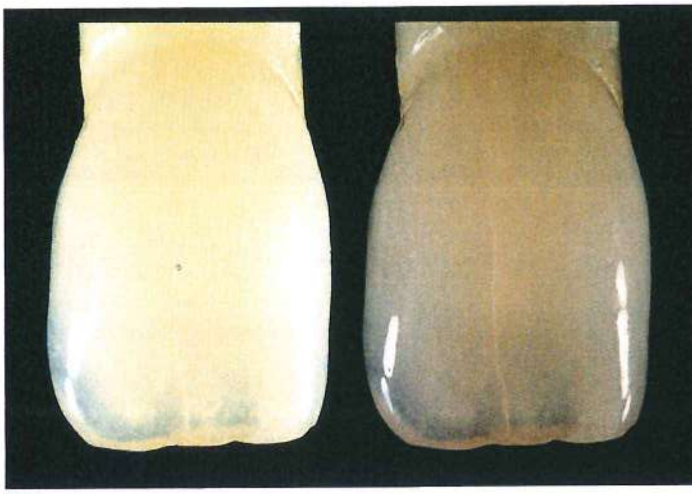
- Crown width/length ratios of incisors and canines are similar, but ranges differ: 77%–86% for white subjects to 67%–78% for Asians subjects.
- There seems to be a threshold between unworn ("young") and worn ("old") teeth, which is about 80% for white subjects and 73% for Asians. Wear logically influences the length but not the width of the teeth.

In prosthodontic patients with altered maxillary teeth, mandibular incisors are often left intact and can be of significant help not only in approximating the dimension of the maxillary central incisors, as illustrated in Fig 2-3h, but also in helping to determine the basic tooth shape.

Note that absolute dimensions of teeth differ from the perceived dimension, which is also influenced by the location and extent of the line angles (see chapter 6, Figs 6-68g and 6-69).

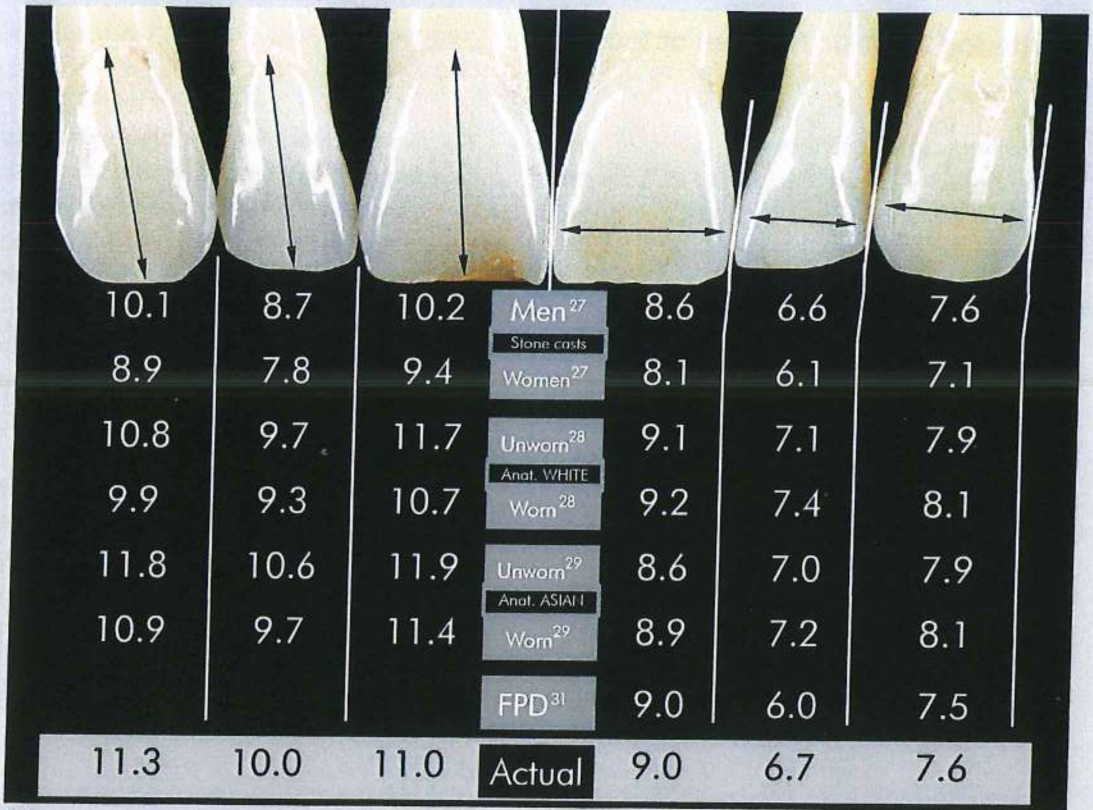


2-3e



2-3f

FIG 2-3 *(cont) (e)* Teeth of equal width but different ratios appear to have different widths. *(f)* In two teeth of the same size, the lighter tooth will appear larger and closer than the darker tooth. *(g)* Average clinical crown height and width measured by Sterrett et al[27] *(rows 1 and 2)*; anatomical measurements of unworn/worn teeth of white subjects *(rows 3 and 4)* and Asian subjects *(rows 5 and 6)*; crown width proposed by Reynolds[31] for abutment selection in fixed prosthodontics *(row 7)*; and actual measurements of anatomical crown height and width of the extracted teeth used in this figure (all from the same patient; *row 8*). *(h)* Mandibular teeth can help to define the approximate maxillary incisor width. The width of the maxillary central incisor is obtained by adding the mesiodistal diameter of the mandibular central incisor plus half that of the mandibular lateral incisor.



Men[27] (Stone casts)	10.1	8.7	10.2	8.6	6.6	7.6
Women[27] (Stone casts)	8.9	7.8	9.4	8.1	6.1	7.1
Unworn[28] (Anat. WHITE)	10.8	9.7	11.7	9.1	7.1	7.9
Worn[28] (Anat. WHITE)	9.9	9.3	10.7	9.2	7.4	8.1
Unworn[29] (Anat. ASIAN)	11.8	10.6	11.9	8.6	7.0	7.9
Worn[29] (Anat. ASIAN)	10.9	9.7	11.4	8.9	7.2	8.1
FPD[31]				9.0	6.0	7.5
Actual	11.3	10.0	11.0	9.0	6.7	7.6

2-3g

2-3h

Criterion 8: Basic features of tooth form

Maxillary central incisors

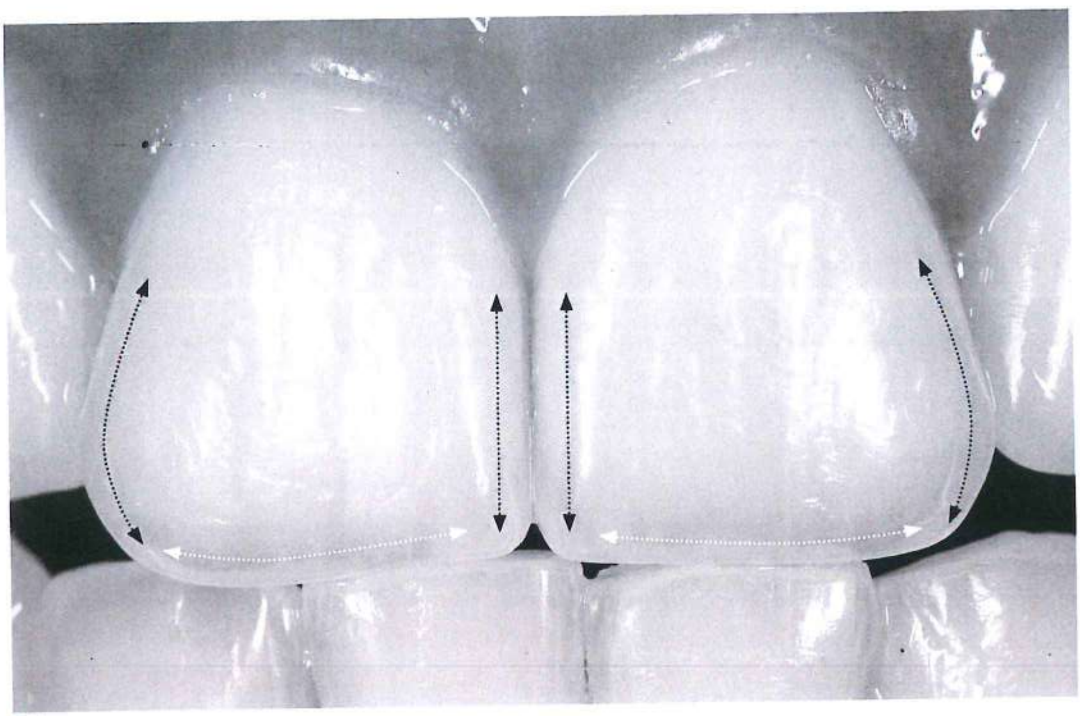
The maxillary central and lateral incisors are anatomically and functionally similar, being used for shearing and cutting. Incisors are characterized as follows[32] (Fig 2-4):

- The mesial outline and lobe of the crown can be straight or slightly convex for maxillary incisors, with a more rounded mesioincisal angle for lateral incisors.
- The distal outline and lobe of the crown is more convex compared to the mesial. Its curvature and inclination can vary significantly according to the typal form of the tooth (see Fig 2-5). The distoincisal angle is rounded.
- The incisal outline of the crown can be irregular or rounded but usually becomes more regular and straight because of functional wear.

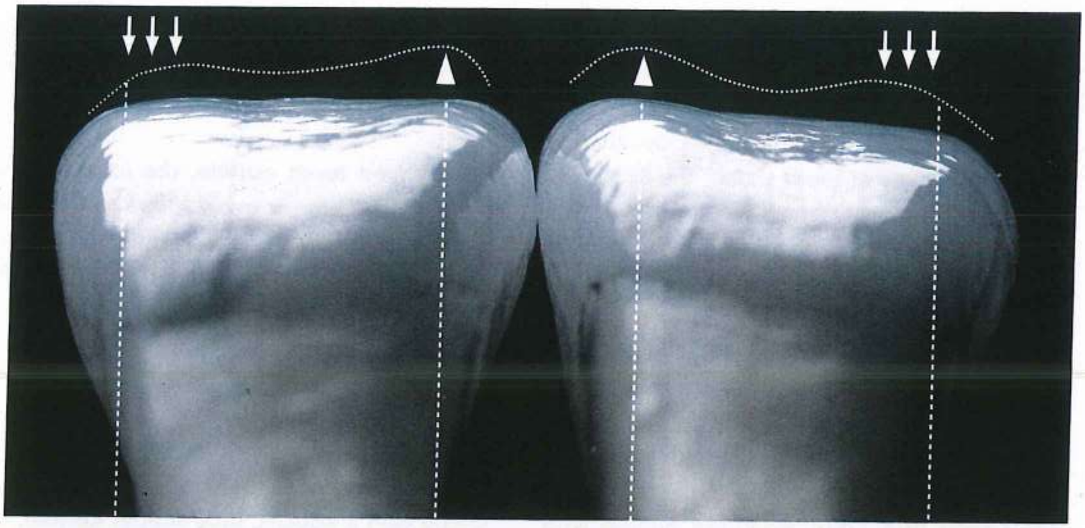
Realistic incisor shape is also related to the anatomy of the interproximal ridges, also called* transition line angles, *which represent strategic light-reflecting areas (Figs 2-4b and 2-4c). These vertical and oblique crests do not influence the crown outline; however, the apparent tooth shape, length, and width can be easily modified by the length, position, and direction of the transition line angles (see chapter 6, Figs 6-68 and 6-69).

Biocorrosion and wear tend to accelerate aging, softening this characteristic architecture of the facial surface and possibly resulting in significant coronal volume loss and disastrous esthetic and mechanical alterations (see chapter 5, section 5.8, Figs 5-20 to 5-28).

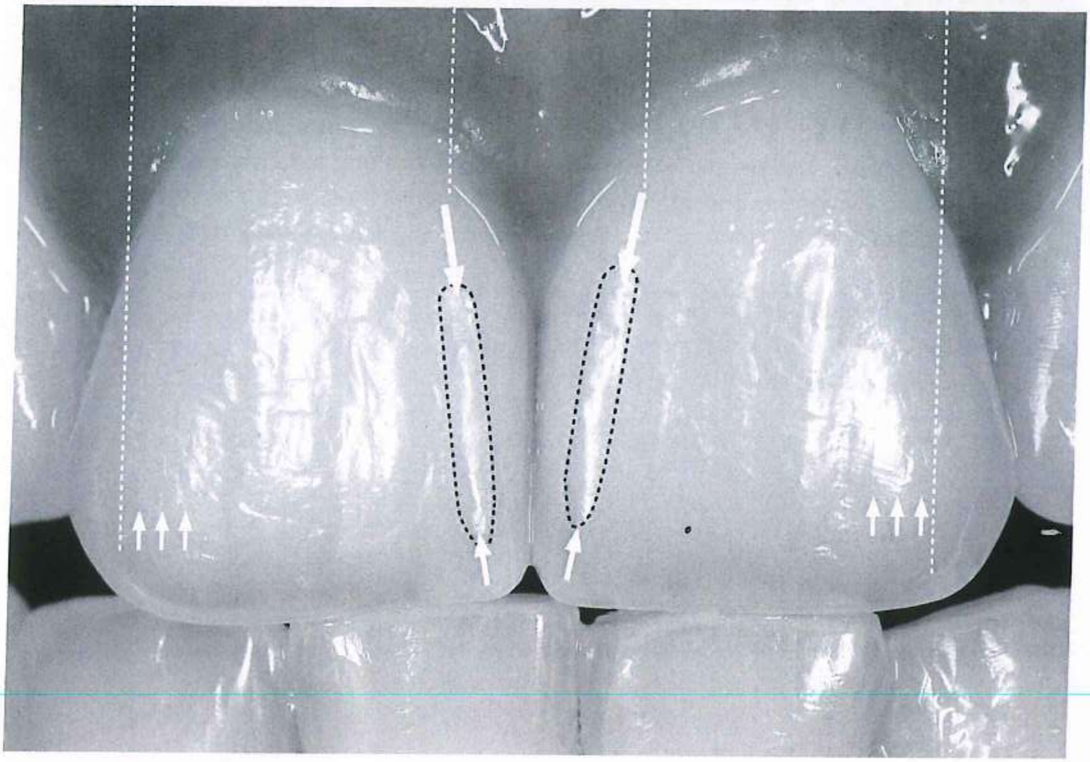
8. TOOTH FORM



2-4a



2-4b



2-4c

FIG 2-4 Central incisor outline and transition line angles. *(a)* Typical facial aspects of central incisors: straight mesial outline *(straight black arrows)*, slightly rounded incisal edge *(straight white arrows)*, and curved distal outline *(curved black arrows)*. Distoincisal angles are more open than mesioincisal angles *(plain white lines)*. *(b)* Tangential view of central incisor facial surfaces: The mesial transition line angle *(single arrows)* is more prominent compared to the softer distal ridge *(triple arrows)*. *(c)* Intraoral photography with a twin light (see device in Fig 5-14e) outlines the mesial crest *(single arrows and dotted area)*.

Due to numerous individual variations (Fig 2-5), the incisor shape to be restored can be derived from neighboring or antagonistic teeth, as well as previous study casts. Above all, because of the subjectivity of tooth shape, the final goal must be tested in the form of a diagnostic wax-up and corresponding intraoral mock-up[33,34] to be approved by the patient (see chapter 5, sections 5.5 and 5.6).

There are three main typal tooth forms (Fig 2-5)[35]:

- **Square** (Fig 2-5a): Straight outline with marked and parallel transition line angles and lobes.
- **Ovoid** (Fig 2-5b): Rounded outline with smooth transition line angles (no lobes) showing incisal and cervical convergence ("barrel" shape).
- **Triangular** (Fig 2-5c): Straight outline with marked transition line angles and lobes showing cervical convergence (distinct inclination of the distal outline).

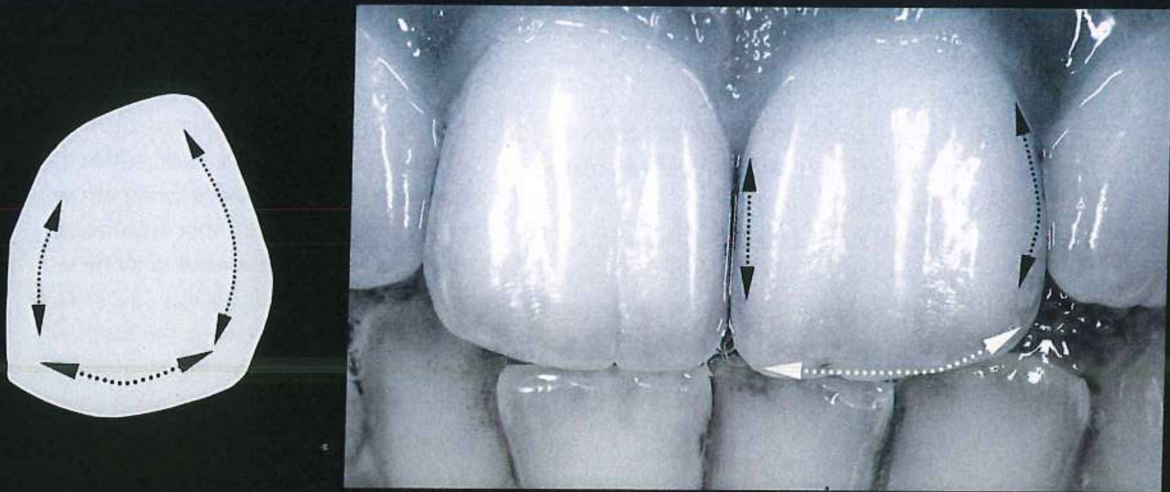
Additional combination groups could be added, such as the squared-tapered. Interestingly, while a survey revealed the general preference of professionals and laypeople for squared teeth,[19] in another study ovoid-based shapes were clearly favored.[36]

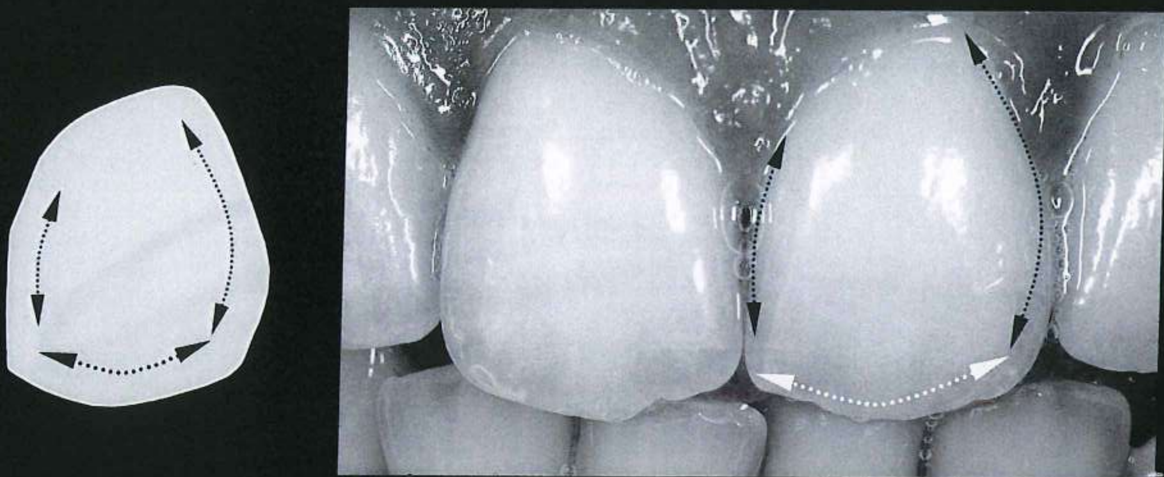
For a given tooth outline, the illusion of a square, triangular, or ovoid shape can also be influenced by the labioproximal line angles, their position, and their shape (see chapter 6, Fig 6-69c).

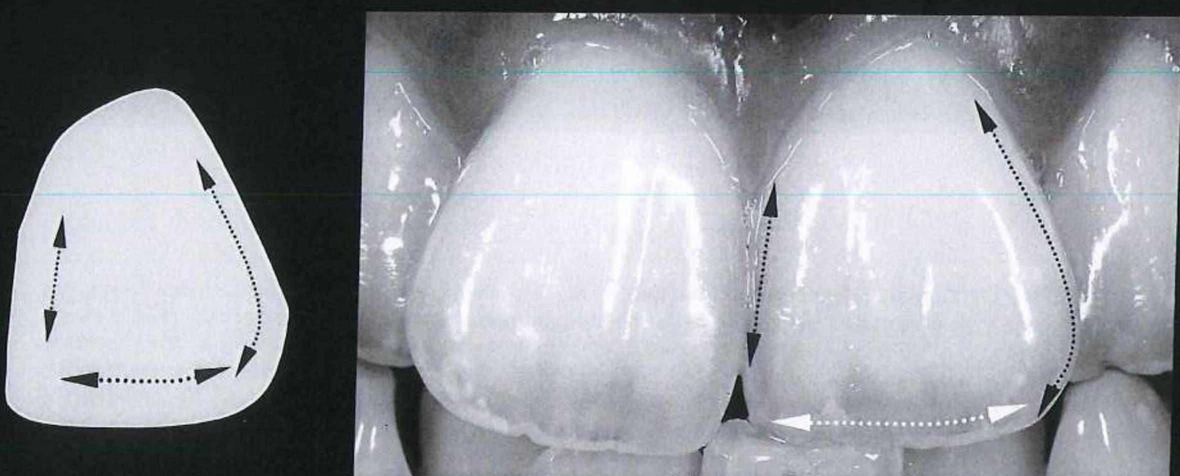
The subject of tooth shape in the perspective of esthetic integration will be discussed more extensively later in this chapter in section 2.3. The discipline of associating a specific tooth shape with a specific face shape, gender, or mental temperament, called *visagism*,[37,38] has not proved to be practical or scientifically relevant.

Note how the photography technique in Figs 2-4 and 2-5 allows the optimal perception of tooth forms and surface texture due to the use of a twin light source. This would not be possible with a ring light (see chapter 5, section 5.9, Fig 5-30c).

FIG 2-5 Extreme variations of incisor outline—typal tooth forms. *(a)* In the square type of tooth, the mesial and distal outlines are straight and parallel and define a large cervical area; the incisal edge is straight or slightly curved. *(b)* In the ovoid type, both mesial and distal outlines are curved and define a narrow cervical area; the incisal edge is narrow and occasionally rounded. *(c)* In the triangular type, the distal outline is not parallel to the mesial outline but clearly inclined, defining a narrow cervical area; the incisal edge is wide and slightly curved.


2-5a

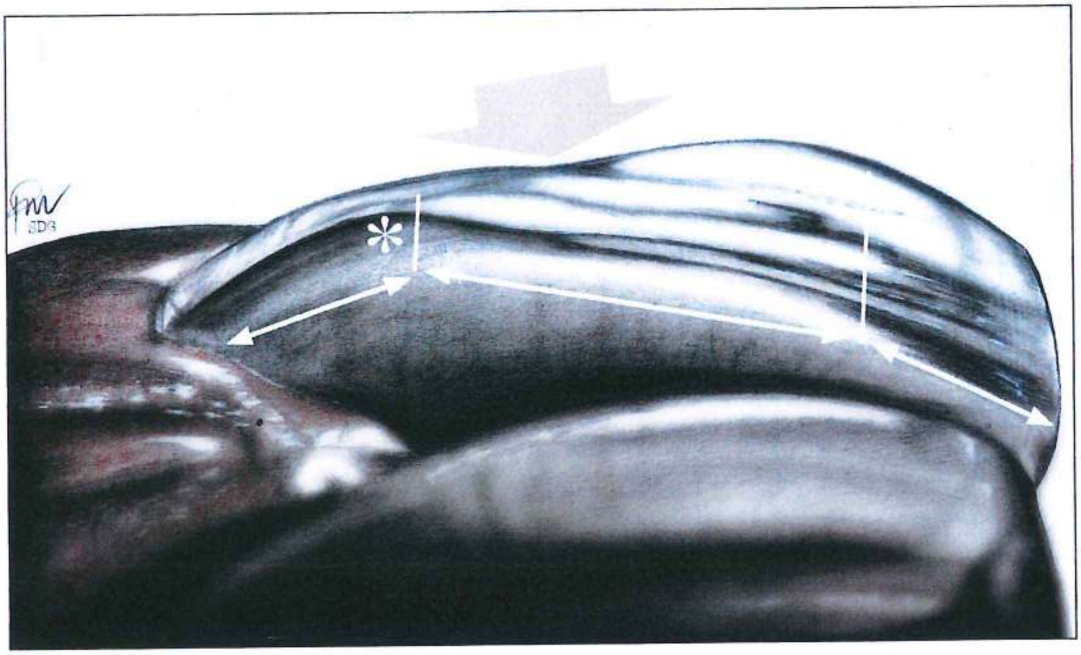

2-5b


2-5c

Some additional features of central incisors include the following:

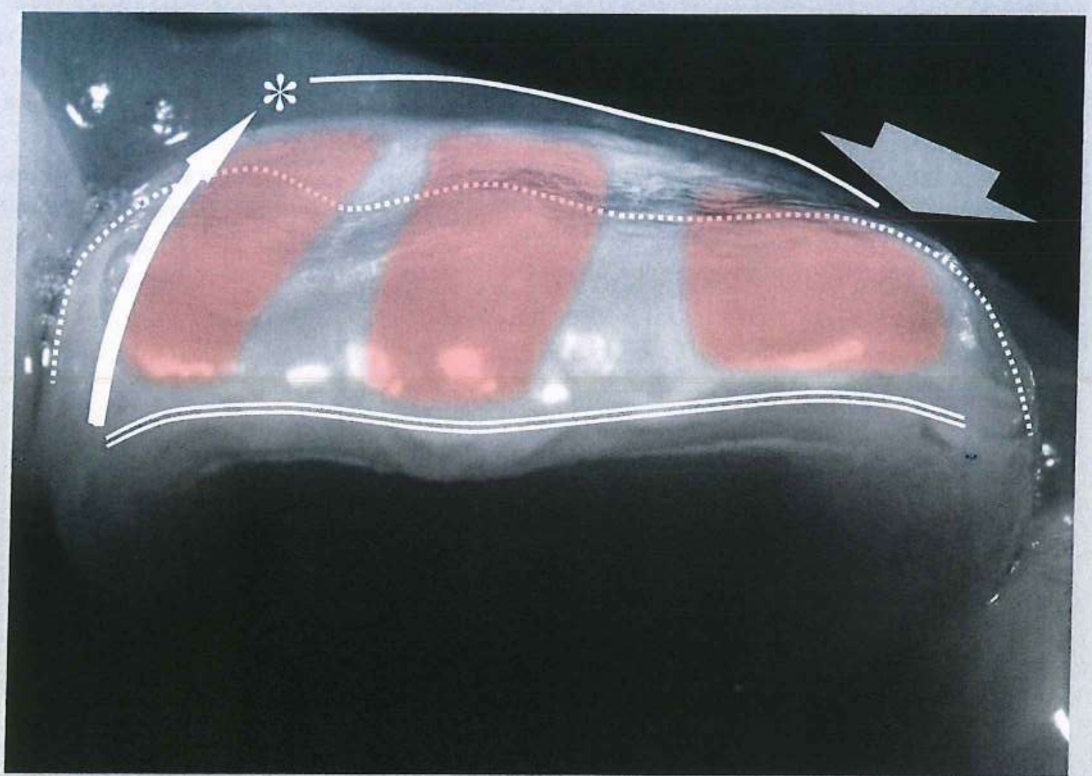
- Labial anatomy divided in three distinct horizontal planes: incisal, middle, and cervical planes (Fig 2-5d).
- A very distinct twist of the labial line angles (also called "torsio dentis"), which was very well described by Kataoka et al in their remarkable book, *Nature's Morphology*[39] (Fig 2-5e; also well visible in Fig 2-5d).

Because of the twist of the labial surface, the distogingival contour features a particularly flat emergence profile, almost even with the root surface. Because of its flush shape (wide arrow in Figs 2-5d to 2-5f), this area does not wear off much and is of particular concern when applying so-called "no-prep" veneers: unless the tooth is prepared with a chamfer, this area will be often overcontoured by the restoration (due the very limited clearance for the ceramics).

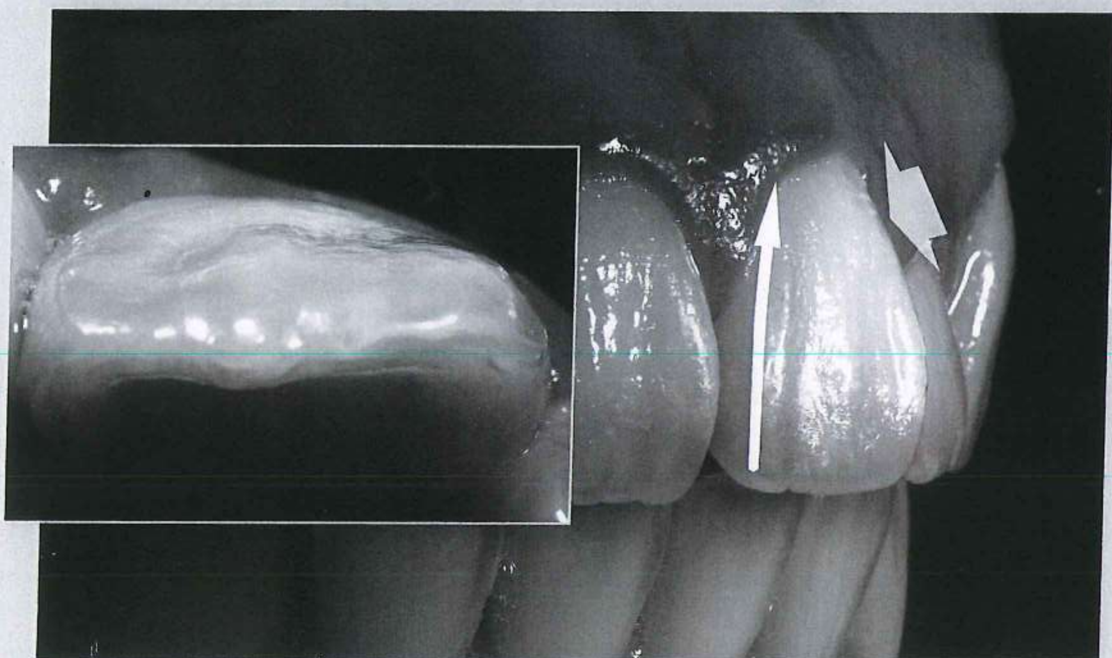


2-5d

FIG 2-5 *(cont)* **Central incisor labial architecture.** *(d)* Realistic drawing (reproduction of actual clinical image) illustrating the three labial planes (mesiolabial view). Note the prominence of the mesial line angle at the cervical third (*). In opposite, note the flat (or even slightly concave) aspect of the distogingival surface *(wide arrow)*. *(e)* When compared to the general orientation of the incisal edge line angle (*double line*, incisal view with three lobes highlighted in translucent red), the cervical line is slightly twisted at an angle *(curved arrow)*. *(f)* Note the very flat emergence of the distogingival surface *(wide arrow)*. This area does not wear off much and is of particular concern when so-called "no-prep" veneers are planned because of the very limited clearance for the ceramics. Unless the tooth is prepared with a chamfer, this area will often be overcontoured by the restoration.

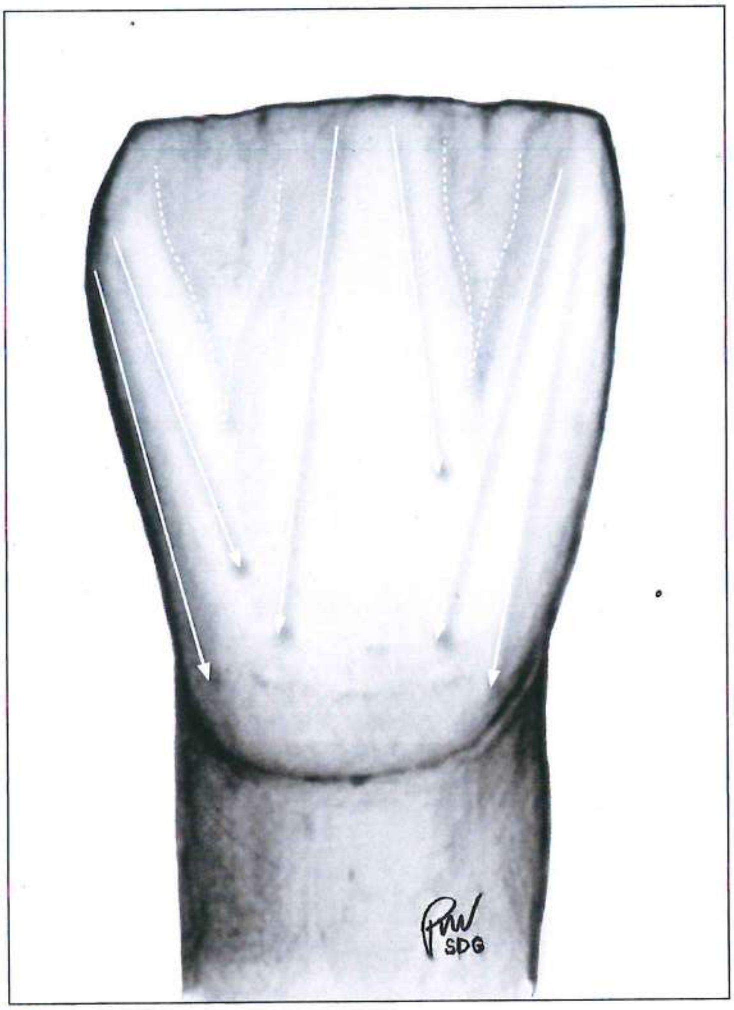


2-5e



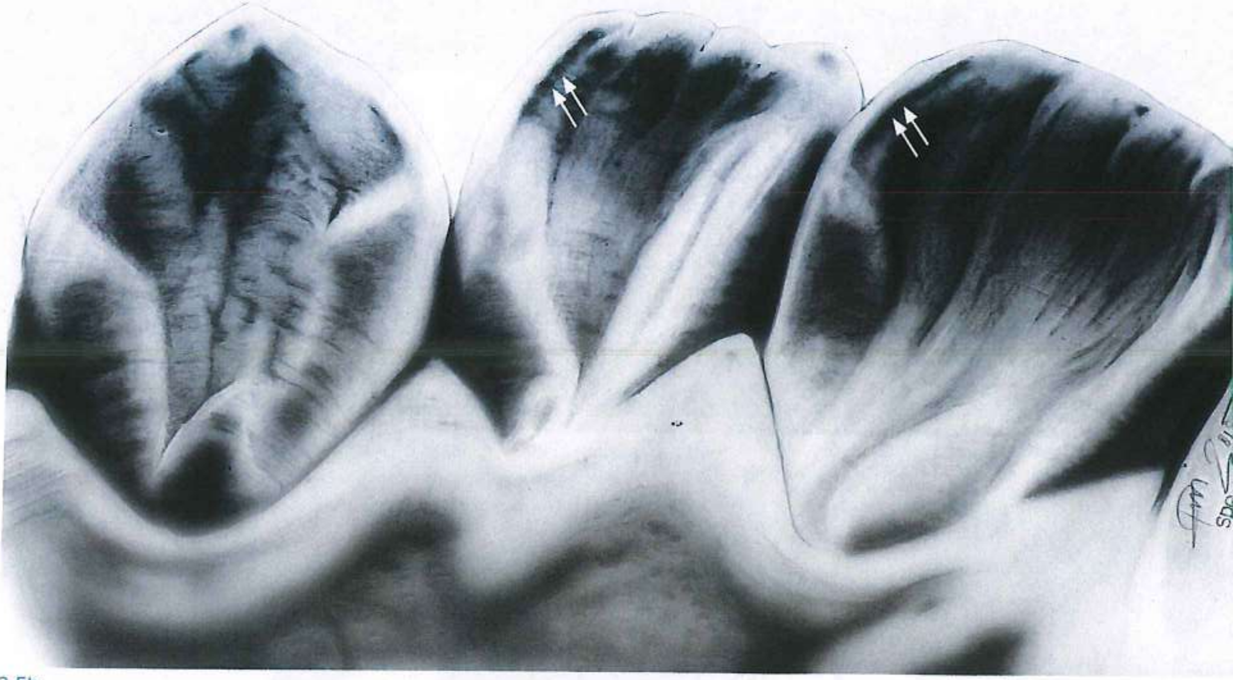
2-5f

- Slightly tapered labial lobes (Fig 2-5g): The three developmental lobes converge cervically. Hence, at the incisal half of the labial surface, they are separated by V-shaped concavities, one mesial and one distal, the distal one generally wider and extending more apically than the mesial one.
- In the unworn incisor, escape routes are located at the mesio- and distoincisal edges, emerging from the lingual aspect of the incisal edge (Fig 2-5h).[39] From the distal view of the incisal edge, the escape route generates a sense of delicate and slender incisal thickness (Fig 2-5i).
- Following incisal edge wear, the escape routes may disappear completely. Labio- and linguoincisal ridges then appear and delineate a well-defined incisal edge wear facet (Figs 2-5j to 2-5m).

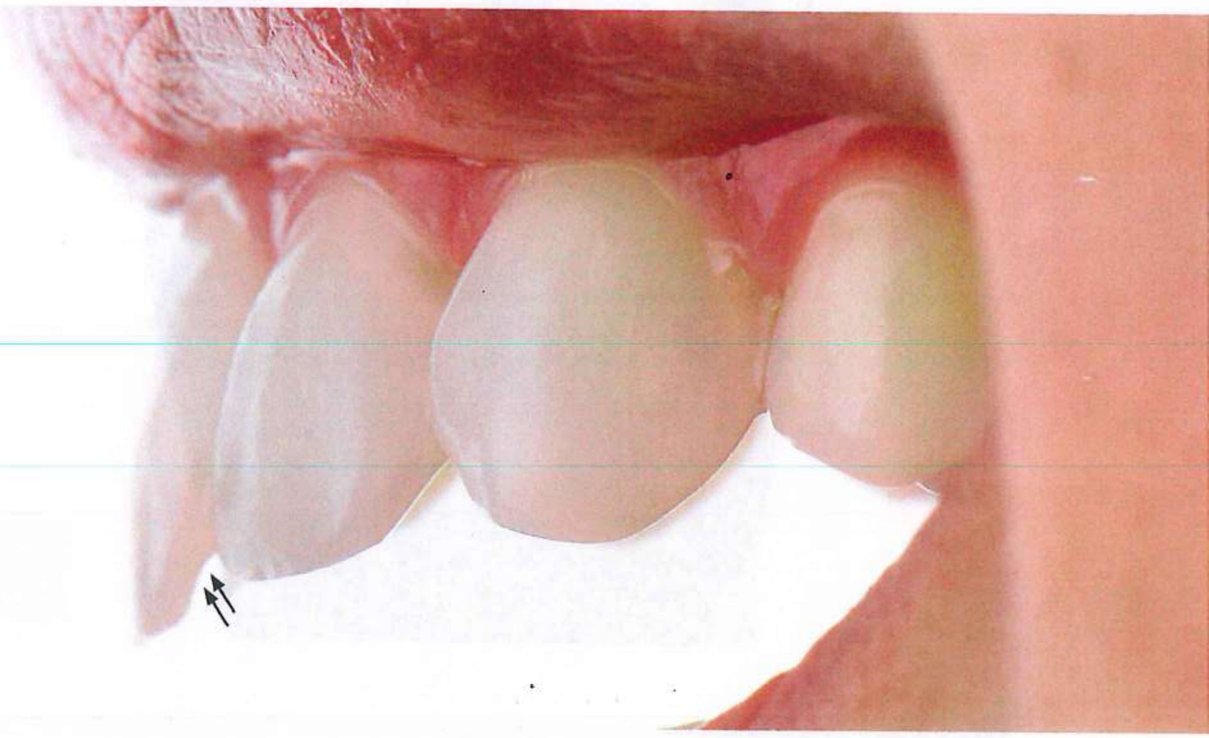


2-5g

FIG 2-5 *(cont) (g)* Drawing showing the slightly tapered labial lobes *(arrows)* and the V-shaped concavities between the lobes at the incisal half of the tooth *(dotted lines)*. *(h)* Other drawing of the lingual view of a "novum" (unworn) dentition with marked escape routes *(arrows)*. *(i)* Clinical case of composite resin veneers (canine to canine) in a young patient with a distinct escape route visible from the distal view of the central incisor *(arrows)*.



2-5h



2-5i

2-5j

2-5k

FIG 2-5 *(cont) (j)* Central incisors with *(left)* and without *(right)* incisal wear. *(k)* Silver powder–coated worn incisor specimen (maxillary left central incisor) showing vestige of mesial escape route only *(double arrows)*.

2-5l

2-5m

FIG 2-5 *(cont) (l and m)* Silver powder–coated specimen (maxillary right central incisor) with mesial incisal wear only. This edge wear is characteristic of the "butterfly" position of the incisors, causing the mesial aspect of the incisal edge to wear shorter than the distal aspect. Note also the escape route vestige left at the distal only *(double arrows)* and the three horizontal planes of the labial surface (distal view).

Maxillary lateral incisors

Lateral incisors bear a close resemblance to central incisors (in basic outline and transition line angles), which they supplement in function. They differ mainly by their reduced size (see Fig 2-3g) and more rounded mesioincisal angle (Figs 2-6a to 2-6f). Their labioproximal transition line angles display more apical convergence than central incisors, especially the mesial lobe and line angle. Lateral incisors, however, can show the greatest variation in form of all teeth, and it is not uncommon for individuals to have peg-shaped lateral incisors (see chapter 6, Fig 6-5) or other anomalies such as a pointed tubercle and a deep developmental groove extending lingually down the root.[32]

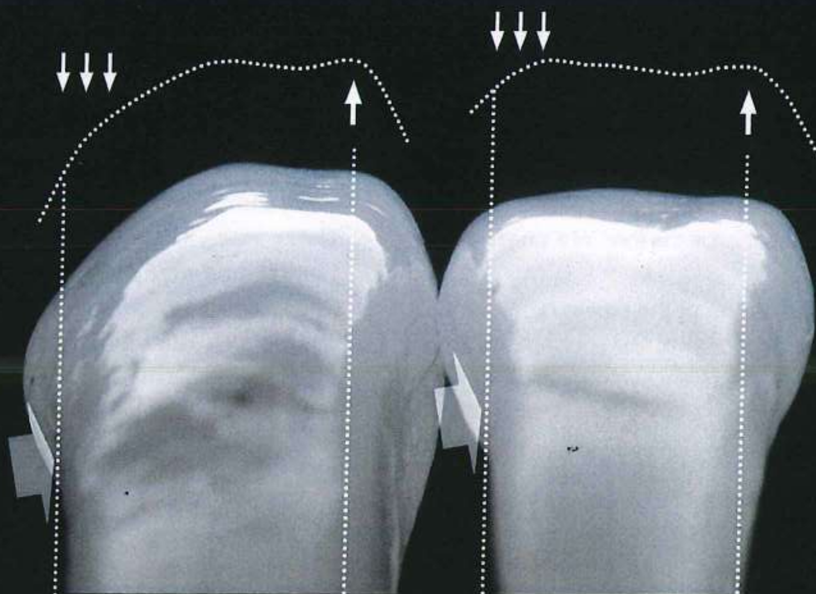
Maxillary canines

The canine is characterized by a series of curves or arcs[32] (Figs 2-6e to 2-6f). Canines are "naturally reinforced teeth," being thicker labiolingually (Figs 2-6g to 2-6k) due to the increased development of the cingulum and central lobe compared to that of incisors (see chapter 1, Fig 1-3).

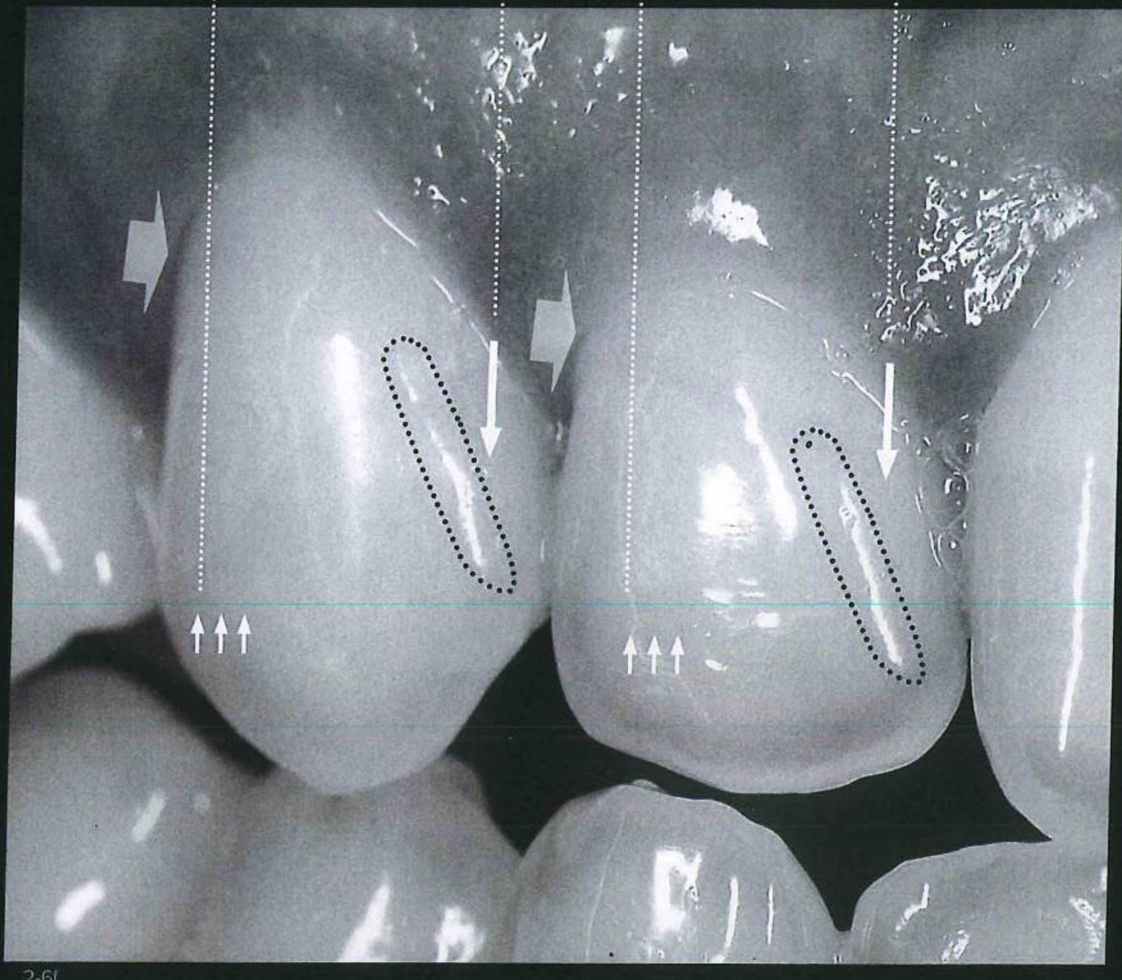
This special anatomy of the canine (wedge shape) seems to offset functional forces and provides this tooth with a unique ability to resist nonaxial loads (see chapter 1, section 1.3).

2-6a 2-6b 2-6c 2-6d

FIG 2-6 Lateral incisor and canine outlines and transition line angles. *(a to d)* Silver powder–coated specimens of maxillary right lateral incisor with moderate wear. *(e)* Tangential views of canine *(left)* and lateral incisor *(right)* facial surfaces. Similar to central incisors, the mesial ridge *(single arrows)* is present and prominent on both teeth but is more oblique; the distal aspect *(triple arrows)* is much softer and, like the central incisor, demonstrates a very flush distal emergence profile with the root *(wide arrow)*. *(f)* Intraoral photography with a dual-point light (see device in chapter 5, Fig 5-30) outlines the mesial developmental ridges *(single arrows and dotted areas)*.



2-6e



2-6f

Some additional features of canines include the following:

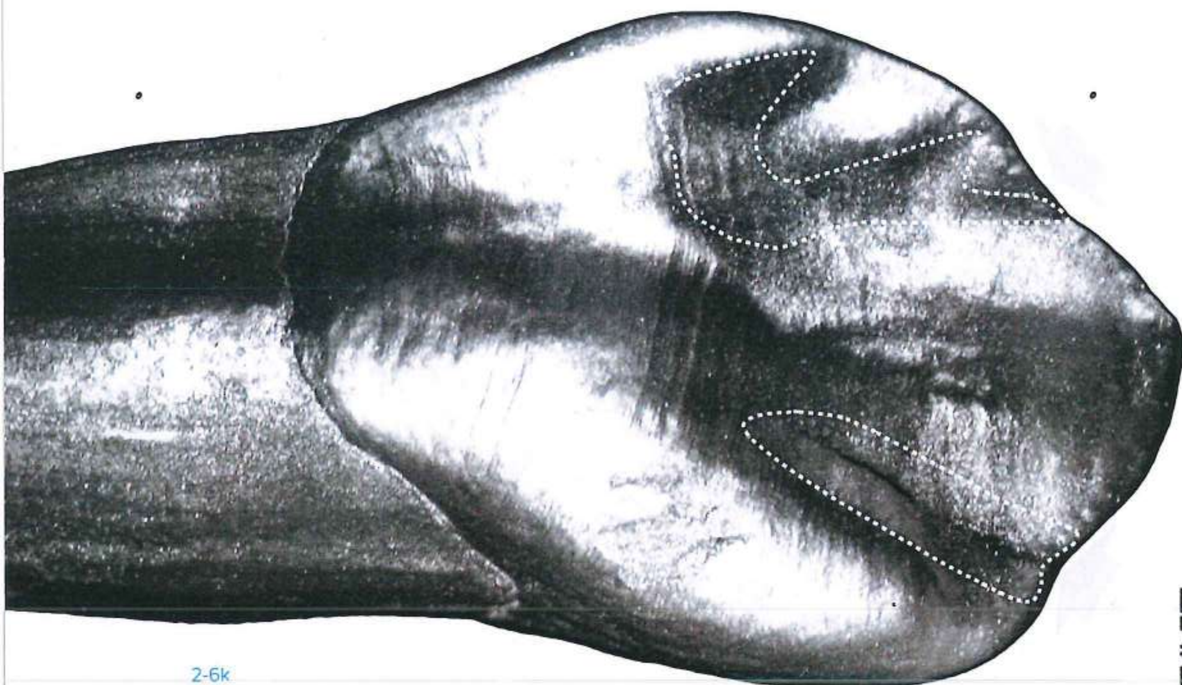
- The mesial outline of the canine can be slightly convex and resemble that of the lateral incisor. The mesial transition line angle is well developed in the form of a small mesial lobe.
- The distal outline of the crown is fuller than mesial, very convex at first (incisal half), then turns flat or even concave near the gingiva.
- The incisal outline of the crown is marked by the cusp tip, which is in line with the center of the root (unworn tooth). The distal slope of the tip is longer and differs from the shorter and more concave mesial slope (Figs 2-6f, 2-6h, and 2-6l).
- Unlike incisors, canines feature a prominent central lobe that defines a strong central ridge extending from the cusp tip to the mesiogingival area with a mesial curve (Figs 2-6k to 2-6m) merging into a mesiogingival convexity (Figs 2-6m and 2-6n).


2-6g

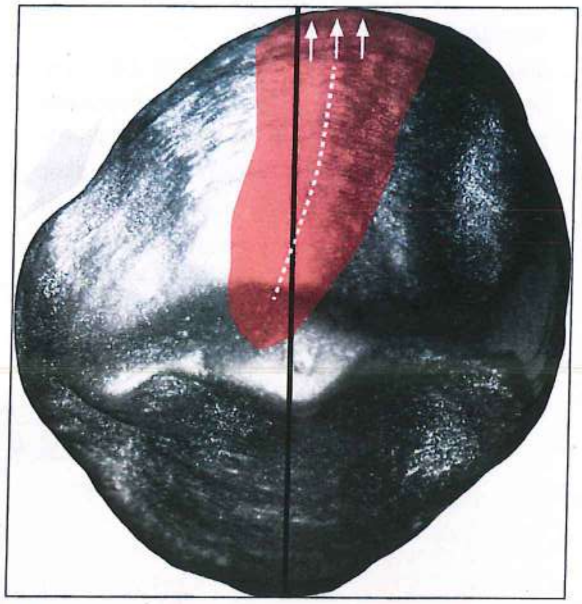

2-6h


2-6i

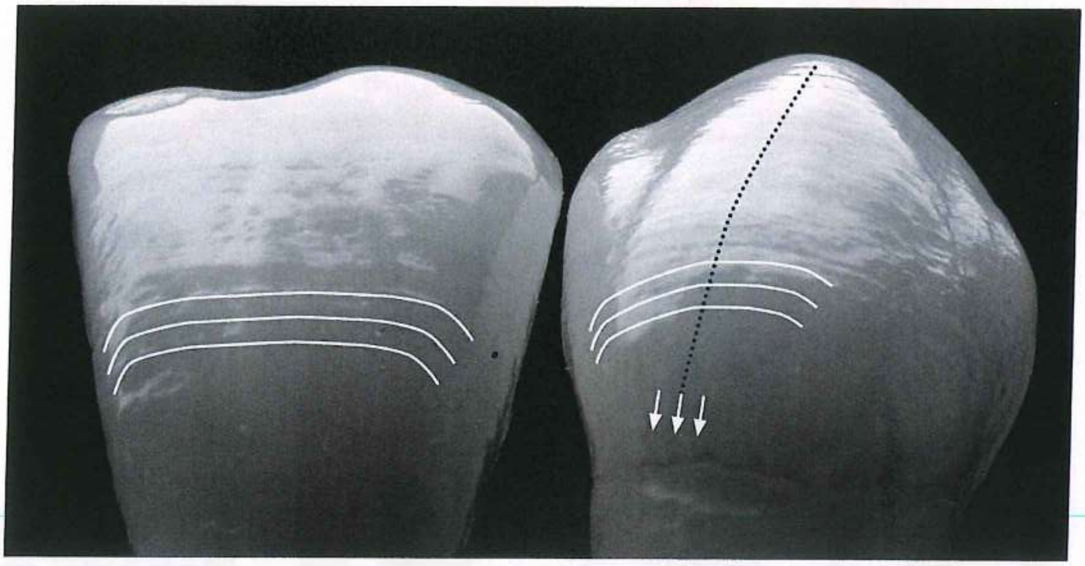

2-6j


2-6k

2-6l



2-6m



2-6n

FIG 2-6 *(cont)* **Canine.** *(g to k)* Silver powder–coated specimens of maxillary right canine without wear. Note the strong labiolingual thickness and how the general outline is mainly constituted of curves (convexities and concavities). Lingually, the prominent central lobe breaks the palatal surface in two fossae *(dotted areas in k*, mesial one with a groove), each one extending toward the labial surface at the concavity of the cusp slopes *(wide arrow in k)*. *(l to n)* Mildly worn canine with central lobe *(red area)* and ridge *(dotted line)* demonstrating a mesial curvature and shift toward the mesiogingival surface *(triple arrows)*. The incisor/canine comparative view shows the marked difference in labial architecture, especially at the cervical level where the canine is much more convex with a convexity shifted mesially *(parallel lines in n)*.

Mandibular anterior teeth

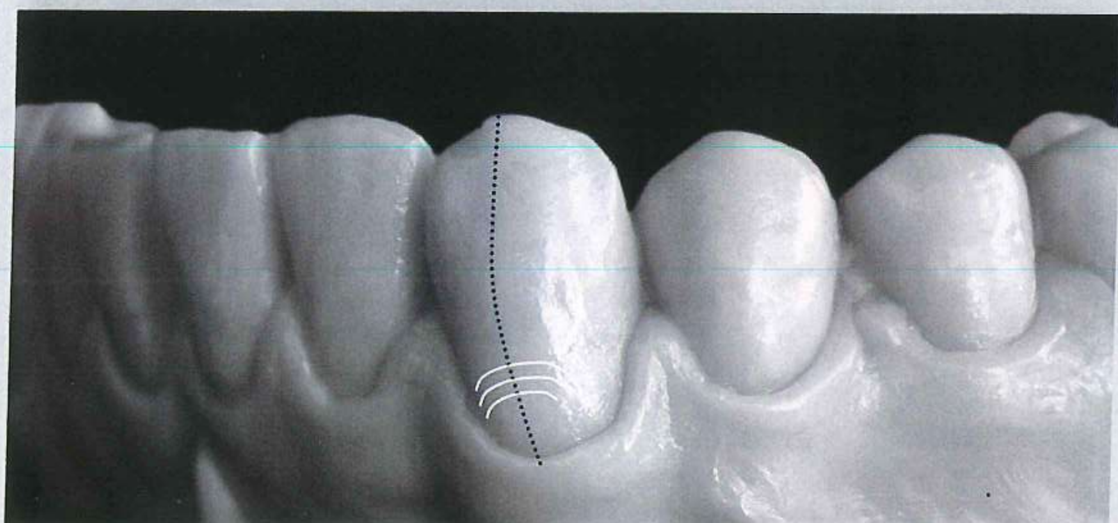
Mandibular incisors and canines (Fig 2-6o) are narrower, slimmer, smoother, and simpler versions of their maxillary counterparts. The central incisors, unlike the maxillary incisors, are smaller than the mandibular lateral incisors and more symmetric mesiodistally (straight mesial and distal outline) with few traces of developmental lobes. The lateral incisors (Figs 2-6p to 2-6t) are not only larger but can also be more tapered than the central incisors with an incisal edge tending to slope downward distally. Canines (Fig 2-6u) closely resemble the maxillary canines but are slightly narrower and have a smoother lingual surface (fewer ridges and cingulum).

2-6o

2-6p 2-6q 2-6r 2-6s

FIG 2-6 *(cont)* **Mandibular anterior teeth.** *(o)* Natural mandibular dentition with slight crowding and moderate wear; traces of developmental lobes are still visible on the lateral incisors. *(p to t)* Silver powder–coated specimen of a mandibular left lateral incisor. This specimen shows asymmetric mesial and distal halves and a tapered outline. Note the smooth contours and softened features of the lingual surface and still perceptible escape routes *(r and t)*. *(u)* Mandibular left canine displaying similar features like its maxillary counterpart, including the strong labial ridge *(dotted line)* and strong mesiogingival convexity *(parallel lines)*.

2-6t



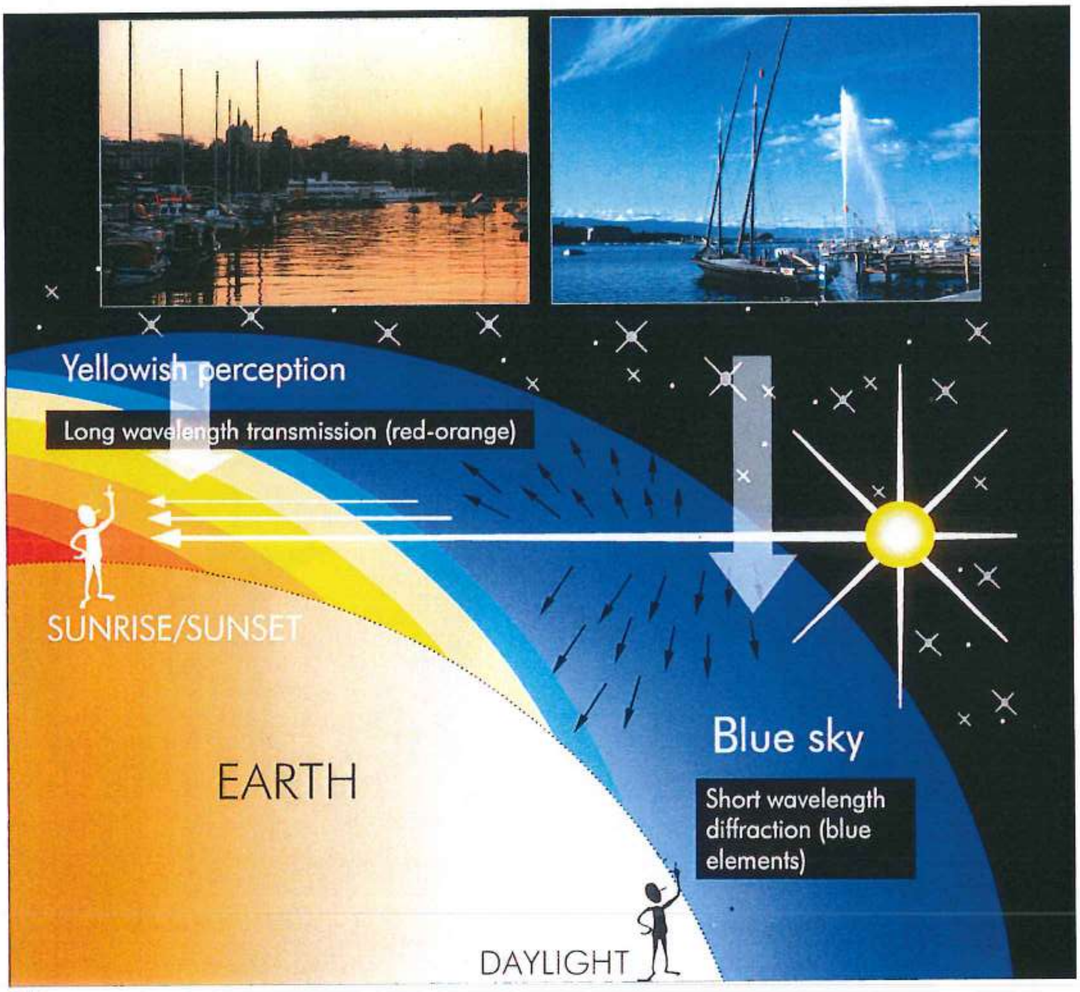
2-6u

Criterion 9: Tooth characterization

Characterization implies complex dynamic light interactions, the phenomenon of reflection/transmission of light (T O F for translucency, opalescence, and fluorescence),[40] as well as intense effects (spots, fissures, dentin lobes, zones of dentin infiltration) and specific effects of form (incisal halo, attrition, abrasion) influencing the perceived age and character of a tooth.

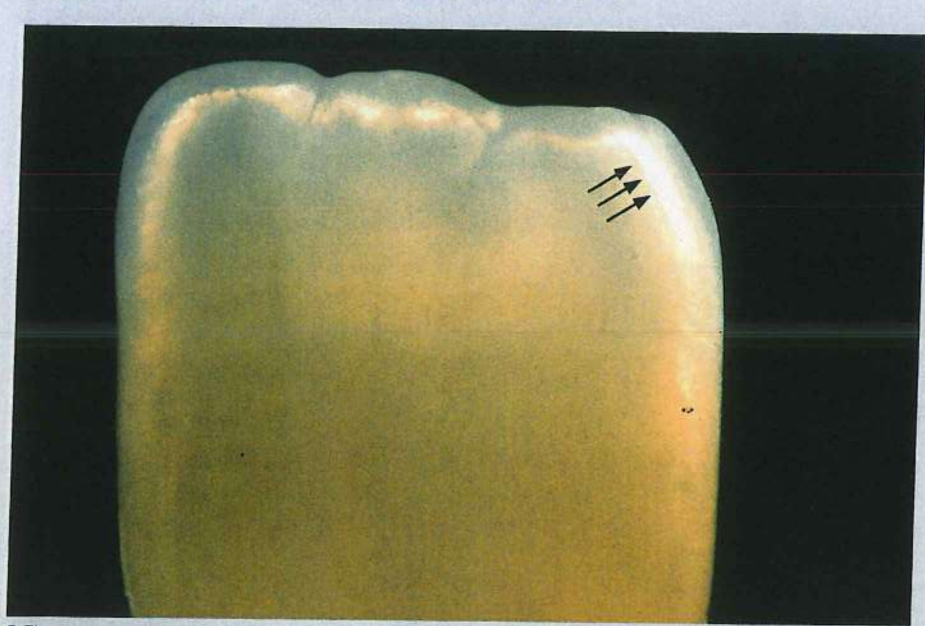
Opalescence

Opalescence, also called the *Rayleigh scattering effect*, is an optical property of enamel and refers to the ability to transmit a certain range of natural light wavelengths (red-orange tones) and reflect the others (blue-lavender tones). Opalescence is easily understood if enamel is compared to the atmosphere of the earth (Fig 2-7a).[41] Because of the presence of small particles like water droplets that interact with the sunlight, the sky can appear either blue (at noon) or red (at sunrise and sunset). A similar effect occurs at the incisal edge due to the scattering of light at the level of the microscopic hydroxyapatite crystals (Figs 2-7b to 2-7h).



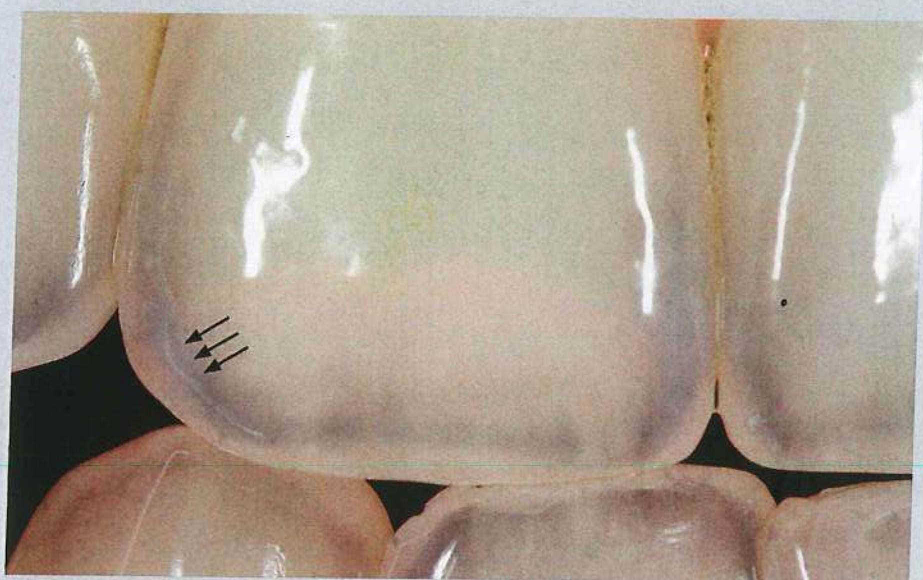
2-7a

OPALESCENCE



2-7b

TRANSLUCENCY



2-7c

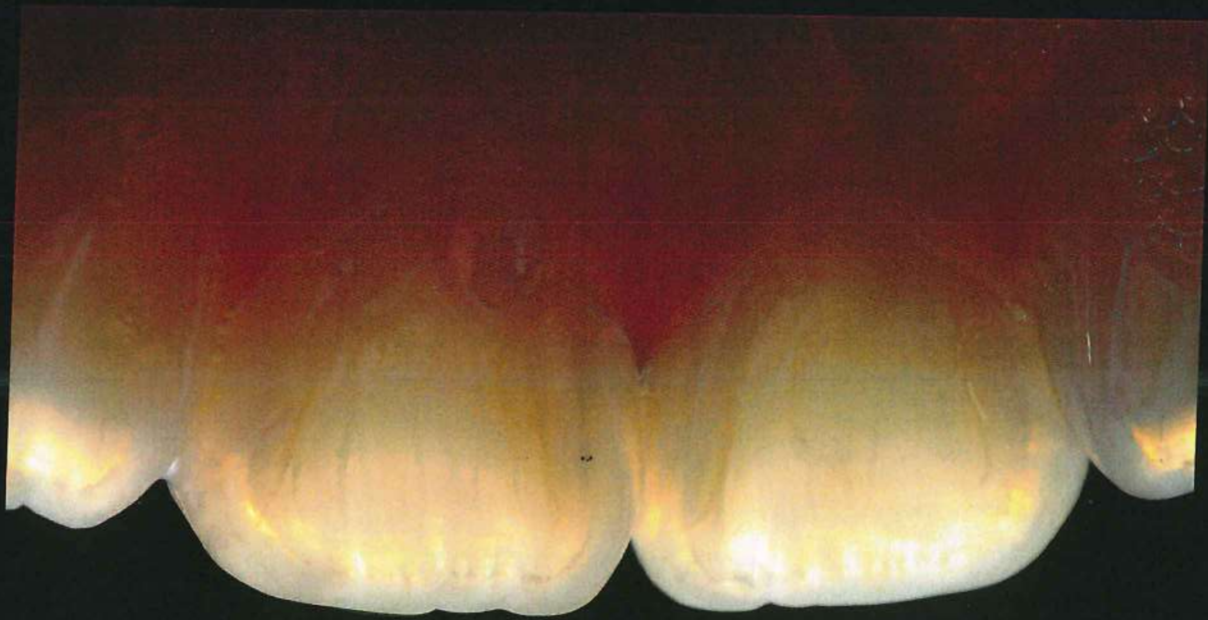
FIG 2-7 Translucency and opalescence (according to Yamamoto[41]). *(a)* The sky appears red-orange in the morning or in the evening and blue during the day. The physical mechanism behind this phenomenon can be explained by small particles suspended in the atmosphere (water droplets) that allow diffraction of sunlight, especially short wavelengths (blue-lavender, *right)*. Most of these short wavelengths are not able to penetrate the thick layer of atmosphere created by the oblique incidence of sunlight found at sunrise and sunset. Only longer wavelengths (red-orange) are able to "travel" tangentially to the earth *(left)*. *(b and c)* Enamel, especially at the incisal edge and the DEJ, acts similarly as the "atmosphere of the tooth." It normally displays a bluish transparent effect under direct lighting *(arrows in c)* or an orange opalescent tone under indirect light *(arrows in b)*.

2-7d

2-7e

2-7f

FIG 2-7 *(cont)* Other examples of the Rayleigh scattering effect (opalescence) in natural teeth. Enamel mineral crystals are smaller than the wavelength of the incident light. *(d)* The resulting scattering of the light produces selective transmission of longer amber wavelength (lingual view with labial incident light). *(e to h)* Another patient shows increasing amber effects in the incisal area as the point of observation moves from buccal *(e)* to incisal *(f)* to lingual *(g and h)*.



2-7g

2-7h

Translucency

Translucency is the appearance between complete opacity (like ivory) and complete transparency (like glass).[42] Teeth, especially incisal edges, show intense characteristics integrating the wide range of effects defined by translucency and transparency.

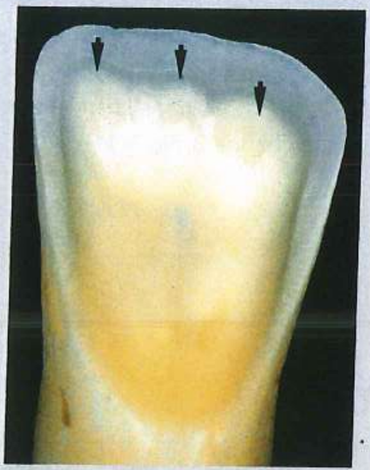
At one end of the spectrum, as illustrated in Figs 2-7b and 2-7c, areas of blue/lavender translucency are present, also showing significant opalescence. Specific porcelains have been designed to simulate these effects. At the other end of the spectrum, more opaque "dentin" effects are found at the incisal edge as revealed by abrasion/attrition. The inner structure of the dentin core and its complex architecture become visible in the form of dentin rays, dentin mamelons, dentin infiltrations, etc (Figs 2-8a to 2-8e). Dentin fluorescence is essential to these kinds of effects.

DENTIN EFFECTS

2-8a

2-8b

DENTIN MAMELONS



2-8c

2-8d

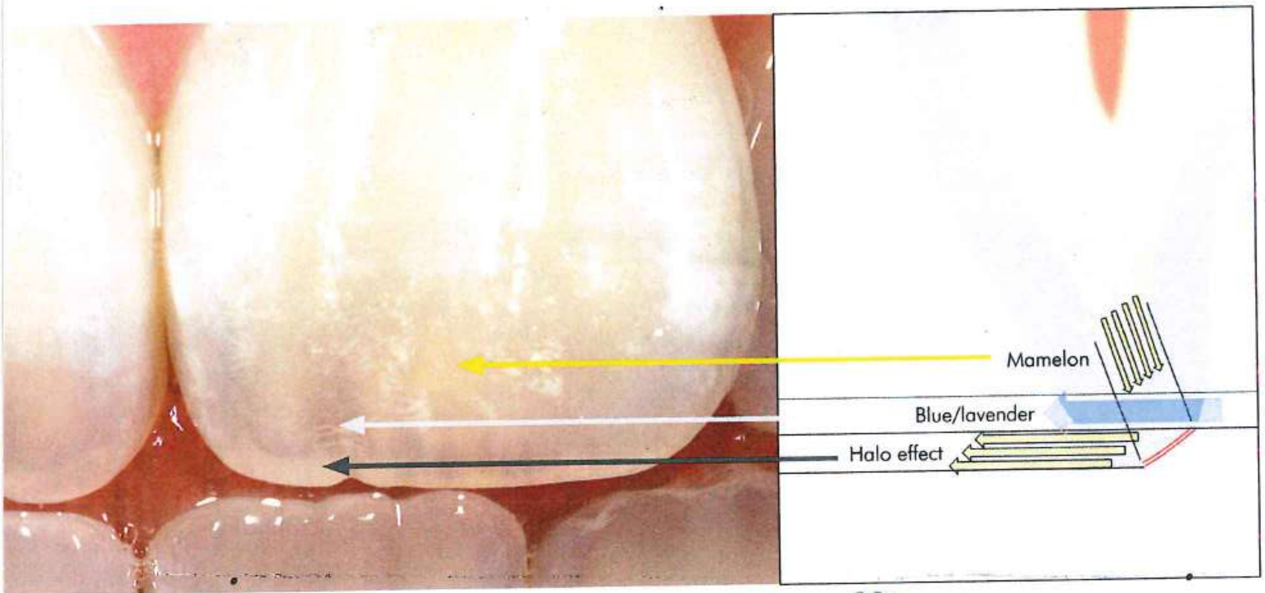
DENTIN INFILTRATION

2-8e

FIG 2-8 Dentin effects. The most complex structural elements of the incisal edge can be better understood by grinding the palatal enamel of extracted teeth *(a, c, and e)*. Vertical palatal attrition of the incisal edge emphasizes the underlying dentin rays *(a and b)*. Dentin architecture usually shows three well-organized dentin mamelons *(arrowheads in c)*. These structures are often seen in the presence of highly translucent enamel *(d)*. Dentin infiltration effects can also be noted; their direction is precisely defined by the convergence of the dentinal tubules, in median and apical directions. External dentin staining typically results from enamel edge chipping *(arrowhead in e)* or progressive wear.

Other important "enamel effects" include white spots or "clouds." They can be random or follow the developmental lines (Fig 2-8f). The incisal white halo effect (Figs 2-8f to 2-8h) is also a critical phenomenon that is not white per se but a mirror effect at the incisal edge. Some composite or ceramic layering techniques advocate to use specific opaque masses to place at the location of this white halo effect. Alternatively, a small adjustment at the linguoincisal edge (creating a flat surface) can create the same effect by mirroring the incisal dentin into the translucent enamel (Fig 2-8g; see also chapter 3, Fig 3-44).

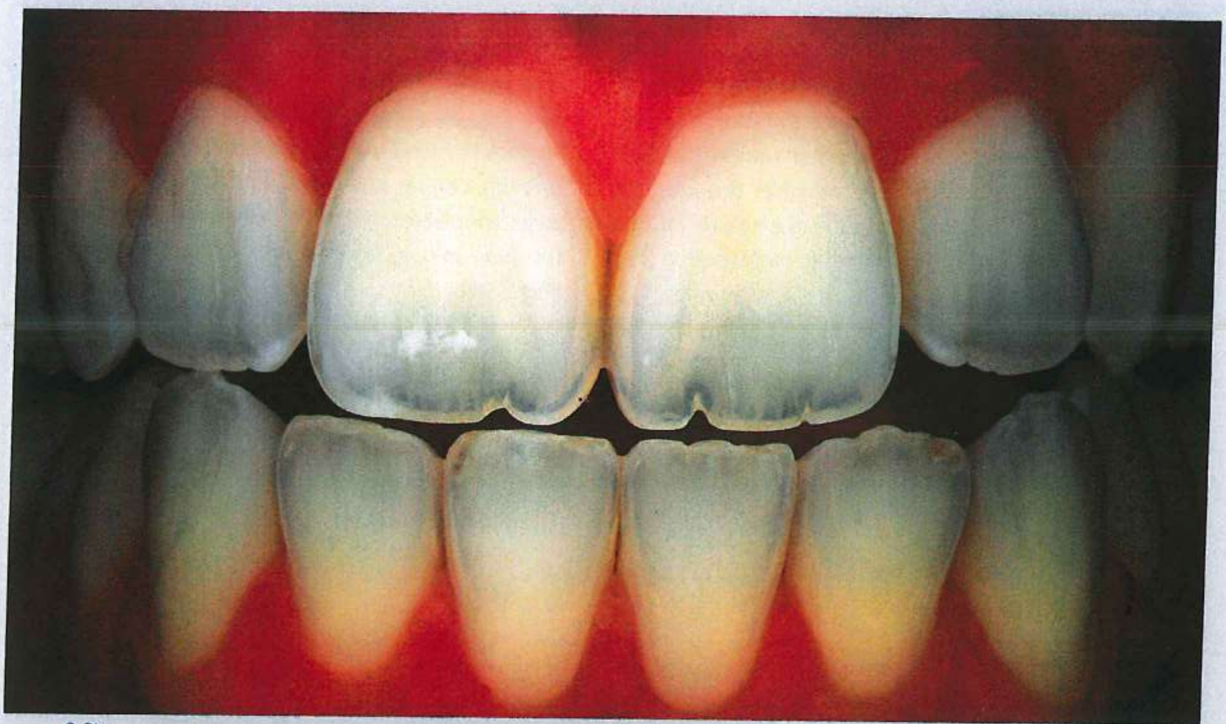
ENAMEL EFFECTS



2-8f 2-8g

FIG 2-8 *(cont)* **Enamel effects.** *(f)* Natural incisor with complex effects including translucency, opalescence, as well as white developmental "clouds" and small random white spots. A white incisal halo effect is also visible in the form of a more opaque area just beneath the blue/lavender translucency of enamel. *(g)* The halo can be explained by an internal mirror effect at the incisal edge. Due to the enamel translucency, the incisal edge *(double red line)* acts like an internal mirror and reflects the incisal dentin *(yellow arrows*; see also chapter 3, Fig 3-44). The area in between the dentin mamelons and the reflection area allows scattering that produces a blue/lavender effect *(blue arrow)*. *(h)* This is particularly visible when using reflective cross-polarized photography (see device in chapter 5, Fig 5-34a). Figures 2-7d and 2-8h are from the same patient. Note the white spots on the right central incisor *(h)* that turn into gray spots under black light *(i*; see device in Fig 2-9f*)*.

CROSS-POLARIZATION



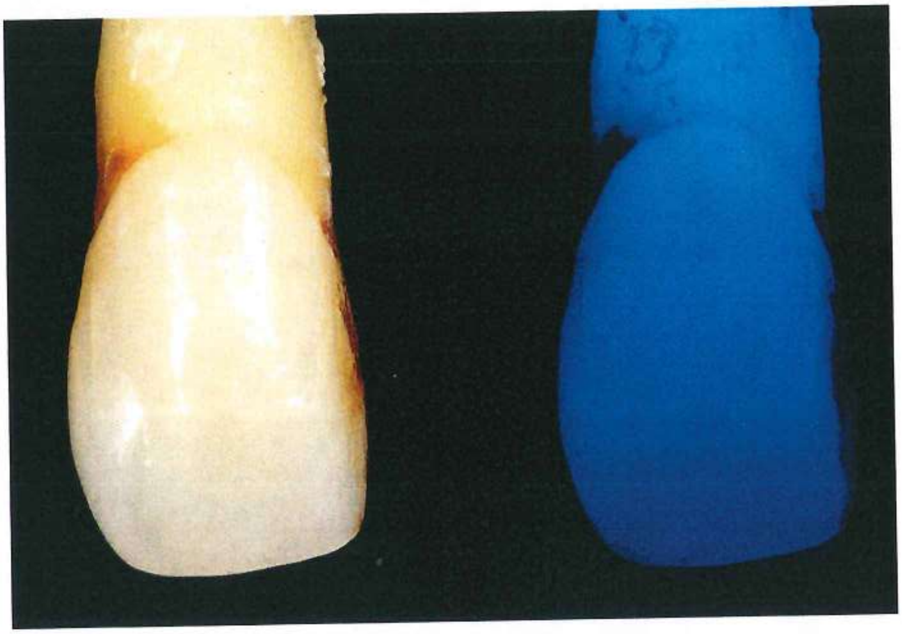
2-8h

FLUORESCENCE

2-8i

Fluorescence

Fluorescence *is defined as the ability to absorb radiant energy and emit it in the form of a different wavelength.*[42] Dentin appears to be three times more fluorescent than enamel, which generates an "internal luminescence." It remains questionable whether the latter is instrumental in the rendering of a natural tooth's vital appearance, also called *vitalescence* (Fig 2-9a). Ceramic and composite resin materials have been optimized with regard to this specific aspect (see chapter 6, Figs 6-66p to 6-66r and 6-67u). However, it is very difficult to faithfully reproduce the luminescence spectra (color and intensity) of enamel and dentin (Figs 2-9b to 2-9d), as demonstrated by in vitro spectral studies.[43,44] Rare-earth elements (ie, europium, terbium, cerium, and ytterbium) have been used as luminophores, but none definitely reproduces the blue-mauve fluorescence of natural teeth (Fig 2-9e).



2-9a

FIG 2-9 Fluorescence. *(a)* Even though it is less saturated and may appear brighter than dentin *(left)*, enamel actually shows less luminescence than the root *(right)*. *(b)* A patient presents with stained teeth and preexisting restorations. *(c and d)* Black-and-white photographs and black light are useful for a quick evaluation of restorative materials. The deficiency of the old Class 4 composite resin restoration on the maxillary right central incisor is evident, as are natural nonfluorescent white spots on cervical surfaces. *(e)* Another patient presents with a porcelain-fused-to-metal crown on the right central incisor, a natural left central incisor, and a porcelain veneer on the left lateral incisor; even though luminescence of ceramic materials seems easier to control, variations with the blue-mauve fluorescence of natural teeth is still perceptible.


2-9b


2-9c

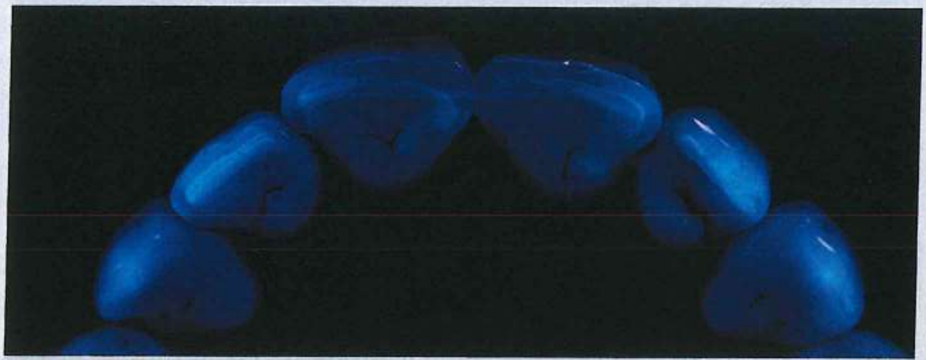

2-9d


2-9e

The significance of fluorescence under ambient light has not been proven. A reality, however, is that UV-rich environments are more common than expected, not limited to nightclubs alone but also gaming arcades and other "glow-in-the-dark" mini-golf facilities and bowling alleys, etc. A single nonluminescent restoration in the anterior dentition could turn a pleasure/leisure moment into the most embarrassing experience for a person ("missing tooth effect"). For the clinician, a simple but efficient way to approximate the fluorescence of a restoration in vivo (or a material) is to check its optical interaction with those black lights.[45] "Glo" neon, however, lacks intensity and requires long exposure times. As a result, clinical images are often blurry (see Figs 2-9d and 2-9e). An innovative approach was developed in the form of a customized fluorescence macro flash (fluor_eyes, Emulation, Fig 2-9f),[46] providing an ideal excitation wavelength of 365 nm. A shutter speed of 1/125 seconds, aperture of f22, and ISO of 200 to 400 are recommended, resulting in sharp images with appropriate depth of field (Figs 2-9g to 2-9i; see also Fig 2-8i). Such images might also be useful for quality control and detecting restorative defects or elements not normally visible in daylight such as brush hairs (Fig 2-9i), restorative material excesses, etc.

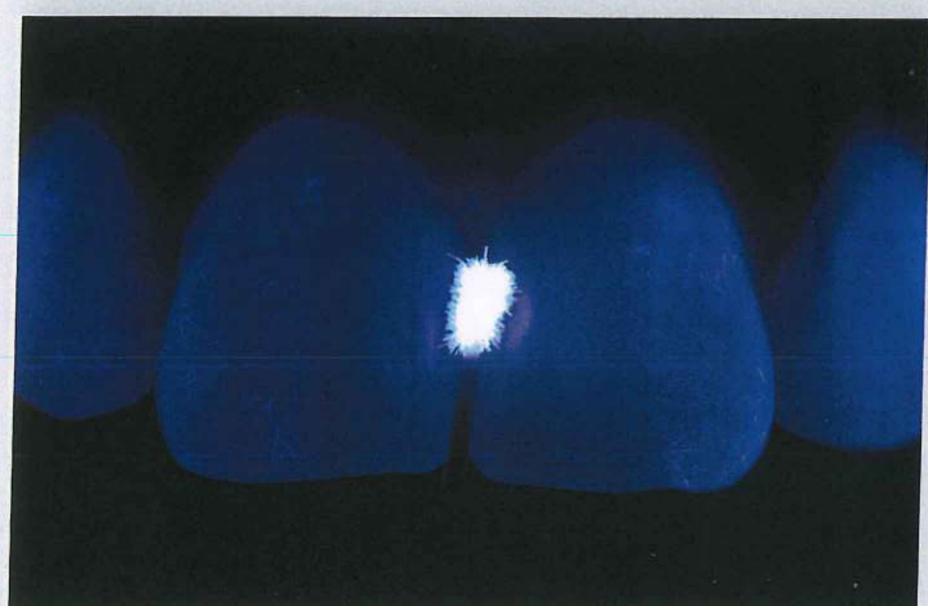
2-9f

FIG 2-9 *(cont) (f)* The fluor_eyes system: Fluorescence macro flash system resulting from the customization of the R1 Wireless Close-up Speedlight System from Nikon. Lingual views are normally very challenging for light conditions with fluorescence, but the system provided high-quality images of this patient *(g and h)*. Note the high tridimensional luminescence of dentin (especially the dentinoenamel junction), approximately threefold compared to that of enamel. *(i)* This defective microbrush left many hairs in the restorative material surface at the distal aspect of both central incisors and could be detected by fluorescence.



2-9g

2-9h



2-9i

Criterion 10: Surface texture, gloss, and luster

Surface texture, gloss, and luster (S G L)[40] are closely related to color (H C V, for hue, chroma, and value)[40] through value, a parameter that it influences directly. The marked surface topography of young teeth causes them to reflect more light and appear brighter (Fig 2-10a). Texture diminishes with age because of attrition, abrasion, and biocorrosion, resulting in decreased light reflection and darker teeth (Fig 2-10b).

The determining elements of texture are essentially oriented horizontally and vertically over the labial tooth surface:

- The horizontal component is a direct result of the lines of growth (lines of Retzius), leaving fine parallel stripes on the enamel surface, also called *perikymata* (Figs 2-10a, 2-10b, and 2-10d).
- The vertical component is defined by the superficial segmentation of the tooth in the different developmental lobes discussed before (Figs 2-10b, 2-10c, and 2-10e).

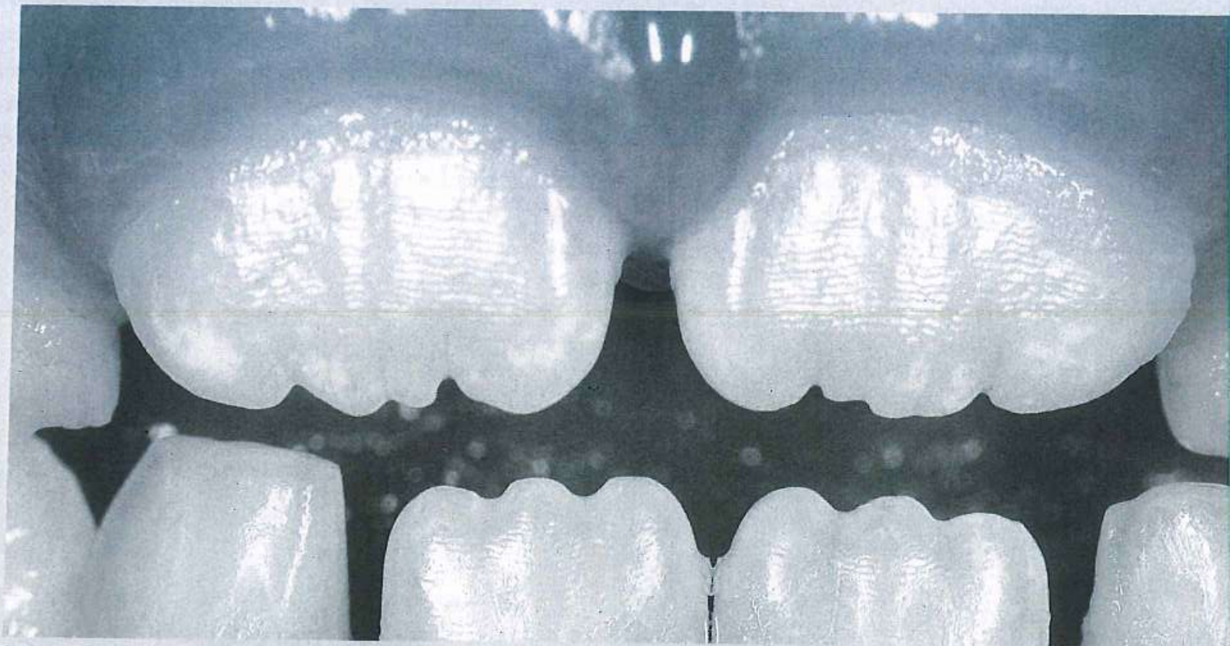
Texturing restorations (either ceramic or composite resin) must follow a specific sequence, always starting with vertical elements and finishing with horizontal ones (see chapter 3, Figs 3-49 and 3-50).

Gloss can be defined as specular (at convex polished surfaces) or matte (likely concave areas or depressions). *Luster* is a more subjective way to describe the reflective aspect of a surface using terms like *satin*, *pearly*, *metallic*, etc.

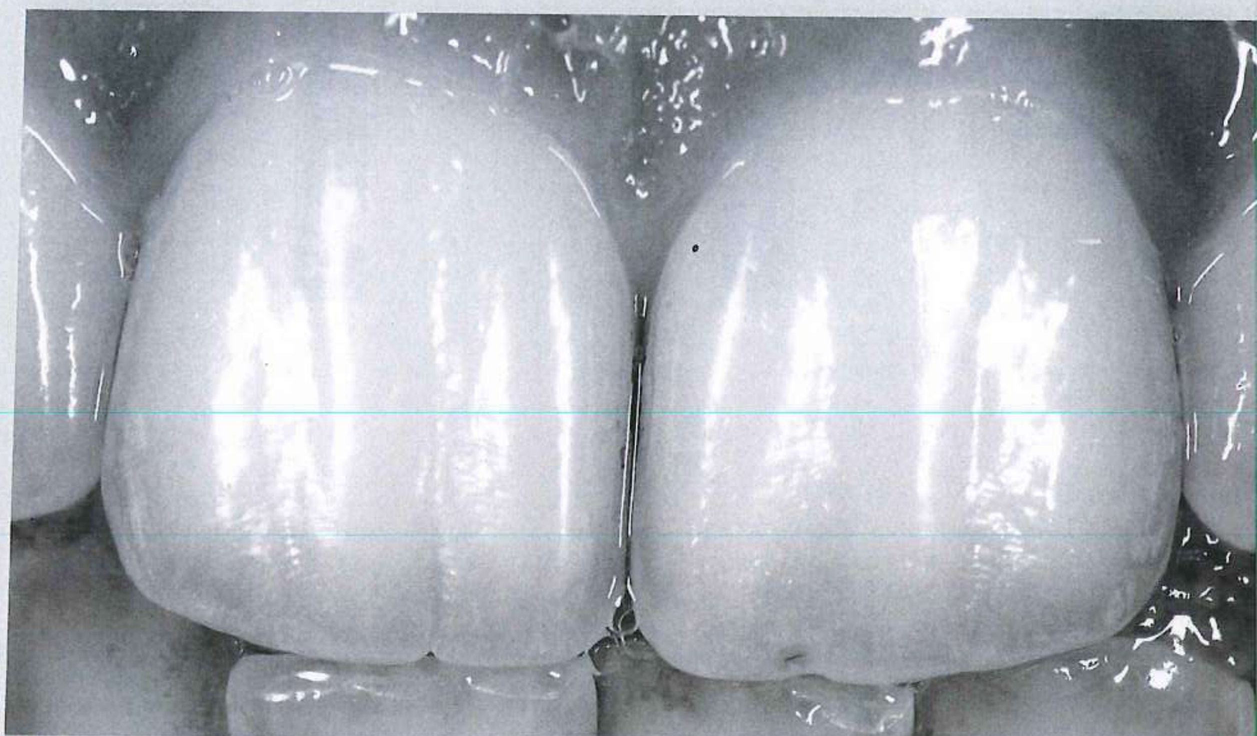
The type of dental photography equipment used is determinant on how texture can be studied, perceived, and reproduced. All images about this topic were made with a twin macro flash system with both flash tubes oriented vertically, one on each side of the lens (see chapter 5, Figs 5-28 and 5-29).

FIG 2-10 Basic components of surface texture. *(a)* The horizontal component of surface texture is particularly obvious on permanent maxillary central incisors at the time of eruption. Note also the intact structure of the lobes at the incisal edge. *(b)* The horizontal component of surface texture often persists even on older teeth, especially between lobes and in concave areas, while the surface of the lobes becomes more polished and glossy, displaying essentially vertical specular reflections.

10. SURFACE TEXTURE

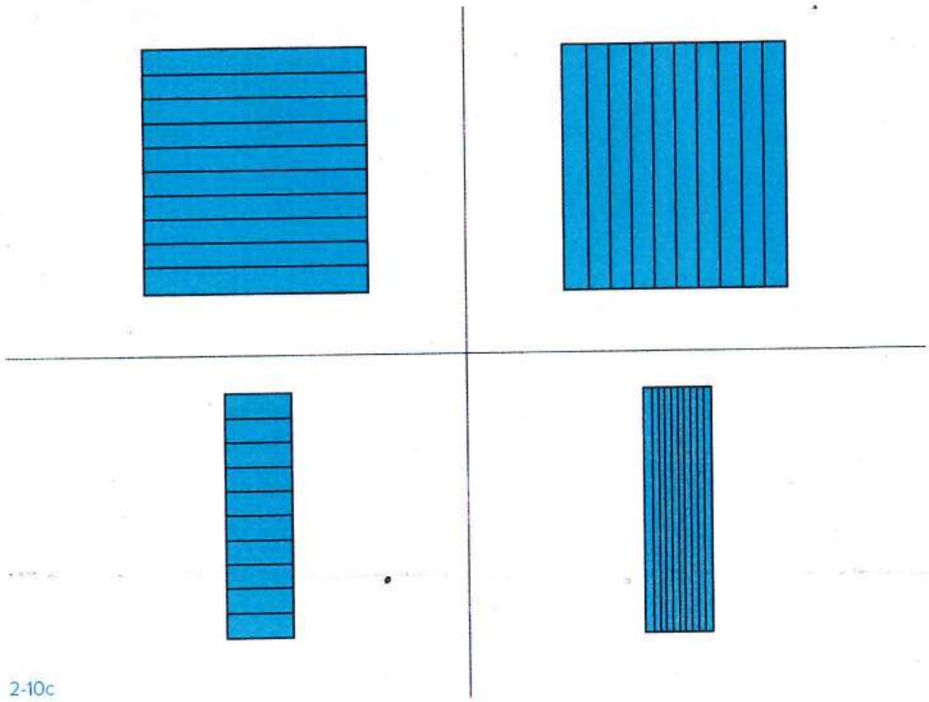


2-10a



2-10b

For a structure that is close to a squared shape, marked horizontal components will make it appear longer or narrower (Fig 2-10c, top); on the other hand, marked vertical components will make a more rectangular structure appear longer or narrower (Fig 2-10c, bottom).[47] Surface texture and morphology can therefore be used to generate illusive effects of size (compare Figs 2-10d and 2-10e). In restorative dentistry (either during composite resin or ceramic finishing), reproduction of such details requires a specific chronology: ***The vertical characteristics must be achieved first, horizontal growth lines being reproduced only at the end of surface finishing, just before the gloss and luster***. Rubbing articulating paper against the tooth surface helps to visualize these effects (Figs 2-10f and 2-10g).

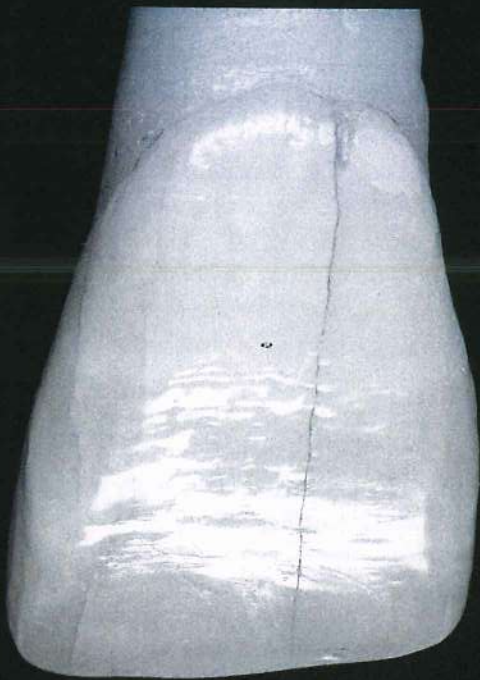


2-10c

FIG 2-10 *(cont) (c)* A structure close to a square shape appears narrower when textured horizontally compared to vertically (compare top left and top right shapes). The effect is opposite on a more rectangular elongated structure where vertical texture makes it look longer (compare bottom left and bottom right shapes). *(d)* A different inclination of the light source reveals a well-defined vertical architecture on the same aged tooth. Note that the tooth in *d* appears wider than the tooth in *e* because of the rectangular outline rather than square. Selective rubbing of articulating paper helps to reveal the horizontal texture *(f,* light rubbing) and the vertical lobes *(g,* more aggressive rubbing); see the practical tips applied to texturing composite resin restorations in chapter 3, Figs 3-49 and 3-50.

HORIZONTAL

VERTICAL



2-10d

2-10e

2-10f

2-10g

Criterion 11: Color

Color is too often considered a major element in the esthetic success of a restoration. However, a minor error in color might not be noticed if the other criteria have been well respected.

> Of the three components of color (hue, value, and chroma),[40,48] value (also called *luminosity* or *brightness*) is most influential,[23,49] followed by chroma (also called *saturation* or *intensity*) and hue (the color itself or "name" of the color).

Hue

Hue is determined by the wavelength and is named after the color family (red, yellow, etc). It is not of critical importance because of the low concentration of hues in dental shades. However, the perception of hue will be influenced by environmental factors. For instance, Lombardi suggested that for patients who wear lipstick, the try-in be made with lipstick on due to the strong effect of complementary colors.[23] For example, intense red will logically call for green, so teeth next to red lipstick may appear green if not colored correctly (Figs 2-11a and 2-11b). The tooth must therefore contain enough red or pink pigments to neutralize the undesired greenish tinge.

Value

Value is the only color dimension that can exist by itself (with no hue and chroma). Value is the relative blackness or whiteness, which is easily perceived when converting an image to black and white. As previously mentioned, brightness might be the most important component of color[23,49] due the high sensitivity of the human eye to value, and it must be prioritized during shade selection (see chapter 5, Figs 5-31 to 5-33). In addition, it is intimately correlated to surface texture. It is quite common to observe a wide range of brightness within the same tooth crown (Figs 2-11c to 2-11e). Generally, the middle third is the brightest, followed by the cervical third. The incisal third often displays the lowest value, which is explained by the higher transparency and light absorption of this area. Brightness can also be used to create illusions of size and position. Brighter teeth will generally appear larger and closer (see Fig 2-3e).

Chroma

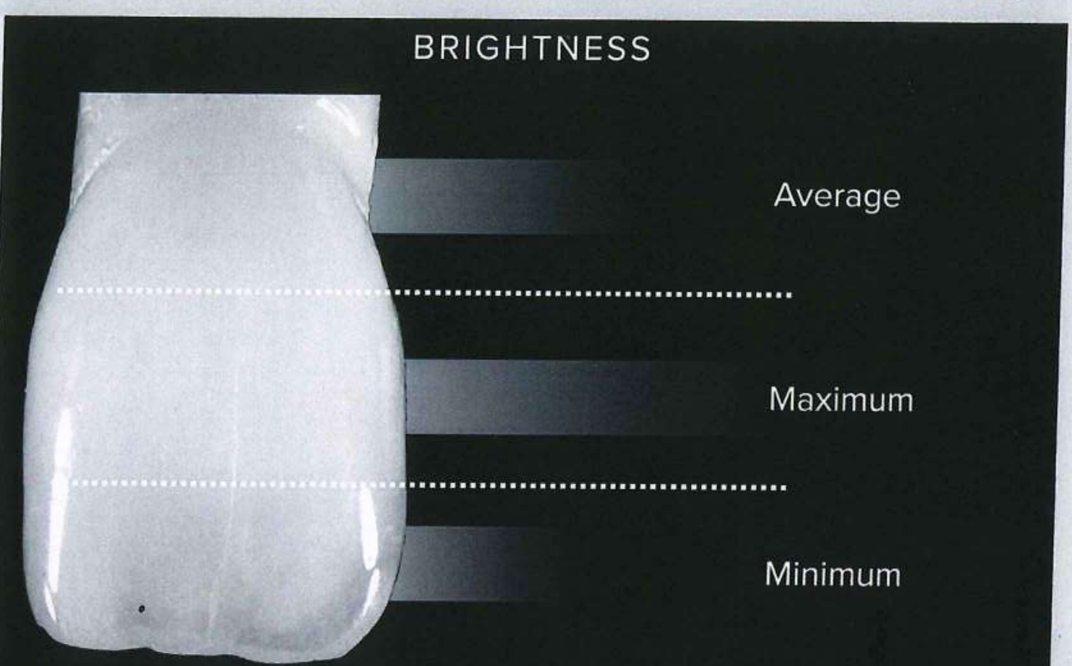
Saturation defines the concentration (intensity, purity, strength) of the hue, and its evaluation is facilitated by cross-polarized photography (see Fig 2-8h and chapter 5, Figs 5-34 and 5-35). A broad range of chroma is present between a young patient with bleached teeth and an older patient with root exposures. It must be emphasized that, from a restorative material perspective, value and chroma are inversely related. An increase in chroma (eg, root dentin) logically induces a decrease in brightness. This accounts for the loss of value in the cervical third, which is influenced by root dentin, compared to the middle third of the crown (Fig 2-11c).

FIG 2-11 Natural tooth hue and brightness. *(a and b)* Red lipstick can make teeth appear green (compare *a and b*). This is explained by retinal fatigue (see *d and e*). *(c)* The middle third of the incisor crown often represents the brightest area, followed by the cervical third; the incisal third usually features the lowest value due to light absorption through transparency and translucency. *(d and e)* Intact teeth in vivo can show extreme variations in brightness within the crown; the middle third remains the brightest.

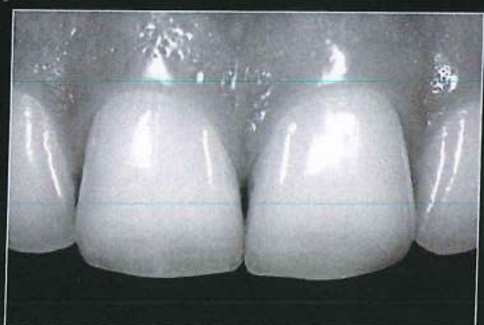
11. COLOR

2-11a

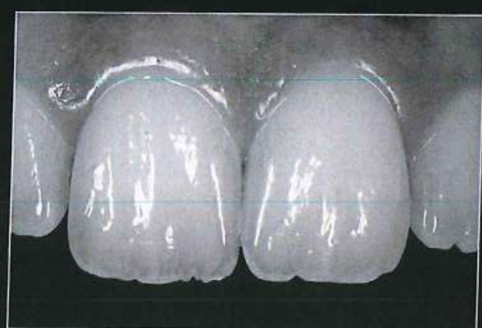
2-11b



2-11c



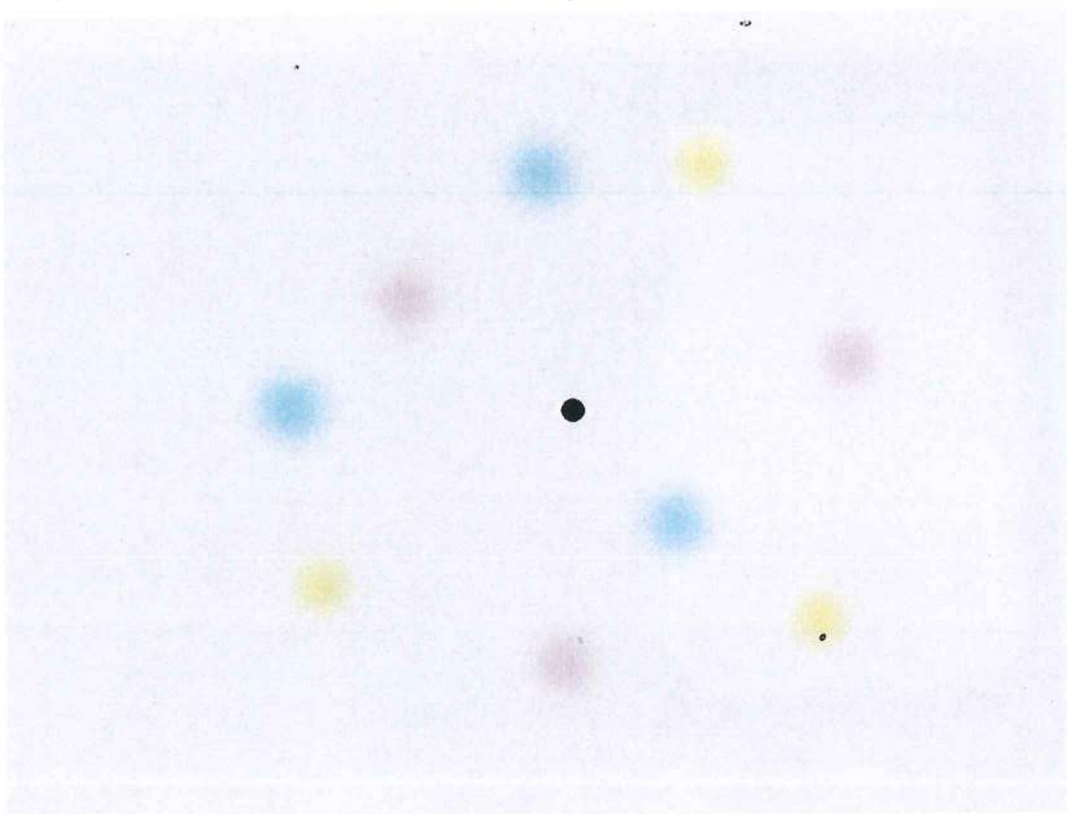
2-11d



2-11e

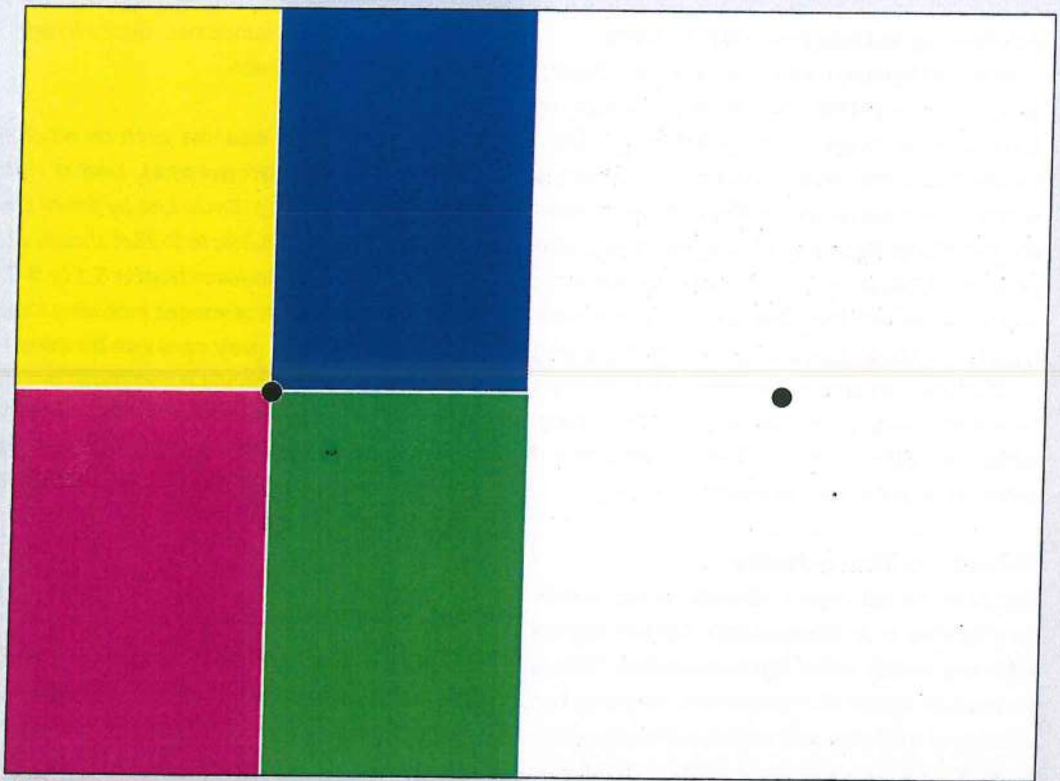
Retinal fatigue and chromatic adaptation

When staring at teeth for shade determination, the retina of the eye will fatigue rapidly in about 5 seconds. This will decrease the ability to differentiate hues (Figs 2-11f and 2-11g). Shade evaluation should therefore not exceed 5 seconds and should be followed by staring at a complementary color to restore acuity for the initial hue (eg, a blue card). Chromatic adaptation is another phenomenon that will influence the way we perceive intensities. The human vision will compensate for different sources of illuminant, a sort of natural "white balance" as it is described for cameras (Fig 2-11h).



2-11f

FIG 2-11 *(cont) (f)* Stare at the point in the image for 10–15 seconds, and the colored dots should disappear because of retinal fatigue. *(g)* For the same reason, staring at the point on the left for 10–15 seconds and then looking at the point on the right should generate afterimages of complementary colors. *(h)* The green tooth *(top left)* should present a more intense green than the same tooth when the entire image is green *(top right)*. This is explained by chromatic adaptation because the human visual system will automatically attenuate the effect of a global illuminant (eg, in this case green). Similarly, the presence of an inflamed gingiva (simulated by digital alteration at *bottom right*) makes the right central incisor look brighter than the same tooth in the unaltered image *(bottom left)*. In such conditions, two operators might disagree on the shade of a single central incisor ceramic restoration depending on their ability to visually "isolate" the tooth from its surroundings.



2-11g

2-11h

Additive vs subtractive color models

Unlike RGB lighting (red, green, and blue lights), which is an additive color model (addition of color sources brighten the object), the CMKY model (cyan, magenta, yellow, and key inks) is subtractive because the addition of colors darkens the object. Pigments in composite resins and ceramics work by subtraction, and dental technicians know well that adding colored pigments usually results in a decrease of brightness (Fig 2-11i). They sometimes anticipate this problem by intentionally creating a brighter restoration, which can be modified to the correct value if color corrections are necessary.

Dynamic optical behavior

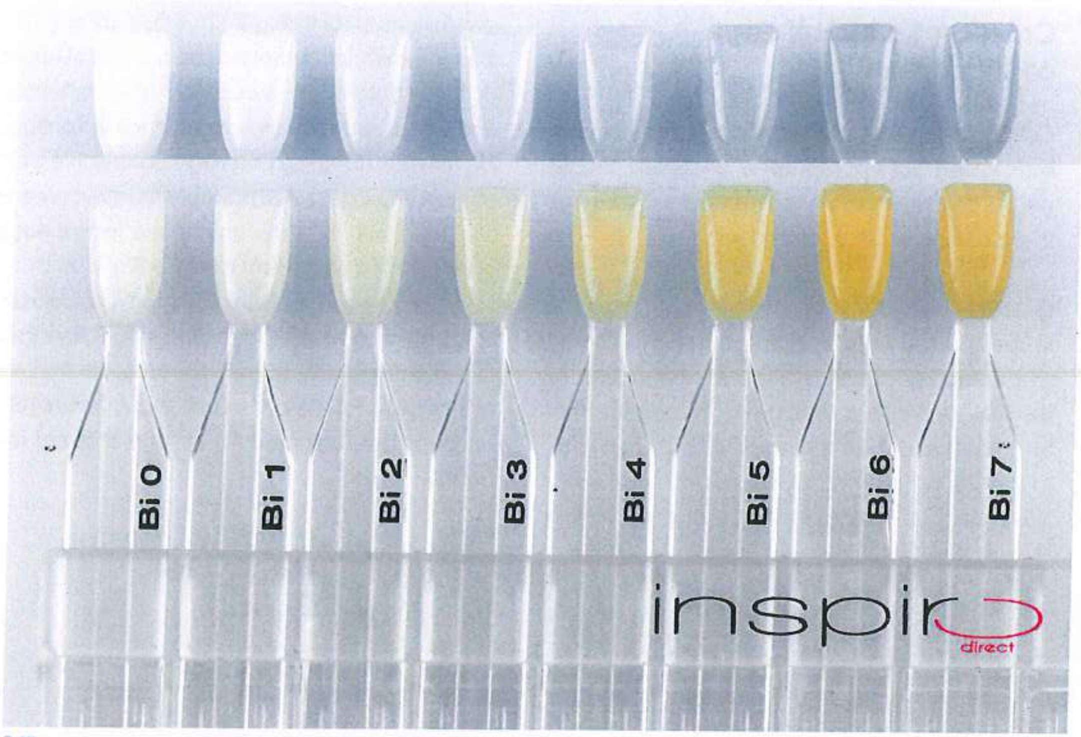
Restorations will match perfectly under operatory lighting or in photographs but will appear different under other light conditions. This is somewhat similar to metamerism, whereby two pieces of clothing will match perfectly when compared inside the store (artificial light) and shockingly mismatch when moving outside into daylight. The key elements in this phenomenon are the wavelengths composing the light source illuminating the object (spectral distribution) and how the object reflects them. Two materials will match successfully when the sum of the reflecting wavelengths of the two materials is close. It is also important to select the shade with similar materials to those that will be used for the restoration. Using a ceramic shade guide for composite resin restoration is not appropriate because of the different ways the two materials scatter the light. By the same token, when surface coloring is used to correct mismatches, dynamic optical differences will increase.

Using various light sources such as daylight, camera flash (photographs), and a light-correcting device (eg, Smile Lite by Smile Line; see chapter 3, Figs 3-38c to 3-38e) should optimize shade selection (see chapter 5, Fig 5-32). Cross-polarized clinical images including shade tabs or a reference gray card can be used for a quick determination via a computer presentation software (see chapter 3, Fig 3-47g plus corresponding video) or a more sophisticated approach with the eLab system (see chapter 5, Figs 5-34 to 5-37).

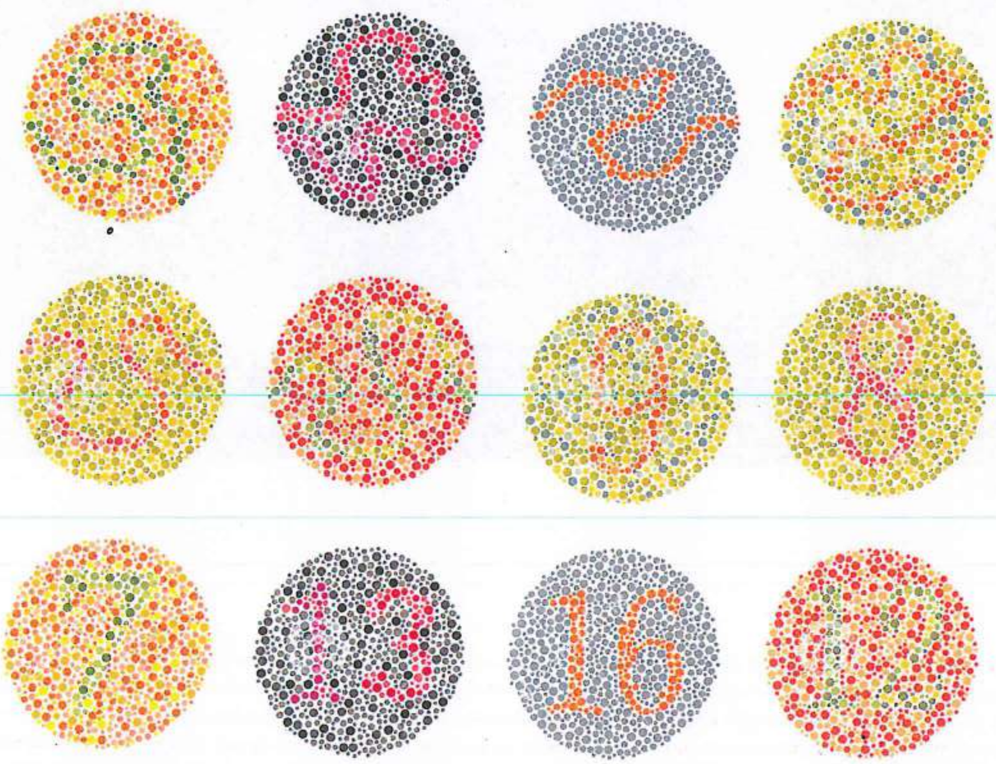
Color vision deficiencies

The human eye uses RGB additive color principles (trichromatic system) with cone cells sensitive to red, green, and blue stimuli. The prevalence of color vision deficiency (CVD) is 8% in men and 0.4% in women (European Caucasian).[50] There are a number of acquired and congenital CVDs including monochromatism (only one color perceived, extremely rare), dichromatism (only two colors perceived), and anomalous trichromatism (altered proportion of each primary color). Basic screening for color blindness can be done either with Dvorine plates or Ishihara plates (Fig 2-11j). Color-correcting contact lenses or glasses can be used to see more colors. While they will not "cure" color blindness, the glasses give color-blind individuals a more accurate experience with a greater spectrum of colors. eLab is the solution.

FIG 2-11 *(cont) (i)* This composite resin shade guide illustrates how an increase in chroma *(from left to right)* is accompanied by a decrease in value (evaluated in the corresponding black-and-white image). *(j)* The Ishihara plates are used to screen for color deficiencies by requiring the individual to recognize "hidden" numbers within an array of colored dots.



2-11i



2-11j

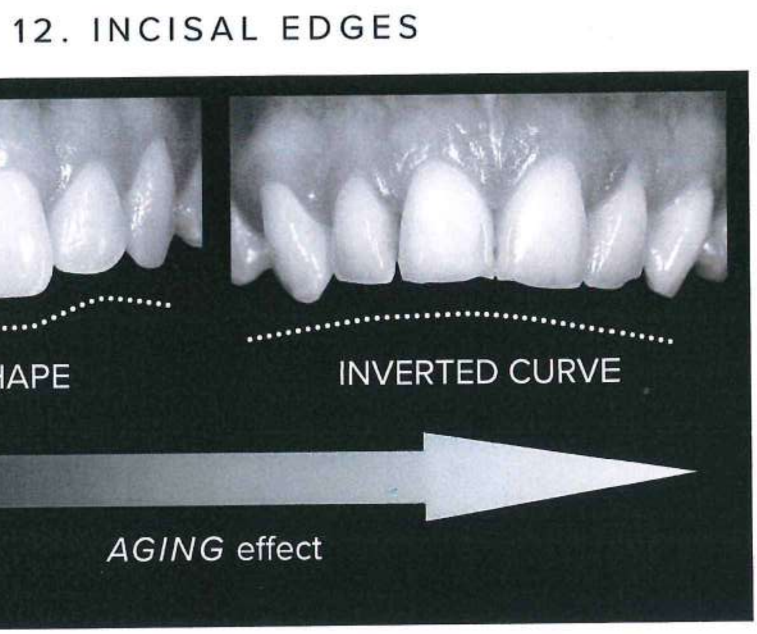
Criterion 12: Incisal edge configuration

Configuration of incisal edges is a critical parameter. When not appropriately designed, incisal edges can make teeth look artificial. There are three components to consider.

General contour

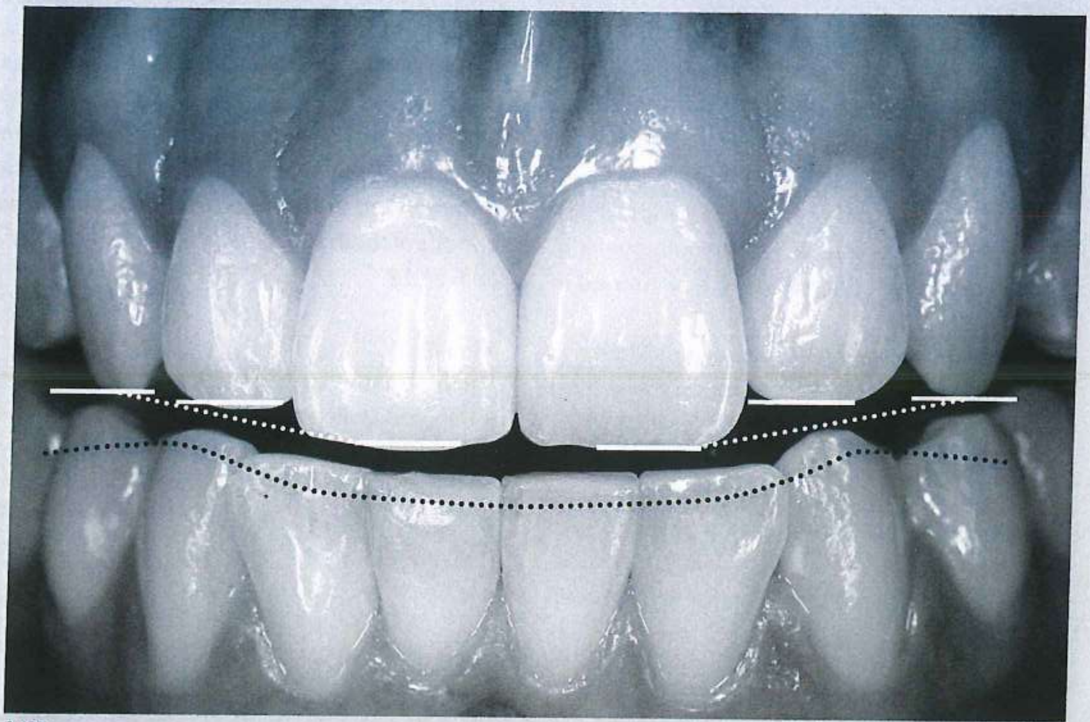
In the old and middle-aged patient, the course of the incisal edges is often a straight line or an inverted curve that generates uniformity and flatness within the smile (Fig 2-12a, right). In the young patient, incisal edges are configured in a "gull" shape due to the original relative dimensions of teeth (Fig 2-12a, left, and Fig 2-12b). It is extremely important to note the incisal edges of mandibular teeth, which are often left intact and can provide significant guidance in configuring maxillary teeth by creating a compatible wear pattern (Fig 2-12c). It is possible to rejuvenate or age the smile by transforming the incisal edge configuration according to Fig 2-12a.

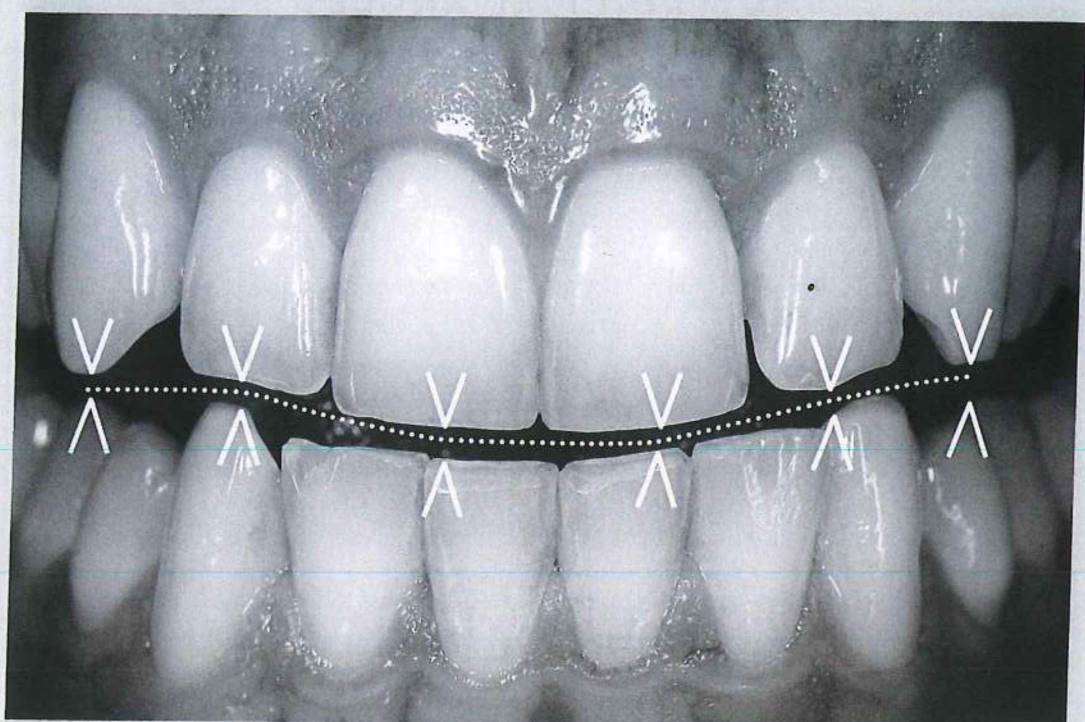
When needed, incisal edges can also be used to create illusive effects of dimension: Rounded incisal edges will compensate for teeth that are too large, and straight worn edges (eventually notched) are indicated for incisors that are too narrow.



2-12a

FIG 2-12 Contour of incisal edges. *(a)* Aged dentitions present flat, worn incisors *(right)*, as opposed to young dentitions that display incisal edges with a gull-shape configuration *(left)*. *(b)* The incisal edge of lateral incisors is 0.5 to 1.5 mm above the straight line joining the most incisal point of the central incisors and canines. *(c)* The incisal wear pattern of antagonistic teeth must also be used as a guide. A harmonious space can be seen between the mandibular and maxillary teeth when the patient opens the mouth slightly from the edge-to-edge position. Note the more "masculine" effect of the upright canines in c.


2-12b


2-12c

Interincisal angles

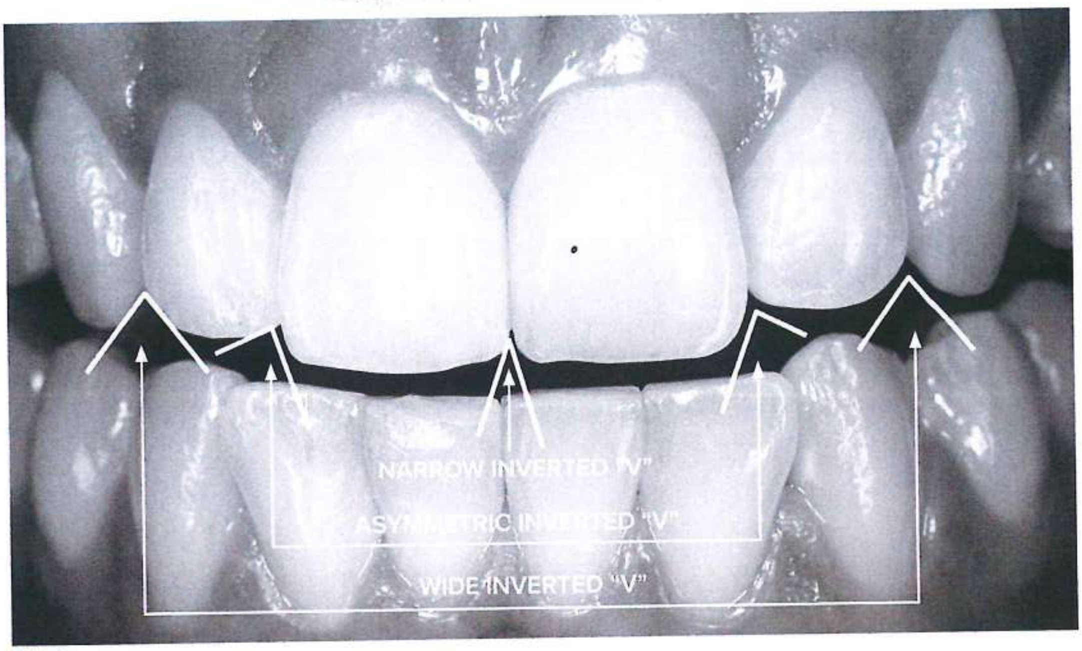
Interincisal angles (incisal embrasures) are closely related to criteria 6 and 8. Mesioincisal and distoincisal angles have a great influence on the definition of the so-called "negative space," ie, the dark space between maxillary and mandibular teeth during laughter and mouth opening. An objective rule ("inverted V") is described in Fig 2-12d.

Closer observation of natural dentitions can reveal a more complex (dynamic) architecture and more faceted interincisal angles (Figs 2-12e and 2-12f). Note, however, that those sharp negative spaces have a strong and vigorous effect and are often not appreciated by patients who are seeking the so-called "perfect/ideal" smile. They perceive those small wear facets and deep incisal embrasures as "defects" that disturb the smile line. They may even request those spaces to be intentionally minimized or even completely closed to provide a sense of evenness. ***Such uniformity, however, is always going to look artificial and monotonous because it forces unnatural tooth shapes*** and infringes with criteria 6 and 8.

Thickness

Youthful, esthetically pleasing incisors display a thin and delicate edge. Thick incisal edges can make teeth look old, artificial, and bulky. Respecting and reproducing the incisolingual escape routes, as illustrated in Figs 2-5h to 2-5m, is essential in this regard.

INTERINCISAL ANGLES



2-12d

FIG 2-12 *(cont) (d)* Inverted V rule of interincisal relationships. Note the dark negative space between the maxillary and mandibular teeth.

2-12e

2-12f

FIG 2-12 *(cont) (e and f)* Other dentitions display deep incisal embrasures—sharp dynamic negative spaces—with faceted interincisal angles. While those can be regarded as extreme, they provide a deep sense of "natural" because they also satisfy criterion 6 (see Fig 2-2g) and criterion 8, which are inherent to natural tooth forms.

Criterion 13: Lower lip line

The ultimate control of crown form, length, and incisal edge configuration is revealed by their harmonious association with the lower lip during a relaxed smile. Taking photographs of such a position can be challenging because patients will tend to give a forced smile when they see the camera. One critical sign that accompanies a natural smile is the involvement of the eyes. A slight narrowing of the eyes should occur when the smile is pushing the cheeks up and should induce tiny wrinkles near the corners of the eyes.

In this position, lateral incisors remain at a distance of 0.5 to 1.5 mm from the lip, whereas central incisors and canines are in close relationship with the lip line (Fig 2-13a).

Coincidence of incisal edges with the lower lip is essential for a pleasing smile. Proximal contacts, incisal edges, and the lower lip define parallel lines (Fig 2-13a), which usually connote harmony[23] and cohesive forces.[2]

An unsightly space between the lower lip and central incisors is typical in dentitions that are prone to accelerated aging, biocorrosion, and wear (Fig 2-13b), which results in the loss of the cohesive forces of the dentofacial composition.[2]

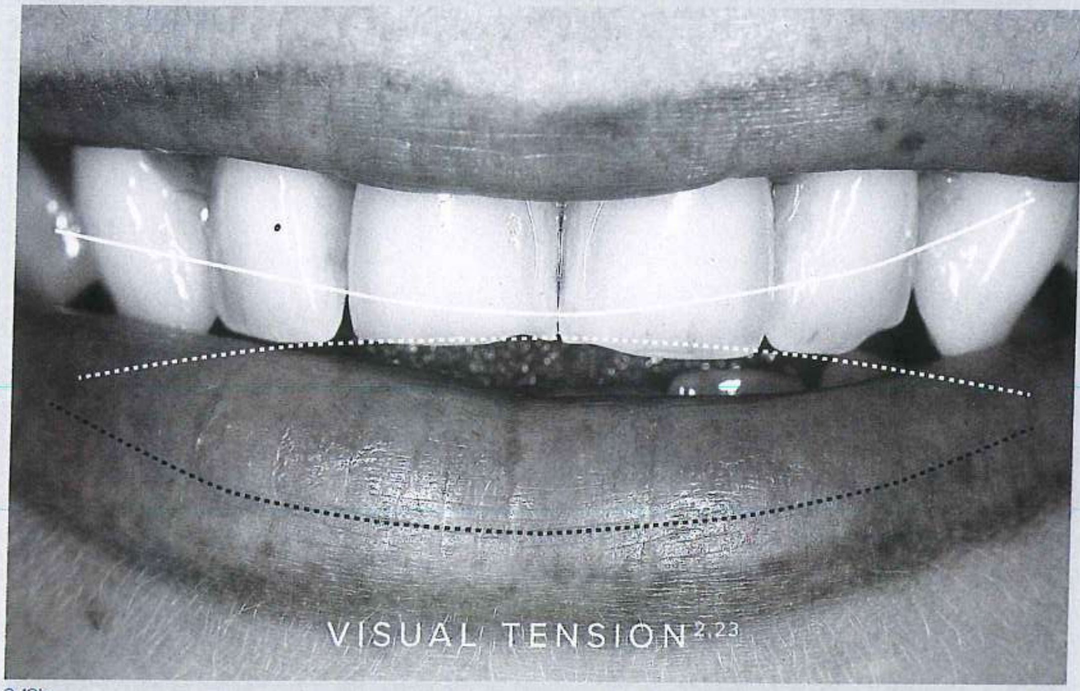
The upper lip contour can vary considerably and, in most cases, does not appear to be as relevant to the pleasing aspect of the smile. Individuals with a high upper lip will display large amounts of gingival tissues, which can require more restorative efforts to respect and optimize the dentogingival relationship. Dentogingival defects will not be visible in patients with a low upper lip line, which becomes a cover for either poor dentistry or major dentogingival inadequacies that are difficult to correct.

On the other hand, some patients with a particularly senile upper lip (extremely long philtrum) could benefit from plastic surgery techniques such as the lip lift to achieve a more youthful appearance.[51] Plastic surgery, however, is beyond the scope of this work.

FIG 2-13 Lower lip as a guide to the dentofacial composition. *(a)* There is a direct coincidence of interdental contacts *(solid white line)*, incisal edges *(dotted white line*, also called the *smile line*), and lower lip *(dotted black line)* that provides cohesive forces to the dentofacial composition as defined by Rufenacht and Lombardi.[2,23] *(b)* This equilibrium is broken by an inverted incisal edge configuration, which produces visual tension. (See chapter 6, Figs 6-48, 6-53, and 6-73 for the various phases of treatment of this case.)

13. LOWER LIP LINE

2-13a



2-13b

Criterion 14: Smile alignment

> Smile alignment refers to the relatively symmetric placement of the corners of the mouth in the vertical plane, which can be directly derived from the interpupillary line (Fig 2-14a).[2] This has proven to be a fundamental biometric reference for 88% of individuals[52] and a prerequisite to the esthetic appraisal of the smile.

The occlusal line should conform to the commissural line, even though slight asymmetries within the dental segment are desirable (Fig 2-14b). ***There are always variations between both sides of the human face, and it is contrary to nature to believe that absolute symmetry is required.*** As a result of those asymmetries, facial and dental midlines only coincide in 70% of people; maxillary and mandibular midlines fail to coincide in almost three-fourths of the population.[53]

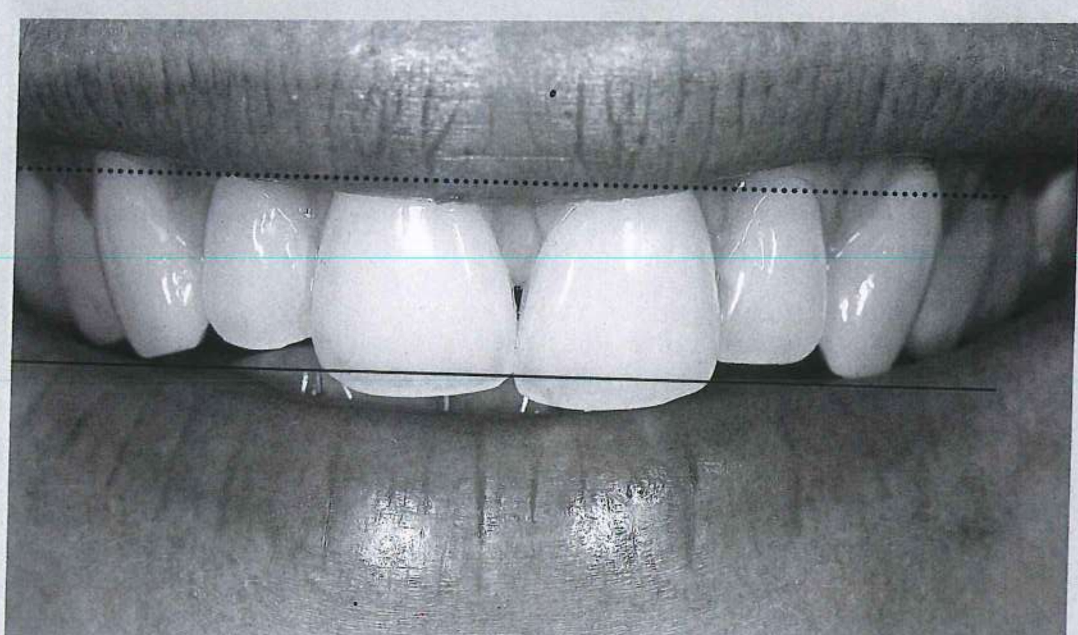
While smile design techniques are now mostly digital,[54] standardized photographs of the patients can be used to evaluate smile alignment and import the data into the virtual database.[55] Other approaches include using a face scanner,[56] or even a mobile device[57] to obtain 3D facial data and merge them with intraoral scans. For the analog approach, a simple portrait photograph with retracted lips imported in an imaging software will already reveal if a major misalignment is present. Another method is to use a regular facebow but align it to the interpupillary line instead of the auditory meatuses. The ultimate analog approach, however, is to use an esthetic transfer device, such as Ditramax (www.ditramax.com),[58] allowing the precise registration of the interpupillary line, the facial midline, and the Camper plane. Those elements can be easily transferred to the study casts (Figs 2-14c to 2-14j), hence facilitating significantly enhanced communication with the dental laboratory. The system is totally independent from the articulator system and facebow. Once marked with the facial landmarks, the study casts can still be mounted on any type of articulator using the corresponding facebow.

For the remaining 12% of patients for whom a vertical asymmetry is found, the average level between the interpupillary line, the intercommisural line, and the perpendicular to the facial midline can be still chosen and assessed using the esthetic transfer device.[52]

FIG 2-14 Alignment of facial landmarks. *(a)* The commissural line *(dotted black line*, defined by the corners of the mouth) and the occlusal line *(solid black line*, defined by the cusp tips) must coincide with the bipupillary line *(dotted white line)*; the latter is an important landmark to be referred to when defining the alignment of the smile. *(b)* Slight asymmetries in lip morphology and tooth position/arrangement do not affect the balance of this smile, which features many other fundamental objective criteria of the esthetic checklist (close-up of smile in *a*).

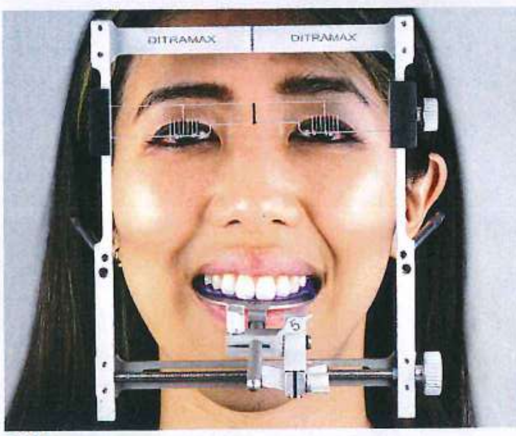
14. SMILE ALIGNMENT

2-14a

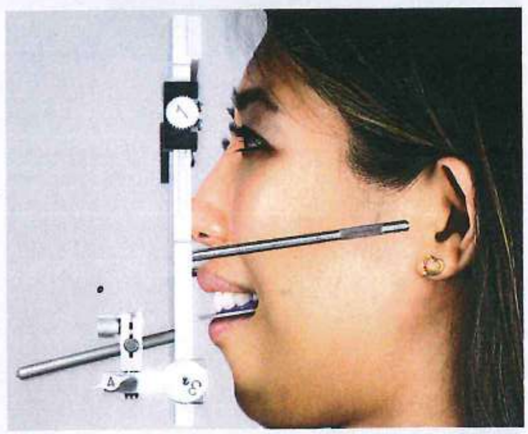


2-14b

2-14c

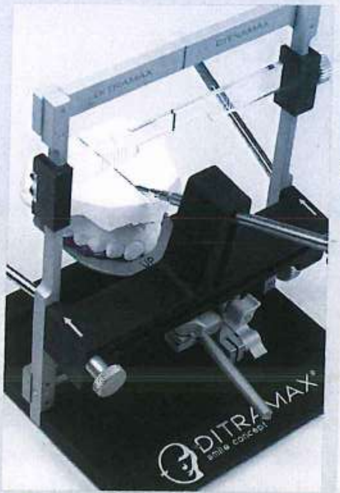


2-14d



2-14e

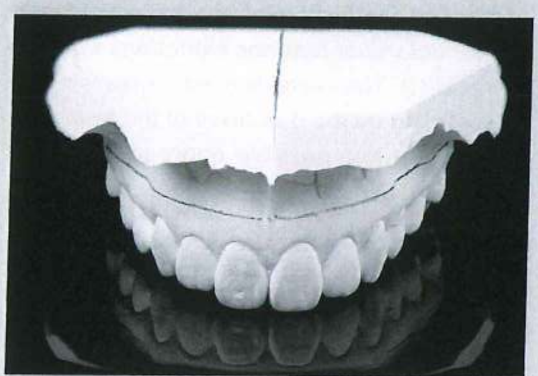
FIG 2-14 *(cont)* **Facial analyzer.** *(c)* The Ditramax system is a complete esthetic transfer device. The main element of the kit is a facial frame connected to the dental maxillary arch with an occlusal fork via bite registration material. The frame is adjusted step by step to match the Camper plane (approximately ala-tragus, *d*) and the interpupillary line and the facial midline *(e)*. *(f)* Once aligned with the face, it is transferred on a table stand, and a tracing jig is screwed to the device. *(g and h)* After placing the study cast onto the fork, a special pencil is used to trace the facial midline and the interpupillary line, which is also parallel to the Camper plane. *(i and j)* The resulting diagnostic casts can be either mounted in the articulator or trimmed parallel to the horizontal reference (see chapter 5, Fig 5-6 for the assembly of the horseshoe-shaped cast to a prefabricated base). The facial midline can be traced again onto the mounting stone if necessary.

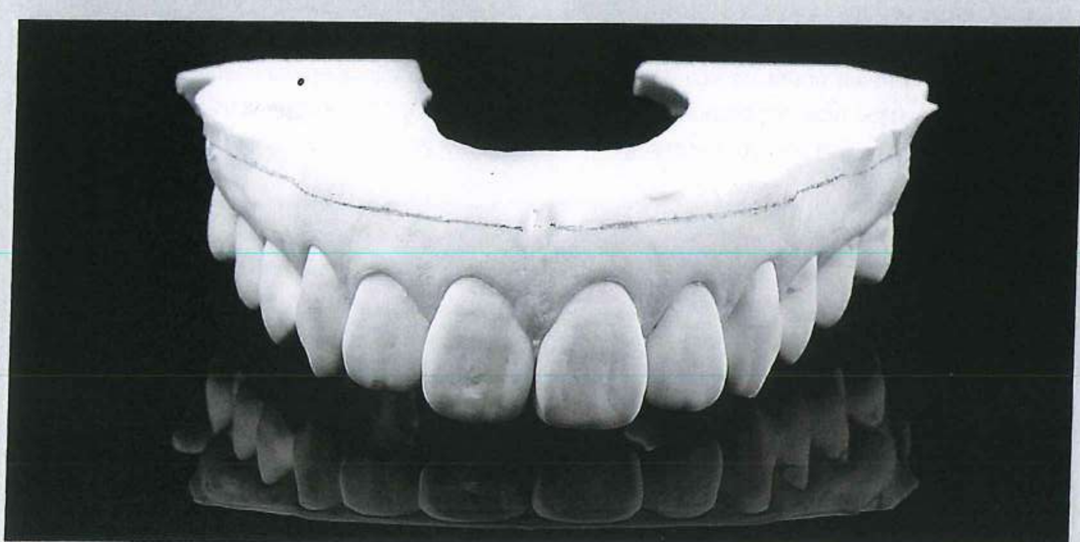


2-14f


2-14g

2-14h


2-14i


2-14j

2.3 ESTHETIC INTEGRATION AND SMILE BALANCE

General considerations—Perfect vs natural smiles?

The 14-point esthetic checklist presented previously could be called a guide to objective "normality." It is a fact, however, that it would be extremely difficult, if not impossible, to find a natural dentition, smile, and face presenting all 14 listed attributes simultaneously. ***Hence, the real goal of the checklist is NOT to create the so-called "perfect smile" but rather to identify potential visual tensions (variations from the checklist).*** The corrective measures will vary depending on the objectives of the treatment. There are two possible approaches to this analysis:

1. ***The removal of visual tensions based on the esthetic checklist.*** Often aimed at absolute symmetry—the so-called "perfect" stereotype smile—this more mathematical approach might require complicated corrective measures such as periodontal surgery and orthodontic treatment in order to eradicate defective criteria. The result of this choice will always be a more static type of composition, qualified by some as dull and uninteresting.[23]
2. ***The balancing of visual tensions (integrating residual defects).*** Integrating asymmetry—the so-called "natural" smile (Figs 2-15a to 2-15c)—this approach might be simpler but requires much more knowledge of optical illusions and visual balance (see Fig 2-16). It will result in a more dynamic type of composition (unity with variety; see Fig 2-1).[6,23] Dominance is an important element in this type of work, with the central incisor dominating the smile in the same way that the mouth dominates the face (see criterion 7).

It is therefore no surprise that global harmony of the final result remains subjective and will depend on the integration of the esthetic criteria in relation to the patient's smile, face shape, age, and character.[33] As discussed throughout the presentation of the checklist, final tooth axis, arrangement, position, and relative length, as well as the determination of incisal embrasures and negative space, are all elements subject to interpretation. Each of these parameters can even vary within the same patient according to his or her cultural environment but also according to geographic, historical, artistic, and psychologic factors (see next sections).[59]

FIG 2-15 Extreme variations of objective esthetic criteria in relation to personality. These three individuals present esthetically pleasing smiles that conform with their personality. Some elements of their smiles, however, largely differ from the aforementioned objective criteria: extreme shift between central and lateral incisor edges *(a)*, irregular negative space and tooth rotations *(b)*, and convergent root axes and prominent central incisors *(c)*.

SENSUALITY

2-15a

CHARACTER

2-15b

FANTASY

2-15c

Art, psychology, and brain dominance

This section provides a few elements of introduction to arts and psychology that are worth sharing with our patients and may help educate them about visual perception and provide better mutual understanding of the treatment goals and challenges.

Individual objective and subjective experiences

Johannes Itten, a Swiss painter and an early instructor at the famous Bauhaus Art School in Germany (1919–1923), covers very well the topic of objective knowledge and subjective taste regarding visual perception in his book *The Art of Color*.[60] While colors can be described objectively (hue, value, chroma) and follow objective rules (eg, additive vs subtractive systems), colors can also be linked to psychologic and emotional values. Itten noticed how student artists usually paint, choose, and use colors in a way corresponding to their personality.

By the same token, a given operator, whether clinician or dental technician, will design a smile corresponding to his own psychologic and emotional state.

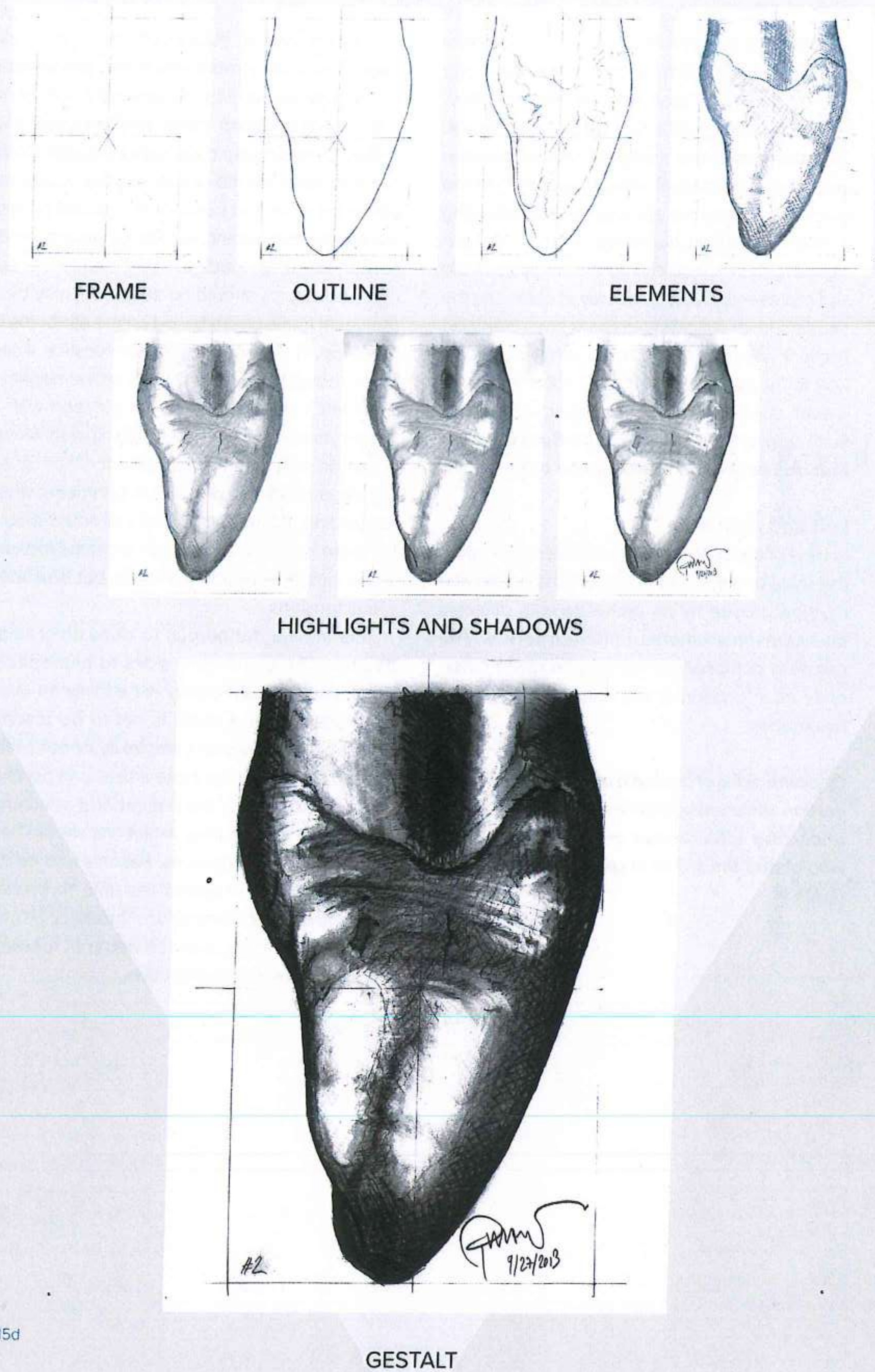
This subjective interpretation adds to the patient's own subjectivity. Patient/operator interpretations may diverge and generate a conflict for the operator. This reality cannot be avoided and must be understood by the patient and mediated. The elements presented later in this section should help both parties to gain flexibility and mutual understanding in order to proceed with the treatment.

Frame of a composition—Perceptual skills

According to Rudolf Arnheim, a perceptual psychologist,[61] the perception of an entire image or art contributes to its overall perception. In the same fashion that a work of art is framed, the face and the smile are also part of a frame, and the content of this frame contributes to the total esthetic effect, also called *Gestalt*.

The perception of edges (frame) is the first of five essential perceptual skills described by Betty Edwards in her work *Drawing on the Right Side of the Brain*.[62] The four other skills are the perception of spaces (outline and negative spaces), relationships (elements), light and shadows (convexities/concavities), and finally Gestalt (Fig 2-15d).

FIG 2-15 *(cont) (d)* **Five fundamental perceptual skills.** (Reproduced with permission from Magne.[63]) This drawing of an incisor was obtained by using the five steps described by Betty Edwards.[62] Drawing according to this method should help develop the right brain's language mode (artistic and creative) and "set aside" the left side (verbal, analytical).


FRAME
OUTLINE
ELEMENTS
HIGHLIGHTS AND SHADOWS
#2
9/27/2013
GESTALT

2-15d

Drawing is a fundamental part of a comprehensive didactic method to teach dental morphology (see section 2.5). Those skills required for drawing are the same skills that will be used by the operator during the designing of a restoration and represent an ideal didactic approach to the learning of dental morphology and esthetics (Fig 2-15d).[63] In addition, the simple exercise of drawing using this method can be extremely soothing and represents a very good way of balancing the artistic and analytical sides of the brain (see next section). Listening to music is another significant way to increase cognitive and motor skills and is even used for recovery after brain damage or brain surgery ("the Mozart Effect"). ***But it is known that arts in general stimulate the brain.***[64]

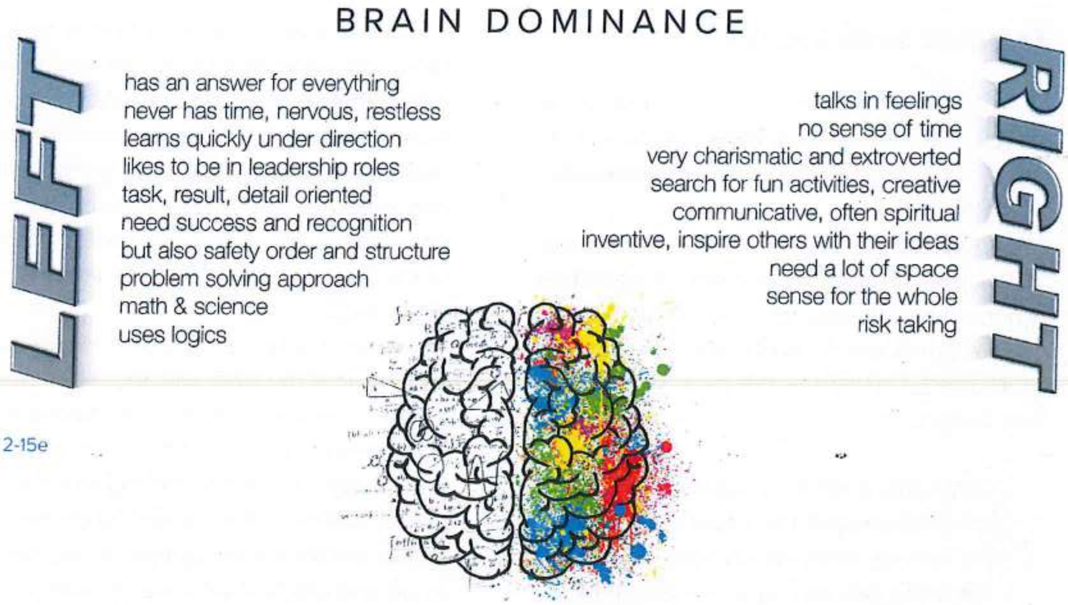
Left and right side

In view of the above, it may also help to compare the smile to a symphony with different parts and rhythms played by an orchestra with different musicians/instruments (different teeth). The resulting composition will be perceived differently as a function of the human brain and its two modes.

Opposite sides of the brain process spatial information differently, with the right hemisphere analyzing information more globally (as a whole) and the left hemisphere analyzing fine detail.[65]

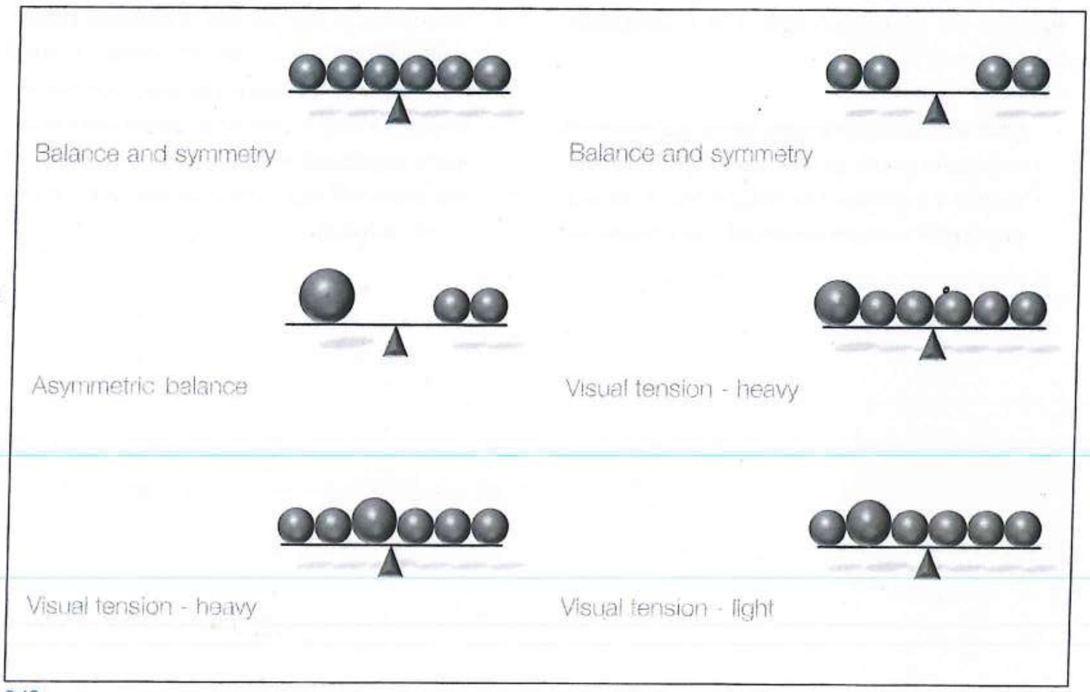
From an artistic standpoint, the right brain "mode" is usually more visual and perceptual, while individuals with a dominant left brain "mode" will be more verbal and analytical (Fig 2-15e).[62] Knowing our main brain language mode can help optimize the communication within the treatment team and between the dental professional and the patient. Numerous assessments of brain language mode can be found online, but most individuals should be able to identify their dominant hemisphere based on the attributes in Fig 2-15e. In view of those characteristics, it can be expected that a patient with a left hemisphere dominance will more likely be pleased with a more symmetric smile devoid of visual tensions. A person with right hemisphere dominance, on the other hand, will perceive a symmetric smile as dull and uninteresting. This individual should be more prone to appreciate a natural-looking smile including residual defects but balanced visual tensions.

It is always dangerous to draw strict rules because there are many sides to hemisphere dominance.[66] Brain duality is certainly an oversimplification, and much is yet to be discovered about the infinite complexity of our brain. Nevertheless, sharing those artistic and psychologic elements with the patient and educating them about the resulting limitations should help resolve major divergences. Patients and dental professionals who spend the time to investigate and discover themselves through personal development might succeed better in reaching a common treatment objective.



2-15e

FIG 2-15 *(cont) (e)* **Brain language mode.** The left and right brain hemispheres have different attributes corresponding to the two L and R brain language modes.



2-16a

FIG 2-16 *(a)* **Visual weight.** The six spheres represent the six maxillary teeth. Note that a visual tension will have more weight when located on a canine *(middle row, right)* or a central incisor *(bottom row, left)* than on a lateral incisor *(bottom row, right).* (Graphics inspired by Michel Magne, MDT, and Dr Luca Dalloca.)

Dynamic smile balance

"The important task of all art is to destroy the static equilibrium by establishing a dynamic one."
—Piet Mondrian

While expanding on the aforementioned concept of "image and frame" by Arnheim,[61] it cannot be ignored that left side/right side considerations have a significant impact on visual perception. Much can be learned on this topic from LeSage and Dalloca.[6,59]

> Obtaining a dynamic balance of the smile means that the visual weight of the various elements on each side of the smile (left and right) is equivalent but not symmetric (Fig 2-16a; see also Fig 2-16e).[23]

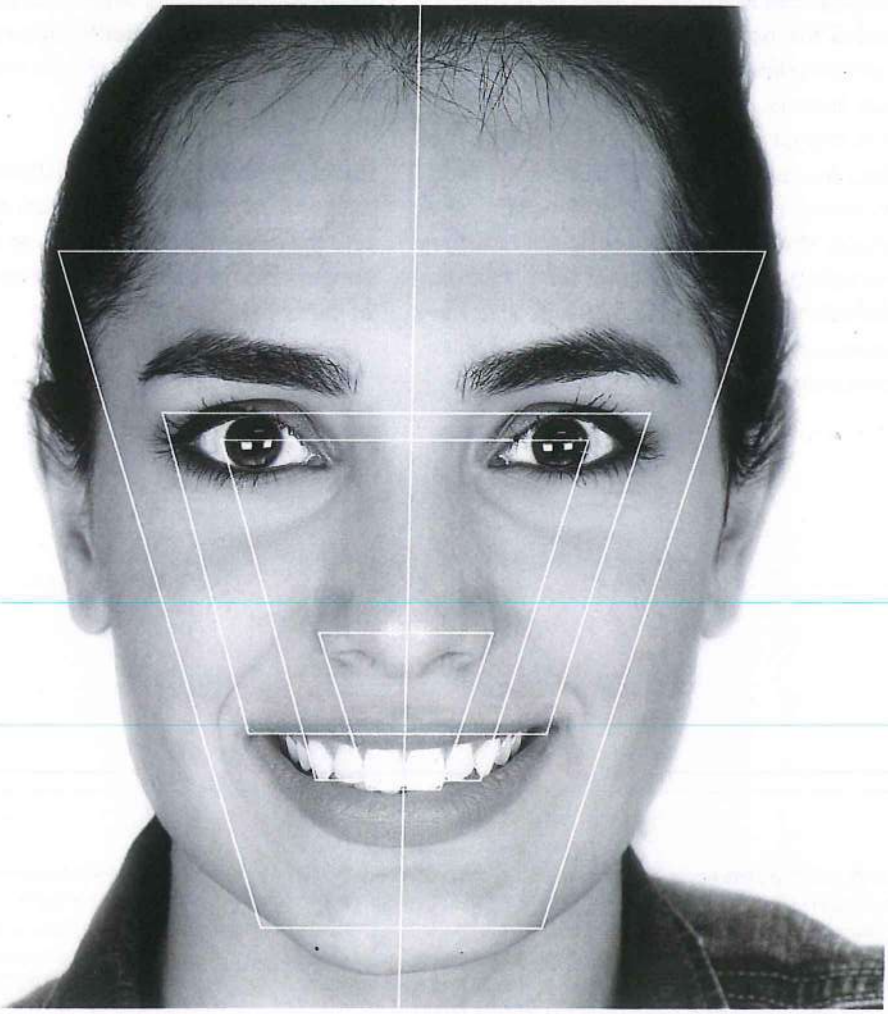
The following conclusions were drawn from a survey about the influence of symmetry and balance on visual perception of a Caucasian female smile[19]:

- Most faces are asymmetric by nature. However, absolute smile symmetry (Fig 2-16a, top row) is a common stereotype and is usually preferred over an asymmetrically balanced smile. Interestingly, when it comes to the face, absolutely symmetric chimeric faces (obtained by mirroring left or right sides of a face) are usually not preferred over the original nonmirrored portrait (compare Figs 2-16b and 2-16c). Yet there is still a natural flow and coincidence between the vestibular frame of the face, corners of the eyes, and mouth (Fig 2-16d).[47]
- Asymmetric balance (Fig 2-16a middle row, left) provides the smile with more character. When a visual tension is not balanced (Fig 2-16a middle row, left, and bottom row), its visual weight will vary depending on location, usually with the highest weight for the central incisor and the canine. Lateral incisors seem to be less affected by visual tensions. This is in agreement with the concept of dominance of the central incisors and confirms the findings of another study showing the minor effect of incisal asymmetries when found in lateral incisors compared to central incisors.[67]
- Two-thirds of the general population have a right-dominant eye.[68] When a defect is away from the midline (canines), eye dominance seems to play a role and makes the defect more significant when found on the side of the dominant eye of the viewer (left canine of the subject).

FIG 2-16 *(cont) (b and c)* **Facial analysis.** The original face of this patient *(b)* is usually preferred over the symmetric chimeric face obtained by assembling mirrored left sides *(c)*. *(d)* The general shape of the face is not indicative of the shape of the teeth, but there is a natural flow between the vestibular frame of the face, the corners of the eyes to the corners of the mouth, and the lateral limits of the iris to the canines' axial direction.[47] (Parts *b* to *d* modified with permission from Magne et al.[19])

2-16b

2-16c



2-16d

- It is well known that tooth shapes cannot be associated to a gender.[37] As stated by Lombardi,[23] it can be confirmed, however, that upright canines look more masculine and vigorous (especially if pointed) compared to slanted and soft canines (rounded tip) that are perceived as more feminine (compare Figs 2-12b and 2-12c).
- The survey[19] revealed a preference for squared incisors, while another study favored ovoid shapes.[35] The square is an intermediate shape between a circle and a triangle. It reflects calm and maturity and therefore our brain processing toward stability. Note that less gingiva was visible in the smile with squared teeth (papillae looked narrower, making the smile less "gummy"). It must be emphasized again that in many rehabilitation cases, the typal shape can be derived from remaining intact teeth, especially the mandibular incisors.
- It is difficult to associate a tooth shape to a face shape. There have been many attempts to relate tooth forms to an inverted face shape. The analytic approach to smile design, including visagism (mental temperament assessment), proved to lack scientific evidence and practicality and is subject to much interpretation.[37,38]

The analysis of a case is presented in Fig 2-16e as an example of assessment of balance in a dynamic equilibrium.

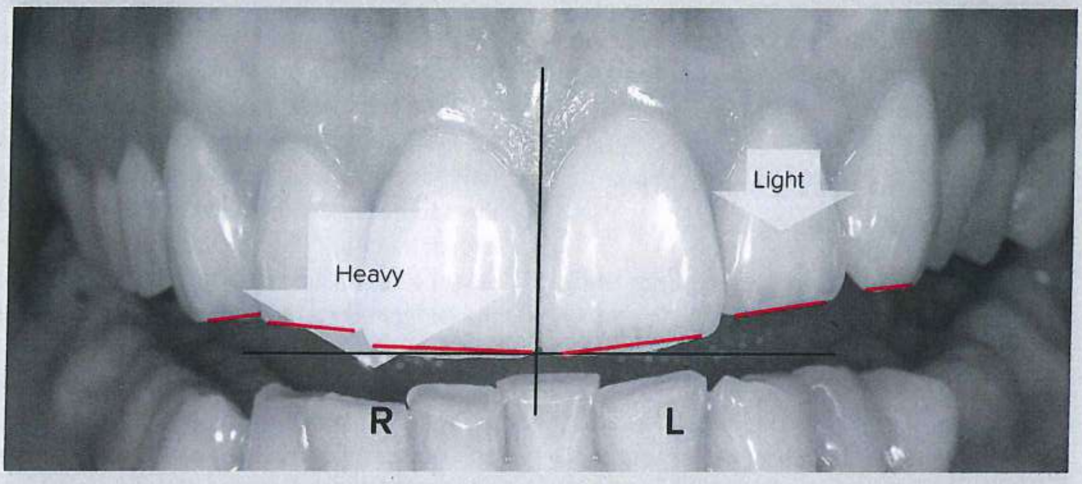
Additional elements

Beware of the mirror

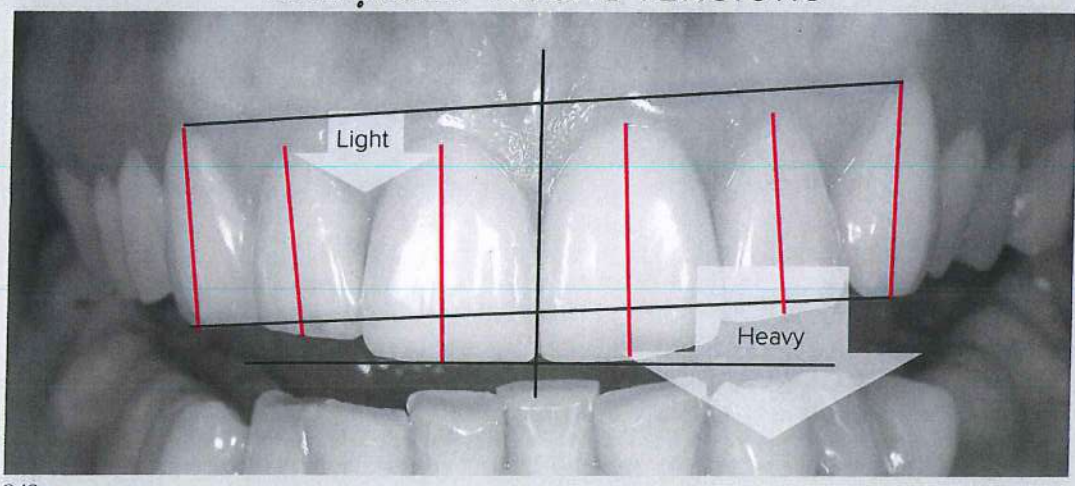
It is typical to provide the patient with a mirror in order to look at the dental work, mock-up, or final restorations. This might prove a critical choice due to the way our brain processes images with lateralization (hemisphere asymmetry). The left brain is dominant for the recognition of self, while the right brain is dominant for the recognition of others' faces.[69] It can be assumed that people are more exposed to their mirror image (looking at oneself in the bathroom mirror) rather than their true image as in, say, a photograph. It was found that female patients undergoing facial esthetic surgery have significant preference for their mirror image.[70]

In order to limit this perceptual difference during assessment of smile design, both the operator and the patient should be looking at the same image, either both looking at the mirror itself or at mirror-reversed photographs.

FIG 2-16 *(cont) (e)* **Intraoral analysis.** Maxillary porcelain veneers (from canine to canine) in a bilaminar approach at 5-year recall visit *(top;* see treatment steps using the Dahl principle in chapter 5, Fig 5-20). The first analysis identifies a significant weight on the right side *(middle)* due to the density of the incisal edges (left side more spaced). There is also a visual weight created by the diverging axis of the central and lateral incisors on the left side *(bottom)*. Overall, the weight on the left is somewhat more powerful and compensates well for the residual slant of the occlusal plane. (Graphics and analysis courtesy of Michel Magne, MDT.)



BALANCED VISUAL TENSIONS



2-16e

Negative spaces

The dark spaces of the mouth between the maxillary and mandibular teeth and between the teeth themselves are clearly the most influential elements of the dental composition. Lombardi proposed the "one, two, three guide"[23] to express how each tooth imparts age, gender, and personality in relation to the negative space:

- One is the central incisor, defining the age (young with mamelons vs worn with wear facets).
- Two is the lateral incisor, expressing gender (square and upright masculine vs soft and slanted/rotated feminine).
- Three is the canine for personality (upright sharp/pointed vigorous vs slanted short/rounded soft).

Mock-up and provisionals—The rubber meets the road

It is often difficult to determine in advance and for a given patient which components will be the key elements of total esthetic integration, which can be defined as the conformity with the individual's personality. A combined technical and artistic effort is necessary and depends not only on the intuition and sensitivity of the operator but also on the capacity to accurately perceive the unique and dynamic character of a patient.

Mastering all the aforementioned knowledge is not an absolute warrant of success, and many confounding variables can still affect and interfere with how the design will be perceived by the patient. The first prototype of smile design is only a prototype, and as such it must be subjected to a test, also referred to as the "test drive" (Fig 2-17).

Individuals with poor preexisting dental work are the most challenging to address because they have lost their own perception of esthetics. They must be "reprogrammed" with different diagnostic templates that will allow the progressive recovery of esthetic landmarks (see chapter 5, section 5.6).

Using a strategic diagnostic approach (wax-up, mock-up, provisionals), clinicians and laboratory technicians should not be afraid to test the subjective components of the smile. The interim mock-up[71–73] or provisional restoration[33] will provide time and allow for multiple editing of the design until a mutual agreement has been reached.

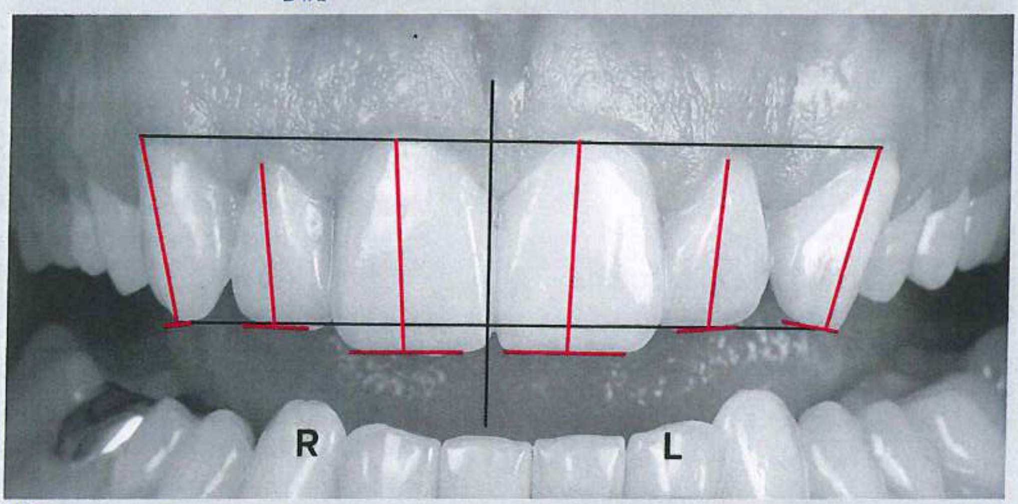
In this way, the final treatment objective will always result from a combination of knowledge and application of the aforementioned objective criteria, time, and the patient's input.

FIG 2-17 Mock-up analysis in a semi-indirect CAD/CAM case. Multidisciplinary case before *(a)* and after surgery and placement of diagnostic mock-up *(b)*. Despite surgical correction, there is a slight residual slant of the occlusal plane. *(c)* Closer analysis reveals slightly higher visual weight on the right side due to incisal edge density, which compensates well for the slant. *(d)* The mock-up was used as a "Biocopy" file for the designing of the final restoration with the Cerec System. An additional visual tension was added to the right central incisor by slightly rotating it, which adds to the visual weight on the right side and makes the slant even less perceptible (compare *d* and e). See all treatment phases of this case in chapter 5, Figs 5-2 and 5-14 (diagnostic approach), and chapter 6, Fig 6-29 (tooth preparations and final restorations).

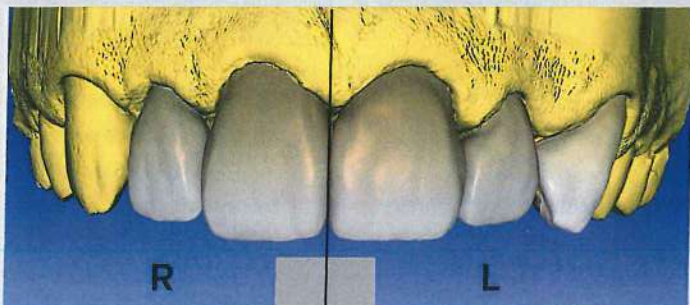

2-17a

MOCK-UP


2-17b



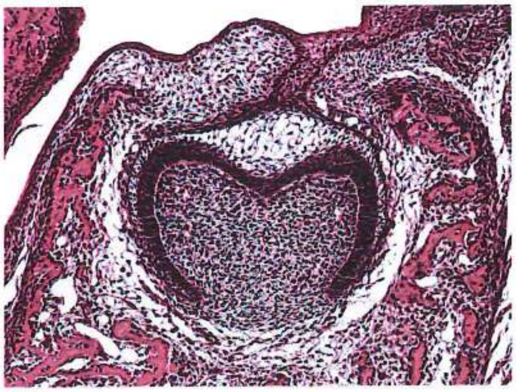
2-17c



2-17d


2-17e

2.4 MORPHOLOGY OF POSTERIOR TEETH


2-18a

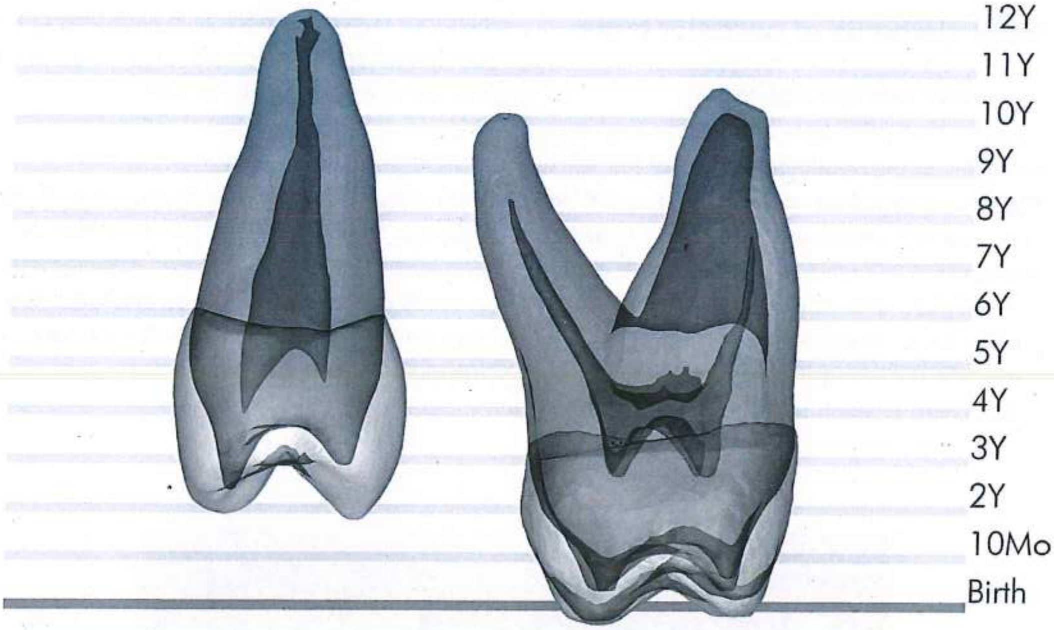
Remembering the miraculous making of a natural tooth

> *For you created my inmost being; you knit me together in my mother's womb. I praise you because I am fearfully and wonderfully made; your works are wonderful, I know that full well.*
> *—Psalm 139:13–14*

Anterior and posterior primary teeth start to form in utero after only 6 to 8 weeks. All begins from the trilaminar embryo and respective internal cavities. The folding of the ectodermal (outer) layer overlaying the mouth (oral epithelium) forms the dental lamina. Its proliferation generates two horseshoe-shaped structures, the future dental arches and tooth rows. Ten rounded swellings develop, one for each primary tooth to form 10 enamel organs for each arcade. The tooth buds soon take the shape of a hat (cap stage), then the shape of a bell, inside of which the neural crest–derived mesenchyme will condense. Following approximately the 10th week in utero, morphodifferentiation (Fig 2-18a, bell stage) starts with ameloblasts and odontoblasts forming from their respective ectodermic and mesodermic tissues. The dentinoenamel junction is formed first (see Fig 1-10d) by the apposition of enamel and dentin, followed by maturation (mineralization). By the time a baby is full term (ie, around birth), the incisal edges and occlusal surfaces of the primary teeth have been already formed, and the process repeats itself: From each primary tooth bud an extension of epithelial lamina gives birth to the succedaneous permanent tooth bud. The permanent tooth crowns start assuming their final shape and slowly grow at a safe rate.

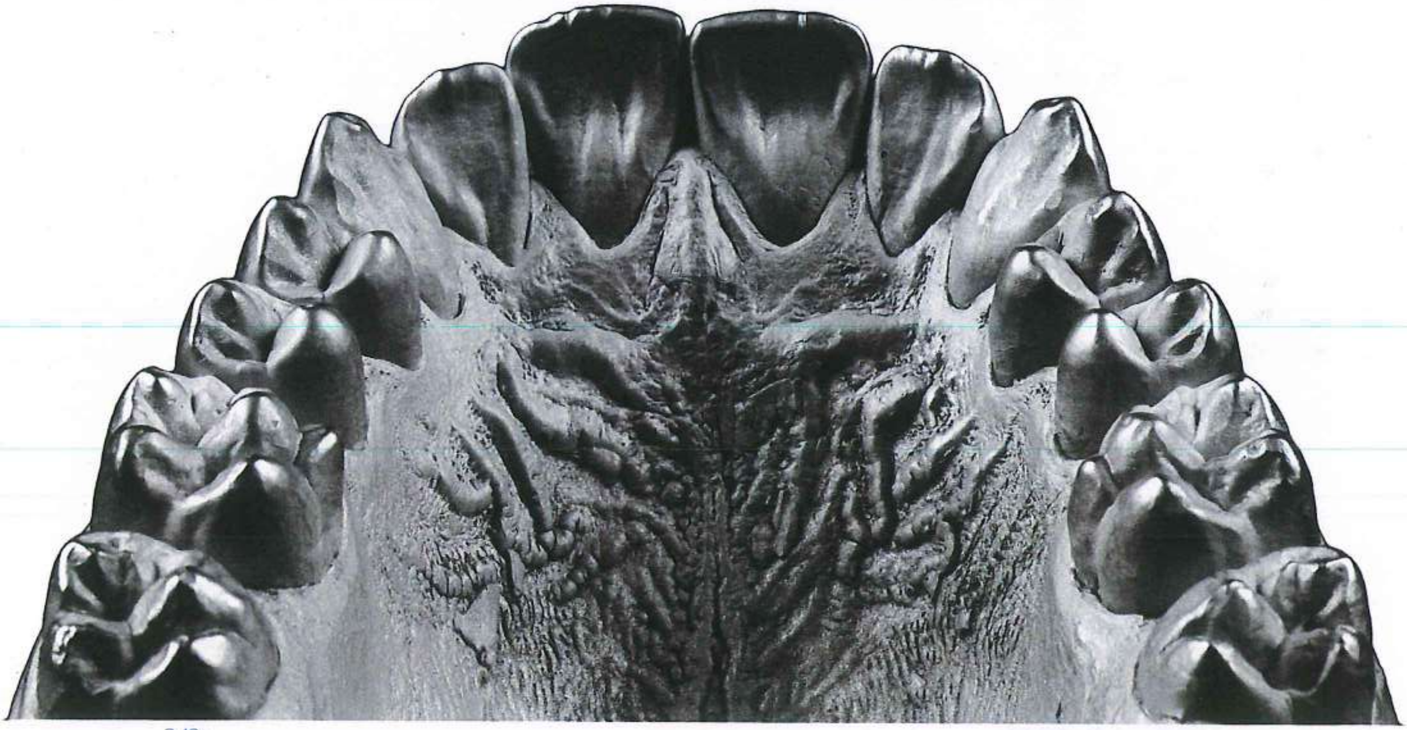
Our patients should be reminded that it takes approximately 9 years for the permanent maxillary central incisor to fully develop (incisal edge to root tip) and 11 years for the first maxillary molar to form (Fig 2-18b).[74,75] And yet how long do we take to restore them? What a difference between God-made and man-made!

FIG 2-18 The formation of teeth. *(a)* Bell stage of E17.5 mouse mandibular first molar. (Courtesy of Dr Jingyuan Li, University of Southern California.) *(b)* The making of a tooth inside the human body is not a rapid process. It is often forgotten, because clinicians restore teeth in a matter of hours at most, that the natural biologic process of tooth formation takes up to 11 years (eg, maxillary first molar). *(c)* The fully formed dental arch is no less than a miracle (silver-powdered natural dentition cast, reproduced with permission from Magne[75]).



2-18b

NATURE



2-18c

Basic elements of posterior teeth

Continuity with anterior teeth

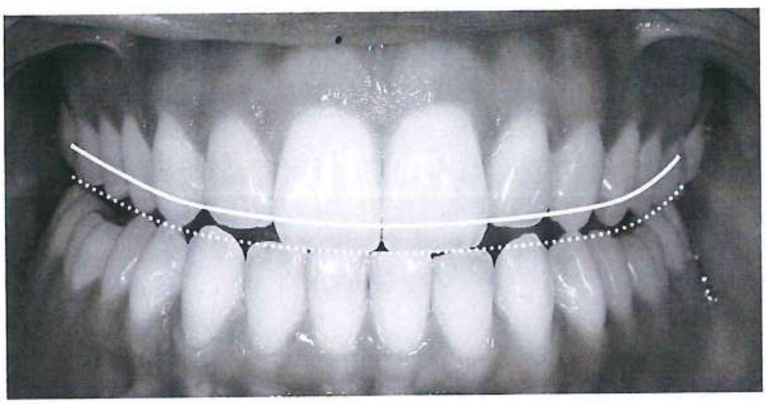
Posterior teeth belong to the smile through their continuity at the vestibular aspect of the smile (Fig 2-19). Premolars should fill the vestibular space up to the mesiobuccal aspect of the first molar, which is commonly found at the corner of the mouth, with its cervical third well visible during smiling. Interdental contacts progressively move from the incisal third (anterior teeth) to the middle third of each tooth (posterior teeth) in harmony with the progressive flattening of the cementoenamel junction (CEJ; Fig 2-19c, loss of the scalloped interdental profile).

Cusps/grooves/ridges

Each cusp or primary developmental unit, also called a *lobe*, is defined by developmental grooves (between cusps) and supplemental grooves (within cusps). Ridges are linear elevations forming the basic element of each cusp, the triangular ridge (Fig 2-20).

2-19a

CONTINUITY

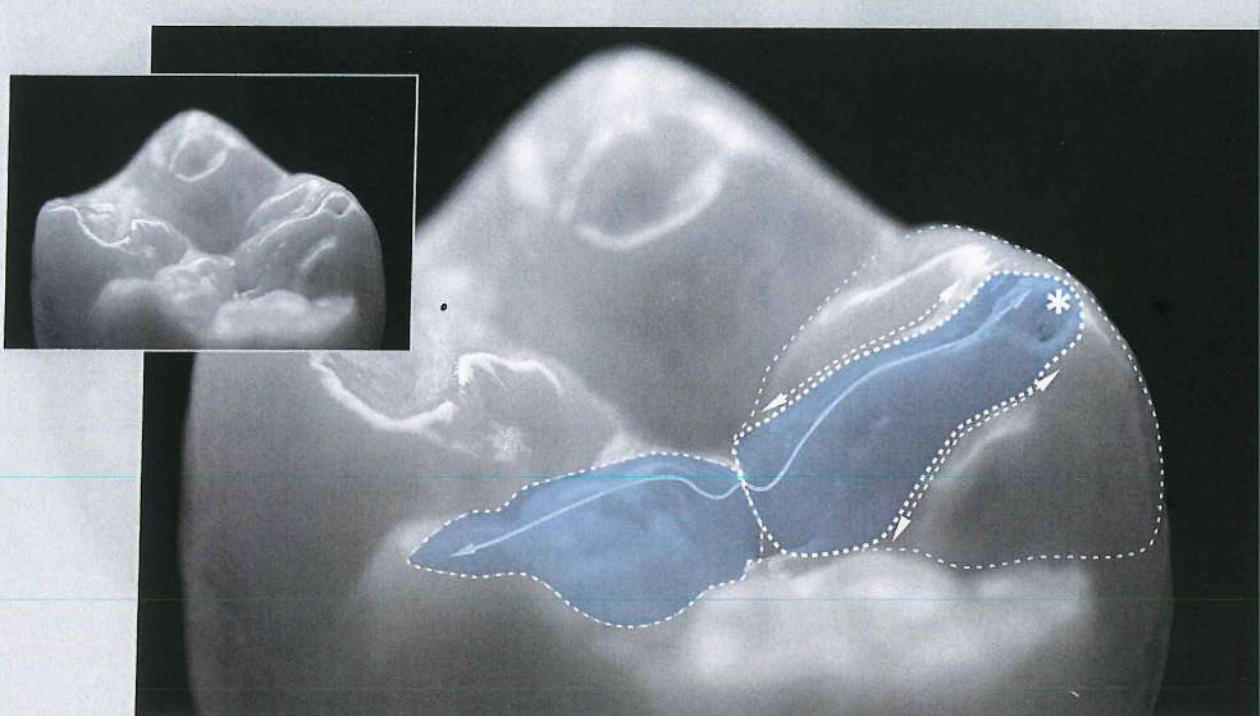


2-19b

FIG 2-19 Anterior and posterior teeth continuity. *(a)* Full smile displaying natural flow between anterior and posterior teeth (maxillary incisors with porcelain veneers; see also chapter 6, Fig 6-47 for treatment steps). Note the mesiobuccal cervical third of the maxillary first molar visible near the corner of the mouth *(arrows)*. *(b)* The cohesiveness between anterior and posterior teeth is confirmed by the coincidence of incisal edges/canine tips/cusp tips *(dotted line)* and the interdental contacts *(continuous line)*. *(c)* Note the mild interdental scalloping of the CEJ on this mesial aspect of a maxillary first premolar.

2-19c

CUSPS



2-20

FIG 2-20 The cusp, the basic unit. This mandibular molar distolingual cusp *(dotted light gray)* features a strong triangular ridge *(blue)* marked with its elevation facing and connecting with that of the distobuccal cusp ridge *(plain arrow)*. Note the diverging supplemental grooves defining each side of the triangular ridge *(dotted arrows)*. Note also the pit at the cusp tip due to biocorrosion of gnarled enamel (*).

There are four types of ridges[76]:

1. ***Marginal ridges*** are the round borders of enamel at the mesial and distal margins of the occlusal surface.
2. ***Triangular ridges***, with their triangular shape, descend from the cusp tip toward the center of the occlusal surface.
3. ***Transverse ridges*** are formed by the union of two triangular ridges (buccal and lingual).
4. ***Oblique ridges*** are formed by the union of two triangular ridges obliquely (distobuccal and mesiolingual).

Maxillary first premolar

This tooth (Fig 2-21) is the only premolar with two roots. The most important features are the following[76,77]:

- The buccal cusp is about 1 mm longer than the lingual one.
- The buccal surface looks somewhat similar to the maxillary (central ridge) canine but is shorter and has a more open "V" shape.
- The distobuccal cusp ridge is shorter and flatter, and the mesiobuccal cusp ridge is longer and steeper (opposite to canine; see Fig 2-21b).
- The lingual surface is smooth and rounded (no lobes).

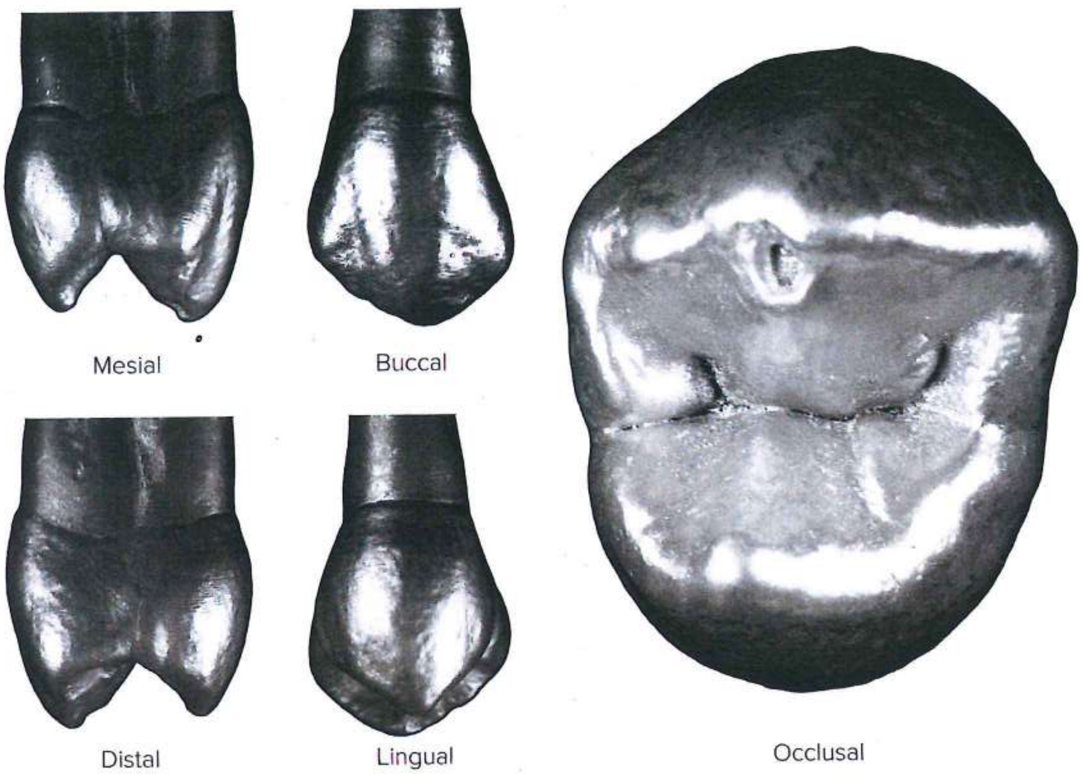
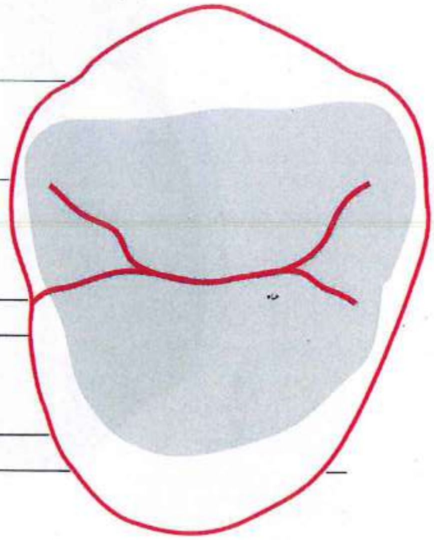


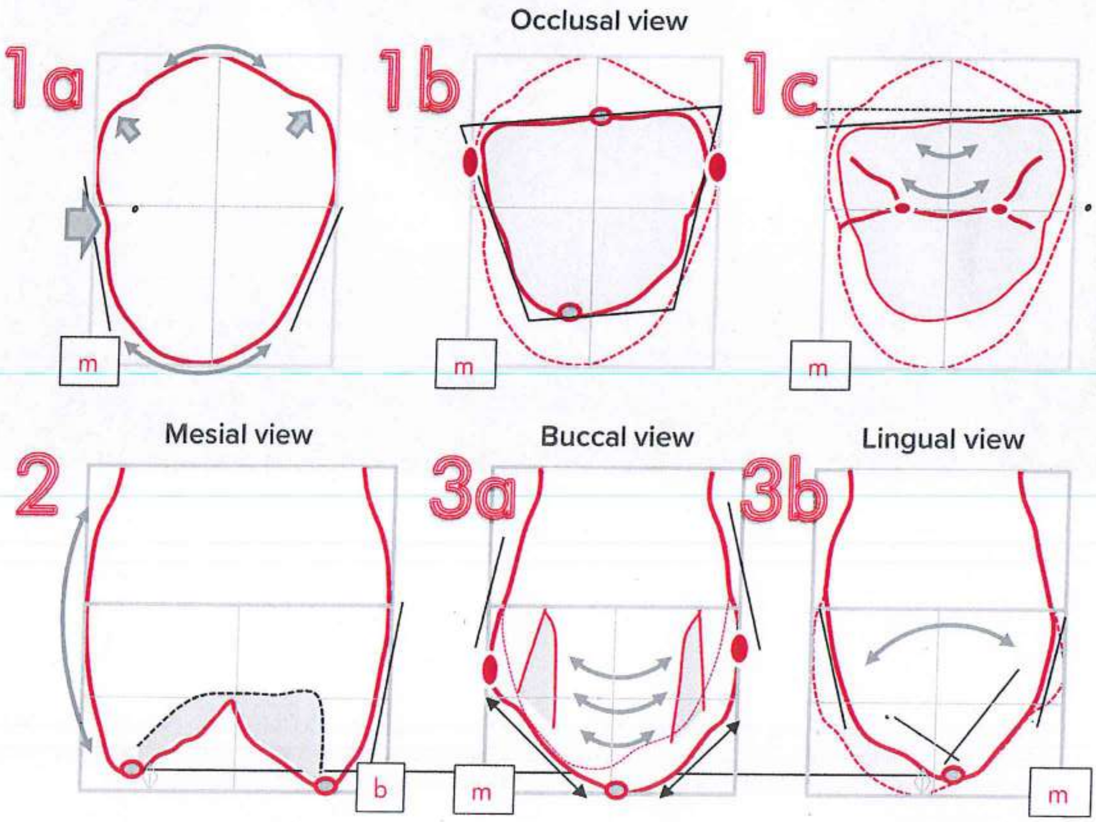
FIG 2-21 Maxillary first premolar. *(a)* Maxillary left first premolar views. All attributes are listed and illustrated by symbols on the opposite page.

MAXILLARY LEFT FIRST PREMOLAR

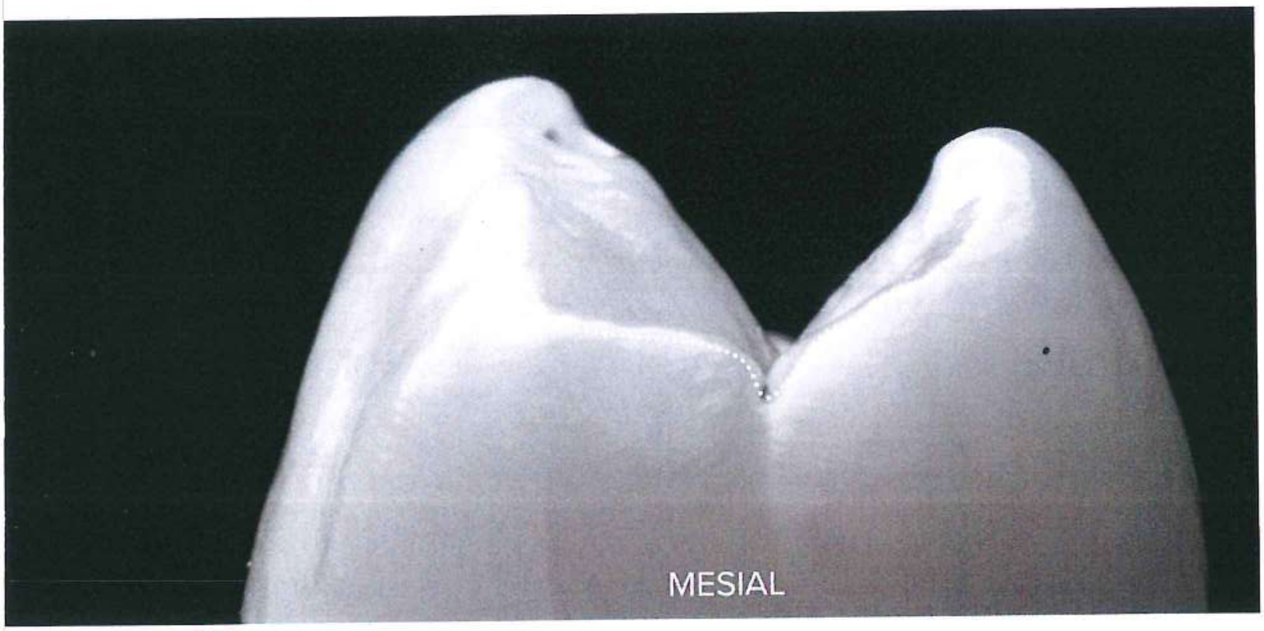
Dimensions: mesiodistal 7 mm, buccolingual 9 mm, height 8.5 mm

Occlusal view	
1a	Tapers toward lingual Mesial developmental groove Circular lingual outline Buccal ridge like canine Sharp buccal line angles/point angles
1b	Trapezoidal occlusal table Buccal cusp centered or shifted distally Lingual cusp shifted mesially Interdental contacts shifted buccally
1c	Larger buccolingually than mesiodistally Long central developmental groove Mesiobuccal and distobuccal developmental grooves (triangular ridge) Mesial and distal pits (and triangular fossae) Buccal cusp ridges not parallel to central groove
Mesial view	
2	Smooth lingual surface Buccal cusp tip 1 mm longer than lingual Buccal surface more "flat" Asymmetric marginal ridge contour
Buccal view	
3a	Distal contact more apical than mesial Mesial and distal depressions (define ridge) Mesial cusp ridge longer than distal one (opposite configuration of canine)
Lingual view	
3b	Lingual cusp tilted mesially Mesial and distal cusp ridge at right angle Pointed lingual cusp Tapers toward occlusal





2-21b



2-21c

FIG 2-21 *(cont) (b)* Buccal view. Maxillary left canine/first premolar comparison. *(c)* Mesial view. Note the asymmetric mesial marginal ridge interrupted by the mesial developmental groove *(dotted line)*. *(d and e)* Other specimen of maxillary left first premolar with all characteristics listed on the previous page (distobuccal view).

2-21d

2-21e

Maxillary second premolar

This tooth (Fig 2-22) has a single root and is very similar to the first premolar[76,77]:

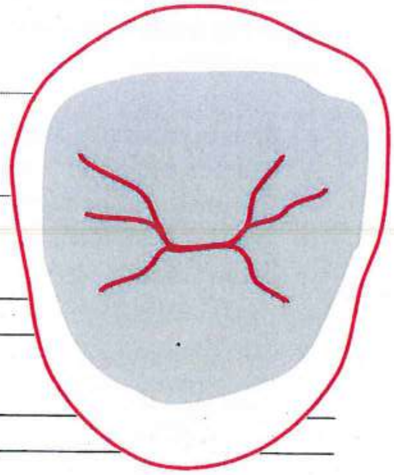
- The general shape is more rounded, softer, more symmetric, and shorter than the first premolar.
- There is no mesial depression and no groove through the mesial marginal ridge.
- The central developmental groove is short.
- Supplemental groves radiate from the center of the occlusal surface.

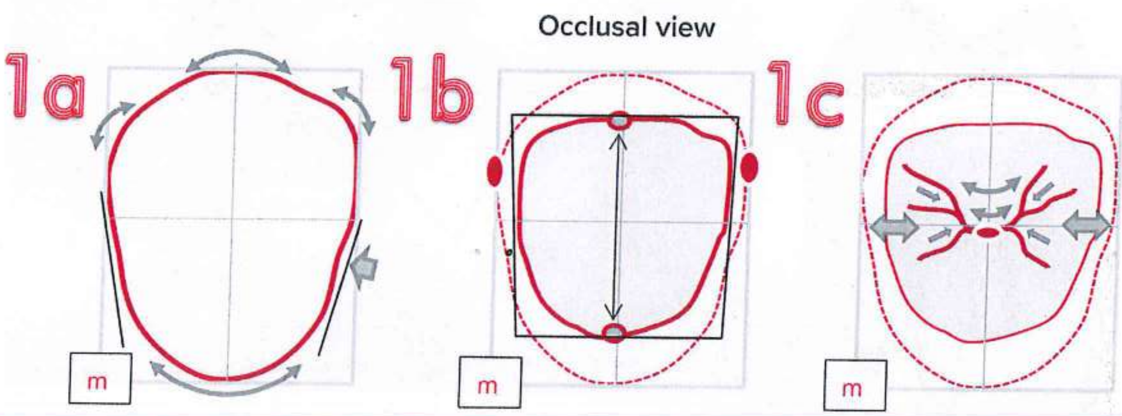
2-22

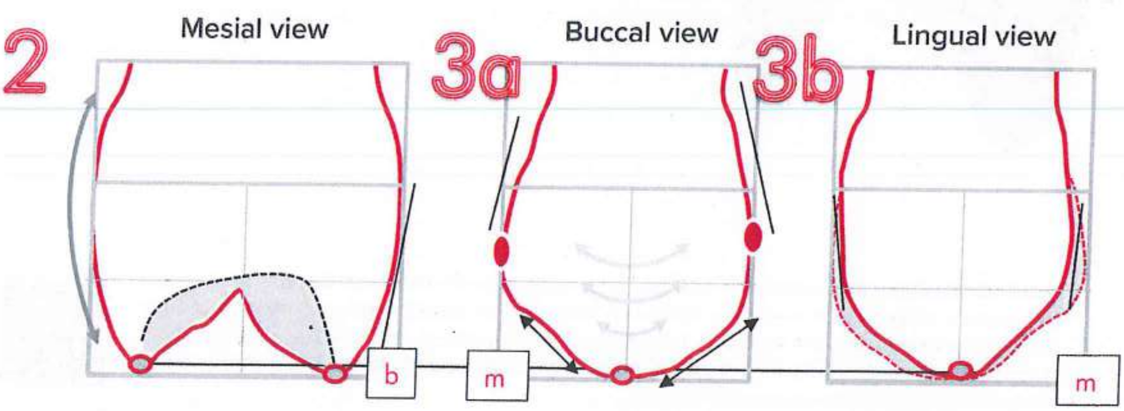
FIG 2-22 Maxillary second premolar. Comparison of maxillary first and second premolars. Note the symmetric and softer shape of the second premolar and its short central development groove compared to the first premolar. All attributes are listed and illustrated by symbols on the opposite page.

MAXILLARY LEFT SECOND PREMOLAR

Dimensions: mesiodistal 6.5–7 mm, buccolingual 8.5–9 mm, height 7.5–8.5 mm	
Occlusal view	
1a	Tapers toward lingual No mesial developmental groove (rather distal if present) Circular lingual outline Buccal ridge like canine Rounded, less sharp buccal line angles/point angles than first premolar
1b	Almost rectangular occlusal table Buccal and lingual cusp centered and slightly mesial Wider intercuspal tip distance than first premolar Interdental contacts shifted buccally
1c	Larger buccolingually than mesiodistally Short centered developmental groove (almost central pit) Multiple supplemental grooves radiating from center groove Thick marginal ridges
Mesial view	
2	Smooth lingual surface Buccal cusp tip slightly longer than lingual Buccal surface more "flat"
Buccal view	
3a	Distal contact more apical than mesial Buccal ridge without mesial and distal depressions Mesial cusp ridge shorter and steeper than distal one (opposite configuration to first premolar)
Lingual view	
3b	Tapers toward occlusal







Maxillary first molar

With its three roots, the maxillary first molar is undoubtedly the most complicated of all teeth (Fig 2-23). Its characteristics include the following[76,77]:

- Rhomboid shape; larger in buccolingual direction compared to mesiodistal
- Three major cusps aligned with the root base (primary cusp triangle), like the maxillary second molar
- Massive mesiolingual cusp with possible tubercle attached (fifth cusp, tubercle of Carabelli) and two triangular ridges (one of them forms the oblique ridge)
- Small distolingual cusp (Talon cusp)
- Massive oblique ridge (between the mesiolingual and distobuccal cusps) separating the central fossa and distal fossae
- Distal developmental concavity in the crown (similar to that at the mesial surface of the maxillary first premolar)

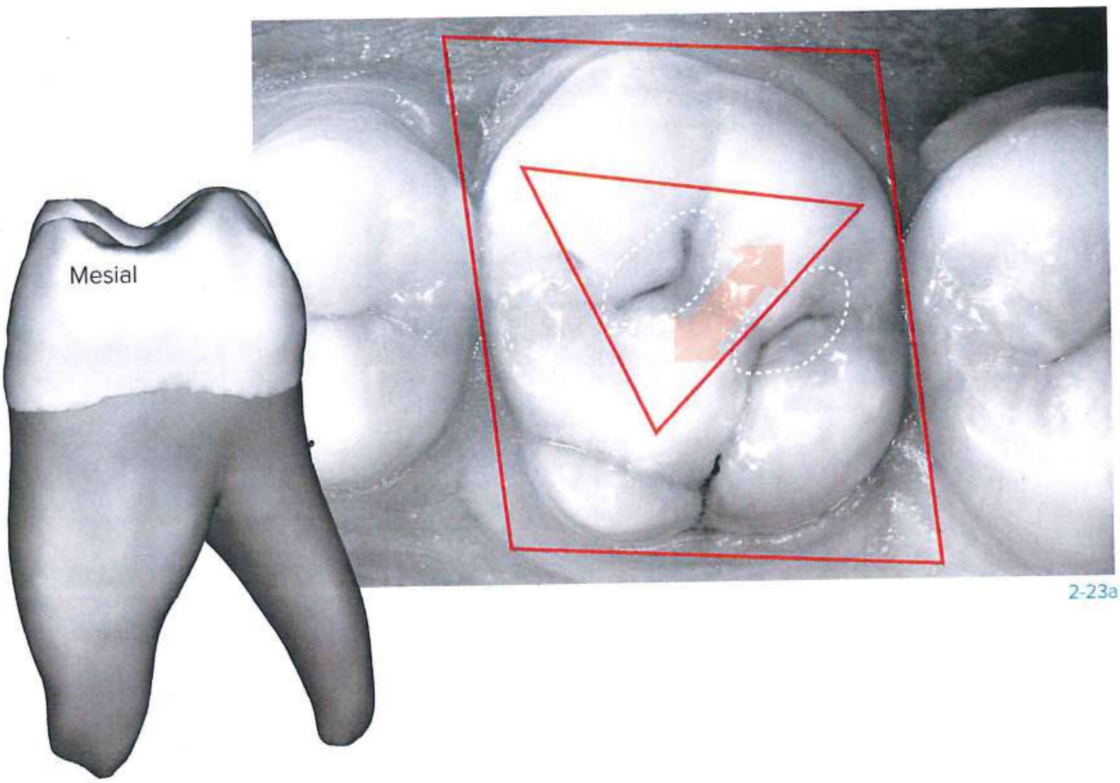


FIG 2-23 Maxillary first molar. The maxillary first molar is a complex tooth. *(a)* Occlusal clinical view of maxillary left first molar reveals its rhomboid shape, primary cusp triangle, and massive oblique ridge *(arrow)* separating the central and distal fossae *(dotted areas)*. *(b to d)* Other specimen from a young dentition displaying extreme characteristics (note prominent tubercle of Carabelli) and all attributes listed on the two subsequent pages.

2-23b

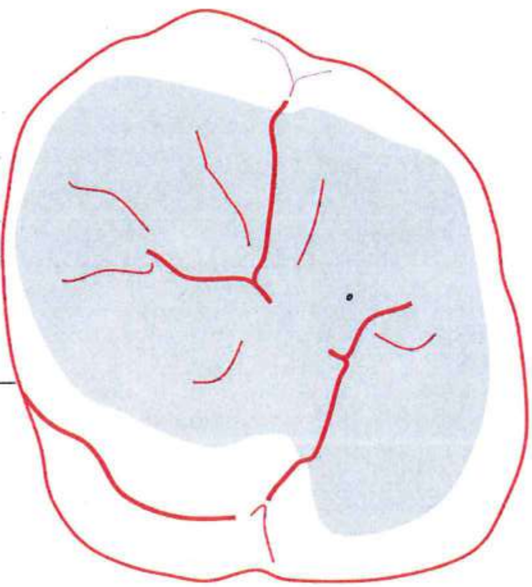
2-23c

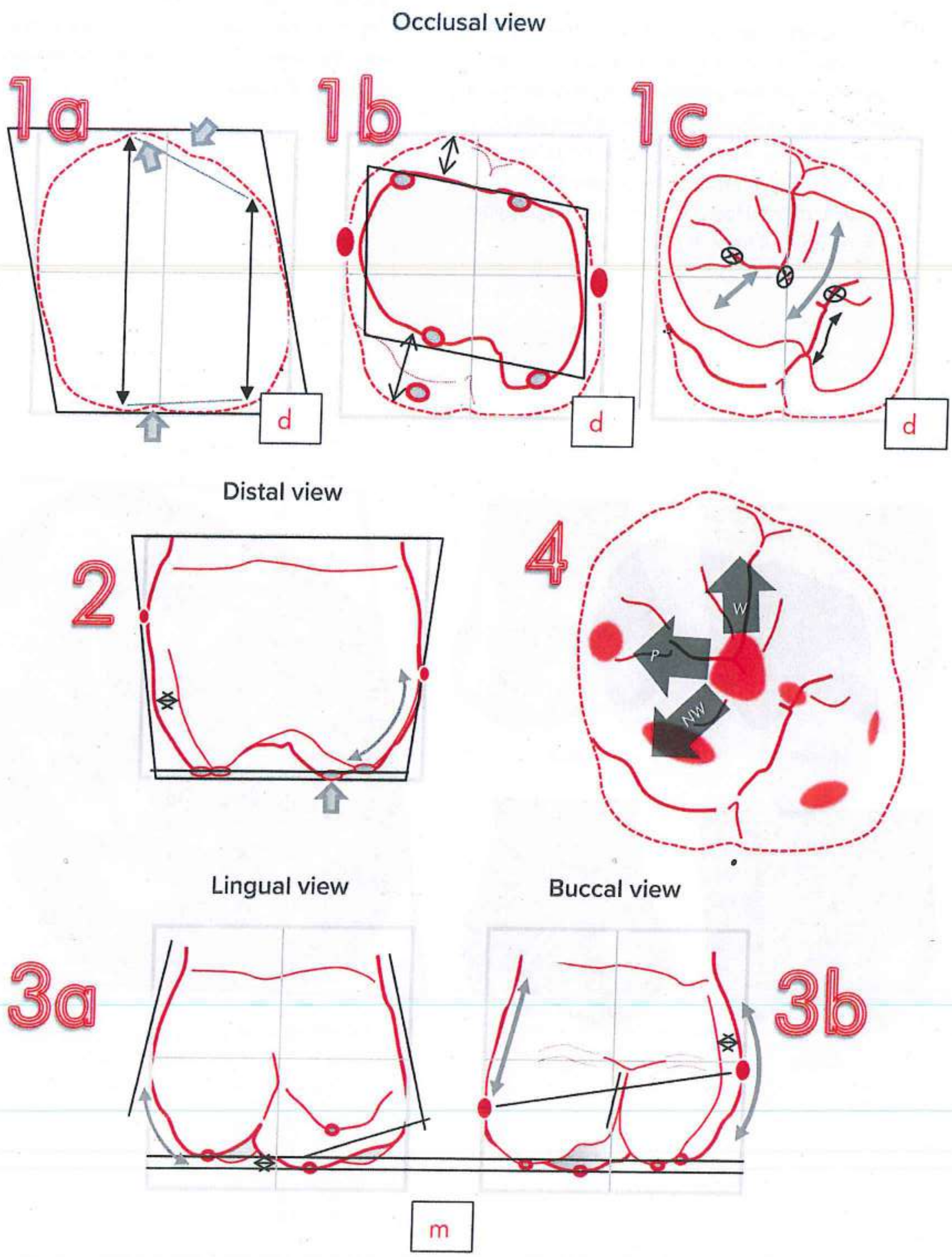
2-23d

MAXILLARY LEFT FIRST MOLAR

Dimensions: mesiodistal 10 mm, buccolingual 11 mm, height 7.5 mm

Occlusal view	
1a	Rhomboid occlusal outline Buccolingual width greater mesially than distally Depressions created by buccal developmental groove and lingual developmental groove
1b	Rhomboid occlusal table shifted slightly buccally Lingual surface well visible (more than buccal) Mesial contact shifted slightly buccally, distal contact centered 5 cusps (larger to smaller): mesiolingual > mesiobuccal > distobuccal > distolingual (Talon) > Carabelli
1c	Three well-defined pits (mesial, central, distal) Mesiopalatal cusp with two triangular ridges (one forming oblique ridge) Supplemental grooves Buccal groove (may end with pit) Distal oblique groove connecting to lingual developmental groove Fifth cusp groove
Distal view	
2	Width > height Buccal surface visible in perspective Buccal cusp tips pointed (blunter contour of lingual cusps) Buccal height contour in cervical third, lingual in middle third
Lingual view	
3a	Mesiolingual cusp is the highest Blunter disto-occlusal contour (compared to mesial) Mesial slope of mesiolingual cusp at 90 degrees with mesial outline
Buccal view	
3b	Mesial contact at junction of middle and occlusal third Distal contact at middle third Mesial outline flat Distal outline spheroidal Mesiobuccal cusp wider than distobuccal Buccal developmental groove slants (parallel to distobuccal root) Horizontal developmental dip Distal side visible Four cusp tips visible
Antagonist cusp paths/occlusal contacts	
4	Antagonist cusp paths from central fossa: nonworking/working/protrusive Potential areas of occlusal contacts: mesial and distal marginal ridges, mesiolingual and distolingual cusp, central fossa/oblique ridge





Occlusal view
1a
1b
1c
d
d
d
Distal view
2
4
W
P
NW
Lingual view
Buccal view
3a
3b
m

Maxillary second molar

The maxillary second molar (Fig 2-24) is very similar to the first molar (rhomboid shape, primary cusp triangle) but smaller, especially its distal aspect and the distolingual cusp. However, there is no fifth cusp and the oblique ridge may be interrupted by a transverse groove joining the central and distal fossae. There are two possible shapes viewed from the occlusal[76,77]:

- Rhomboid: most common, with more extreme rhomboid shape than the first molar
- Heart-shaped: resembles the shape of the maxillary third molar with almost nonexistent distolingual cusp

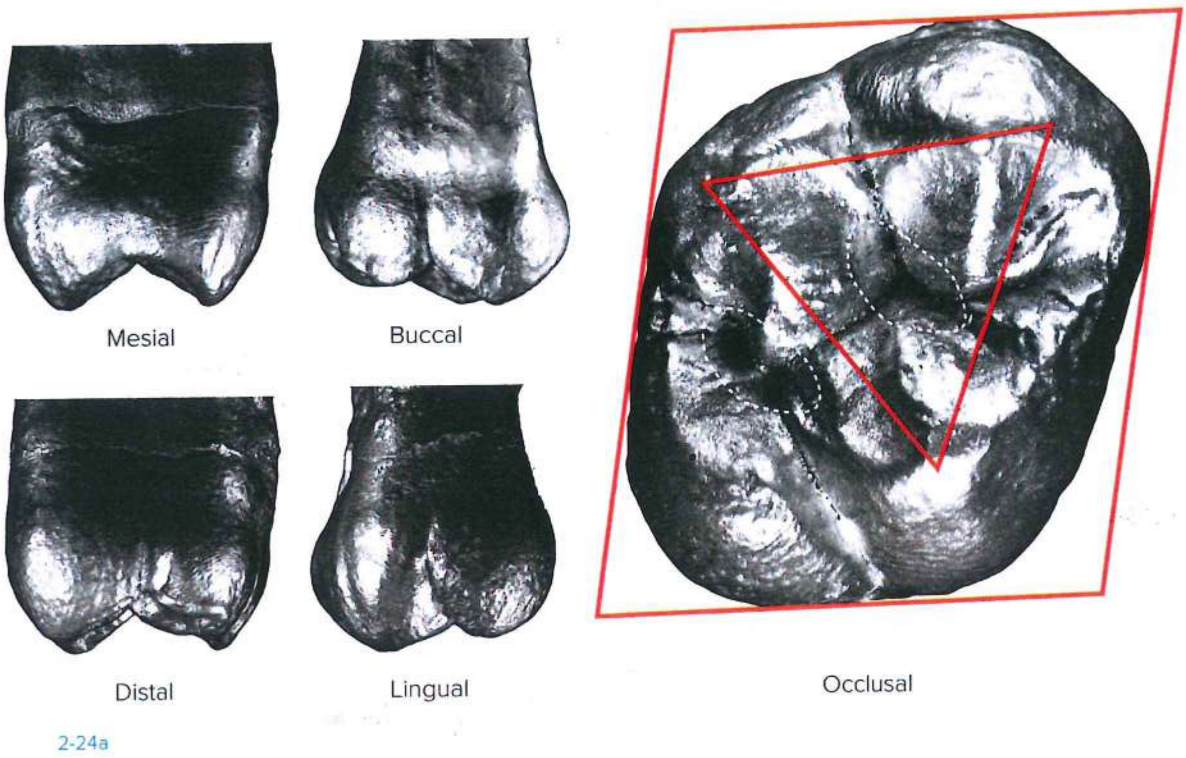
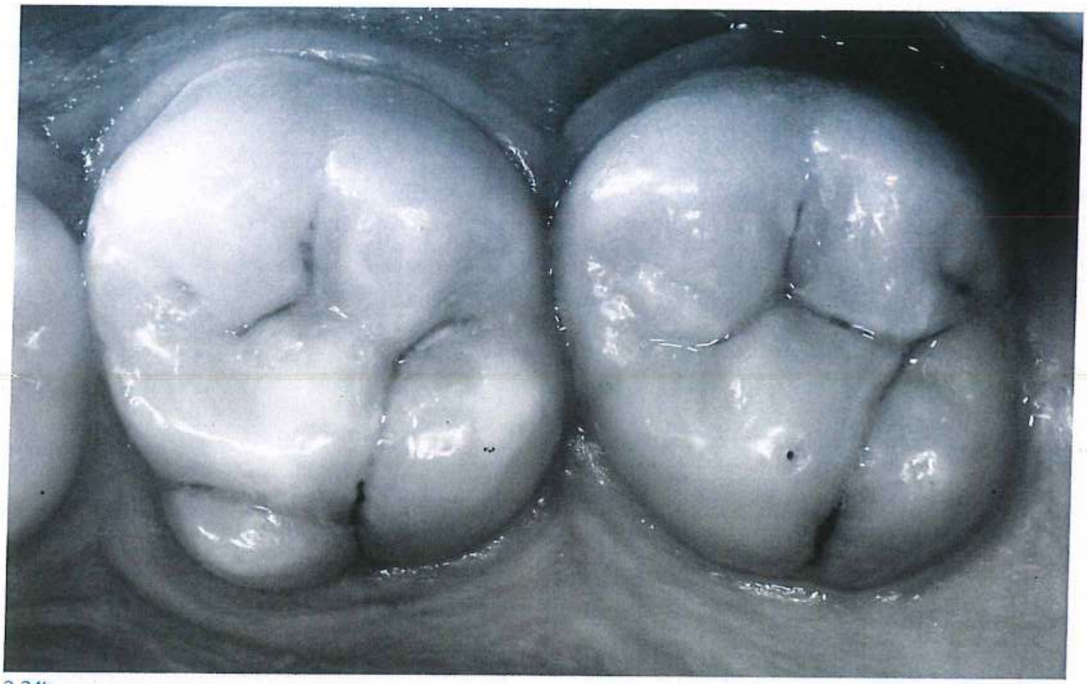
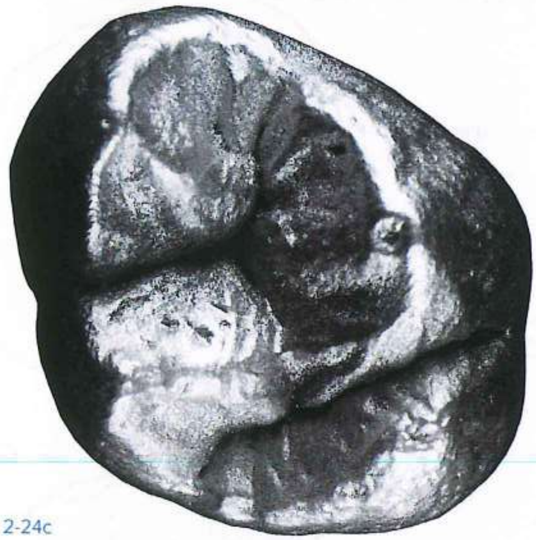


FIG 2-24 Maxillary second molar. *(a)* Maxillary right second molar views. Note the similarities with the first molar (central and distal fossae, rhomboid shape, primary cusp triangle). *(b)* Clinical occlusal view of maxillary left first and second molars for comparison. Note the transverse groove through the oblique ridge on the second molar. *(c and d)* Other specimen from a young dentition displaying strong rhomboid shape and all attributes listed on the two subsequent pages.



2-24b



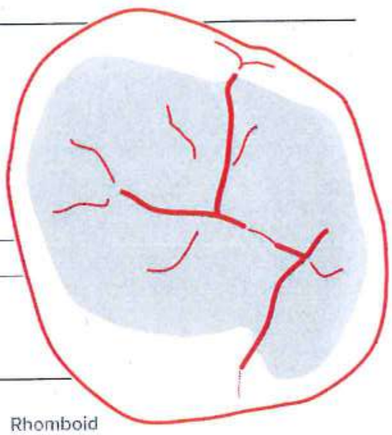
2-24c

2-24d

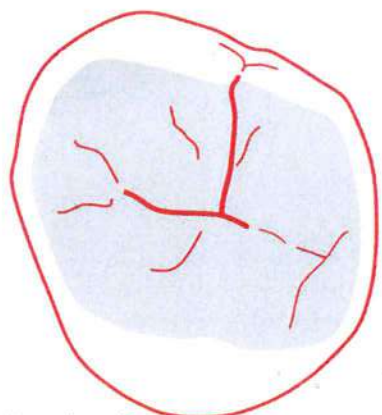
MAXILLARY LEFT SECOND MOLAR

Dimensions: mesiodistal 9 mm, buccolingual 11 mm, height 7 mm

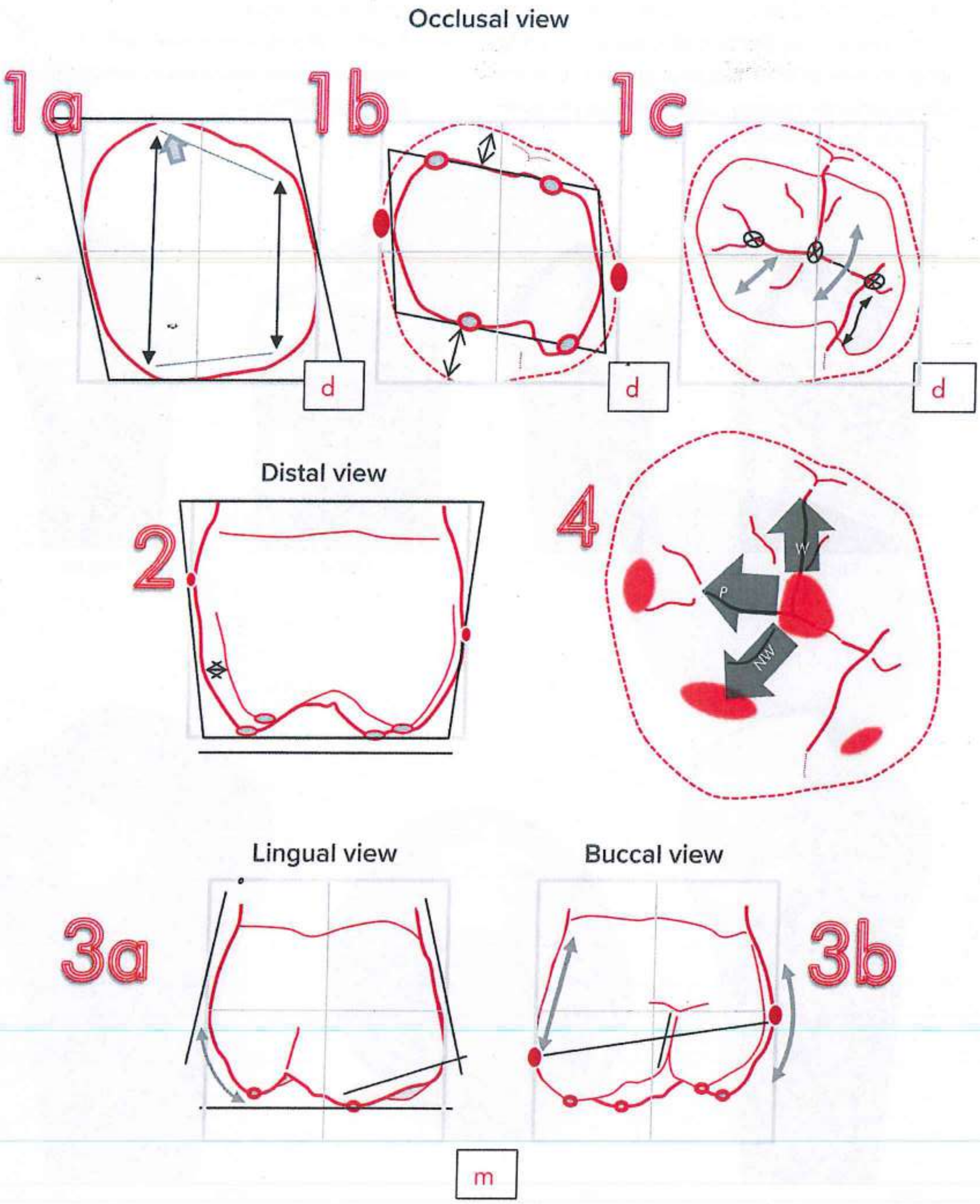
Occlusal view	
1a	Rhomboid occlusal outline (but more rounded than first molar) Buccolingual width greater mesially than distally
1b	Rhomboid occlusal table shifted slightly buccally Lingual surface more visible than buccal Mesial contact shifted slightly buccally, distal contact centered or shifted lingually Four cusps (larger to smaller): mesiolingual > mesiobuccal > distobuccal > distolingual *or* Three cusps (heart-shaped type)
1c	Three well-defined pits (mesial, central, distal) Mesiopalatal cusp with two triangular ridges, one forming the oblique ridge Supplemental grooves Buccal groove Transverse groove through oblique ridge Distal oblique groove connecting to lingual developmental groove
Distal view	
2	Width > height Buccal surface visible in perspective Buccal cusp tips pointed (blunter contour of lingual cusps) Buccal height contour in cervical third, lingual in middle third
Lingual view	
3a	Mesiolingual cusp is the highest Blunter disto-occlusal contour (compared to mesial) Mesial slope of mesiolingual cusp at 90 degrees with mesial outline
Buccal view	
3b	Mesial contact at junction of middle and occlusal third Distal contact at middle third Mesial outline Distal outline convex Mesiobuccal cusp wider than distobuccal Buccal developmental groove slants (parallel to distobuccal root) Horizontal developmental dip Distal side visible Four cusp tips visible
Antagonist cusp paths/occlusal contacts	
4	Antagonist cusp paths from central fossa: nonworking/working/protrusive Potential areas of maximum intercuspal contacts: mesial marginal ridge, mesiolingual and distolingual cusp, central fossa/oblique ridge



Rhomboid



Heart-shaped



Occlusal view
1a
d
1b
d
1c
d
Distal view
2
4
W
P
NW
Lingual view
Buccal view
3a
3b
m

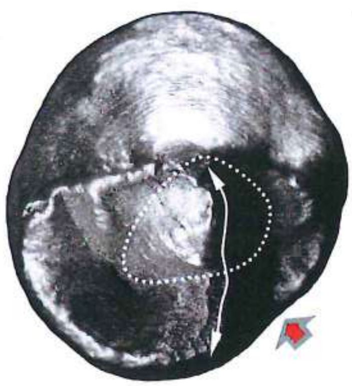
Mandibular first premolar

This tooth (Fig 2-25) is very similar to the mandibular canine. Only the buccal cusp is occluding, and its mesial cusp ridge is shorter than the distal (alike the canine). Other important features include the following[76,77]:

- Curved central developmental groove
- Strong buccal triangular ridge (becomes transverse ridge)
- Small nonfunctional lingual cusp
- Mesiolingual developmental groove starting at the mesial fossa

2-25a

2-25b



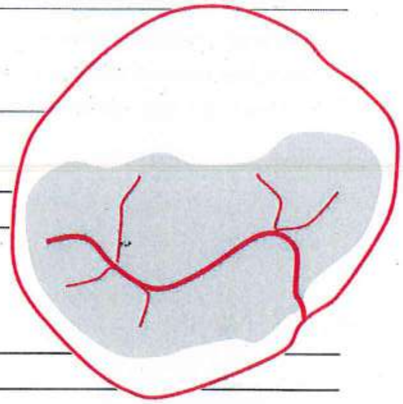
2-25c

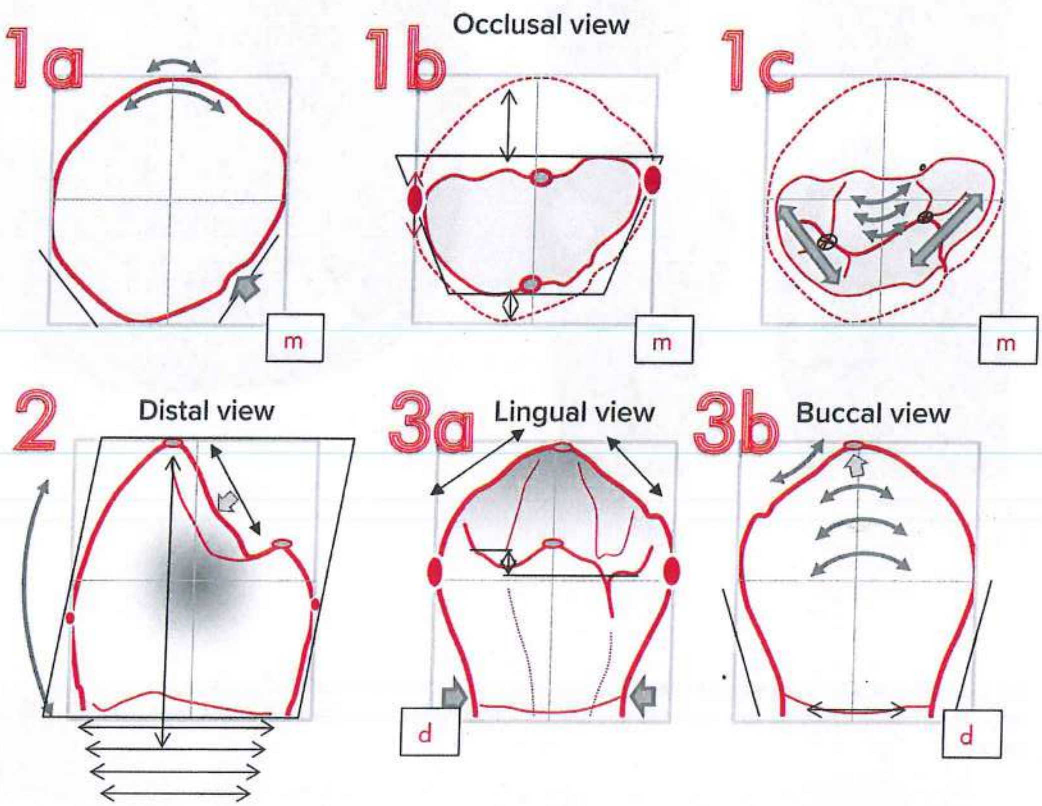
2-25d

FIG 2-25 Mandibular first premolar. *(a)* Mandibular left first premolar views. *(b)* Same specimen as in *a* (occlusolingual view). *(c and d)* Other younger specimen of mandibular left first premolar (occlusal and lingual views) with all attributes listed on the opposite page. Note the strong buccal triangular ridge *(dotted area in c)* connecting to the lingual cusp (transverse ridge, *white arrow in c)* and lingual developmental groove *(red arrow)*.

MANDIBULAR LEFT FIRST PREMOLAR

Dimensions: mesiodistal 7 mm, buccolingual 7 mm, height 8.5 mm	
Occlusal view	
1a	Occlusal outline like that of canine (circular or diamond-shaped) Buccal surface especially convex at middle and cervical thirds (ridge) Tapers toward lingual Mesiolingual developmental groove
1b	Large buccal cusp slightly mesial Very small centered lingual cusp Buccal surface well visible; occlusal table markedly shifted lingually Distal contact broader than mesial
1c	Heavy buccal triangular ridge (becomes transverse ridge) Possible distal pit (and even smaller mesial pit) Lingual convergence of marginal ridges
Distal view	
2	Rhomboid shape Occlusal table slopes sharply (like the mesial marginal ridge) Buccal cusp tip nearly centered on root (slightly buccal) Buccal and lingual height of contour near cervical third, lingual above buccal Spheroidal distal surface
Lingual view	
3a	Mesial cusp ridge shorter than distal one Mesial marginal ridge lower than distal marginal ridge Mesial and distal contact at same level just above midheight Mesial and distal surfaces well visible (lingual taper) Narrow root base
Buccal view	
3b	Buccal ridge well developed (but without mesial and distal depressions) Long sharp buccal cusp tip, shifted slightly mesially Trapezoidal shape Mesial cusp ridge concave; distal cusp smooth (possible concavity) Flat cervical line





Mandibular second premolar

This tooth is the strongest of all premolars with its cubical coronal shape. Like the first premolar, only the buccal cusp is occluding and its mesial and distal cusp ridges are equal (cusp is centered mesiodistally), and the central developmental groove is curved.

There are two common types[76]:

- The three-cusp type is more frequent. It is more angular from the occlusal aspect and features a third small cusp (distolingual cusp, smaller and shorter than the mesiolingual cusp) and a central pit (Figs 2-26a and 2-26b).
- The two-cusp type is more rounded from the occlusal aspect (Fig 2-26c).

There are intermediate variations between these two types (Fig 2-26d).

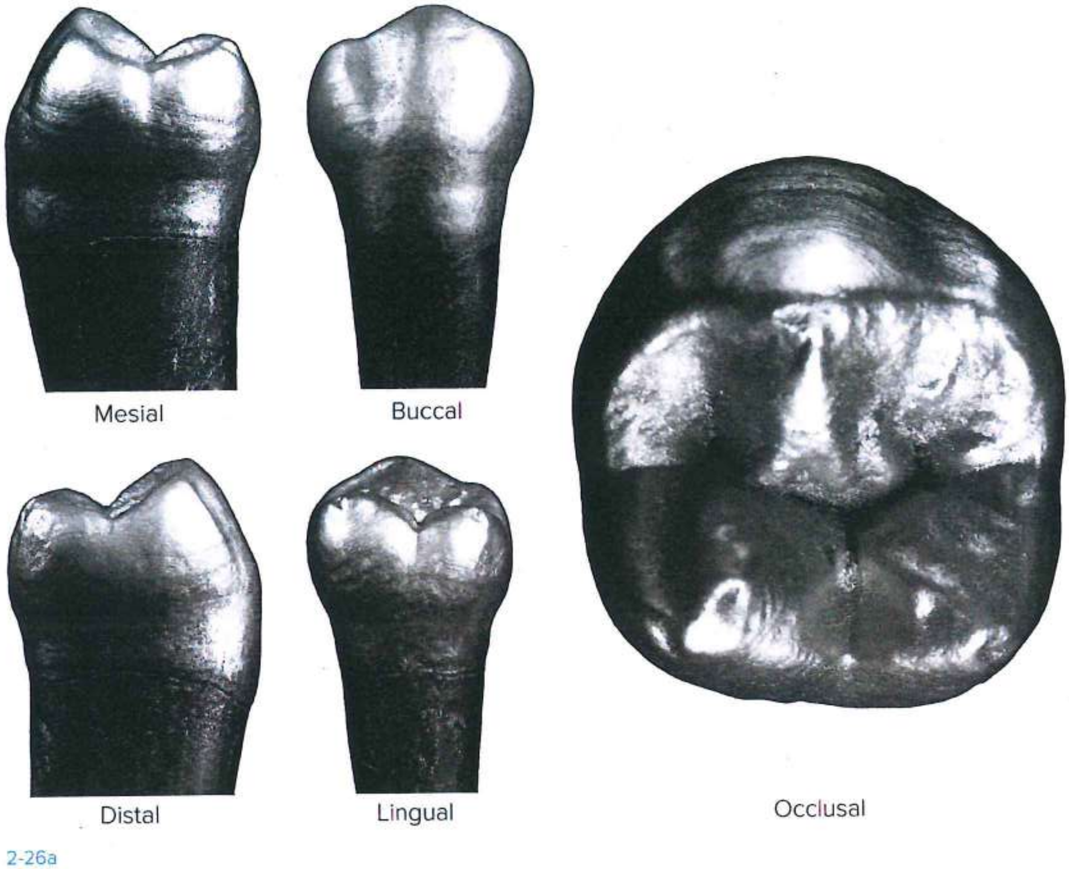
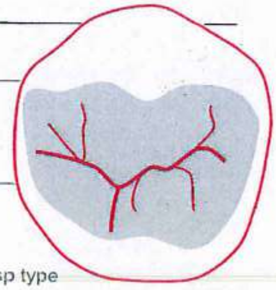
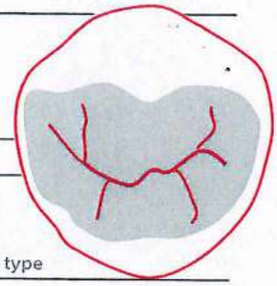


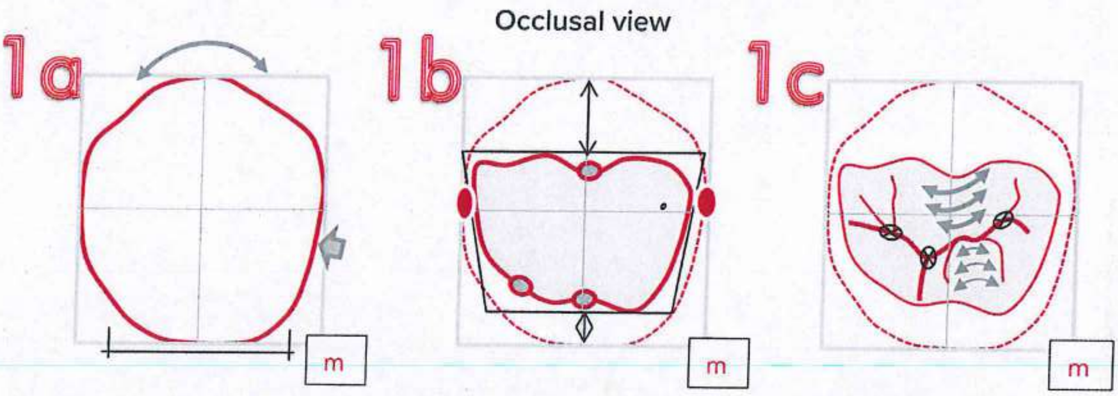
FIG 2-26 Mandibular second premolar. *(a)* Mandibular right second premolar views with a particularly strong three-cusp typal form. All attributes are listed and illustrated by symbols on the opposite page.

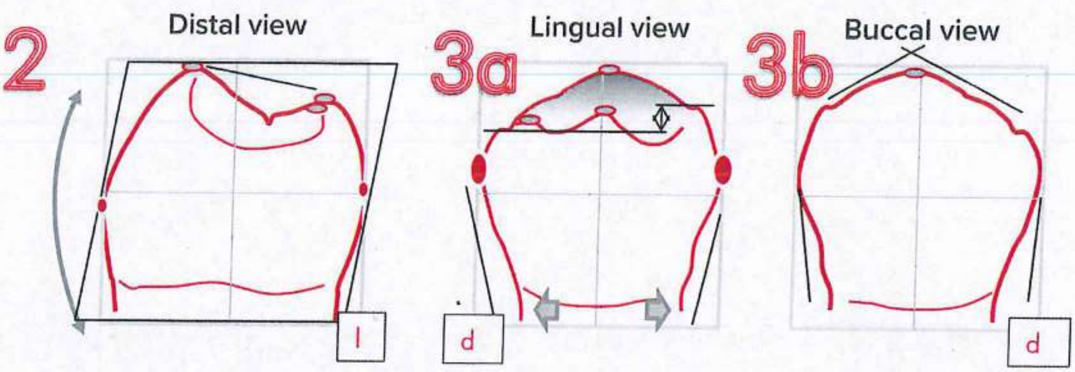
MANDIBULAR LEFT SECOND PREMOLAR

Dimensions: mesiodistal 7 mm, buccolingual 8 mm, height 8 mm	
Occlusal view	
1a	Squared lingual outline (three-cusp type) Convex buccal outline like first premolar
1b	Two- or three-cusp types (buccal > mesiolingual > distolingual) Buccal surface well visible; occlusal table shifted lingually Buccal and mesiolingual cusp centered and slightly mesial Interdental contacts shifted buccally
1c	Buccal and mesiolingual cusps with well-developed triangular ridges Central pit (slightly distal and lingual to center) Possible mesial and distal pits Deep Y-shaped developmental grooves (no transverse ridge) Lingual developmental groove shifted distally to center
Distal view	
2	Rhomboid shape Occlusal table slopes slightly Marginal ridges not sloped (unlike first premolar) More occlusal surface seen than mesially Height of contour in middle third, lingual above buccal
Lingual view	
3a	Smooth lingual surface (with possible lingual groove) Mesial marginal ridge higher than distal marginal ridge (opposed to first premolar) Mesial and distal contact at junction of occlusal and middle thirds Root base broader than first premolar
Buccal view	
3b	Mesial and distal cusp ridges less angulated than first premolar


Three-cusp type


Two-cusp type





2-26b

FIG 2-26 *(cont) (b)* Labio-occlusal view of a mandibular right second premolar (same specimen as in *a*; note the three pits*). *(c)* Linguo-occlusal view for comparison of left first premolar and typical two-cusp second premolar. *(d)* Other linguo-occlusal view of two-cusp specimen with small distolingual lobe still visible (*) (see also corresponding occlusal clinical view in Fig 2-27c).

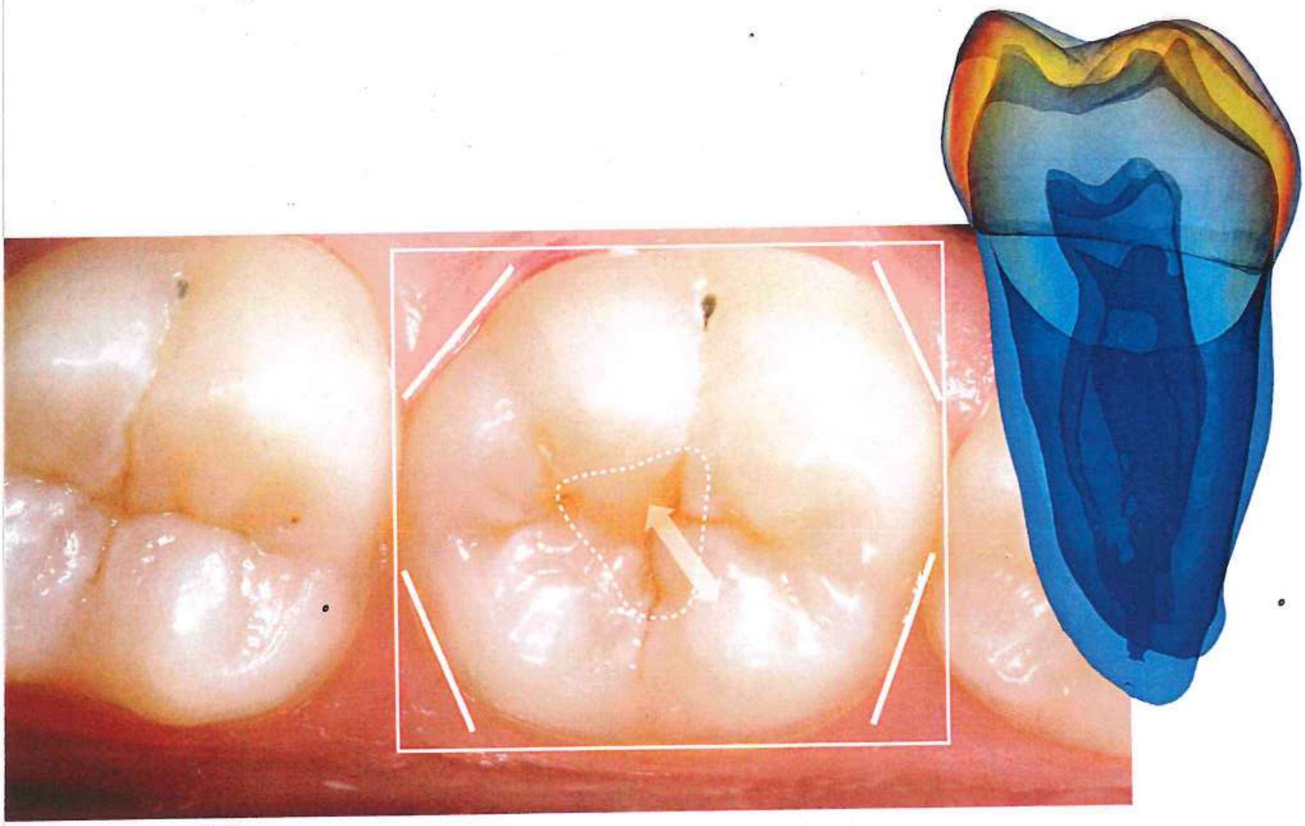
2-26c

2-26d

Mandibular first molar

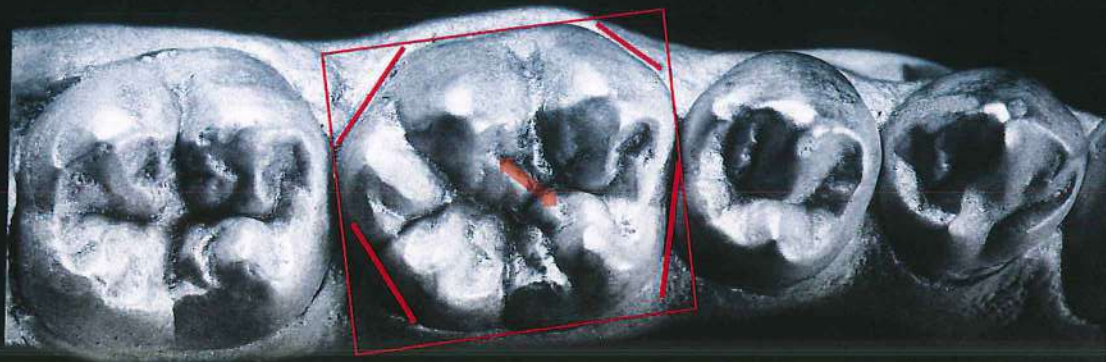
This tooth (Fig 2-27) is a cornerstone of the dentition because it is usually the first permanent tooth to erupt, hence the most likely to be affected by decay. Unlike the mandibular premolars, the lingual cusps are higher than the buccal cusps. Its characteristics also include the following[76,77]:

- Larger dimension mesiodistally compared to buccolingually (opposite to maxillary molars); somewhat hexagonal shape
- Five cusps: two buccal, two lingual, and one distal (smallest)
- Mesial and distal surfaces that converge lingually



2-27a

FIG 2-27 Mandibular first molar. *(a)* Occlusal clinical view of mandibular left first molar revealing almost a hexagonal shape and four primary cusps with central fossa *(dotted area)*. The triangular ridge of the mesiolingual cusp often converges toward the distobuccal cusp *(arrow)*. *(b)* Mandibular left quadrant with other specimen displaying similar characteristics and all attributes listed on the two subsequent pages. *(c)* Young atypical specimen with extrawide occlusal table, extreme lobes, and numerous supplemental grooves (see also corresponding stone replica in Fig 2-26d). *(d)* Linguo-occlusal view of typical mandibular left quadrant.



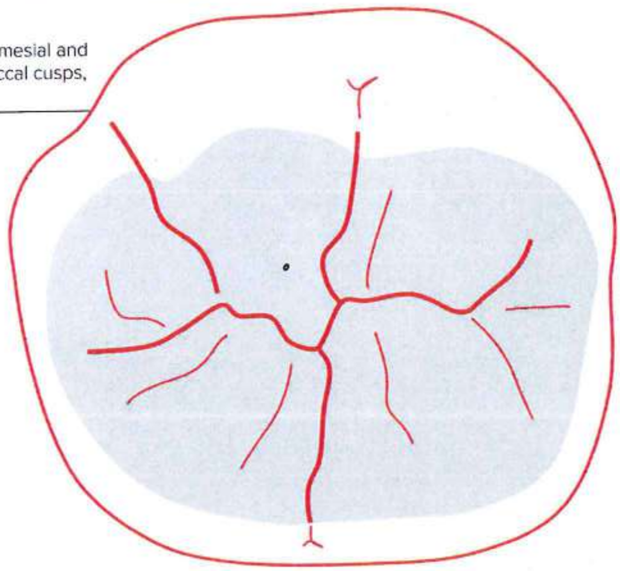
2-27b

2-27c

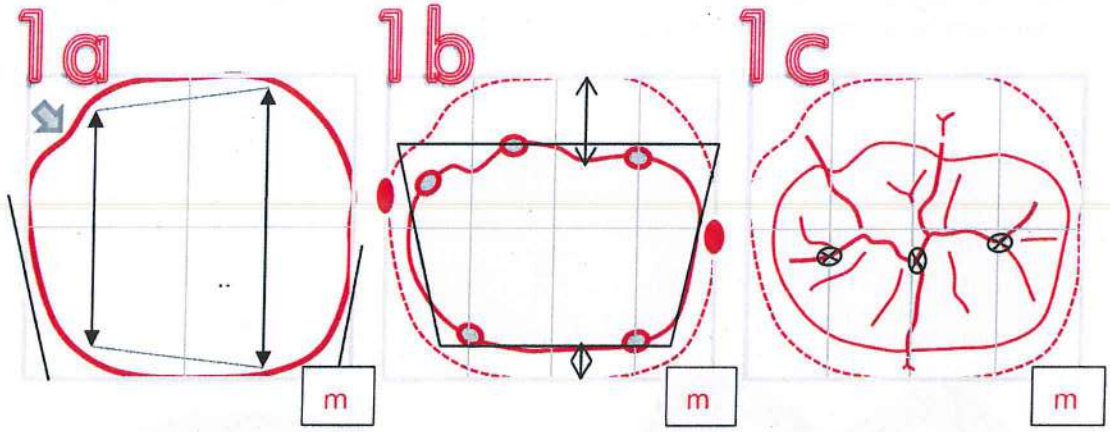
2-27d

MANDIBULAR LEFT FIRST MOLAR

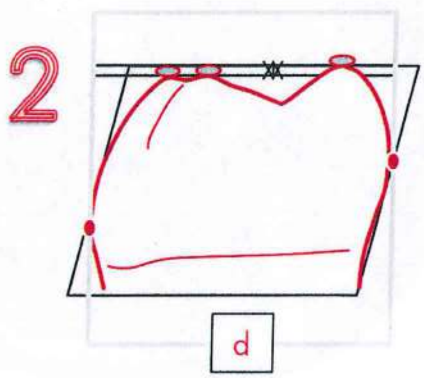
Dimensions: mesiodistal 11 mm, buccolingual 10.5 mm, height 7.5 mm	
Occlusal view	
1a	Crown converges lingually Buccolingual distance greater mesially than distally Depression created by distobuccal developmental groove
1b	Buccal surface well visible (unlike lingual) Mesial contact centered, distal contact shifted slightly buccally Trapezoidal occlusal table shifted slightly lingually Five cusps: mesiobuccal, mesiolingual, and distolingual > distobuccal > distal
1c	Three well-defined pits (mesial, central, distal) Sharp developmental grooves Supplemental grooves
Distal view	
2	Lingual cusp tips pointed and higher than buccal ones Blunter contour of buccal cusps Buccal height contour in cervical third, lingual in middle third
Lingual view	
3a	Distal contact more cervical than mesial Blunter disto-occlusal contour (compared to mesial) Short lingual developmental grooves
Buccal view	
3b	All five cusp tips visible Mesiobuccal developmental groove with possible pit Distobuccal developmental groove
Antagonist cusp paths/occlusal contacts	
4	Antagonist cusp paths from central fossa: nonworking/working/protrusive Potential areas of maximum interdental contacts: mesial and distal marginal ridges, mesiobuccal and distobuccal cusps, central fossa

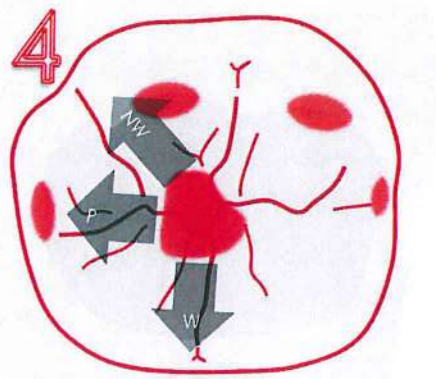


Occlusal view

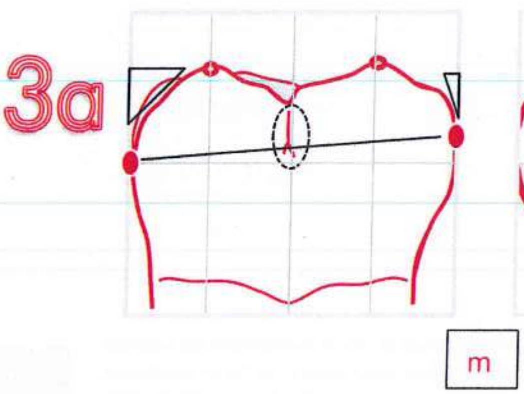


Distal view

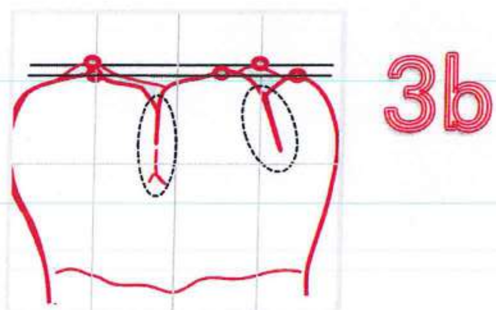




Lingual view



Buccal view



Mandibular second molar

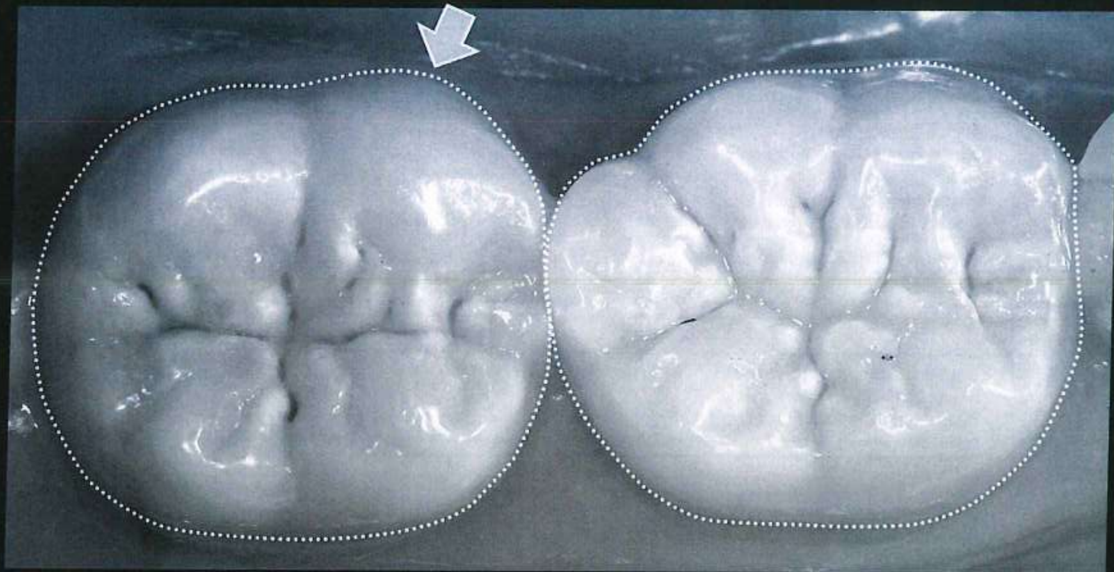
The mandibular second molar (Fig 2-28) is slightly smaller than the first molar, more rectangular, and more symmetric, with four equivalent cusps. Its characteristics also include the following[76,77]:

- A cervical prominence at the mesiobuccal aspect
- A semicircular distal outline compared to mesial
- Developmental grooves forming a "cross pattern"

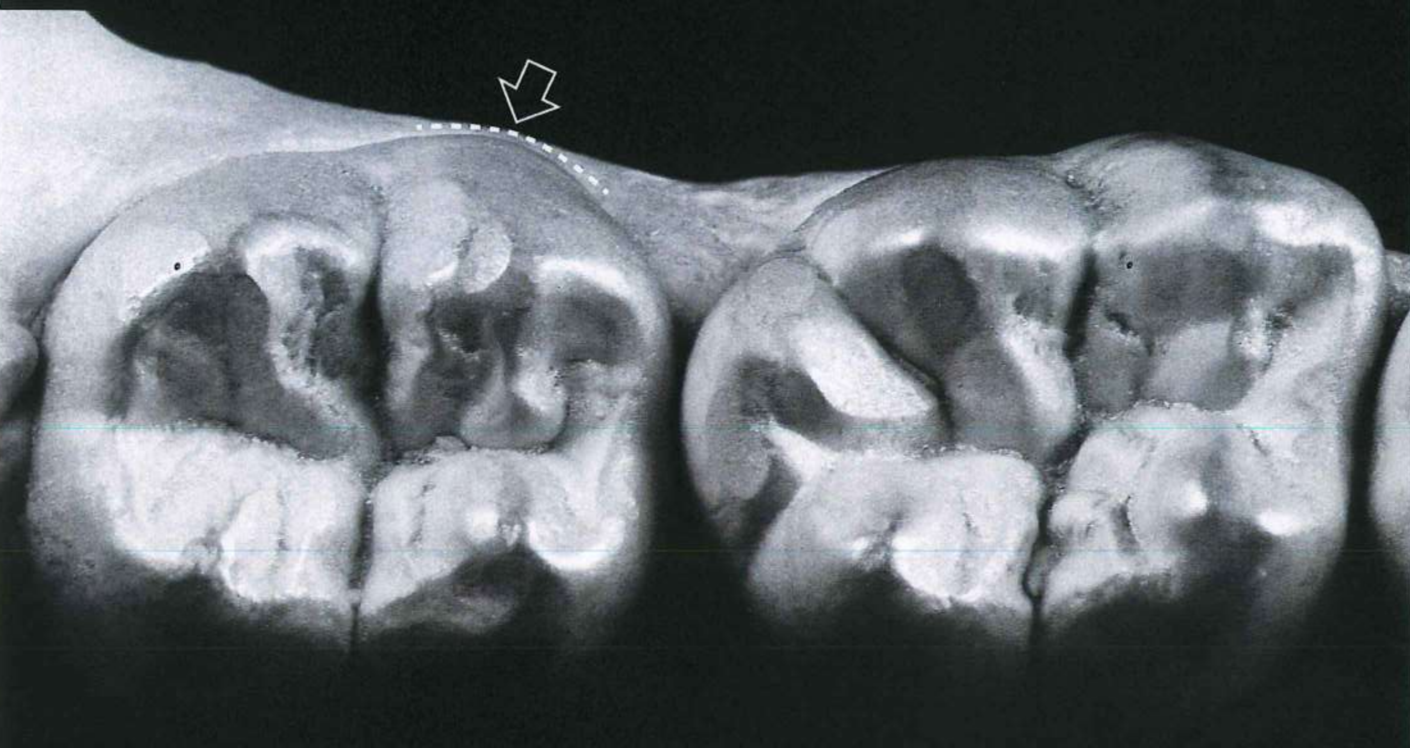
2-28a

2-28b

FIG 2-28 Mandibular second molar. *(a and b)* Distal and occlusal views of mandibular left second molar. *(c)* Clinical view for comparison of mandibular left first and second molars. *(d)* Other specimen (mandibular left molars) with all attributes listed on two subsequent pages (note the mandibular first molar with strong angular features). All three specimens feature the "cross pattern" of the developmental grooves and numerous supplemental grooves, as well as the mesiobuccal cervical prominence *(arrow)*.



2-28c

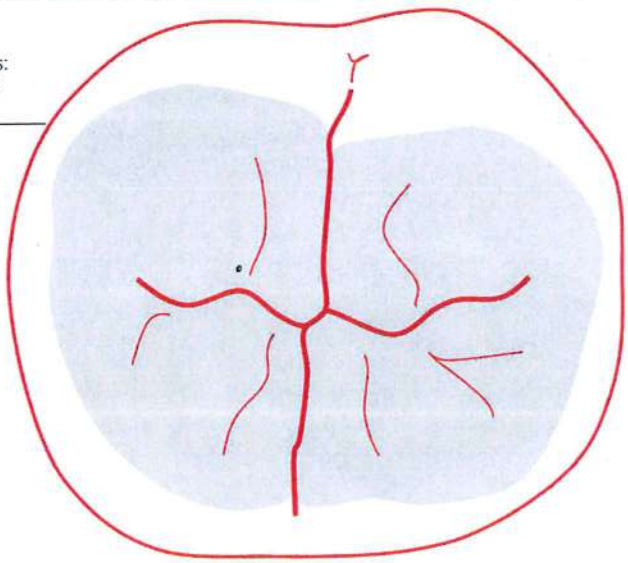


2-28d

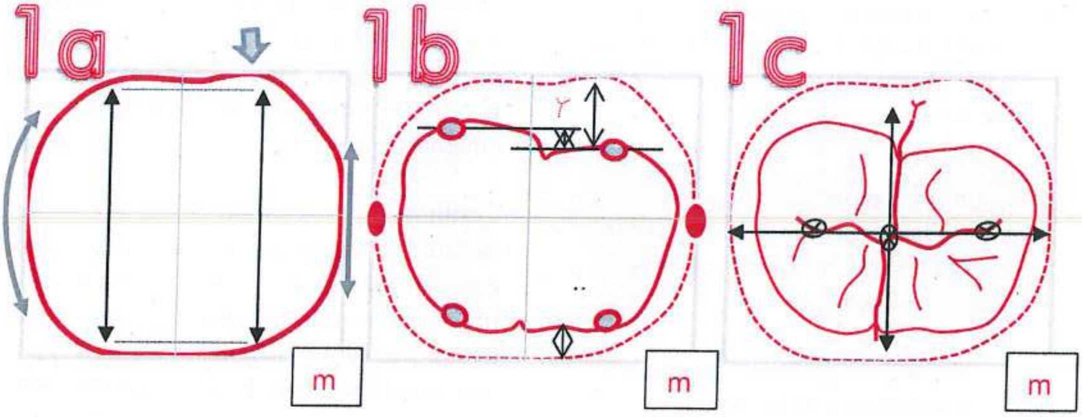
MANDIBULAR LEFT SECOND MOLAR

Dimensions: mesiodistal 10.5 mm, buccolingual 10 mm, height 7 mm

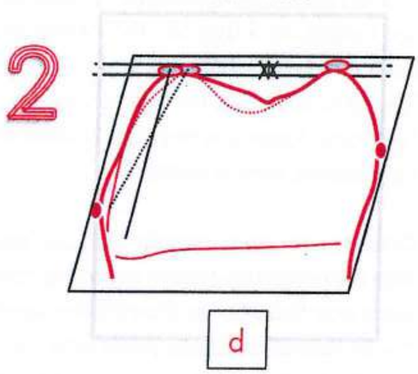
Occlusal view	
1a	Basic rectangular outline Distal outline rounded, mesial flat Mesiobuccal cervical prominence
1b	Buccal surface well visible (especially mesially) Mesial and distal contact centered Rectangular occlusal table shifted slightly lingually Four equal cusps Distobuccal cusp tip more buccal than mesiobuccal cusp
1c	Three well-defined pits (mesial, central, distal) Developmental grooves form a cross Multiple supplemental grooves radiating from center groove
Distal view	
2	Lingual cusp tips pointed and slightly higher than buccal ones Blunter contour of buccal cusps Buccal height contour in cervical third, lingual in middle third Inclination of mesiobuccal cusp (cervical prominence) compared to distobuccal cusp
Lingual view	
3a	Distal contact more cervical than mesial Blunter disto-occlusal contour (compared to mesial) Short lingual developmental groove
Buccal view	
3b	All four cusp tips visible Buccal developmental groove with possible pit
Antagonist cusp paths/occlusal contacts	
4	Antagonist cusp paths from central fossa: nonworking/working/protrusive Potential areas of maximum intercuspal contacts: mesial and distal marginal ridges, mesiobuccal and distobuccal cusps, central fossa

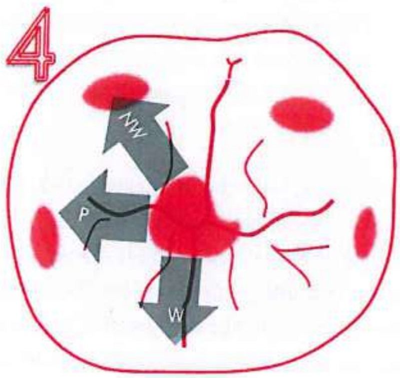


Occlusal view



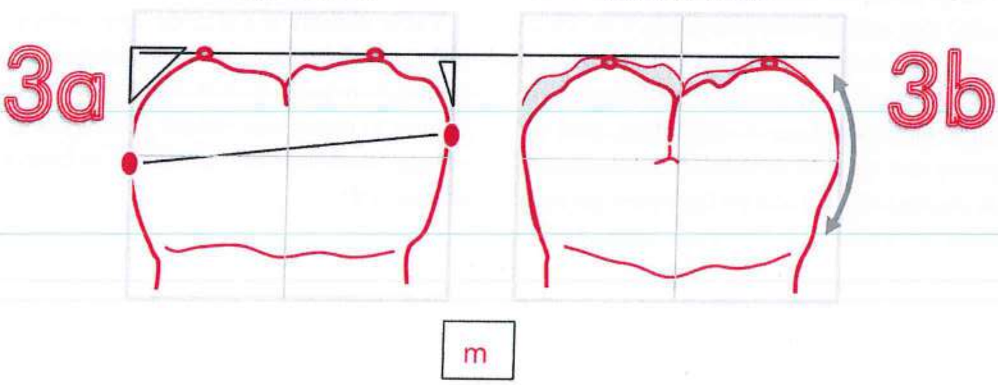
Distal view





Lingual view

Buccal view



Considerations about "normal occlusion" and contacts

There is a wide diversity of doctrinaire schools and concepts about what is called "ideal" occlusion, and it is beyond the scope of this work to cover the broad topic of occlusion and temporomandibular disorders (TMDs).

> Dogmatic approaches to occlusion have been challenged over the past few decades,[78] and the following elements are now accepted:
>
> - There are significant variations in morphology and function.
> - Patients have an individual capacity to adapt to a given occlusal scheme.
> - Changes in occlusion are happening throughout the course of life; occlusion is not set in stone once for all.

Teeth along with the neuromuscular system, temporomandibular joints, and craniofacial bones are all part of this complex equation regulating the stomatognathic system. For a majority of patients in real life (and within the scope of this work), the restorative treatment should simply not interfere with the existing balance of their stomatognathic system.

Many patients deviate from established "ideals" but still function normally.[79] In those asymptomatic cases, major occlusion changes should be used only as tools to facilitate and allow a minimally invasive restoration, such as opening the vertical dimension using physiologic deprogramming and the Dahl principle (see chapter 5, section 5.8).[80–82] Basic principles of biomechanics are also followed to avoid excursive interferences known to cause major stresses in the teeth (eg, nonworking interferences; see Fig 1-9b in chapter 1).[83,84]

It is also known that those occlusal "deviations" have minor influence on periodontal health and/or TMDs.[85] Hence, those conditions should not be used to justify extensive treatments, either orthodontic or restorative, to correct occlusion.

Contacts

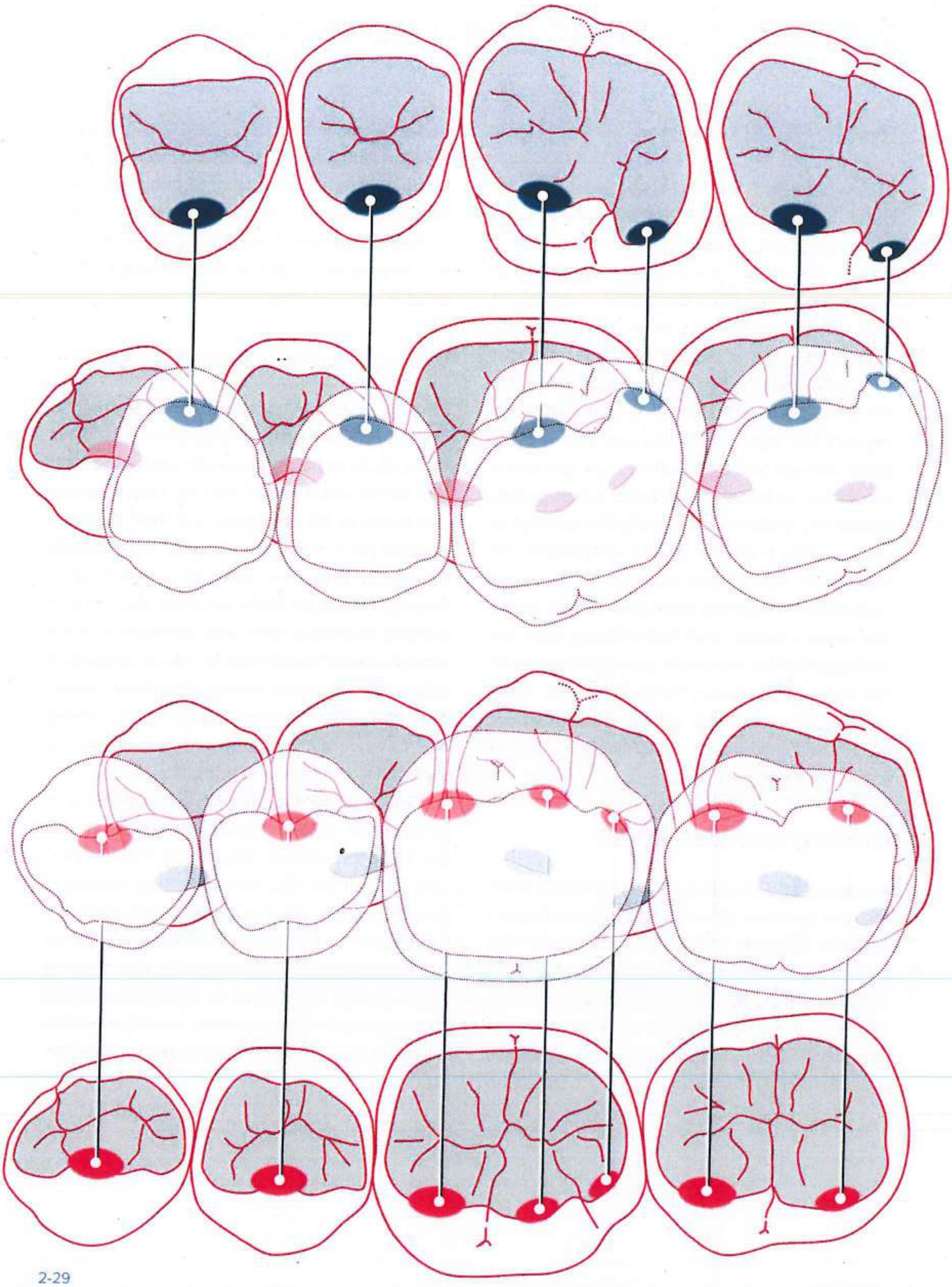
Because of natural dental morphology, normal occlusal contacts are formed by the fitting of *(1)* maxillary lingual cusps into the central fossae (or marginal ridges) of mandibular teeth (Fig 2-29, top) and *(2)* mandibular buccal cusps into central fossae and embrasures (or marginal ridges) of maxillary teeth (Fig 2-29, bottom).

The cusp/fossa "idealization," however, should not constitute a dogma. The reality of natural dentitions is that contacts are few and not always ideally located (eg, on inclined planes); hence, functional forces are not only located along the longitudinal axes of teeth.[86,87]

Occlusal contacts should include immediate side shift and long-centric spaces to provide the room and flexibility for the inherent variability of the temporomandibular joints while effectively distributing forces (to decrease stress and wear) and counteracting tooth-eruptive forces.[87]

Tooth stability will also be ensured by the tongue and cheeks, as well as adequate interproximal contacts. Further aspects of occlusion related to biocorrosion/wear and opening the vertical dimension are discussed in chapter 5, section 5.8.

FIG 2-29 Static occlusion and potential contacts in maximum intercuspation.



2-29

2.5 DIDACTIC STEPS TO DENTAL MORPHOLOGY

The 2D-3D-4D concept

A new didactic method was developed to better prepare students for the novel biomimetic approach to restorative dentistry.[75,88,89] It implies that, to be emulated faithfully, the natural dentition's structural (functional, mechanical) and esthetic properties must be thoroughly understood. The innovative part of the didactic method is the emphasis on visual arts and the 2D-3D-4D concept that logically starts with drawing (2D/3D), then partial wax-ups, followed by labial wax-ups and finally full wax-ups with some innovative technical aids (electric waxer, prefabricated wax patterns, etc). Finally, the concept of strata and the histoanatomy of enamel/dentin, as well as the optical depth, are taught through the realization of layering exercises (acrylic mock-ups and composite resin restorations). All of the aforementioned materials and techniques are not only used to teach morphology and occlusion but also constitute essential tools that will be of significant use for the students when they reach the clinic floor.

Drawing exercises: 2D-3D

A conceptual part of the didactic method is learning how to draw in 3D using an approach inspired by Betty Edwards and the five perceptual skills of drawing (see also Fig 2-15d). Those five skills (Edges, Spaces, Relationship, Light and Shadows, Gestalt) were adapted to the situation of a tooth drawing (Frame, Contours, Elements, Shadows and Highlights, Composition). This increases a student's creativity by stimulating the right brain's creative language mode. Each student is given 20 images (8 anterior teeth, 12 posterior teeth) with specific dimensions as a model for drawing in their sketchbook. The following pages provide the step-by-step manual and drawing models used for this exercise.

Wax-ups and mock-ups: 3D-4D

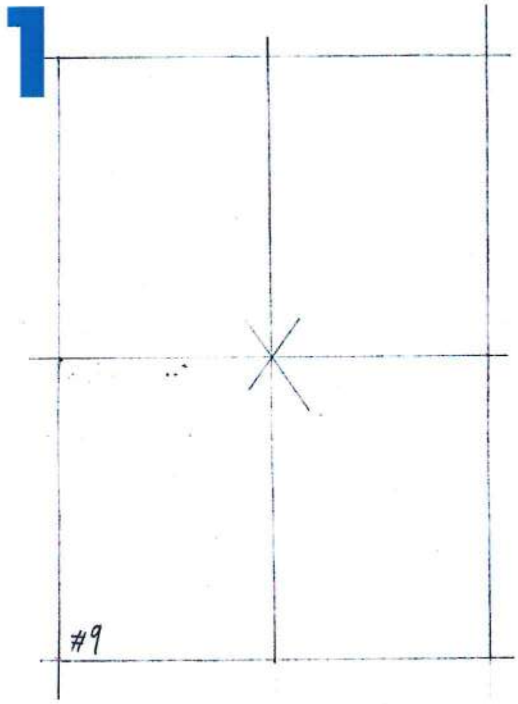
Another emphasis of the new didactic method is the progressive approach to the "3D" additive wax-ups, from partial coverage (class IV defect in anterior teeth, single missing cusp in posterior teeth) to full coverage and from single to multiple teeth. In this way, students are gradually introduced to the new materials and techniques. Because students often question the value of carving exercises and also because current dental restorative techniques use an apposition approach (composite resins) rather than carving as in the case of amalgam, wax block carving exercises were abandoned and replaced by various additive techniques using wax.

One important motivation for students is to present the Typodont model (simulation model) as "their first patient" and asking them to plan the case all the way from the study models to the diagnostic approach (progressive wax-up technique and trial smile/mock-up/provisional restoration using acrylic resins). The anterior smile design is followed by the same progressive approach in the posterior dentition, ending with the layering of composite resins (the final "4D" aspect).

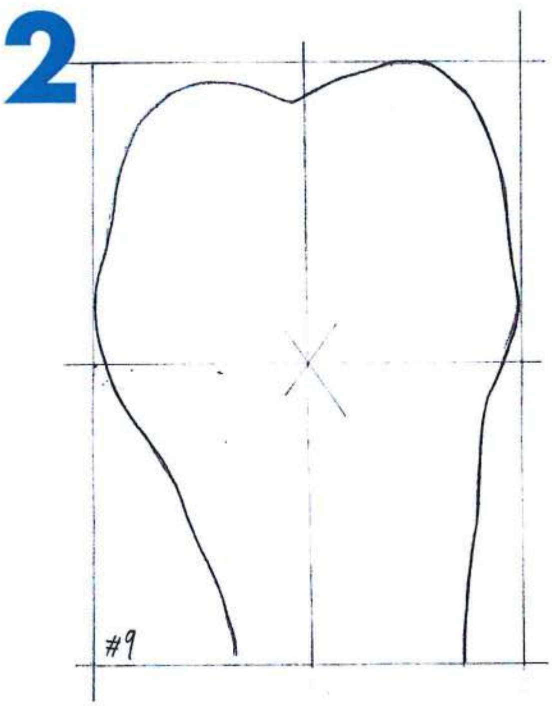
STEP-BY-STEP INSTRUCTIONS FOR TOOTH DRAWING

Step	Instruments and methods	Notes
Material preparation	• White sketching paper • #2 pencil with eraser • T-Metric ruler • Smudge tool (or finger)	
1. Frame and quadrants	Create a four-paned grid on your paper that is sized according to the recommended dimensions; bisect the length and width to create four identical quadrants.	Exact dimensions of the frame are indicated for each drawing.
2. Outline	Begin sketching the outline of the tooth quadrant by quadrant. Try not to think about drawing a tooth as you sketch; rather focus solely on reproducing (copying) each line or shape, including the negative space with the frame, as you see it in the original (right-brain mode).	The printed image allows you upside-down drawing, which stimulates right-brain mode.
2+. Rendering (optional step)	After you have drawn the outline of the tooth, you can render the shape, which means to *very lightly* shade the entire tooth with an even shade of gray. The significance of this step will become apparent when you add highlights to your sketch. If the background is slightly darker than pure white, it will facilitate creating highlighted areas with an eraser.	This will make your job much easier when you put the final touches on your masterpiece.
3. Elements: Outlining shaded areas	Once the general outline has been rendered, begin to section off areas of shading within the tooth. *Use a very light pencil mark.*	You won't actually be shading these areas at this step, which will come next. For now, just create the boundaries for the areas to be shaded.
4. Shading	There are several ways to shade your drawing to create areas of light and shadow. To understand how the shadows are created on the tooth you are drawing, remember that convex areas of the tooth will usually appear white or lighter, as they are receiving direct light from the light source. Conversely, concave areas will tend to be shadowed, as the convex regions block the light from fully illuminating these spots on the surface of the tooth. • The simplest way to create shadow—and therefore depth—is through *cross-hatching.* • Begin to shade the areas of the tooth that you created in the previous step. • Start with the lightest areas first. Then add consecutive sets of parallel lines (see Notes) to the regions that appear darker. • In areas with no shadowing, leave the background untouched. • Blend the shaded areas to create a uniform appearance using a blending (smudging) tool or your finger. • Go back and redefine the darkest areas of the tooth, including ridges and grooves that are most prominent.	In cross-hatching, one creates a series of parallel lines in the area to be shaded. One set of parallel lines creates the lightest shade beyond white. Also, the farther apart the lines, the lighter the shading appears. Adding a second, third, fourth, etc, set of parallel lines (in different directions relative to one another) creates the illusion of darker shading. Similarly, the closer together the lines are placed, the darker the region will become.
5. Highlighting	The final step is to highlight the lightest areas of the tooth—areas where light from the source is really bouncing off the surface (light reflections). This is where that initial background shading (rendering, step 2+) is helpful. Use an eraser to remove the background shade in areas that appear most "white" on the tooth. This highlighting technique goes a long way in lending a 3D appearance to your drawing.	
6. Details	Look carefully at the original picture; add and refine all the details that you have missed. Sign and date your work—you are an artist!	
7. Scan/print or photocopy each drawing	Make a good-quality black-and-white copy of each drawing (high-contrast mode) to improve rendering.	

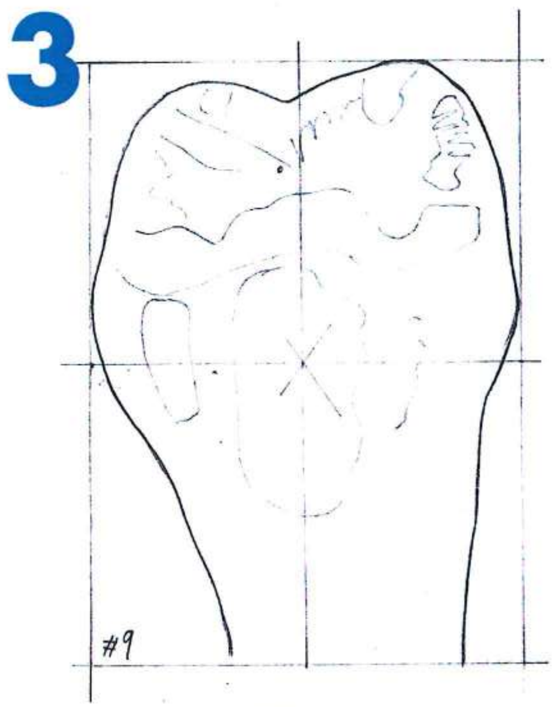
Original



Frame

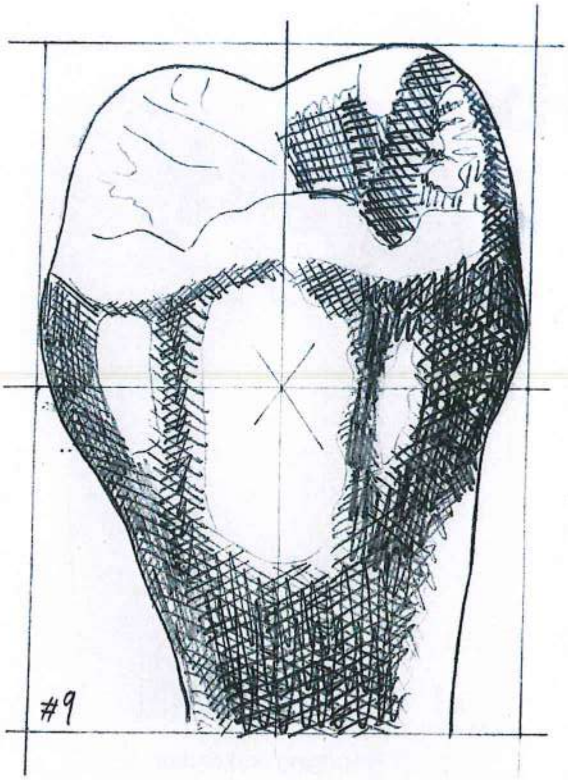


Contour

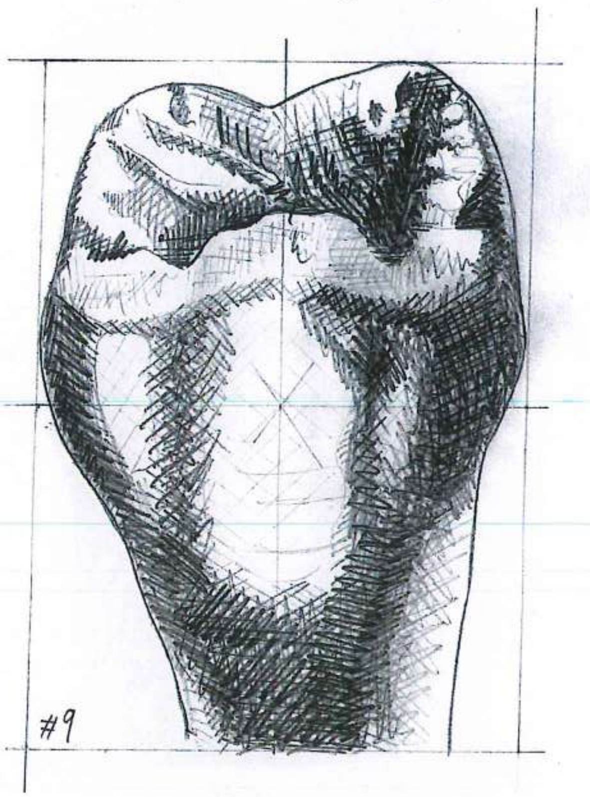


Elements

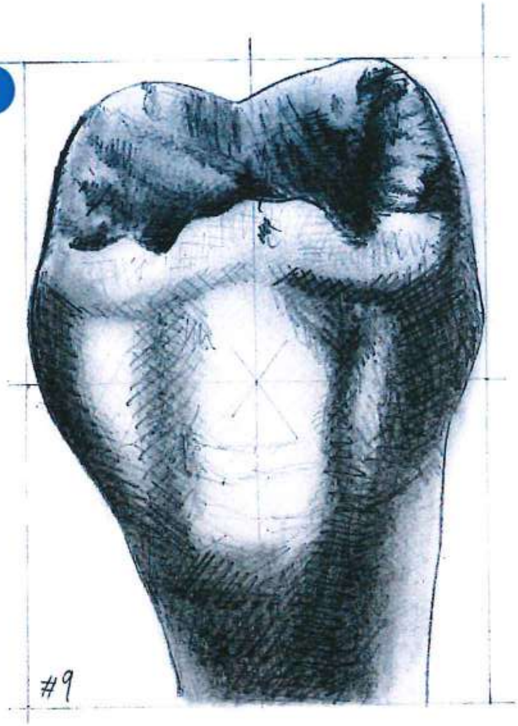
4a



Shading: cross-hatching technique

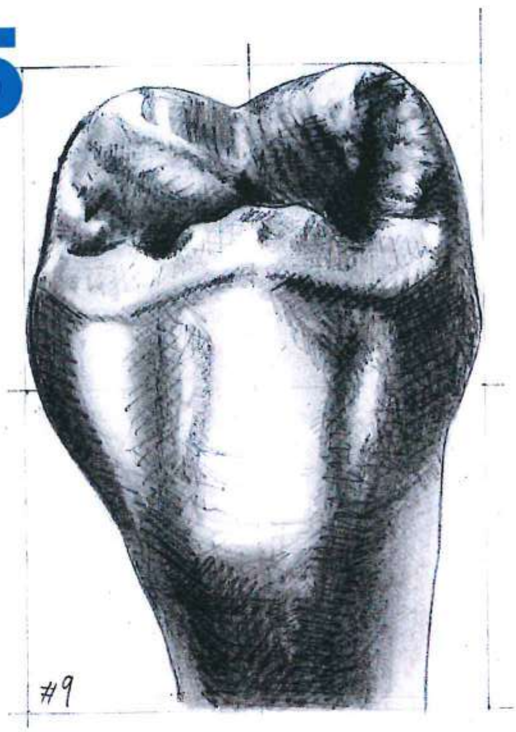


4b



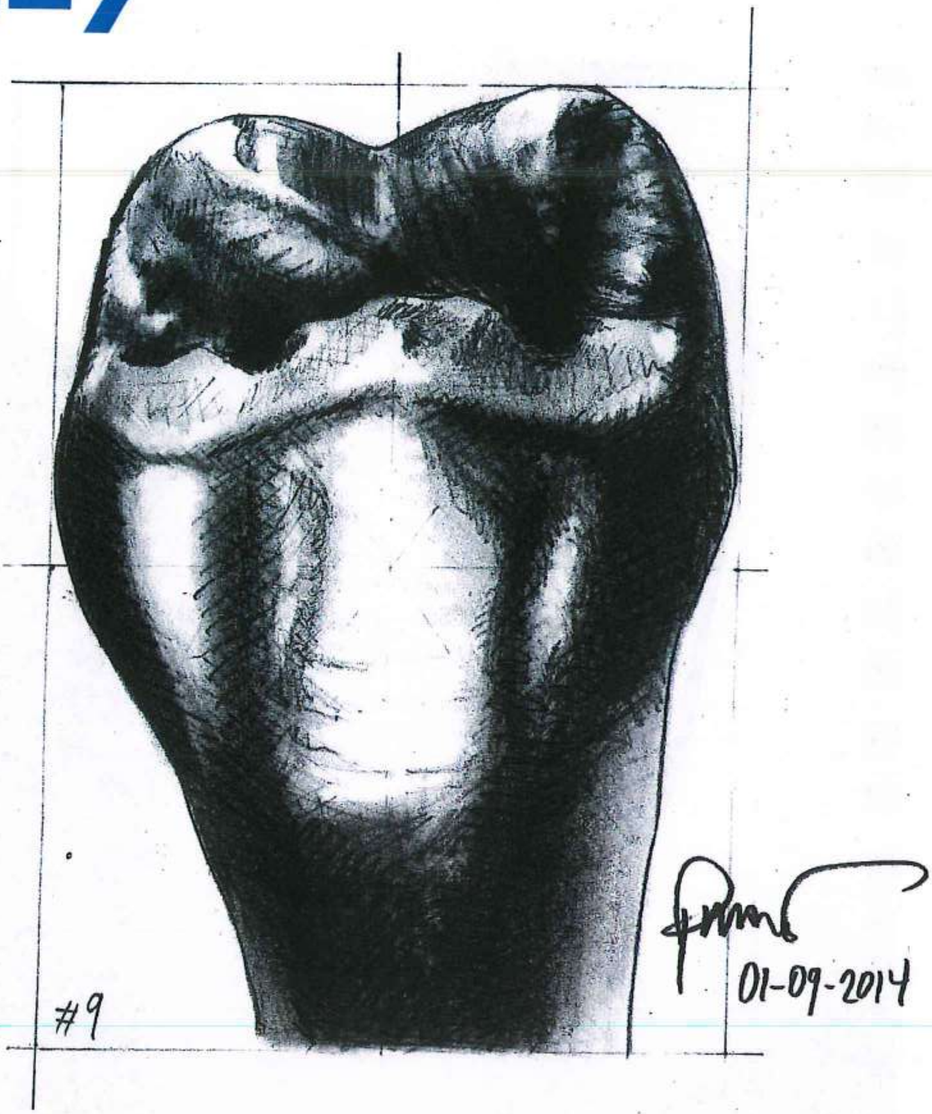
Smudging and darkening

5



Highlights

6–7



Details, date, and SIGN!

2.6 DRAWING MODELS

Anterior teeth

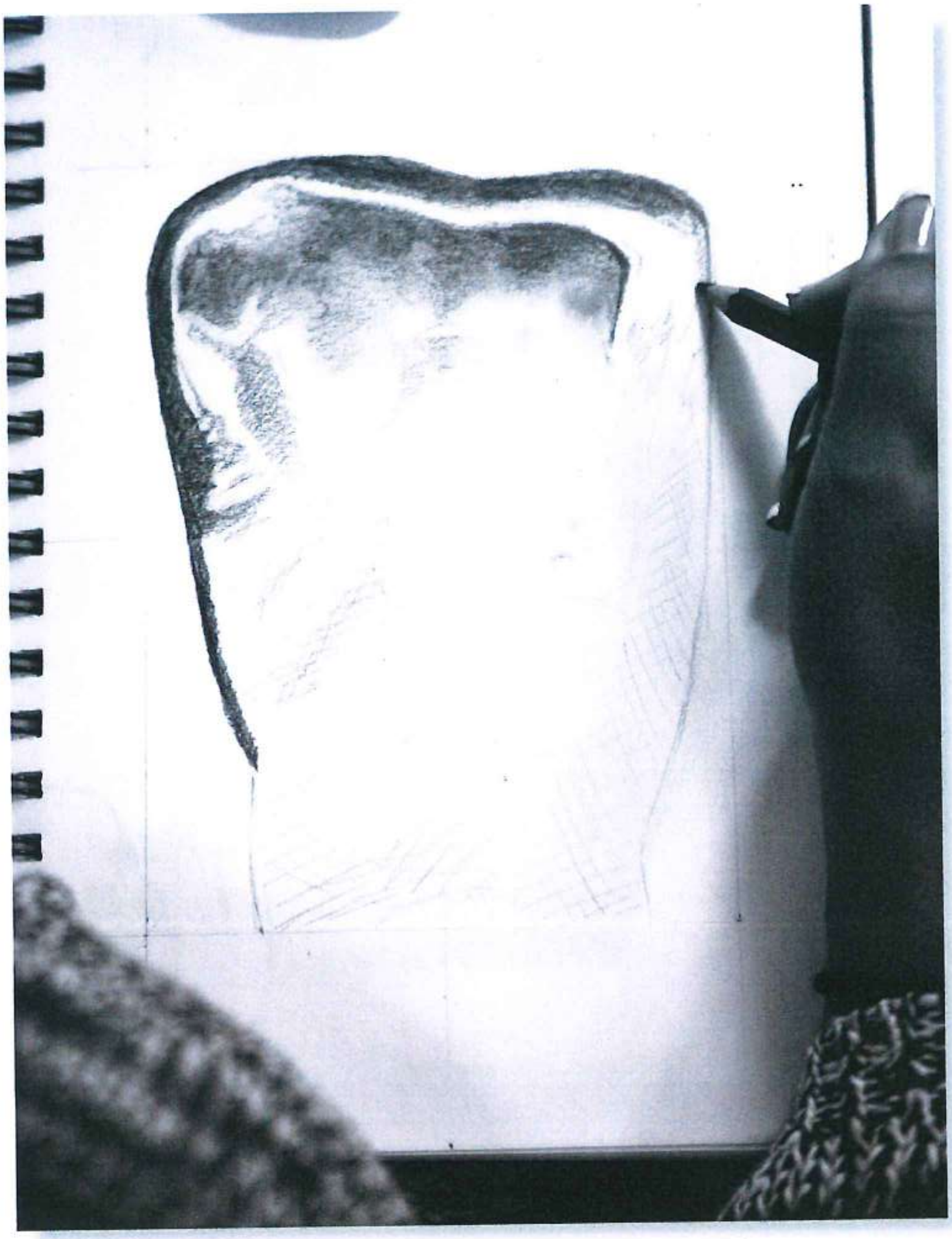
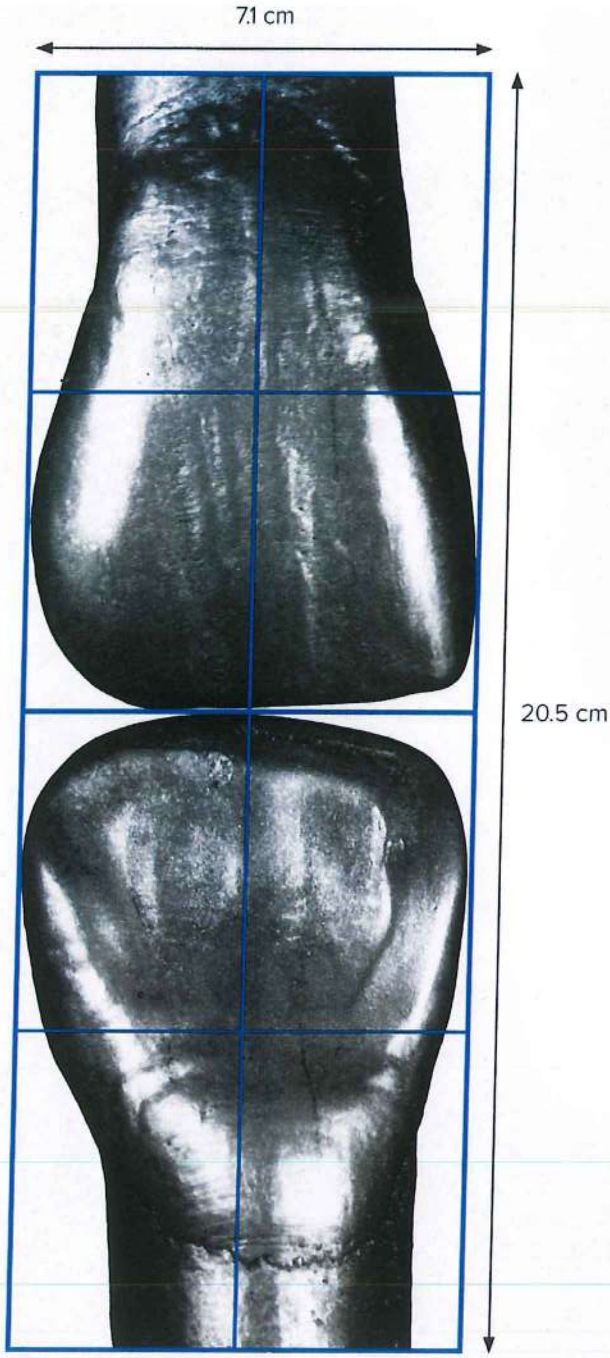


Image reproduced with permission from Magne.[75]

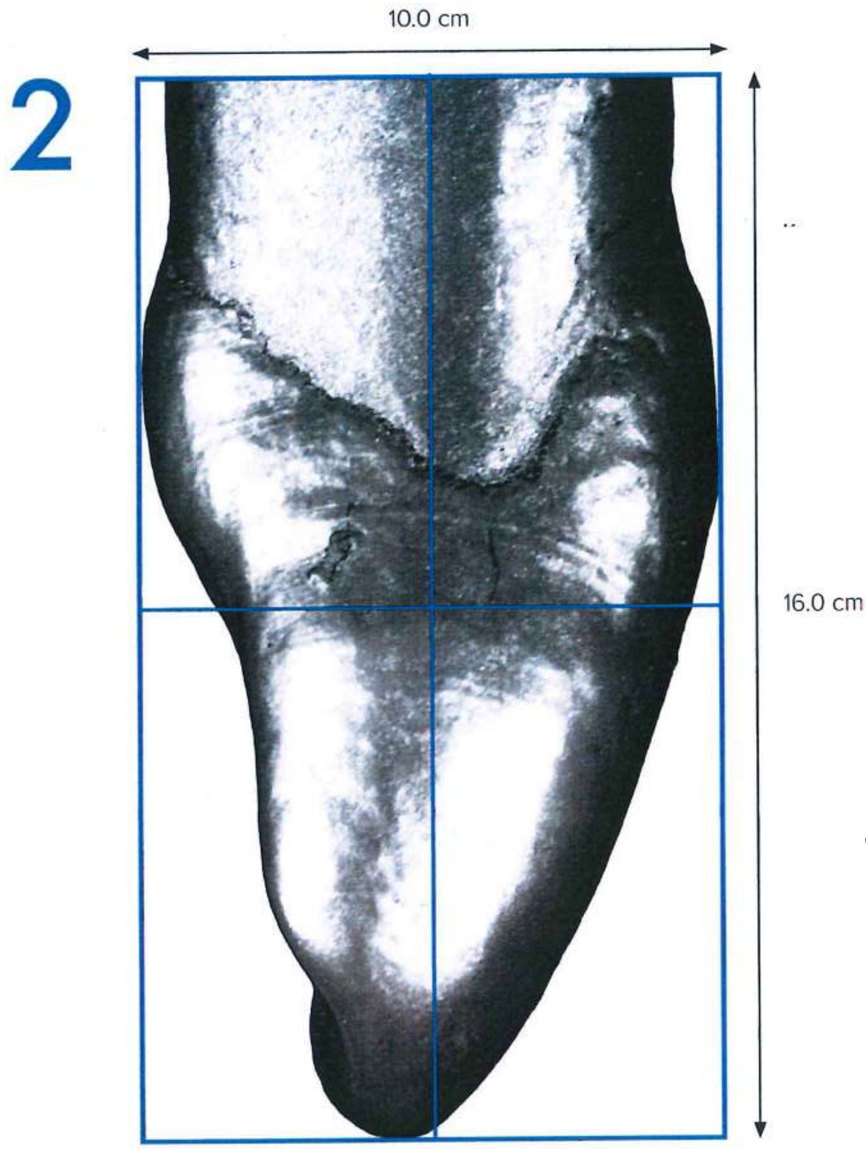
1



DRAWING #1 Page setup.

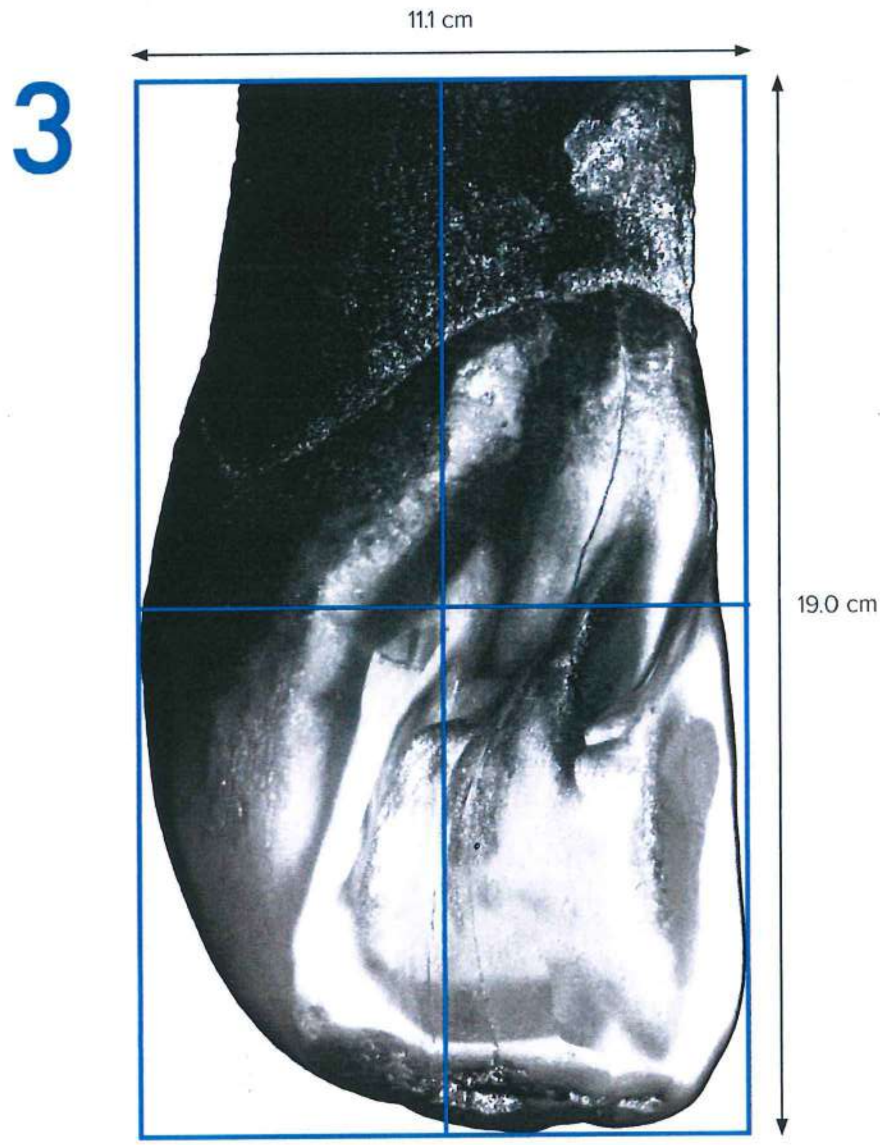
1a

1b



DRAWING #2 Page setup.

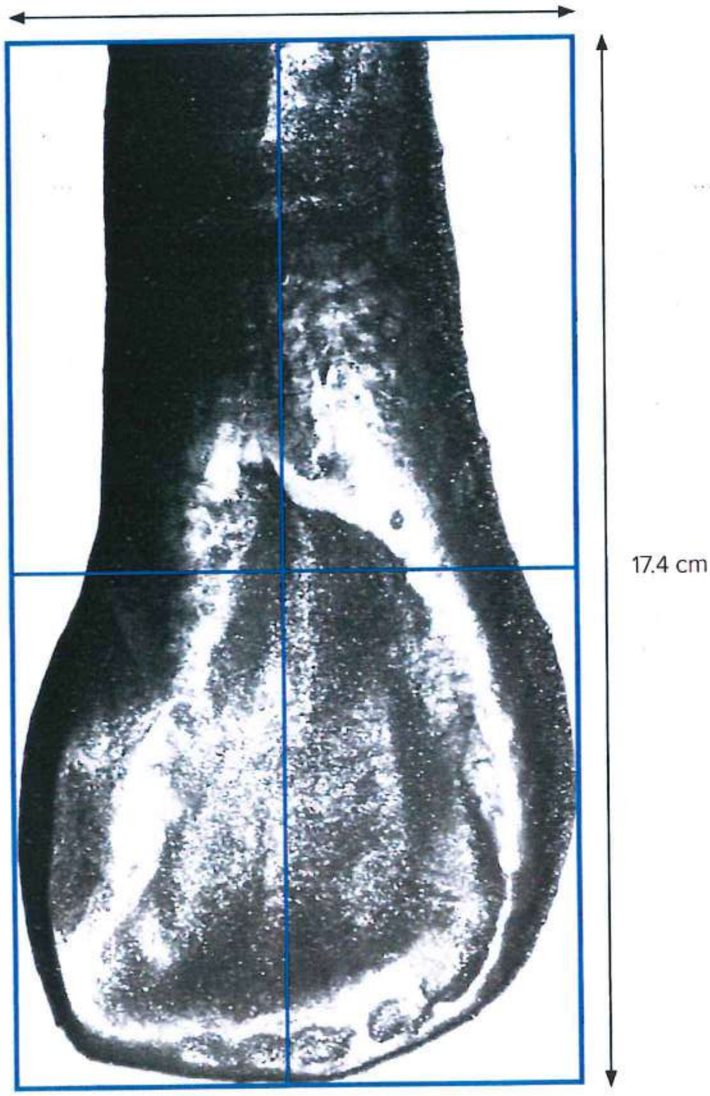
2



DRAWING #3 Page setup.

3

4



DRAWING #4 Page setup.

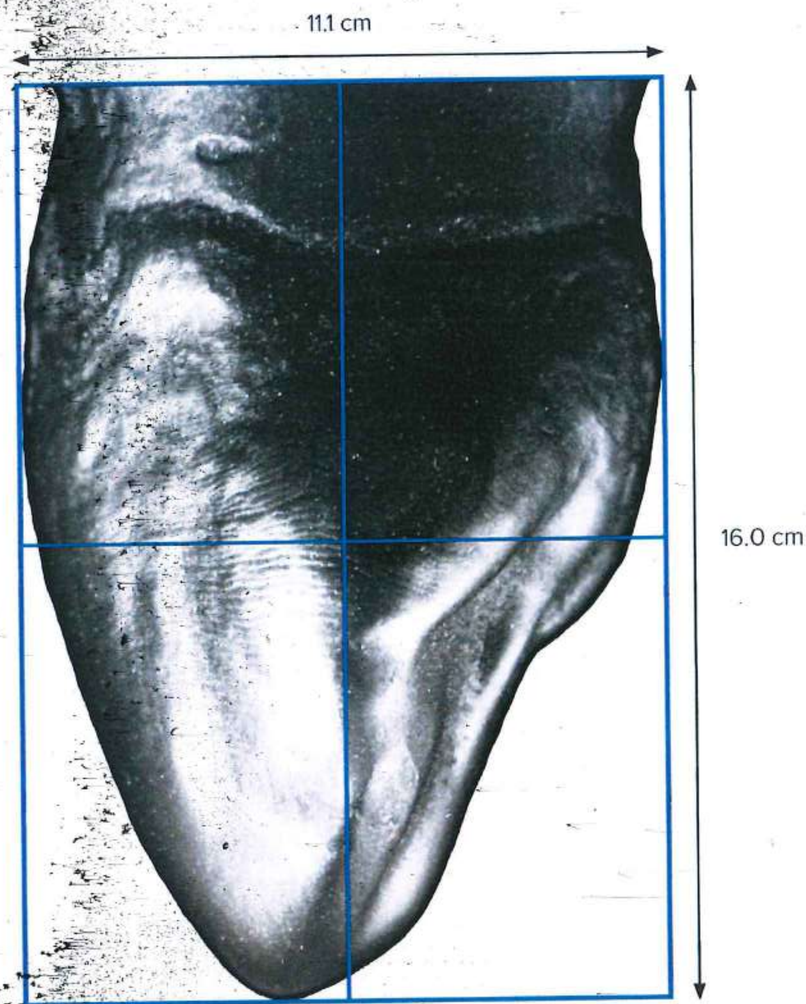
4

5

DRAWING #5 Page setup.

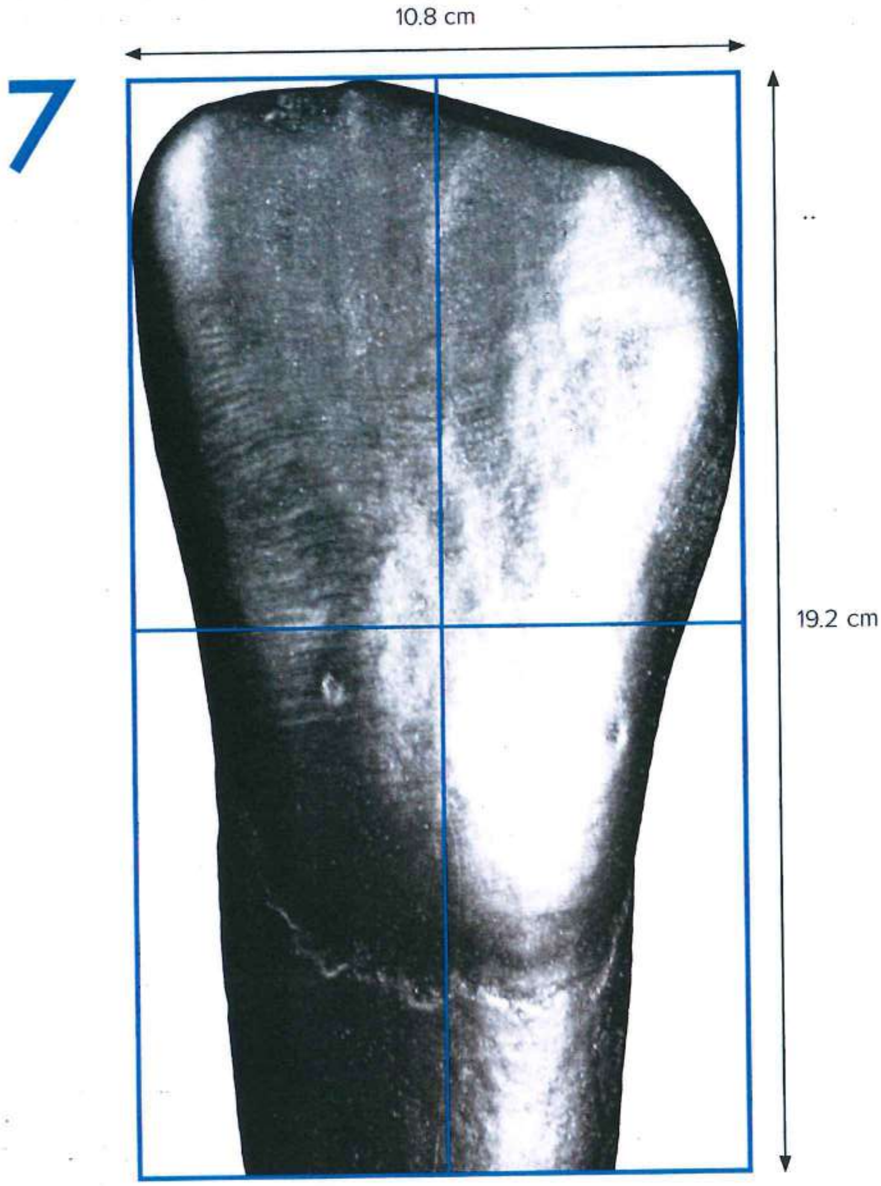
5

6



DRAWING #6 Page setup.

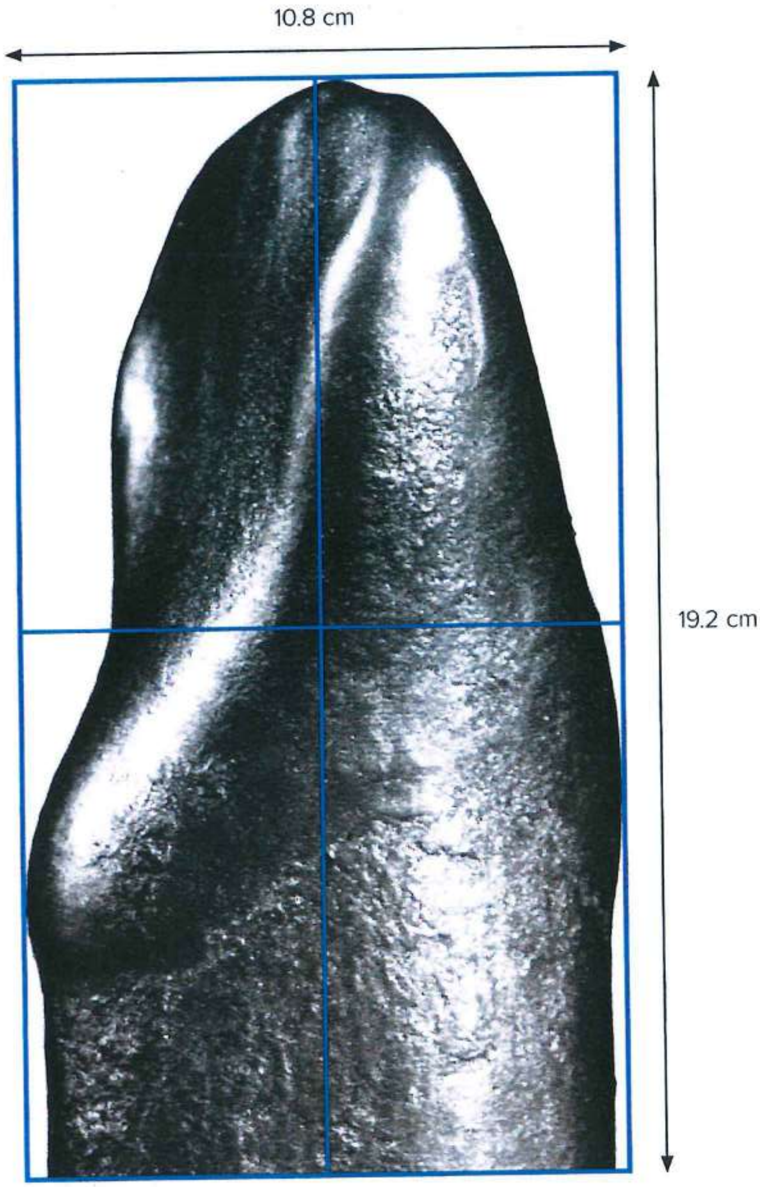
6



DRAWING #7 Page setup.

7

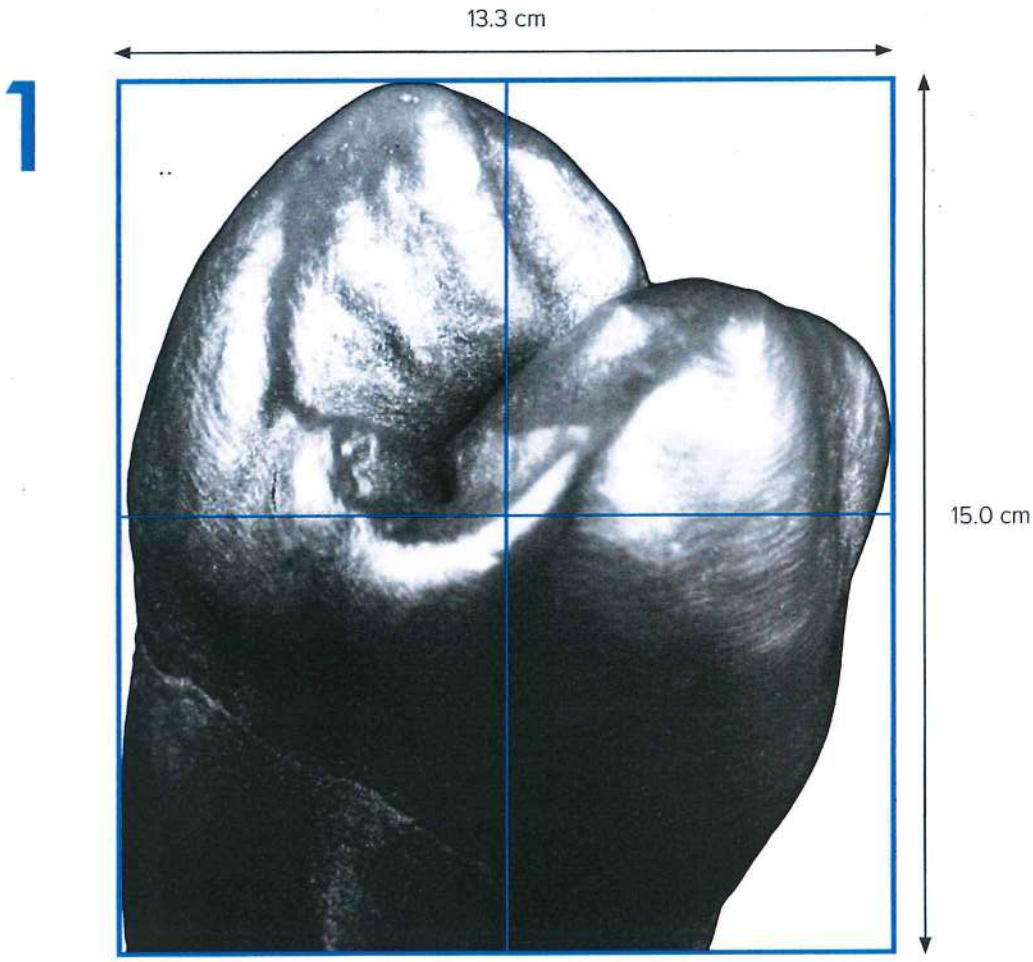
8



DRAWING #8 Page setup.

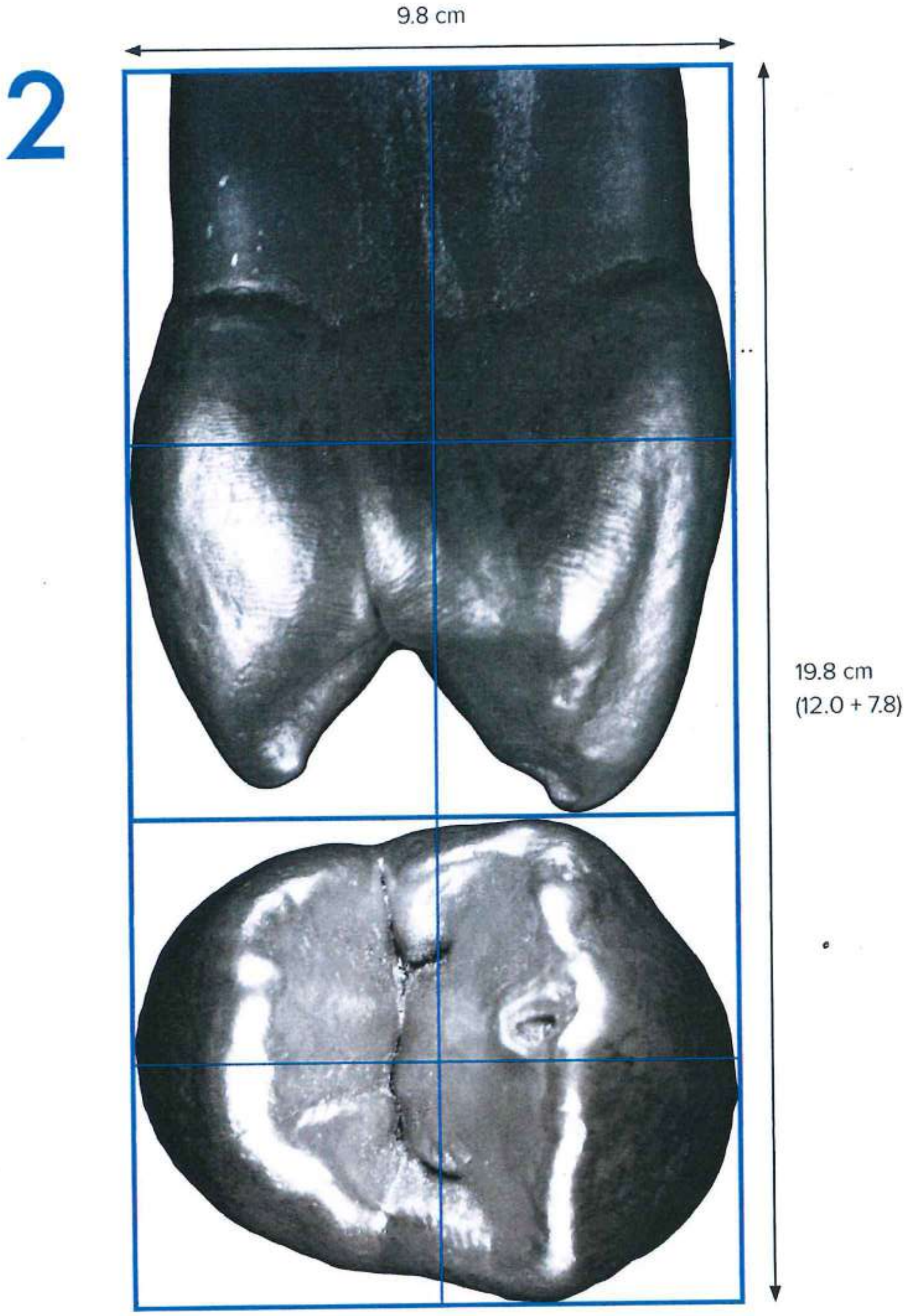
8

Posterior teeth



DRAWING #1 Page setup.

1



DRAWING #2 Page setup.

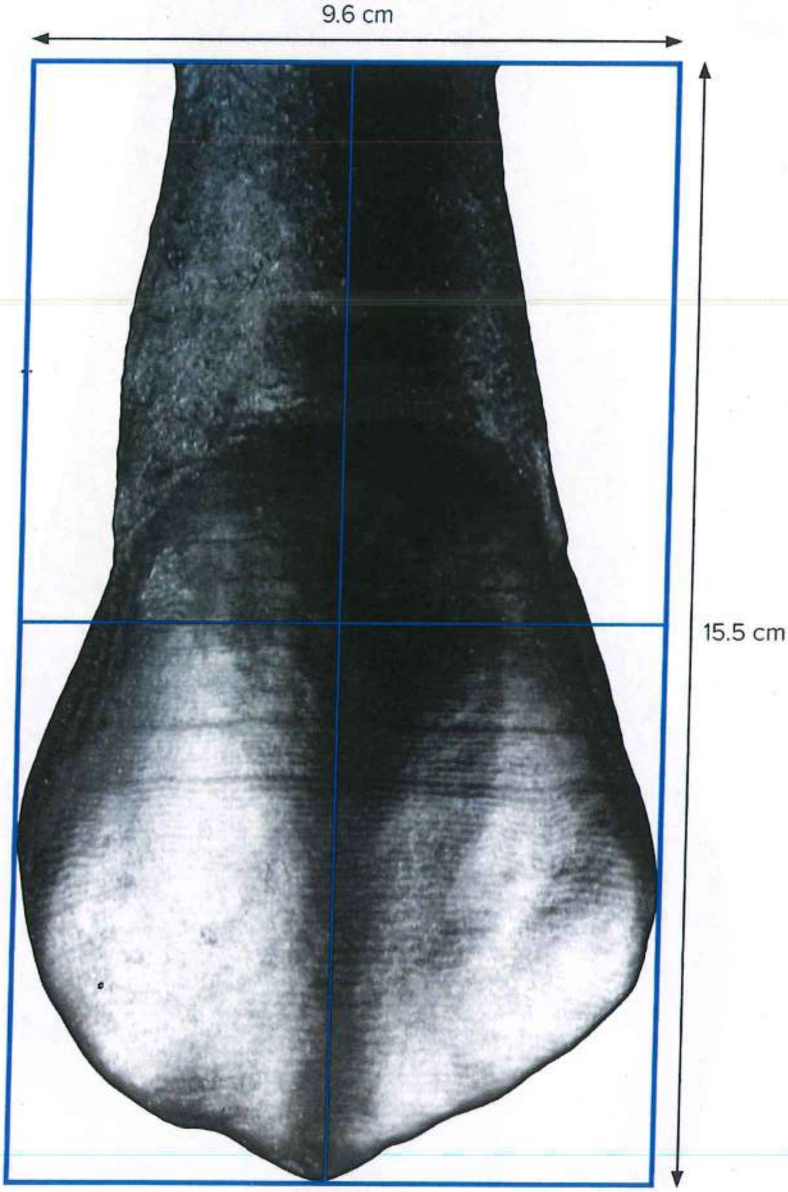
2a

Height **12.0 cm** by width **9.8 cm**.

2b

Height **7.8 cm** by width **9.8 cm**.

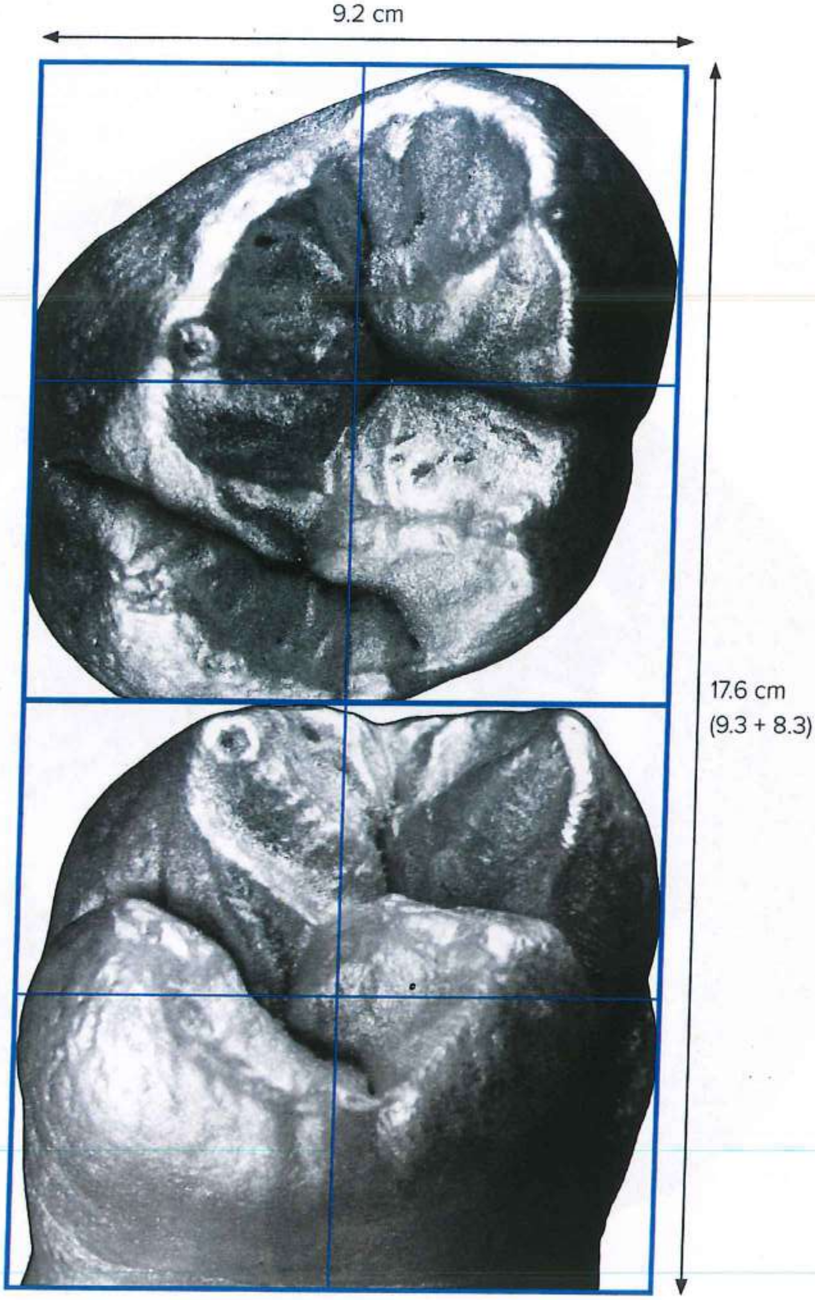
3



DRAWING #3 Page setup.

3

4

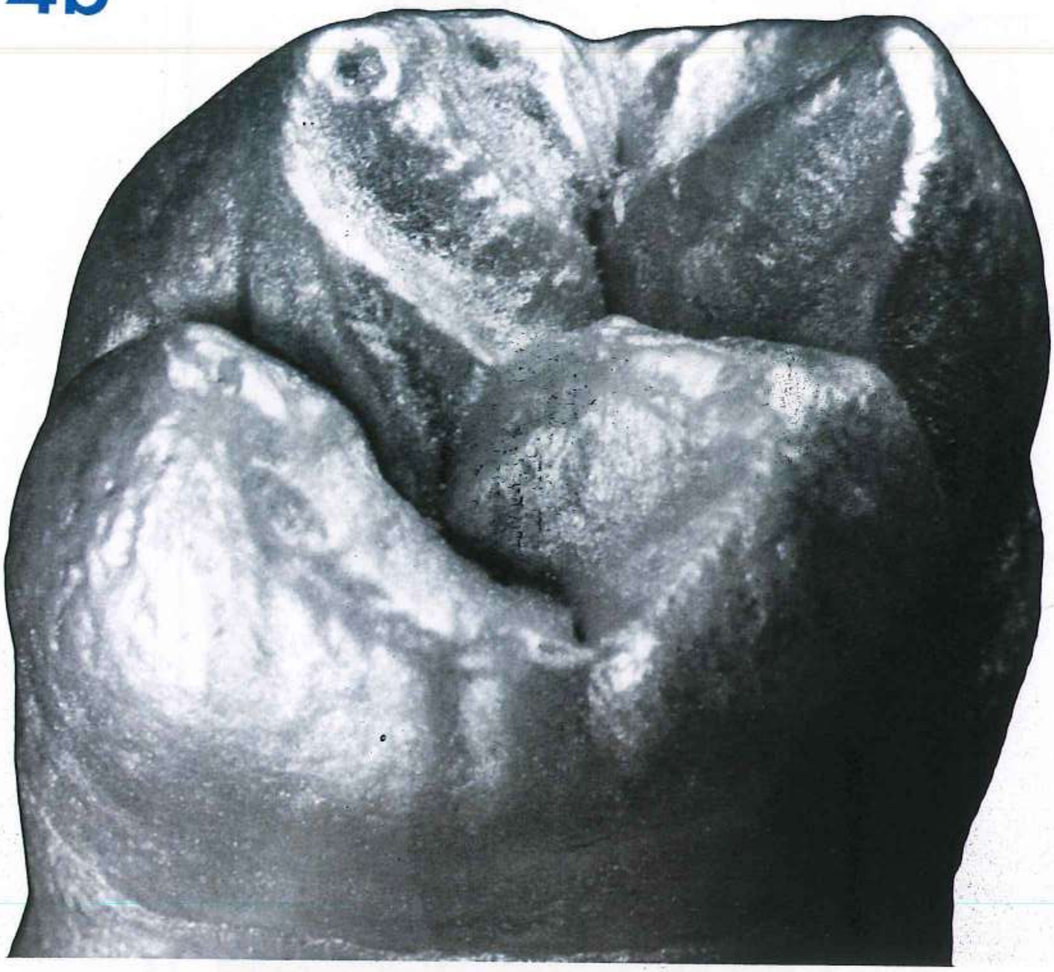


DRAWING #4 Page setup.

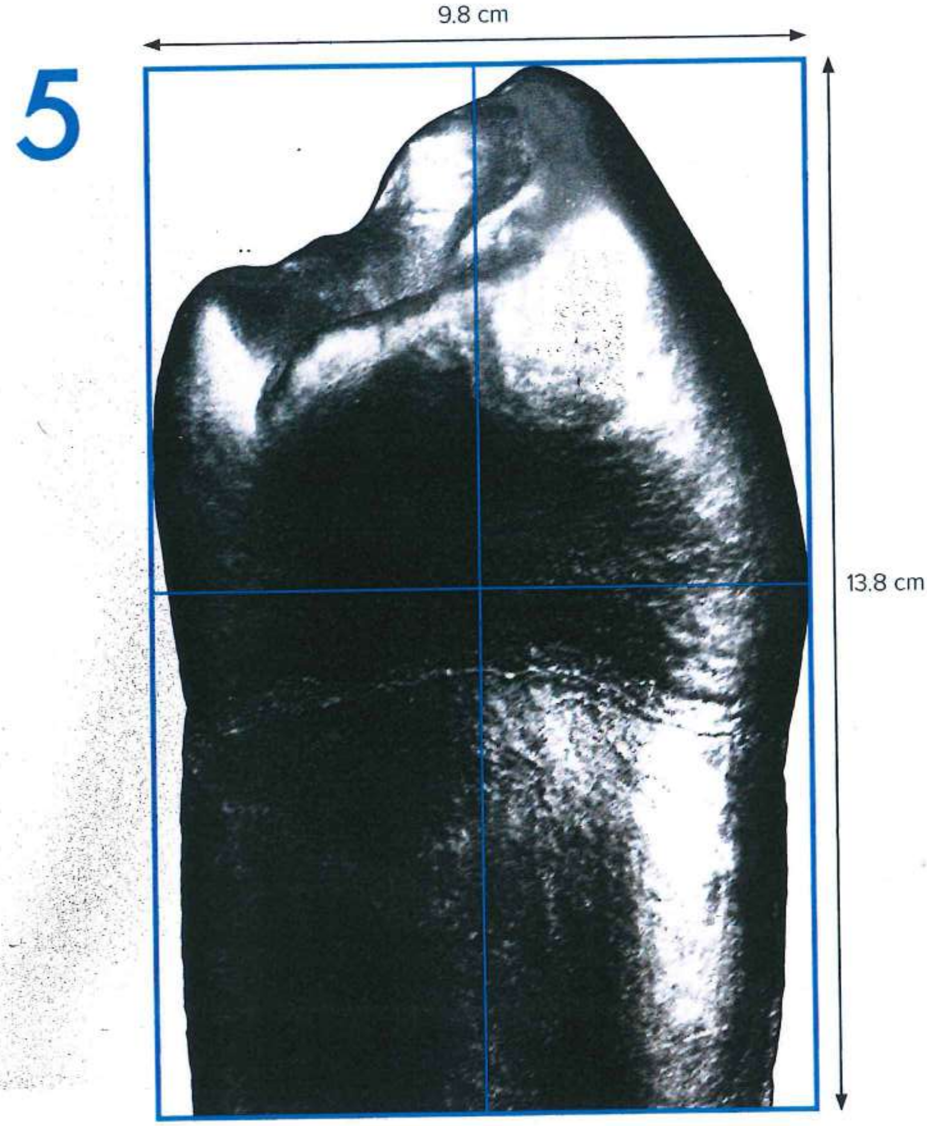
4a

Height **9.3 cm** by width **9.2 cm**.

4b



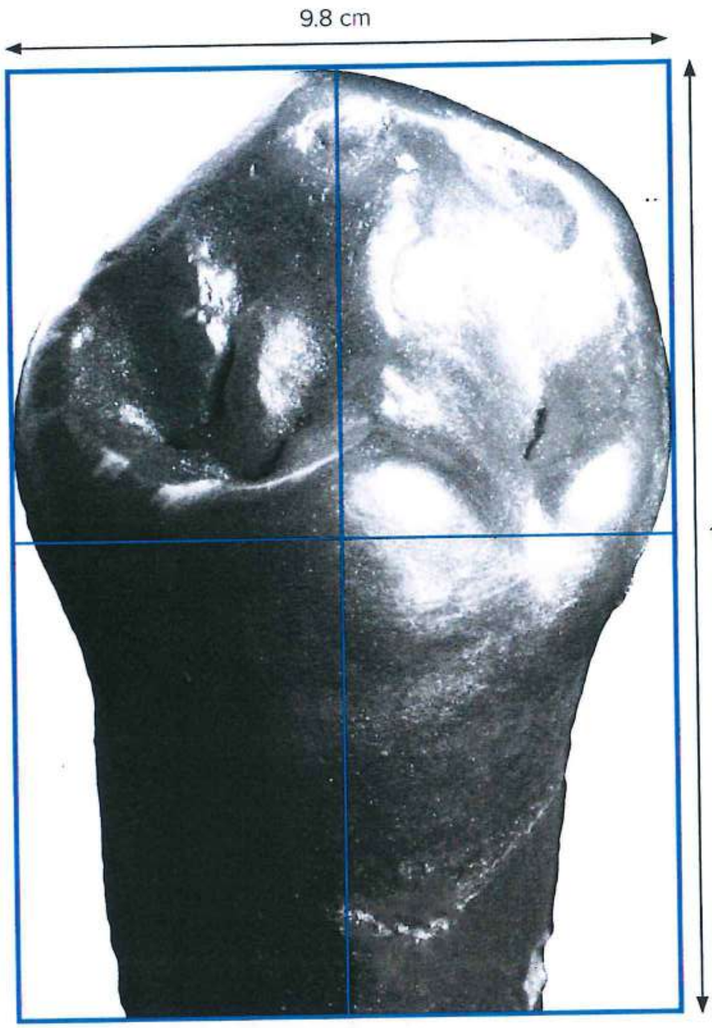
Height **8.3 cm** by width **9.2 cm**.



DRAWING #5 Page setup.

5

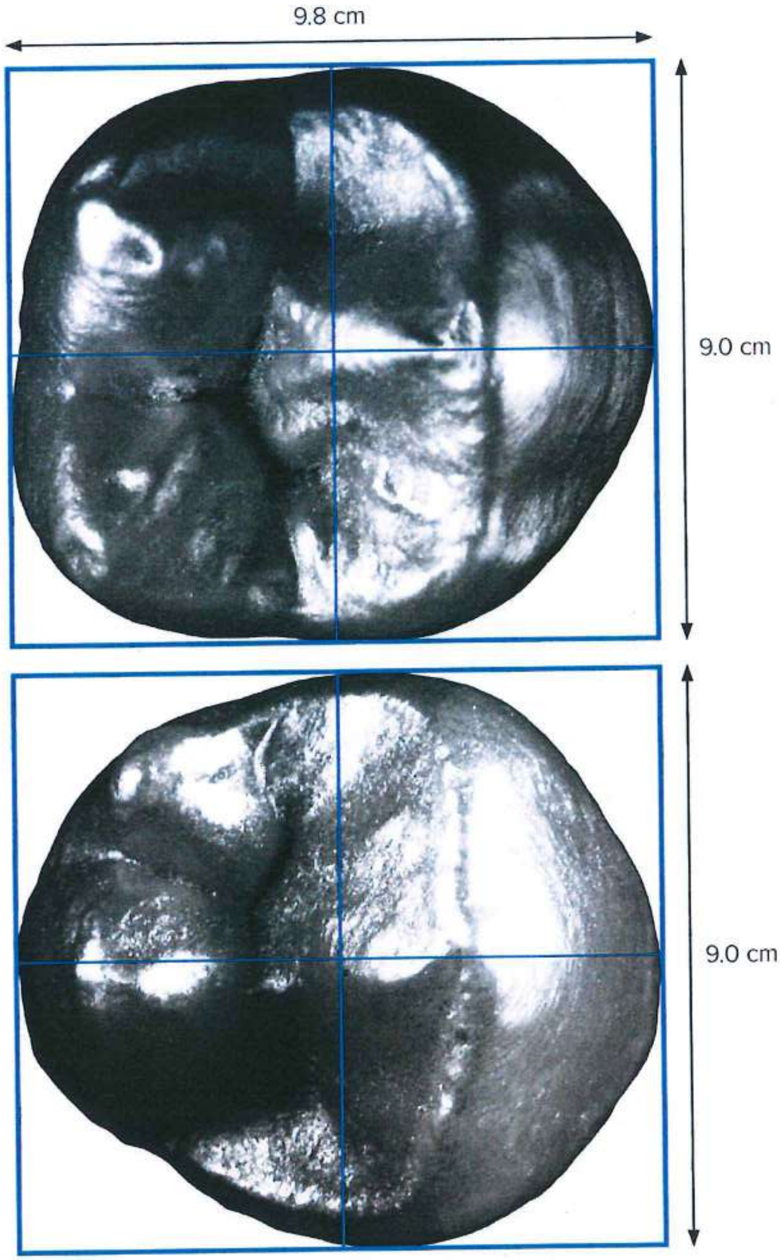
6



DRAWING #6 Page setup.

6

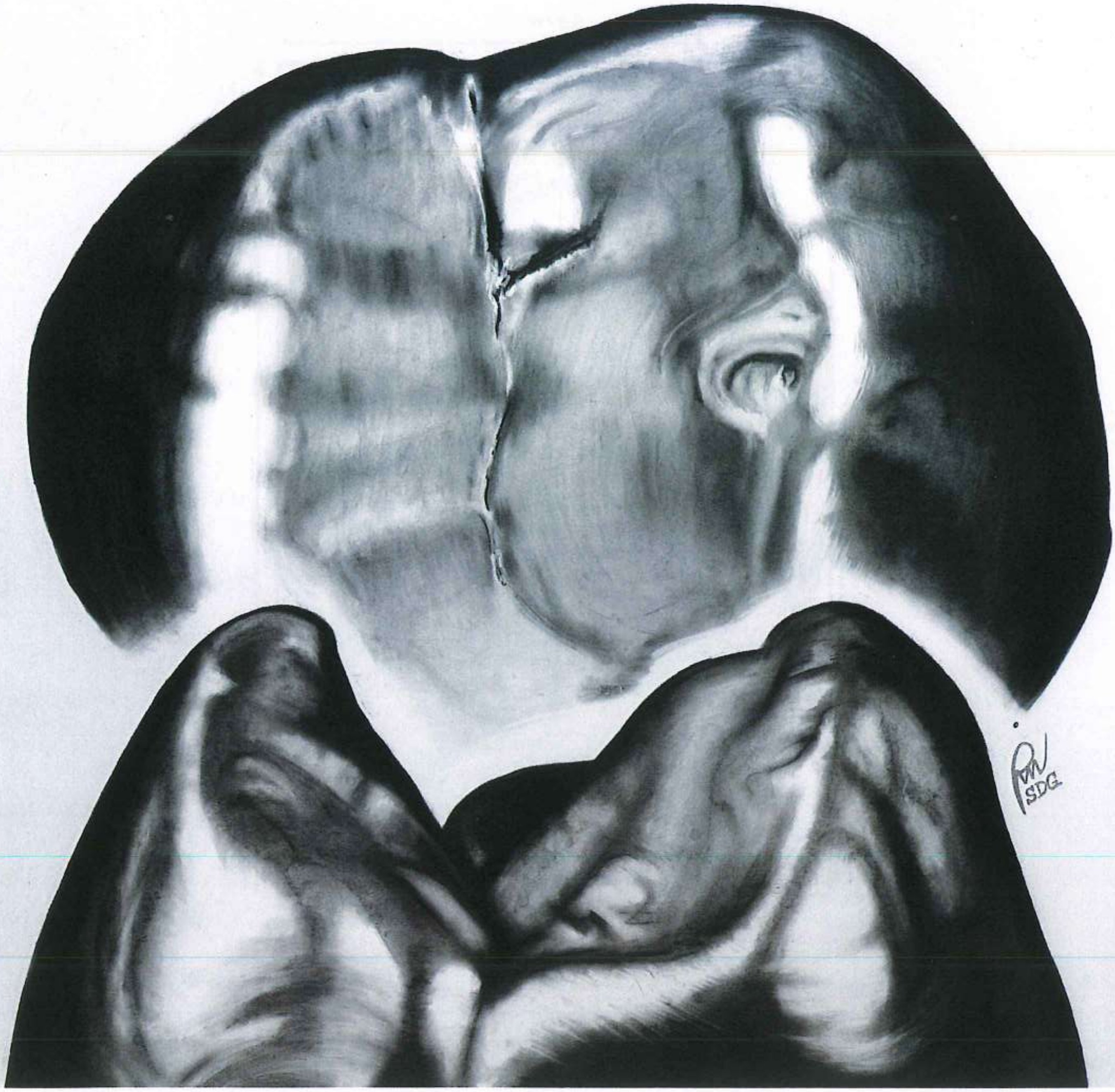
7



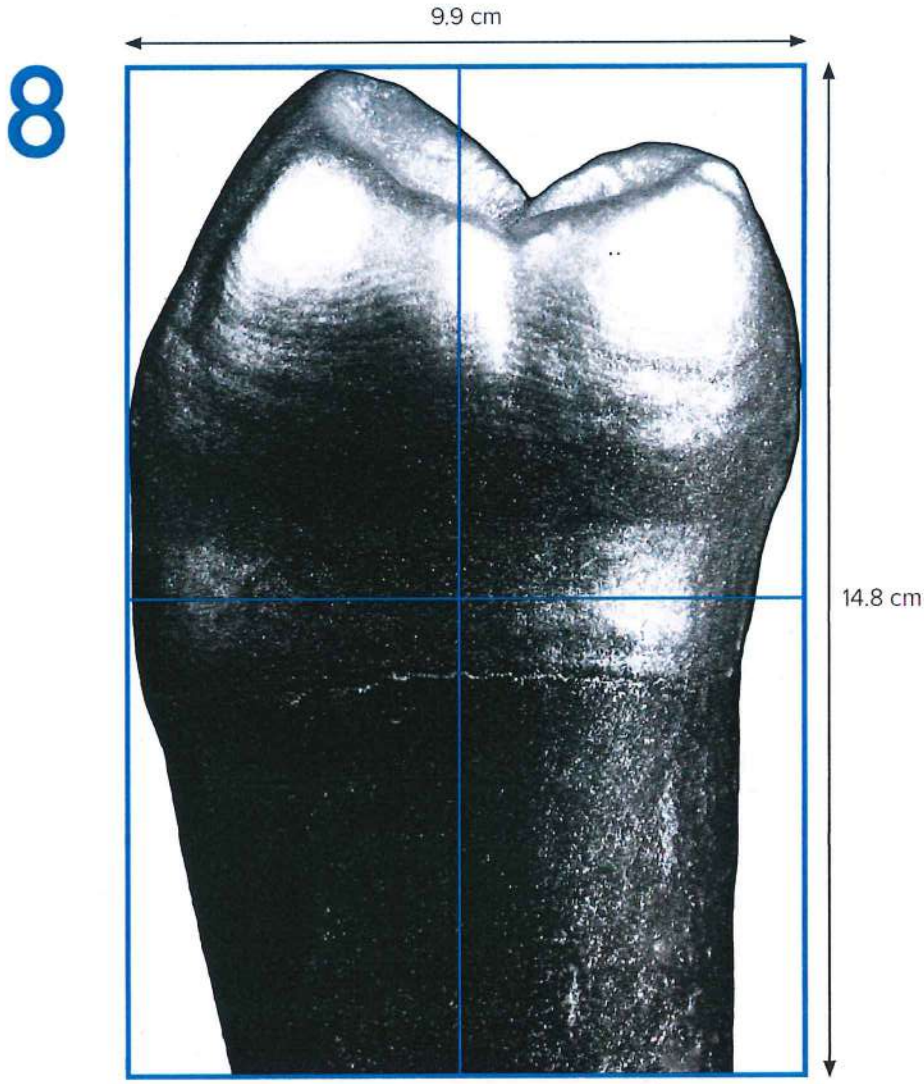
DRAWING #7 Page setup.

7a

7b



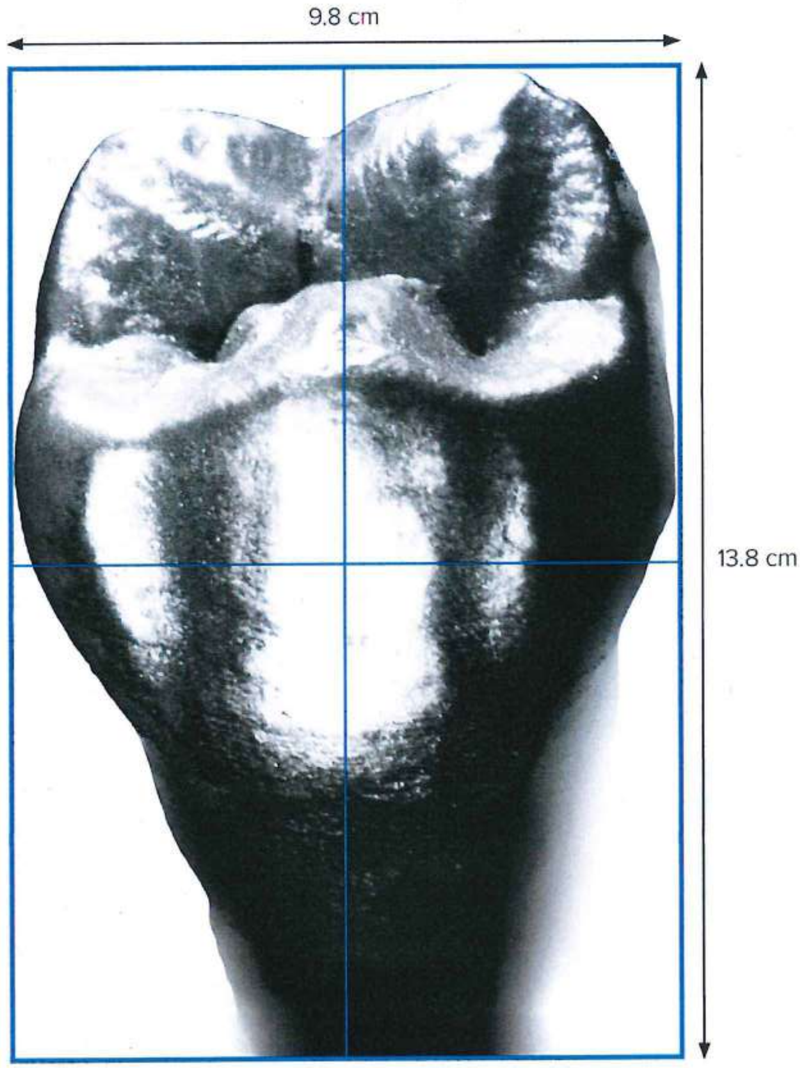
Large drawing example.



DRAWING #8 Page setup.

8

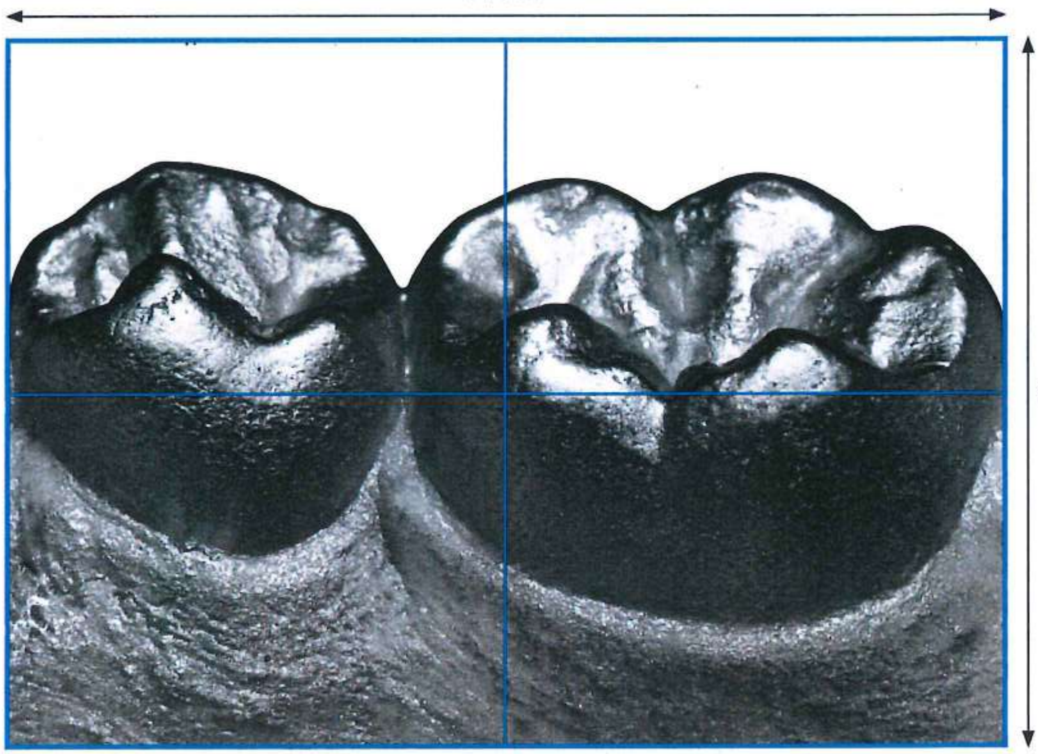
9



DRAWING #9 Page setup.

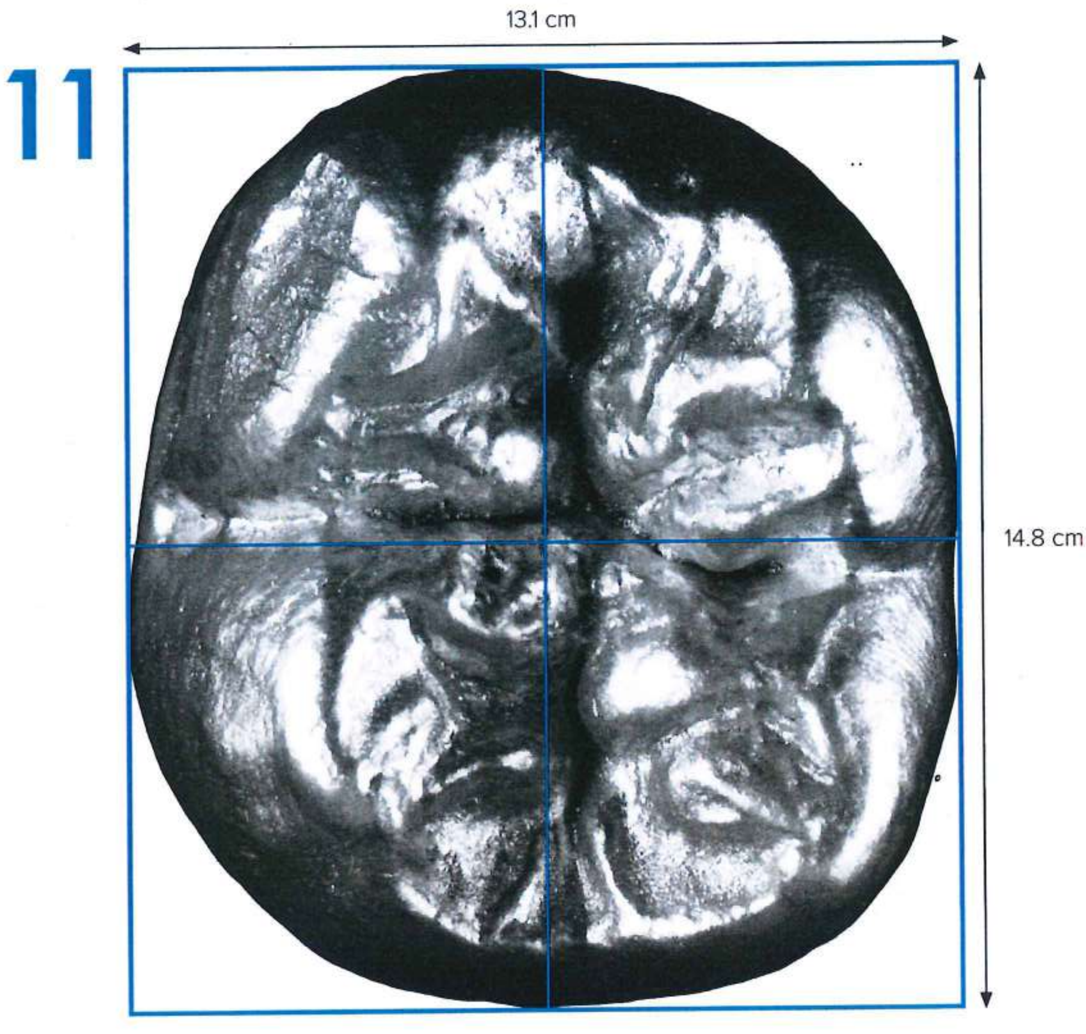
9

10



DRAWING #10 Page setup.

10



DRAWING #11 Page setup.

11

Acknowledgement

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3 ULTRACONSERVATIVE TREATMENT OPTIONS

Although bonded ceramics seem to represent the ultimate biologic, functional, mechanical (see Figs 1-15c and 1-25b), and esthetic restoration for compromised anterior and posterior teeth, the number of ultraconservative treatment strategies continues to grow, and the clinician is faced with many esthetic treatment modalities. The major disadvantage of this evolution is that it becomes increasingly difficult to make the appropriate choice in a given clinical situation. On the other hand, the availability of various treatment alternatives often allows for selection of socioeconomic options that conserve the maximum amount of intact tissues while still complying with the biomimetic principle. Treatment options should always first include the simplest procedures (such as chemical treatments and freehand composites) and then progress toward more sophisticated approaches (laminate veneers and full-coverage crowns) only when required and if the patient can afford it.[1] This chapter's aim is to determine which clinical situations do NOT require bonded ceramics and can be approached with ultraconservative techniques.

3.1 CHEMICAL TREATMENTS AND BIOMIMETICS

Among ultraconservative modalities, chemical treatments of discolored teeth represent the most biomimetic options due to the total conservation of remaining intact tooth substance. ***Precise knowledge of these techniques combined with a well-defined selection of indications frequently allows more invasive treatment modalities to be delayed or even avoided and, by the same token, prevents any risk of violating the biomechanics of the original tooth.***

A chemical treatment can often be proposed as a semidefinitive alternative and allows a more radical approach to be postponed. A classic example is the young patient with trauma to one or more permanent anterior teeth. Discoloration may appear because of posttraumatic pulp hemorrhage and, occasionally, due to physiologic retraction of the coronal and radicular extension of the pulp by apposition of secondary dentin. External bleaching (if the injured tooth shows no symptoms and no radiographic evidence of pathology; Fig 3-1) or the internal walking bleach technique (if the tooth has received a root canal treatment) can be repeated to reestablish and maintain acceptable esthetics over many years. When the described methods no longer ensure esthetic and mechanical success, more invasive treatment modalities such as porcelain veneers can be adopted. The latter are not recommended in children due to immature tooth position and periodontium.

For most vital teeth, chemical treatment can be proposed as the definitive therapy for reduction of idiopathic spots and stains or different degrees of fluorosis (Fig 3-2). Whitish and brownish stains can occasionally be eliminated permanently by combining bleaching with mechanical abrasion treatments.

Chemical treatments have significantly reduced the original indications for bonded ceramic restorations or other more invasive approaches.

This chapter begins with the topic of vital bleaching, for which much credit is due to pioneer Prof Van B. Haywood (Dental College of Georgia, Augusta, Georgia). He authored the very first publication on nightguard vital bleaching in 1989 and followed up with numerous works and a textbook[3] sharing his invaluable research and experience.

FIG 3-1 Successful bleaching of a single vital tooth with posttraumatic discoloration. *(a)* Preoperative view. *(b)* The tooth shade was totally recovered after bleaching with 10% carbamide peroxide (CP) in a nightguard. A special approach was used to ensure bleaching in the cervical area (see details described in Fig 3-3). Note that the original translucency of the incisal edge was not affected by bleaching and matches the contralateral tooth. *(c)* The radiograph shows physiologic pulp closure as a consequence of trauma. *(d and e)* The tooth did not react to traditional vitality tests but proved positive to an electrical test with a vitality scanner.[2]

3-1a

3-1b

3-1c

3-1d

3-1e

3.2 NIGHTGUARD VITAL BLEACHING

Whitening vs bleaching

Tooth whitening is a superficial cleaning that will restore tooth color by removing dirt and stains. Any product with mild abrasiveness, such as whitening toothpastes, can be considered a whitener. Bleaching is a much deeper process that involves a special property of enamel and dentin called *semipermeability*. It allows small molecules to diffuse into the tooth. Within 5 to 15 minutes, molecules such as hydrogen peroxide and carbamide peroxide can reach the pulp. Bleaching is therefore effective both at the surface of enamel (ie, whitening of extrinsic discolorations) and in depth of enamel and dentin (ie, bleaching of intrinsic discolorations, among others, in patients treated with tetracycline during tooth formation).[4,5]

Vital bleaching techniques

Vital bleaching represents the most conservative esthetic treatment of a discolored vital tooth. At least four different options are available:

1. The **original in-office bleaching[6]** had to be performed under strict isolation with rubber dam and suffered from extensive chair time, inconvenient use of heat (through a halogen activation light), and usually 30% to 35% hydrogen peroxide (capable of burning the skin upon contact). This danger along with the major discomfort prevented it from being universally accepted, even though it can be traced back to the late 1800s.
2. **Nightguard vital bleaching (NGVB)** represented a turning point in chemical treatments in the late 1980s with the first publication by Haywood and Heymann,[6] which made chemical bleaching more accessible and economical. The active ingredient of NGVB, carbamide peroxide (CP; Fig 3-2c), had been used since the 1960s as an oral antiseptic after surgery. Gly-Oxide by GlaxoSmithKline is a form still on the market today for this indication. ***NGVB has not only proved its efficiency and stability,[7–9] but after decades of use of 10% CP gel in custom-fitted vacuum-formed trays (8–10 hours per night for treatment times ranging from 2 weeks to 6 months), it is clear that NGVB provides patients with satisfaction, safety, and minimal side effects.[10]*** No evidence of malignancy or any other soft tissue pathology has been found, but it is recommended that clinicians adhere to the original protocol and avoid higher concentrations of CP,[10,11] which tends to induce more gingival irritation.[12] CP was found to have an adverse demineralization effect on enamel in vitro but not in vivo because of the protective effect of saliva.[13]

The original NGVB with 10% CP remains the most studied of all bleaching techniques, with the highest level of safety also from a legal standpoint.[3]

FIG 3-2 *(a and b)* **Permanent removal of brownish fluorosis stains.** The diffuse brownish discoloration has practically disappeared after 2 to 3 weeks of nightguard vital bleaching (NGVB) with 10% CP. The patient is 100% satisfied, and no further treatment is desired. (Patient treated in collaboration with Dr Olivier Duc, University of Geneva.) *(c)* Chemical formula for CP (carbamide peroxide).

3-2a

3-2b

$$CP\ (10\%) = H_2O_2\ (3.5\%) + CH_6N_2O_3$$

Carbamide peroxide | Hydrogen peroxide | Urea (cariostatic, stabilizer)

3-2c

3. **Over-the-counter (OTC) bleaching options** are luring patients with low-cost alternatives to NGVB. There are numerous products that can be purchased OTC (toothpastes, mouth rinses, whitening trays, wraps, strips, paint-on products, etc), and there are even dental bleaching booths available to customers at shopping malls. Whitening strips introduced in 2002 constitute the most popular product and may be used as a maintenance tool in very specific situations (Fig 3-3).[14]

   While using OTC products and avoiding the supervision by a dental professional might seem cost-effective and convenient to patients, discoloration might be caused by serious pathologies. As such, OTC whitening is not a substitute to a proper dental examination and diagnosis, as well as selecting the most appropriate approach according to the nature of the problem, which the patient might ignore or underestimate.

4. **In-office power bleaching** is a modern version of the original in-office bleaching. Instead of hydrogen peroxide and rubber dam, however, it uses simplified isolation techniques (lip retractors plus paint-on rubber dam) and lower concentrations of hydrogen peroxide (such as 35% CP). Newer activation lights are also used (laser, LED, plasma arc lamps, etc), even though the commercial claim that the light improves the result is still to be proven.[15] The contribution of the light may only be through isolation and dehydration. Considering that up to four chairside treatments are required with this technique, the patient is certainly unlikely to be in favor of this technique compared to NGVB in terms of efficiency, convenience, and cost analysis. It seems, however, that dental professionals can use in-office bleaching as a "tool" to counter the use of OTC products and then encourage the use of NGVB as a safer and more effective long-term maintenance approach.

Properties of hydrogen peroxide and carbamide peroxide

Low concentrations of hydrogen peroxide can be traced back to the late 1800s as a rinse to prevent tooth decay in children with pitted teeth.[3] As mentioned before, the use of 10% CP can be traced back to the 1960s. It was also applied in the form of drops to the throat of newborn infants to treat candidiasis or throat infections. In fact, 10% CP has numerous beneficial effects besides bleaching, including on gingival health (Fig 3-4).[16] The most noticeable is the caries-control effect[3]: It is bactericide by pH elevation to 8.0 in less than 5 minutes (decay in dentin will start below pH 6.8, enamel 5.5). As a result, significant prevention of white spot lesions was demonstrated with CP rinse in orthodontic patients since the 1970s. It has even been suggested to use 10% CP as a chemotherapeutic approach to prevent decay in the elderly patient.[3]

FIG 3-3 Ten-year follow-up of veneer case maintained with OTC bleaching strips. *(a)* This patient originally presented with old composite resin restorations on her fractured maxillary central incisors. Bonded porcelain restorations were placed and originally matched the color of her other teeth. *(b)* At her 10-year recall visit, she admitted having used OTC bleaching strips to maintain the color of her own teeth and keep the color match with the veneers. (Part *b* reproduced with permission from Magne and Magne.[14])

FIG 3-4 Gingival health improved by NGVB. *(a)* This patient presented with gingivitis and old existing composite resin restorations on her central incisors. The old restorations were carefully removed before applying NGVB for 6 weeks. *(b)* Note the recovery of the gingiva.

3-3a

3-3b

3-4a

3-4b

Splotchy stage

Bleaching may occur more quickly on a given tooth within the same mouth. By the same token, an area of a given tooth might begin changing shade more rapidly than other areas of the same tooth. This may create white spots that may not please the patient. The treatment must be continued, however, because ultimately the bleached areas will grow and merge to produce a uniform shade (Fig 3-6).

Children and pregnancy

Young teeth are usually whiter than adult ones because of the marked surface texture. The need for bleaching in children should be limited to situations where self-confidence and social interactions are impaired by the discoloration (Fig 3-7).[19] There is no scientific evidence that birth defects and other diseases can be caused by bleaching. Pregnant women, however, should be advised not to bleach their teeth but rather focus on their pregnancy and the related concerns, especially during the first trimester. The recommendation not to bleach can be extended until months after delivery when breastfeeding has been discontinued.

Translucency

NGVB will generally not affect the natural translucency of a tooth (see Figs 3-1a and 3-1b). When a patient's original complaint is the discoloration due to enamel translucency (Fig 3-8), it is important not to expect this problem to be solved by bleaching. Differential diagnosis with actual gray discoloration (eg, tetracycline stains) can be made by blocking the background of the teeth with a white card.

NGVB step by step

The soft thin bleaching tray (eg, Sof-Tray Classic Sheets, Ultradent) can be fabricated from a good alginate impression and the corresponding cast trimmed like a horseshoe shape with a flat base (no vestibule and open lingual/palatal space). A heat-vacuum former is used to suction down the thermoplastic tray material (Fig 3-9a). After complete cooling, the tray can be inverted and removed from the cast. It should adapt well and reproduce the details of the cast (Fig 3-9b).

FIG 3-6 Splotchy stage. *(a to c)* Note the differential bleaching of tooth areas, which are progressively merging together as the patient continues bleaching. (Images courtesy of Dr Dominique Plagnat and the late Prof Giorgio Cimasoni, University of Geneva.)

FIG 3-7 Turner's hypoplasia. *(a and b)* This young patient is still in the mixed dentition. He had a trauma to his primary incisors that affected the enamel of the permanent succedaneous tooth with a brownish discoloration. His mother is concerned about this because other children have begun to mock him. *(c)* NGVB was used first and revealed a large underlying white spot. *(d)* Rather than abrading away the white spot, it was etched and partially infiltrated with resin and masked using blueish effect resins to fake the incisal edge translucency (see also resin infiltration technique in section 3.4). Regular translucent composite resin was used to cover the effects. (Reproduced from Magne.[19])


3-6a


3-6b


3-6c


3-7a


3-7b


3-7c

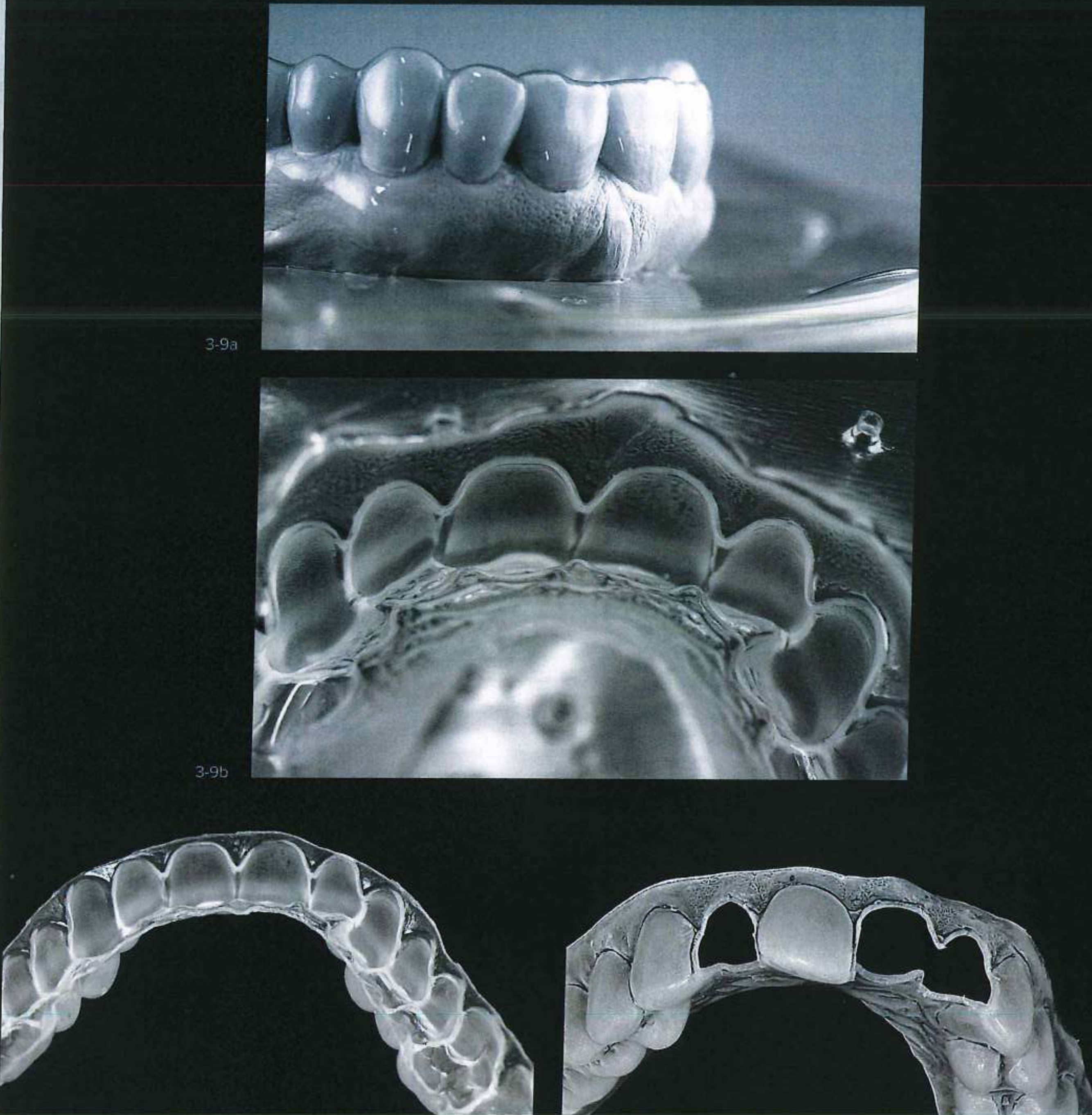

3-7d

The tray can be cut smooth with small scissors about 1 mm beyond the cervical line (Fig 3-9c), avoiding overlap with the frenulum, canine eminences, and incisive papilla.[3] Bleaching will occur beyond the tray limits,[20] so there is no need to redo slightly short trays (Fig 3-10). Reservoirs are no longer used. They were originally designed by placing a spacer on the facial surface of the teeth before fabricating the tray, but this did not improve efficiency[21] and required more material (to fill the space) as well as caused more material leakage. Another option is to scallop the tray and strictly follow the gingival line (see Fig 3-11). This will allow the patient to clean excesses of CP from the gingiva (in case of irritation). This is not the preferred design because it causes the tray to lose some rigidity and thus may leak even more.

Only a pea-sized amount of CP should be applied to each tooth inside the tray (against the labial surface). Upon insertion, the material should spread evenly (see Fig 3-10). Localized application is also possible for single-tooth bleaching (Fig 3-11). An information/consent form as well as written instructions should be provided to the patient (typal forms can be found at www.vanhaywood.com).

3-8a 3-8b 3-8c

FIG 3-8 Differential diagnosis of translucency vs discoloration. *(a and b)* This patient noticed the extreme grayish appearance of the incisal edges *(arrows in a)*. *(c)* In this case, the discoloration is caused by the translucency of the tooth because this problem disappears when blocking the background with a white surface. NGVB will not likely help in such a case and might even cause the problem to be more visible by increasing the contrast of the incisal edge with the part of the tooth that will bleach.



3-9a

3-9b

3-9c

3-9d

FIG 3-9 Nonscalloped nonreservoir bleaching tray design. The tray material was sucked down directly onto a horseshoe-shaped cast with a heat-vacuum former *(a)*, then checked for perfect reproduction *(b)*, and trimmed 1 mm below the cervical line *(c)*. This nonscalloped nonreservoir tray is the most comfortable for the patient. *(d)* Recommended design for a single-tooth bleaching tray, which was modified to ensure that bleaching would occur only on the desired tooth (right maxillary central incisor; image courtesy of Dr Van Haywood). A similar tray can be used in conjunction with the walking bleach technique in order to increase efficiency and save chairside time and patient time.

Management of tooth hypersensitivity

Transient but always reversible inflammatory response of soft tissues and pulp is possible throughout NGVB. Tooth hypersensitivity is therefore common and often unpredictable. Two ingredients are typically used to limit tooth hypersensitivity[22]: *(1)* 3% to 5% potassium nitrate acts like a topical anesthetic by blocking nerve depolarization, and *(2)* fluoride acts by occluding dentinal tubules. Both are present in a commercial formulation (Ultra EZ, Ultradent), which can be applied with the tray for 10 to 30 minutes prior to and after bleaching. Another option is 5% potassium nitrate, present in a desensitizing toothpaste called Sensodyne Pronamel (GlaxoSmithKline), which can be used in the tray on demand for 10 to 30 minutes. Other toothpastes containing sodium lauryl sulfate should be avoided for this purpose because they can irritate the gingiva and create mouth sores.

Amorphous calcium phosphate (MI Paste, GC), either applied separately or mixed with CP, has also been proposed to reduce hypersensitivity,[23] likely by precipitating and blocking the dentinal tubules.

Preventive use of Sensodyne Pronamel toothpaste for about 2 to 3 weeks before bleaching, as well as alternating CP and fluoride in the tray during bleaching, may also help prevent or alleviate tooth hypersensitivity. Finally, CP formulations including fluoride and potassium nitrate can be used (eg, Opalescence PF, Ultradent) as well as a "slow-start" regimen (only bleaching a few hours per day for the first 3 to 4 days).

3-10

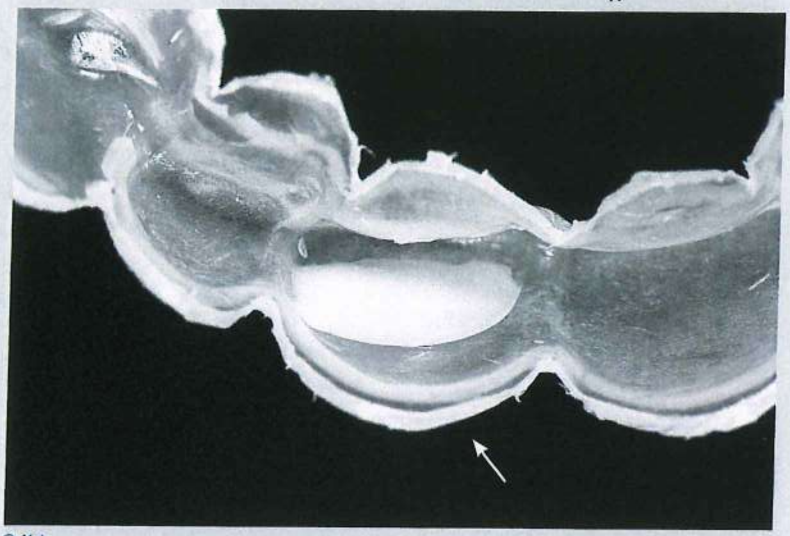
FIG 3-10 Bleaching trays in place. Bubbles form through the production of hydrogen peroxide and oxygen. The trays are tight but slightly short; however, there is no need to redo them because teeth will bleach beyond the tray borders.

FIG 3-11 Selective nightguard bleaching for maximum effect in the cervical area. *(a)* The posttraumatic discoloration is more intense cervically (same patient as in Fig 3-1). *(b)* After 2 weeks of single-tooth NGVB, the incisal edge shade has recovered, but more bleaching is required in the cervical area. *(c)* A scalloped reservoir tray was customized by relining to prevent further bleaching in the incisal area. A retentive hole was drilled through the facial aspect. *(d)* A small amount of unpolymerized composite resin was applied into the incisal edge area of the tray. *(e)* The tray was then repositioned in the mouth, and the composite resin was polymerized. *(f)* The tray is now tightly adapted to the tooth except for the cervical area, where the bleaching agent will be selectively applied.

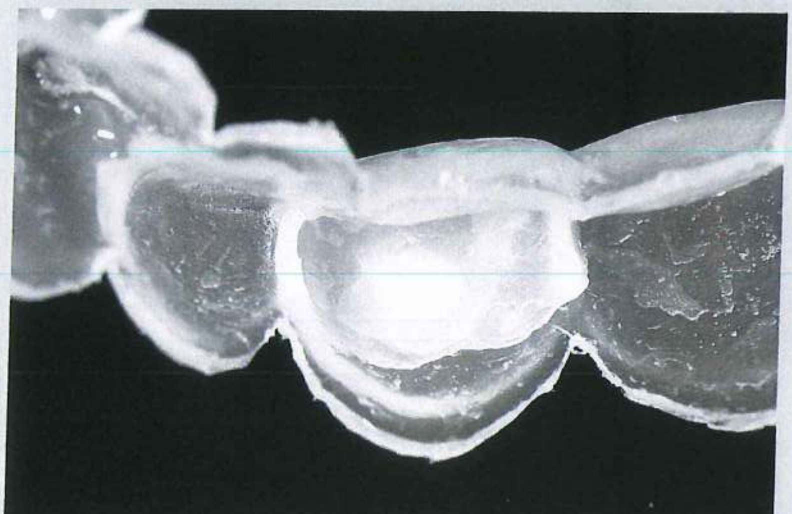

3-11a


3-11b


3-11c


3-11d


3-11e


3-11f

Limitations of NGVB alone

In summary, bleaching alone may be efficient for treating endogenic discolorations, including those due to physiologic pulp obstruction in vital teeth (calcific metamorphosis; Fig 3-11). It is also useful for permanently removing brownish discolorations resulting from fluorosis (see Fig 3-2) or other origins (see Fig 3-7)[1,24] and of course, classically, for brightening an intact dentition at a patient's request. Whitish fluorosis stains might be efficiently treated by bleaching alone without microabrasion (Fig 3-12).

Vital bleaching alone, however, can require longer treatment times to achieve the desired color in severe cases of tetracycline staining (up to 6 months) or nicotine discoloration (up to 3 months), or for a tooth stained via dentin infiltration, which frequently begins at a worn incisal edge.

NGVB in conjunction with another procedure

Freehand placement of composite resin often complements bleaching (eg, esthetic additions, cases of traumatic hypoplasia; see Fig 3-7 and note‡ in Table 3-1). Severe discoloration resistant to bleaching (eg, tetracycline) is best addressed with laminate veneers. Even in these difficult cases, it is still suggested to bleach first to lighten the base color of the tooth and make the future restorations more lifelike.

A word of caution must be emphasized. Any type of bleaching (internal, external) with peroxides reduces enamel adhesion strengths.[25] A similar effect was demonstrated on the dentin bond strength.[26] In all cases, any bonding procedure should be delayed for 3 weeks after completion of bleaching[27] to allow for leaching of peroxide remnants, especially from dentin, but also for shade stabilization.

FIG 3-11 *(cont) (g)* Final result following additional cervical bleaching. The overlay view shows the preoperative situation for comparison.

FIG 3-12 White fluorosis stains treated with bleaching only. *(a)* These "leopardlike" teeth would be ideal for microabrasion. *(b)* Vital bleaching alone, however, was sufficient to eliminate the contrast between the previous dark and white areas. The patient's primary expectation has been fulfilled, and no further treatment is desired.

3-11g

3-12a

3-12b

3.3 MICROABRASION AND MEGABRASION

Etiology of white enamel defects

Anterior white spot lesions[28] are very common and normally involve only enamel. They can be caused by **demineralization** (early caries lesions, typically after orthodontic treatment), **fluorosis**, as well as various **developmental disturbances**. Developmental defects can take many forms and can be classified as the following:

- **Hypomineralization:** The enamel surface is intact—traumatic hypomineralization and molar incisor hypomineralization (MIH)
- **Hypoplasia:** Structural loss of enamel—eg, Turner's hypoplasia (Fig 3-13; see also Fig 3-7) and idiopathic hypoplasia

Demineralization, hypomineralization, and hypoplasia all cause the enamel refractive index to decrease from 1.62 to about 1.33, producing the "white cloud effect."[28]

Microabrasion

For lesions caused by moderate fluorosis and involving superficial enamel, the original microabrasion technique[29] would be indicated. It consists of rubbing enamel with a mixture of abrasive particles and hydrochloric acid (HCl). As a result, the surface texture of enamel is modified. Smooth and thinned microabraded enamel absorbs more light (increased refraction index), and, as a consequence, tooth brightness is decreased and chroma is increased. These negative side effects are easily compensated by combining microabrasion with bleaching.[30] If a tooth exhibits mild fluorosis, however, microabrasion is usually not needed because bleaching alone is able to provide good results by decreasing the contrast between the white spots and the surrounding tissues (see Figs 3-2 and 3-12 and note* in Table 3-1).[19]

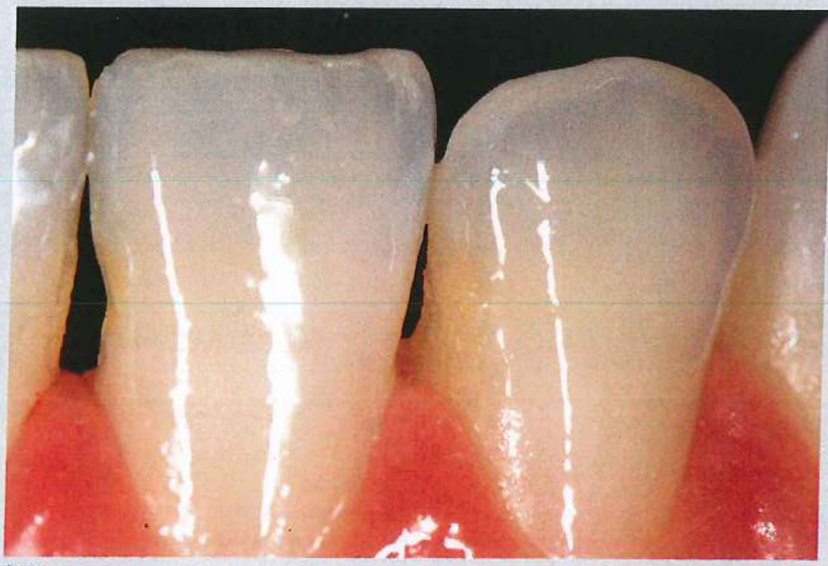
FIG 3-13 Megabrasion/restoration to treat developmental hypoplasia. *(a and b)* Preoperative views (same patient as in Figs 3-1 and 3-11). *(c)* Coarse diamond burs used at low speed (about 5,000 rpm) or airborne-particle abrasion allows safe and controlled removal of the enamel lesion. Polishing is not needed before restoration because a rough enamel surface is a better substrate for adhesion. *(d)* A neutral composite (Herculite Incisal, Kerr) was applied along with the classic acid-etch technique. *(e)* Postoperative view after rehydration.

3-13a

3-13b

3-13c

3-13d



3-13e

Megabrasion

Microabrasion is ineffective and contraindicated for deep enamel defects because the opaque area would become more visible after treatment, revealing the internal aspect of the lesion. Instead, the megabrasion technique,[19] also called *macroabrasion*,[31] is a radical but predictable approach for the elimination of deep developmental white enamel lesions (Fig 3-13 and Table 3-1).

Clinicians are often intimidated by the idea of mechanically removing the defective enamel. Electric handpieces (high torque combined with low speed; see Fig 3-27, section 3.7) or airborne-particle abrasion facilitates the process significantly. The removal of enamel through megabrasion can be justified by the nature of the lesion, as it involves a disturbance in the maturation stage of the tooth mineralization.[32] The defective enamel is not an ideal substrate for bonding. Because the lesion usually does not extend into dentin, only a limited amount of enamel must be replaced with direct composite resins. Above all, the underlying intact dentin provides the natural optical effects of the tooth (color, dentin lobes, fluorescence, etc). The simple freehand application of neutral, translucent, and slightly fluorescent composite allows restoration of the enamel surface morphology without overcontouring, leading to the most natural appearance of the tooth (Fig 3-13g).

There is no need to remove the deepest part of the lesion and risk dentin exposure (see Fig 3-13c). Enamel etching, resin infiltration with the adhesive, and subsequent restoration with a neutral and translucent composite will usually produce enough attenuation effect through partial recovery of the enamel refraction index.

If a more conservative approach is pursued, partial megabrasion (removing only the ceiling of the lesion) can be associated with the resin infiltration technique (see next section and Table 3-1).

As previously explained, the brownish aspect possibly associated with the lesion may be eliminated efficiently with preliminary NGVB. In such a case, application of adhesive restorative materials must be delayed for 3 weeks (safety elapsed time for enamel bond recovery) after the end of NGVB.[27]

TABLE 3-1 Ultraconservative approaches to white enamel defects and their indications

Clinical situation	Microabrasion[29]	Bleaching[6]	Megabrasion[19,31]	Resin infiltration[34]
Demineralization, early caries lesions	Yes†	Yes††	No	Yes
Mild fluorosis, white and brown	Yes*	Yes	No	Yes*
Mild fluorosis, white	Yes*	Yes	No	Yes*
Developmental defects, white and brown spots, and surface defects	No	Yes‡	Yes	Yes‡
Developmental defects, white and brown spots	No	Yes‡	Yes	Yes‡
Developmental defects, white spots	No	Yes**	Yes	Yes‡‡

†Indicated only prior to remineralization.[33]
††Indicated only to improve shade after microabrasion/remineralization.
*Indicated only when preliminary bleaching does not provide a satisfactory result.
**Does not remove white spots but may lighten the background enough to be acceptable.
‡Preliminary bleaching to eliminate yellow-brown discolorations prior to megabrasion (deep lesions).
‡‡In combination with megabrasion (deep lesions).

3-13f

3-13g

FIG 3-13 *(cont) (f)* Final result following rehydration. The overlay view shows the preoperative situation. *(g)* Another patient was treated with the same technique, ie, without the use of colorants but only with the application of translucent composite that reveals the inner optical effects of dentin. (Part *g* reproduced from Magne.[19])

3.4 REMINERALIZATION AND RESIN INFILTRATION

Other more sophisticated strategies to treat white spot lesions are to remineralize them[33] or infiltrate them with a low-viscosity monomer resin (Figs 3-14 and 3-15).[34–36]

Remineralization

This approach should be the first line of action when a noninvasive strategy is chosen. However, even for lesions found around orthodontic brackets, it has been suggested to eliminate the intact superficial hypermineralized layer of enamel first by microabrasion (see note + in Table 3-1) followed by immediate chairside and daily application of amorphous calcium phosphate (MI Paste).[33] NGVB can also be added for final touches with residual white spots and to compensate for increases in chroma created by microabrasion (see note ++ in Table 3-1).

Resin infiltration

This technique originates from the idea of infiltrating noncavitated enamel caries with resin adhesives.[37–39] Infiltration with mixtures containing smaller and less viscous resin monomers such as triethylene glycol dimethacrylate (TEGDMA) proved to better penetrate the lesions.[40] With a refractive index of 1.52 (vs 1.62 for intact enamel), TEGDMA also proved to be efficient in restoring the refractive index of enamel in white spot lesions.[28,36,41] A commercially available system (Icon Caries Infiltrant Smooth Surface, DMG) is used and requires three steps:

1. **Etching** the enamel with 15% HCl (Icon-Etch) for 2 minutes, followed by rinsing for 30 seconds and air drying
2. **Dehydrating** the porous enamel with ethanol (Icon-Dry) for 30 seconds, followed by air drying
3. **Infiltrating** with TEGDMA (Icon-Infiltrant) for 3 minutes, followed by light polymerization

There are two distinct resin infiltration approaches based on the clinical situation[36]:

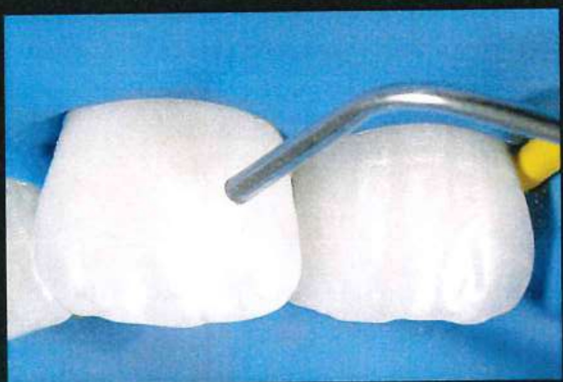
1. **Superficial lesions**, developmental or originating from a demineralization process, typically such as early caries lesions and white spots around orthodontic brackets[42]: The infiltrant resin can be applied directly to the existing surface of the tooth and yield excellent results without adjunct treatment.[43]
2. **Deep developmental defects:** The process will usually require adjunct procedures because the ceiling of the lesion needs to be eliminated first by megabrasion or airborne-particle abrasion to facilitate the application and penetration of the infiltrant resin into the core of the lesion.[36,44] Similar to the megabrasion technique, enamel needs to be restored after the infiltration process (Figs 3-14 and 3-15).

FIG 3-14 NGVB, airborne-particle abrasion, resin infiltration, and restoration. *(a)* This patient was treated with a combined approach starting with 3 weeks of NGVB (to brighten this yellow dentition and attenuate the brown discoloration on the maxillary left lateral incisor). *(b)* After the safety elapsed time (required for enamel bond strength recovery), the white defects on the maxillary right central and left lateral incisors were abraded (airborne-particle abrasion), treated with Icon Caries Infiltrant (including the three steps described above), and restored with translucent composite resin. (Clinical case and photography courtesy of Dr Gil Tirlet, Paris, France.)

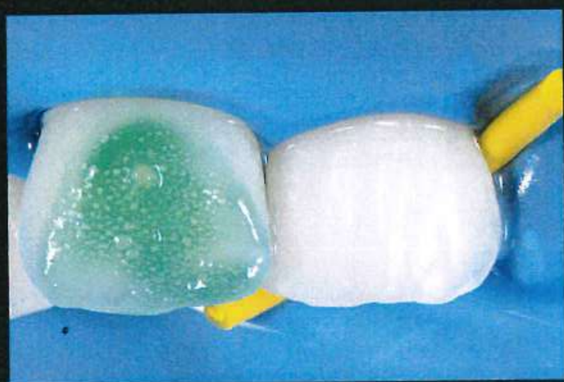
3-14a

3-14b

3-15a

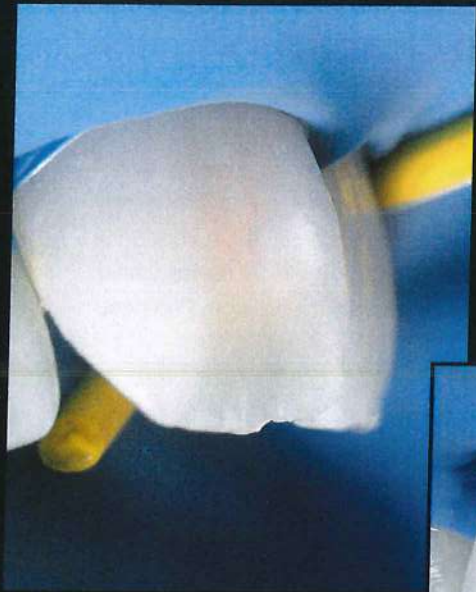


3-15b



3-15c

FIG 3-15 Deep developmental enamel defect treated with partial megabrasion, resin infiltration, and restoration. This deep enamel defect on the maxillary right central incisor *(a)* was partially removed by airborne-particle abrasion *(b)*, then treated with Icon Caries Infiltrant: Icon-Etch, Icon-Dry, and Icon-Infiltrant *(c to e)* and restored with translucent composite resin *(f)*. Note the extraordinary recovery of the native incisal edge translucency. (Clinical case and photography courtesy of Dr Gil Tirlet; reproduced with permission from Tirlet.[45])


3-15d


3-15e


3-15f

3.5 NONVITAL WALKING BLEACH TECHNIQUE

Dark internal discolorations caused by traumatic extravasation of blood products, their subsequent degradation, protein degradation of the necrotic pulp, or endodontic materials can be treated by the application of an oxidant paste, a mixture of sodium perborate and water or 3% to 10% hydrogen peroxide placed directly into the pulp chamber. Adequate endodontic treatment must precede this procedure.

Biomechanics of the endodontically treated tooth

Restorative procedures can make the tooth crown more deformable (see chapter 1).[46–49] This knowledge applies to the way anterior tooth flexure is affected during various restorative procedures.[50–52]

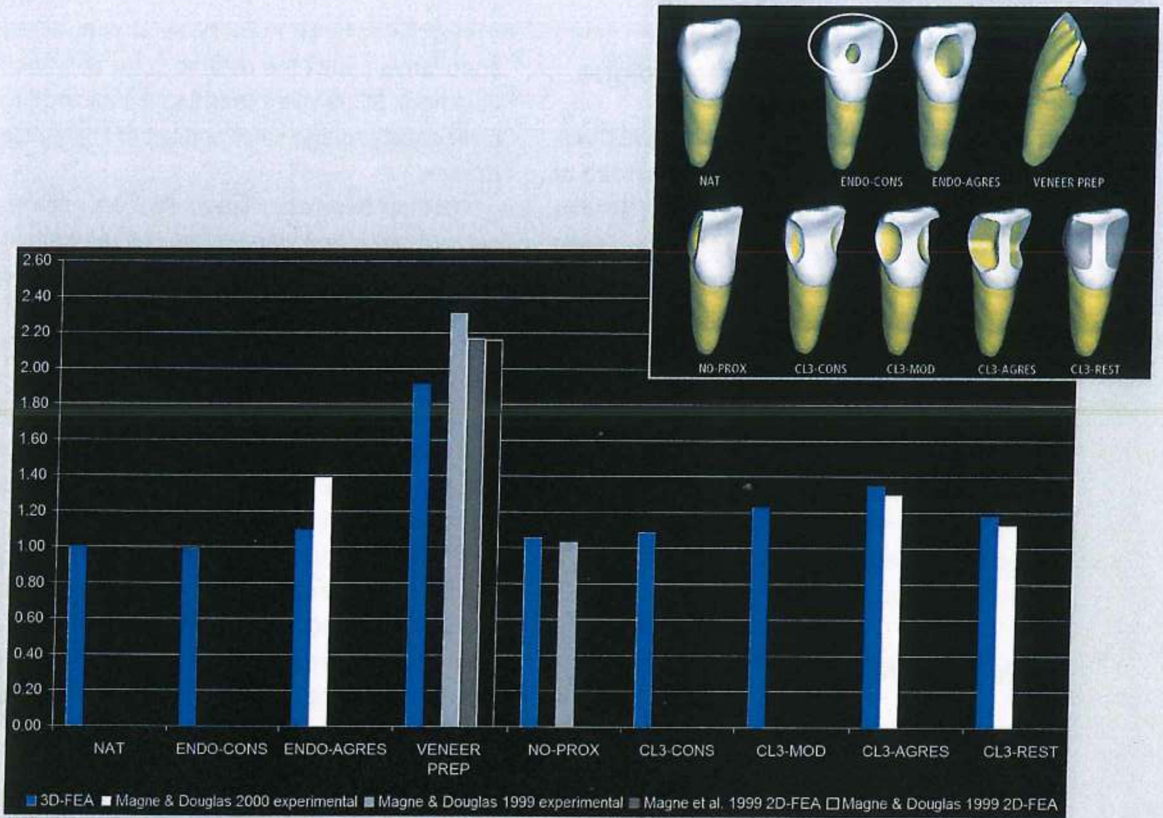
> Endodontically treated teeth present impaired crown stiffness due to the structural loss of hard tissues.[50,53,54] Such teeth deserve the same utmost respect for the remaining intact tooth structure as vital teeth. Hence, further loss of enamel and dentin must be prevented at all costs by *(1)* microinvasive endodontic access and *(2)* the most conservative restorative approach possible ("no post, no crown").

When the mesial and distal lingual marginal ridges of an incisor are not altered by the endodontic access preparation, the loss of coronal stiffness is significantly limited.[55,56] The biomechanical alteration might even become insignificant when the endodontic access preparation is microinvasive (Fig 3-16a).[56]

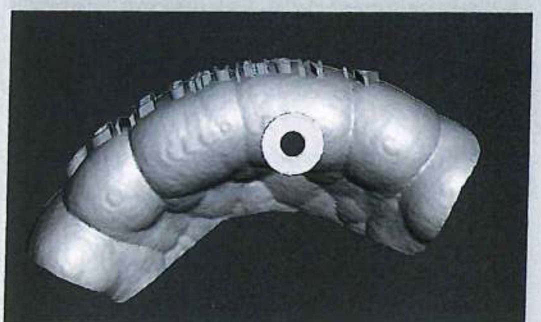
Thus, endodontists who are able to work through reduced-size access cavities can significantly improve long-term prognosis of the restored tooth.

The microinvasive approach to endodontics, or microguided endodontics, must be emphasized through the use of dental microscopes, CT-scan based printed teeth, printed surgical guides (similar to those used in guided implant surgery), and miniaturized instruments (Figs 3-16b to 3-16e).[57–60]

FIG 3-16 Microguided endodontics. *(a)* Several studies demonstrate that the cumulative loss of tooth structure makes the crown more deformable. Deformation is doubled when labial enamel is lost (Veneer Prep in *a*; see also chapter 1, Fig 1-15c) relative to the intact tooth. Microinvasive endodontics (Endo-Cons in *a*, *circled*) does not affect the crown. *(b to e)* Clinical example of intact tooth with posttraumatic pulp necrosis, ideal for microguided endodontics and possible through virtual planning with CT scan data used to print a surgical guide (*b*, virtual guide; *c*, printed guide). The original access is only 1 mm wide (*d*, dental microscope view). *(e)* Final radiographic control. (Part *a* reproduced with permission from Magne and Tan[56]; parts *b* to e courtesy of Dr David W. Kelliny, Torrance, California.)



3-16a



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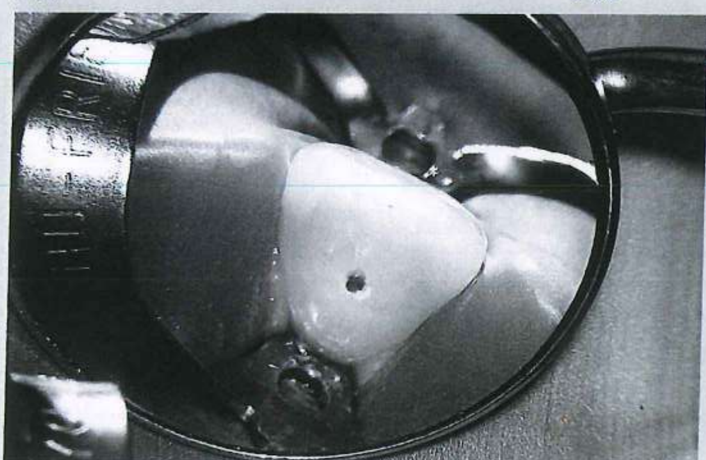
3-16c



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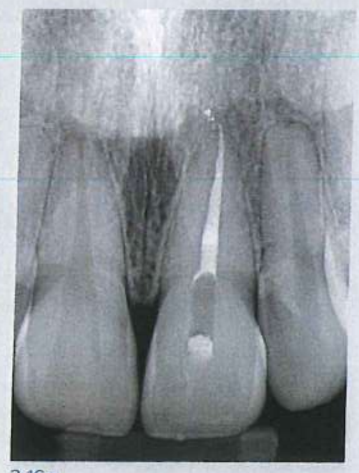


3-16e

Original walking bleach technique

The original walking bleach technique (WBT) was proposed by Spasser in 1961 and consisted of sealing sodium perborate mixed with water into the pulp chamber.[61] Bleaching would occur while the patient was walking out of the office. In 1963, Nutting and Poe proposed modification of the WBT,[62] which involved the temporary sealing of a mixture of 35% hydrogen peroxide (superoxol) and sodium perborate into the pulp chamber (Fig 3-17a). WBT was also frequently combined with the thermocatalytic technique to enhance the result. This method was a chairside approach where the superoxol was placed inside the pulp chamber and activated with a hot instrument.[63]

Safety of WBT

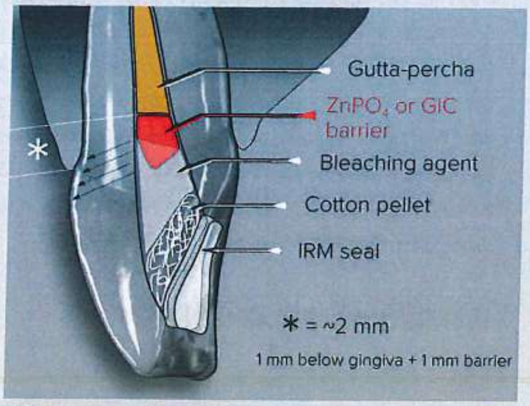
The WBT can still be recommended safely today; however, some caution must be applied. Like NGVB, WBT should be avoided in pregnant and lactating women. The density and quality of the root canal filling and the integrity of existing restorations must be confirmed radiologically and clinically. The process normally requires two to three applications (with an interval of a few days up to 1 week in between), and no more than five to six applications should be performed. No heat should be applied. The bleaching mixture should be covered by cotton pellets and perfectly sealed with IRM (Caulk/Dentsply) or composite resin between sessions (see Figs 3-19h and 3-19i) and replaced with fresh product at each consecutive appointment (until the desired color has been obtained). Slight overbleaching is indicated to compensate for the small amount of immediate relapse.

WBT has been associated with a risk of external root resorption. Interestingly, no resorptions were found in two clinical reviews of 258 and 112 WBT-bleached teeth followed over 4 years and 5–15 years, respectively (sodium perborate mixed with 30% hydrogen peroxide, no cement barriers used).[64,65] In both studies, all patients had tetracycline-stained teeth without history of trauma. This result is not surprising knowing that most root resorptions are caused by orthodontics (24.1% of teeth, most common sole factor) and trauma (15.1% of teeth) but rarely by intracoronal bleaching alone (3.9% of teeth).[66]

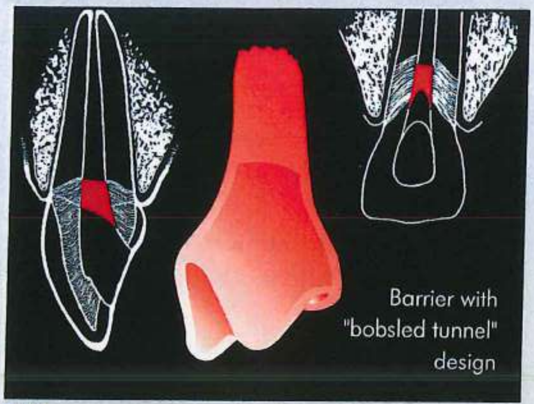
However, based on etiologic factors of root resorptions (mostly case reports), it is suggested that:

1. ***Application of heat (thermocatalytic technique) and superoxol (> 30% hydrogen peroxide) should be avoided.*** Internal bleaching is possible with sodium perborate mixed with water, 3% hydrogen peroxide, or 10% CP.[67,68]
2. ***The bleaching agent should not be placed too deep in the root canal.*** Critical factors include a dense root filling and the application of an anatomical cement barrier to prevent diffusion of the oxidant into the proximal periodontal ligament area (Figs 3-17b to 3-17j).[67,69,70]

FIG 3-17 WBT—application of adequate barrier material in large access preparations. *(a)* Configuration of materials used in the walking bleach technique (see also Figs 3-19g to 3-19i). The endodontic material is removed no more than 2 mm below the gingiva *(asterisk)*. *(b)* A zinc phosphate ($ZnPO_4$) or glass-ionomer cement (GIC) barrier is applied[69,70] and reproduces the spatial configuration of the periodontal membrane or cementoenamel junction (ie, scalloped buccal contour and proximal "wings"). *(c)* To create this barrier, the cement is initially applied in an "IRM-like" consistency and condensed into the canal. *(d)* After setting, excess barrier material is removed with a diamond bur at low speed in a slight buccolingual direction. *(e to g)* The configuration of the barrier is ultimately controlled by probing. *(h to j)* This procedure should leave cement excesses (barrier wings in *h*, *arrows*) against the proximal walls and prevent diffusion of the bleaching agent in the critical proximal zone. (Parts *b, d, f,* and *i* modified with permission from Steiner and West.[69])

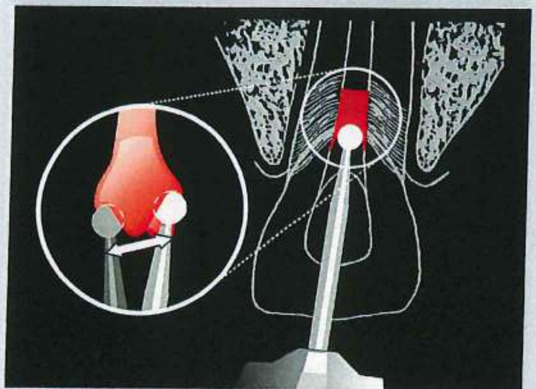


3-17a



3-17b


3-17c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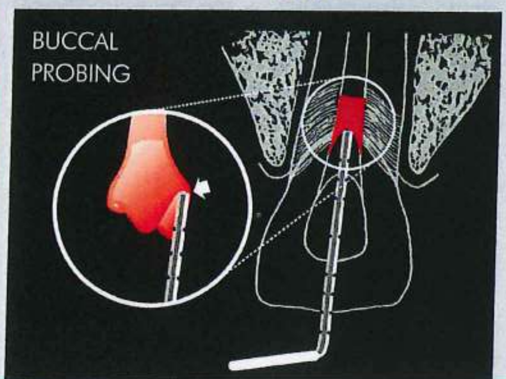
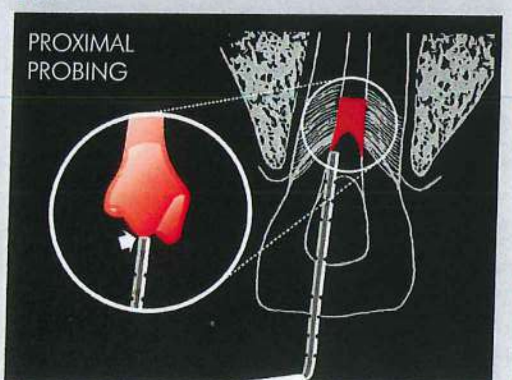


3-17f


3-17g


3-17h



3-17i


3-17j

Bleaching mixtures and mechanism of action

Various bleaching mixtures can be used for WBT, in the order of efficiency:

1. **Sodium perborate with water:** Hydrogen peroxide is released by the decomposition of the perborate.
2. **10% CP:** The same product used for NGVB can be easily injected into the pulp chamber with the dispensing syringe or even mixed with sodium perborate.[71]
3. **Sodium perborate with 3% to 10% hydrogen peroxide:** This remains the most efficient mixture (Fig 3-18).

The sodium perborate increases the pH of carbamide and hydrogen peroxides. All of these mixtures will also produce nascent oxygen (gas) and generate a potential increase of internal pressure. The placement of a cotton pellet between the mixture and the IRM seal (see Fig 3-19h) will provide a small compressible volume of air as a compensation and likely prevent the seal from being lost. The probable reason for the bleaching effect is the oxidizing of the chromogenic organic molecules into smaller compounds.[68] The loss of molecular tridimensional structure explains the change of color.

A typical bleaching session is described in Fig 3-19. While the use of rubber dam may provide a safety net for the novice operator during the application of the mixture, the presence of rubber dam also limits the field of view during the preparation of the access and placement of the barrier and "hides" potential leaks into the tissues.

Inside/outside bleaching (IOB)

IOB – Open approach

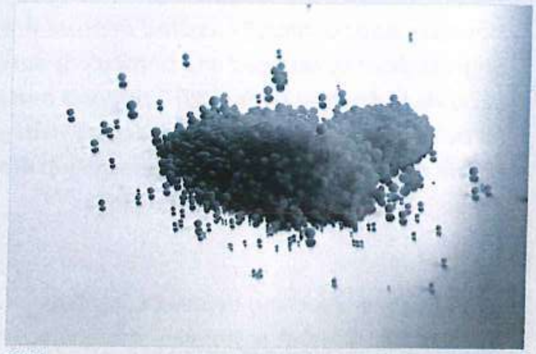
This practice consists in leaving the pulp chamber open for the patient to place 10% CP inside the tooth and proceed with NGVB simultaneously.[72] It may work well with skilled patients but remains controversial because of the lack of control over bacterial leakage in the open tooth and the potential effect on the long-term success of the endodontic treatment.[68,73]

IOB – Closed approach

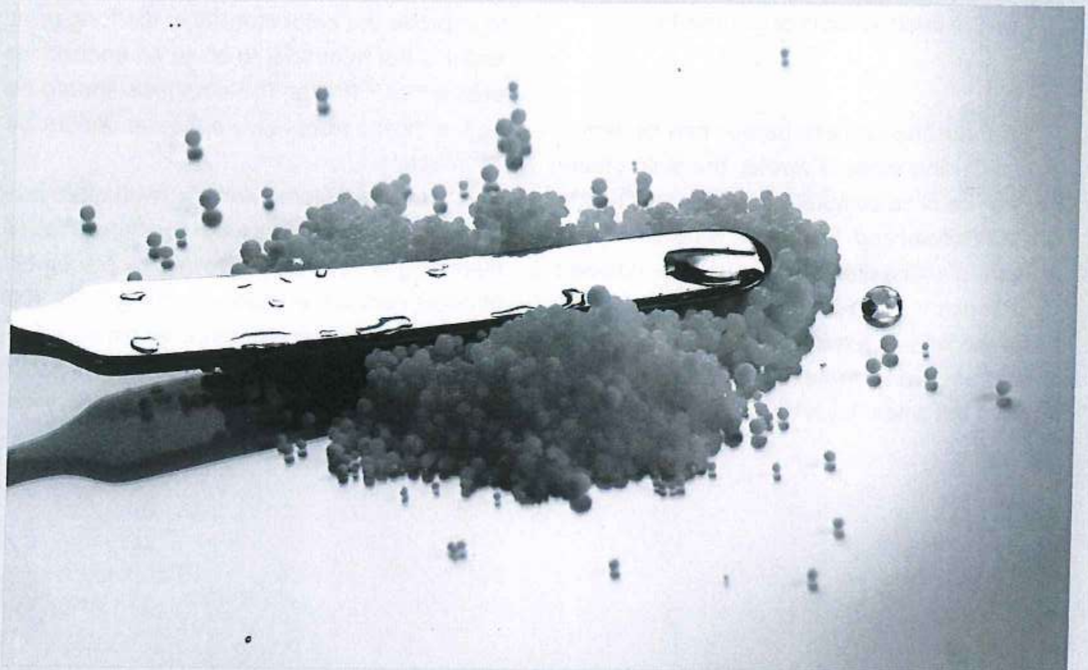
To prevent accumulation of food debris in the access cavity and avoid the colonization of coronal dentin by bacteria, a "closed" version of IOB has been proposed.[73] IOB in general represents a useful alternative in countries where the use of sodium perborate is prohibited.

FIG 3-18 Preparation of bleaching mixture for WBT. Water or 3% hydrogen peroxide *(a)* and sodium perborate granules *(b)* are mixed to a paste consistency *(c and d)*. The mixture should be viscous enough to be carried into the pulp chamber without splashes (see also Fig 3-19g).

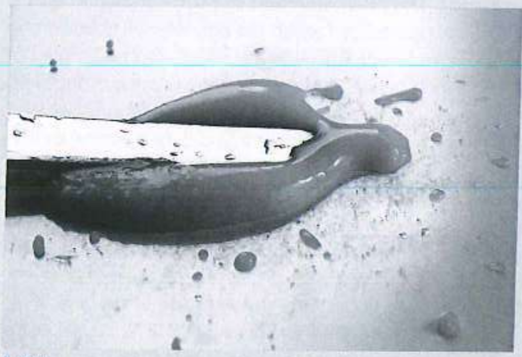
3-18a



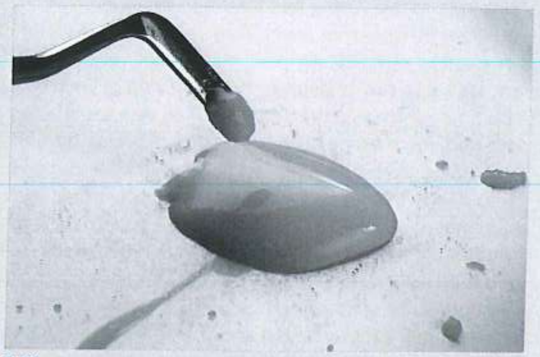
3-18b



3-18c



3-18d



3-18e

Because endodontically treated incisors are only temporarily restored and particularly susceptible to fracture during WBT, patients must be advised to be cautious and not apply heavy masticatory forces in the area, especially in the presence of large existing restorations.

After any bleaching treatment, application of adhesive restorative materials must be delayed for 3 weeks[7] because of the inhibiting effect of oxygen residues on the bond strength of composites.[25,26]

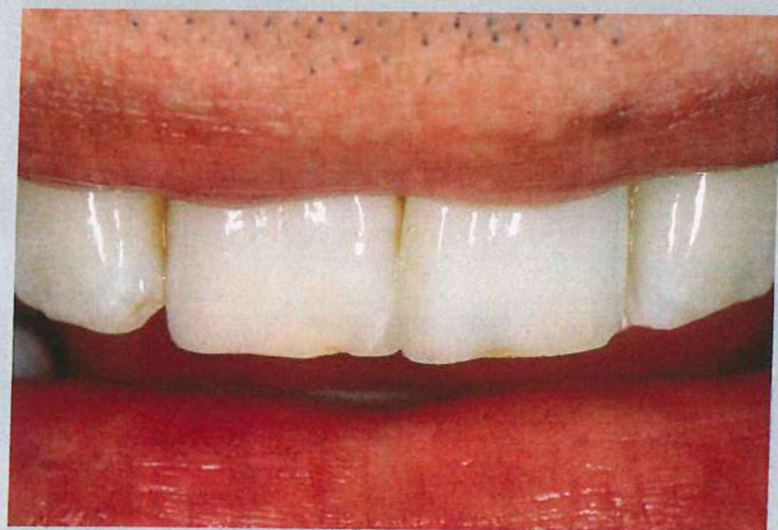
The existing cement barrier can be left in place. During those 3 weeks, the pulp chamber can be filled completely with a bright shade of GIC. Beforehand, the dentin walls should be refreshed with a diamond bur and conditioned for 20 seconds with 5% sodium hypochlorite[74,75] or ethylenediaminetetraacetic acid (EDTA) plus 1% sodium hypochlorite[76] or polyacrylic acid to remove the smear layer and increase adhesion of glass ionomer. The dentin should not be desiccated before applying the GIC.

Optional: Calcium hydroxide[77] or catalase[78] can also be applied in the pulp chamber (instead of GIC) during the 3-week safety elapsed time to neutralize and inactivate any peroxide that may have leaked into the root canal. Hereafter, restoring of the entire pulp chamber with composite is not advisable. Retreatment may be required in the future, and having a GIC base instead of composite resin in the pulp chamber facilitates reentry. A bright opaque GIC base also seems to improve the color stability in the long term, and it is not beneficial to place an endodontic post either.[79] Rather, the emphasis should be on the most conservative adhesive restorative approach.

Because discolored nonvital teeth often present some loss of incisal tooth structure, nonvital bleaching is frequently followed by placement of direct composite restorations (Fig 3-19). This is often necessary in children, in whom it is advisable to postpone the use of bonded ceramic restorations.

FIG 3-19 Extreme indication for WBT and freehand restoration. *(a)* The patient was originally seen by a general practitioner for prosthetic treatment of the left central incisor. *(b and c)* Instead, the tooth was treated successfully with internal bleaching and freehand restoration of the incisal edge. Detailed treatment steps are shown in *d* to *s*. *(d and e)* Preoperative views show deep dentin discoloration. Bleaching could be carried out only after elimination of a preexisting intraradicular post, endodontic retreatment (Dr Jean-Pierre Ebner, Basel, Switzerland), and placement of an adequate zinc phosphate barrier. *(f and g)* Each bleaching session consisted of rinsing and cleaning of the pulp chamber, which was then partially filled with the sodium perborate mixture. *(h and i)* A condensed cotton pellet was inserted, followed by hermetic closing of the cavity with IRM. Intense burnishing of the margins during setting of IRM is required to ensure a perfect seal, which is imperative for the success of the procedure. *(j)* Five to six sessions at 5- to 10-day intervals allowed complete recovery of the original color. Following the last bleaching session, it can be recommended that calcium hydroxide be applied for 3 weeks to neutralize and release peroxide remnants. The existing cement barrier can be left in place. *(k and l)* After this delay, the pulp chamber is rinsed with 5% sodium hypochlorite and filled with traditional glass ionomer. *(m and n)* At the last session, a 1- to 2-mm layer of glass ionomer was removed. Oscillating instruments (see also Fig 3-27e) are the most conservative tools to generate clean proximal margins. After acid etching, adhesive resin and enamellike composite were used to fill the palatal cavity. *(o and p)* The incisal edge was layered using a three-increment technique, in which a dentinlike increment is applied and then covered by enamellike and incisal masses (see also Fig 3-40). *(q)* A slight concavity created in the incisal edge allowed application of ochre stains to simulate dentin exposure. The final result is presented in *r* and *s*. The patient was satisfied, even though further application of a bonded ceramic restoration could be indicated to restore the original crown strength and compensate for an eventual bleaching-resistant color relapse. *(continued on next pages)*

3-19a

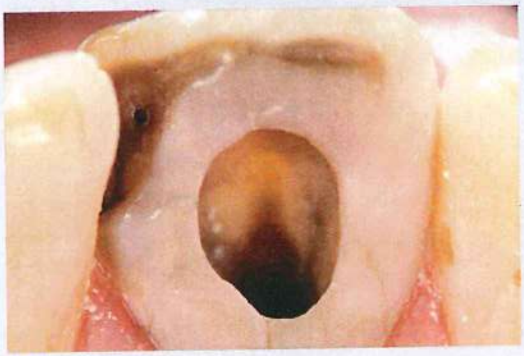


3-19b

3-19c

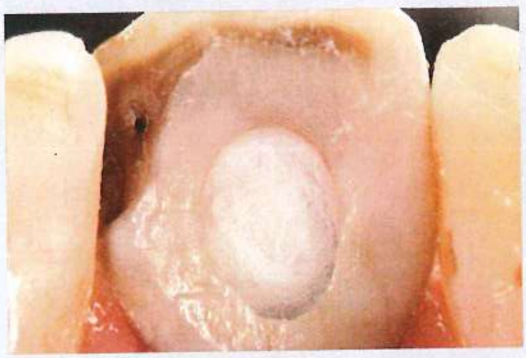
3-19d

3-19e



3-19f

3-19g



3-19h

3-19i

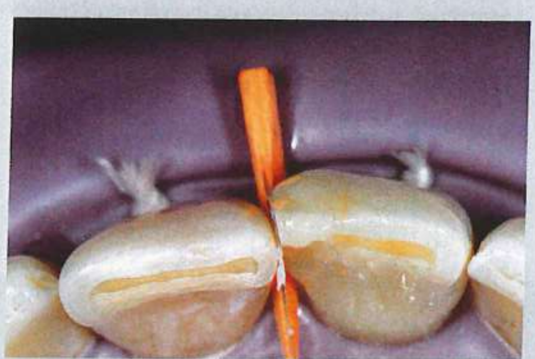
3-19j

3-19k


3-19l


3-19m


3-19n


3-19o


3-19p


3-19q

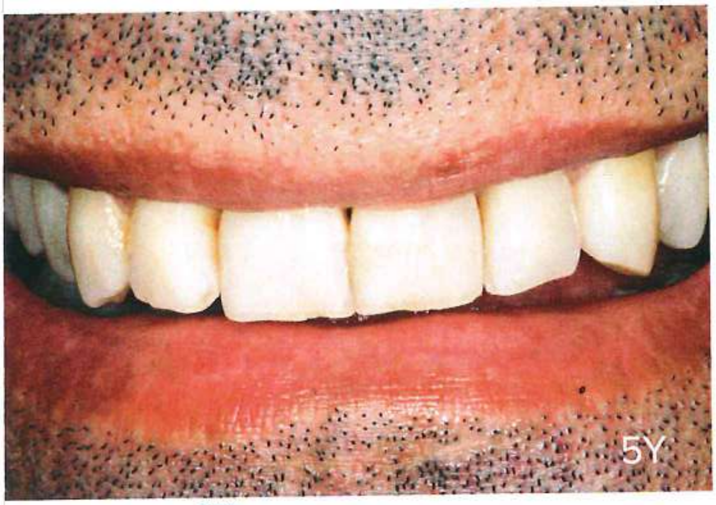

3-19r


3-19s

Final restoration after WBT

Complete sealing of the enamel surface is critical to prevent reinfiltration and color relapse. Enamel bond strength recovery will require at least 3 weeks.[27] Following this delay, only the superficial layer of the GIC base (about 2 mm) can be removed and replaced with a layer of composite resin bonded to the cleaned and etched palatal enamel (Figs 3-19a to 3-19s and 3-20). Keeping the GIC as the main dentin volume will work as a nonshrinkage base and limit the effect of polymerization contraction of the overlaying composite resin (sandwich restoration).

Due to the impaired crown stiffness of endodontically treated teeth,[51,54,55] and numerous enamel cracks often present on the remaining palatal enamel, ***the composite resin restoration should be as additive as possible and extend 2 to 3 mm beyond the endodontic access over the intact palatal enamel*** (cleaned beforehand with airborne-particle abrasion, etched, and resin bonded). When allowed by the occlusion, the composite should be modeled to recreate ridges/lobes across palatal fossa (Figs 3-20 and 3-21; see also Fig 3-19s). Such convex structures will better distribute the functional stresses, which might partially compensate for the more flexible behavior of the endodontically treated tooth (see Fig 1-7a).



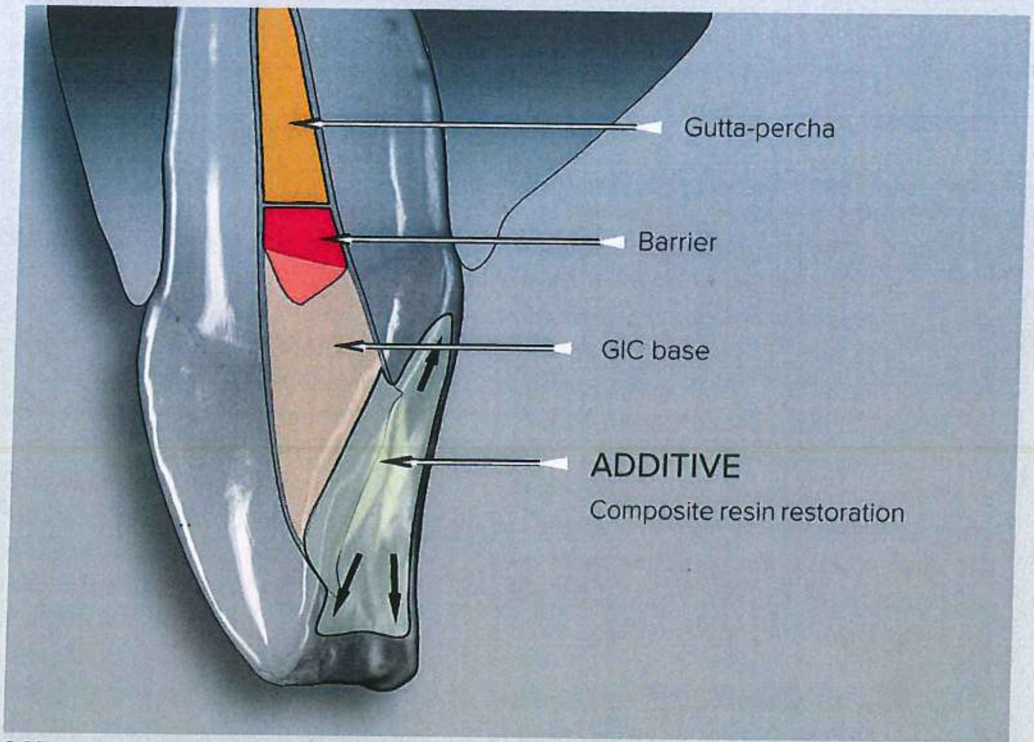
3-19t

3-19u

FIG 3-19 *(cont) (t and u)* The situation remains unchanged 5 years following intervention.

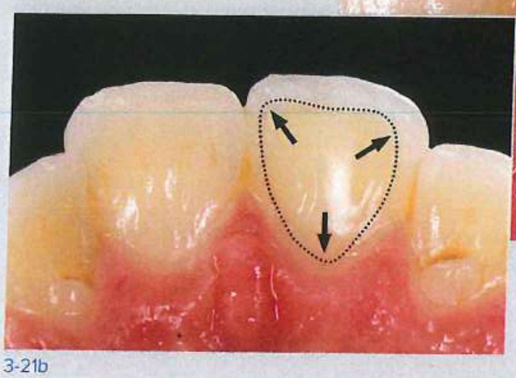
FIG 3-20 Final material configuration following WBT. Note the main cavity volume filled with GIC, the additive surface (*arrows*, overlapping the remaining palatal enamel), and the simulation of ridges/lobes with the composite restoration.

FIG 3-21 Palatal restoration following WBT. *(a)* Preoperative clinical view. *(b and c)* Following successful internal bleaching, the pulp chamber was filled with GIC, and, after the 3-week delay, the palatal surface was restored additively with composite. Note the strong central ridge in order to reinforce the remaining tooth substance *(c)*.

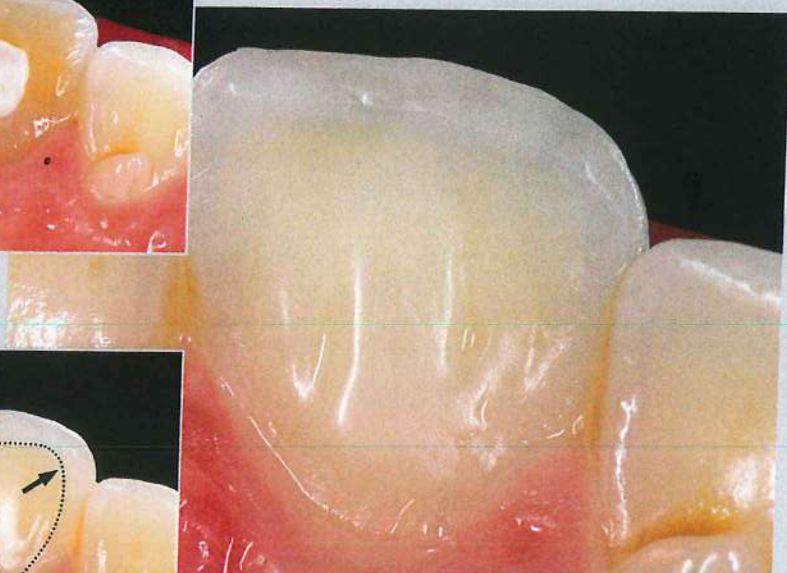


3-20

3-21a



3-21b



3-21c

Prognosis of the WBT

When the aforementioned elements are not respected, the long-term success of internal bleaching can be disappointing. Discolorations from organic origin (trauma- and necrosis-induced) are more successfully bleached than those from metallic ions (restorations, medicaments, etc; Figs 3-22 and 3-23).[67] The pulp chamber must be perfectly cleaned before starting WBT. The use of high magnification (loupes minimum 8.0× or operatory microscope) will improve detection of old restorative material. Remnants of resin and GIC often preclude the bleaching agent from reaching its target, and old restorations left inside the pulp chamber are a common cause of failure of WBT.

Recurrent discolorations and nonresponding pigmentations (eg, metallic ones) may have to be masked by restoration with composite resins or bonded ceramics (see chapter 6, section 6.2, Figs 6-4 and 6-16).

The following elements will improve the efficiency and prognosis of WBT:

- Clean pulp chamber before starting WBT.
- Compressible volume of air (ie, cotton pellet) under provisional restorations during WBT.
- Perfect seal during WBT and after final restoration.
- After WBT, brightest shade of GIC placed inside the pulp chamber for 3 weeks and left later as a base material (avoid use of posts and composite resin as definitive restoration inside the canal and pulp chamber).
- After a 3-week delay, final restoration over partially cutback GIC base using **additive surface** (entire palatal enamel etched and sealed) and **additive volume** (convex elements across palatal fossa rather than concavity, if allowed by occlusion) of composite resin.

FIG 3-22 Successful WBT of organic discoloration. *(a)* Preoperative view of nonvital mandibular right central incisor with dark brown discoloration. *(b)* WBT was successful with a slight but desired overbleaching. *(c)* Final result after final restoration with composite resin.

FIG 3-23 Long-term follow-up of WBT. Maxillary right lateral incisor with similar problem *(a)* and 12 years after successful WBT *(b and c)*. Note the lingual ridges and the natural extrinsic staining of the lingual fossae due to the detailed morphology of the restoration. (Reprinted with permission from Magne.[80])


3-22a


3-22b


3-22c


3-23a

3-23b

3-23c

3.6 REATTACHMENT OF A TOOTH FRAGMENT

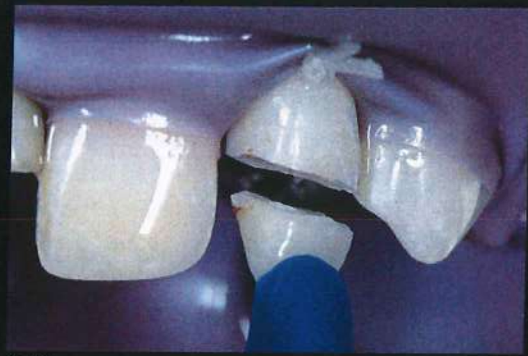
General principles

Traumatic fractures of maxillary incisors are extremely common. Adhesive reattachment of a coronal fragment, when possible, should always be considered because it will simplify the treatment, facilitate the esthetic outcome, and decrease the amount of restorative material.[81,82] It can prove successful even in the case of pulp exposure (see Fig 1-1).. Early clinical experience, however, demonstrated that 50% of reattached fragments are lost within 2.5 years after initial bonding.[83] For this reason, supplementing reattached fragments with a porcelain laminate has been suggested by Andreasen et al,[84,85] who also demonstrated that this method could restore or even surpass the original tooth strength (see chapter 6, Fig 6-11). Placement of bonded porcelain restorations in children, however, should not be recommended due to the evolving tooth positions and ongoing maturation of the soft tissues. Instead, rebonded fragments can easily and noninvasively be complemented by a thin layer of composite resin overlapping the fragment and the remaining surface of the tooth. This "overcontour" method (tooth-fragment overlap with composite resin addition) increases the longevity of teeth restored by fragment reattachment (Fig 3-24).[86,87]

Creation of additive contours to enhance tooth morphology (in the form of crests and transition line angles) is a universal concept for strengthening. This principle, which will be further discussed in chapter 5 (see Fig 5-5), can be recommended for all cases of freehand application of composite resin, especially in Class 4 restorations (see Figs 3-42 and 3-43), and for palatal restoration following internal bleaching (see Figs 3-20 and 3-21).

FIG 3-24 Trauma in a 15-year-old patient—interim treatment. *(a)* The right central incisor, which had been endodontically treated before trauma, and the left lateral incisor have fractured. The fragment of the lateral incisor was recovered *(b)* and reattached using the acid-etch technique (including the use of a dentin bonding agent) and a regular light-polymerized restorative composite resin *(c and d)*. The bonded fragment was then supplemented with a thin composite resin addition. *(e)* Enamel at the mesial aspect of the tooth was roughened with a bur and etched, and adhesive and composite resins were added to enhance the mesial transition line angle (articulating paper has been rubbed on the tooth surface to emphasize the mesial addition of composite). *(f)* The tooth-restoration transition is invisible. *(g)* The same principle (creation of an additive contour with a composite overlap) was used to reinforce the cracked left central incisor; the right central incisor was treated with WBT and restored with freehand application of composite resin (postoperative view). *(h)* Tangential light outlines the translucent facial lobes and ridges that contribute to the enhanced esthetic and mechanical treatment outcome. This procedure, while meant as an interim treatment only, will usually last many years; the patient can now be referred to the orthodontist. The case should be carefully monitored, and bonded porcelain restorations might be indicated once the patient reaches adulthood.


3-24a


3-24b


3-24c


3-24d


3-24e


3-24f


3-24g


3-24h

Technique and materials

It is important to keep the fragment hydrated before reattachment (eg, in saline or milk).[88] It is not unusual, however, for the fragment to be brought to the dental office completely dehydrated. In such case, reattachment is still advisable after rehydrating the fragment for at least 15 minutes if immediate reattachment is needed,[89] which will significantly improve the bond strength when using multimode adhesives. Longer rehydration times (30 minutes up to 24 hours) are normally recommended if possible.[90] Matching the rehydration time and dehydration time might be a good approach.

Materials that are compatible and show the best mechanical properties must be used for the reattachment procedure[91]: *(1)* an efficient adhesive system, preferably a three-step etch-and-rinse system (see Fig 3-29), and *(2)* a light-curing restorative composite resin, rather than flowable or dual-cure materials. The technique therefore resembles the luting procedure used for inlays/onlays and veneers (see chapter 6, section 6.13) and is completed by the additive/overcontour reinforcement technique. Hence the fragment should be reattached in two steps (Fig 3-25):

1. Fragment positioning by adhesive luting (Figs 3-25a to 3-25o). In the presence of large marginal discrepancies (Fig 3-25c), using a dentinlike composite resin will improve tooth-fragment optical continuity.
2. Reinforcing by additive contouring (Figs 3-25p to 3-25y) using preferably an enamel-like composite resin.

Reattachment in case of pulp exposure

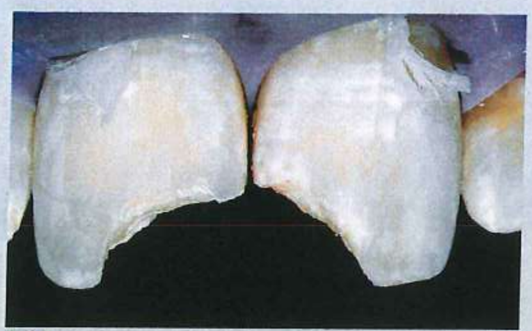
The reattachment technique is compatible with direct pulp capping as long as a small concavity is prepared in the fragment dentin surface to create a physical space for the direct capping material (biocompatible dressing plus cement barrier).

The key to success is keeping the microorganisms from entering the pulp. Hence, various pulp capping materials can be used as long as a good peripheral seal is obtained through strict isolation, hemostasis, and proper bonding procedures.[92]

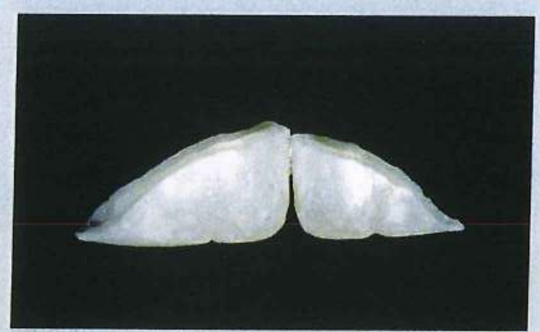
Reattachment to endodontically treated teeth

The same protocol can be used, and there is no need to place a root canal post.[93] Post placement involves additional removal of root dentin, increasing the risk of catastrophic failures without benefit on strength.

FIG 3-25 Step-by-step fragment reattachment. *(a)* Uncomplicated fracture involving both central incisors. *(b)* The fragments were brought by the patient. *(c and d)* The fit is very good at the lingual surface but not labially. *(e to g)* The fractured surfaces were cleaned with airborne-particle abrasion and conditioned for bonding, starting with the left central incisor. *(h to j)* The tooth and fragment were conditioned identically using a three-step etch-and-rinse adhesive system (etching/priming and bonding). *(k and l)* A dentinlike composite resin (Shade S1, Miris2, Coltène) was gently placed onto the defect, and the fragment was carefully positioned in its closest fit to the tooth.



3-25a



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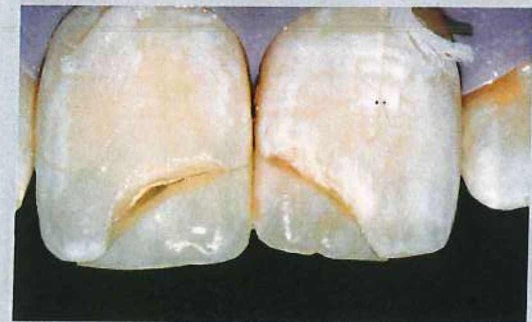

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3-25d

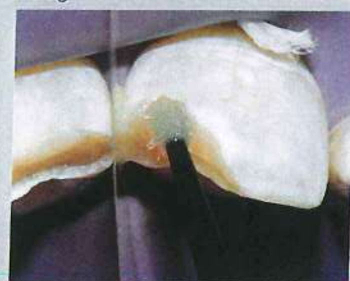
3-25e

3-25f

3-25g

3-25h

3-25i



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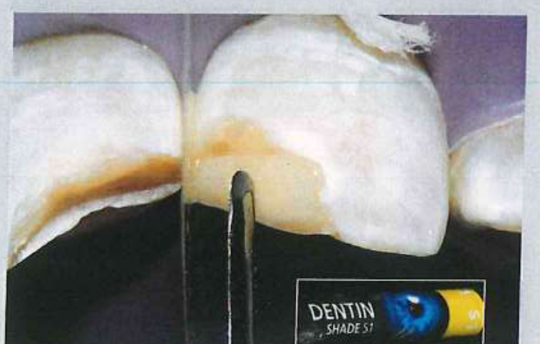
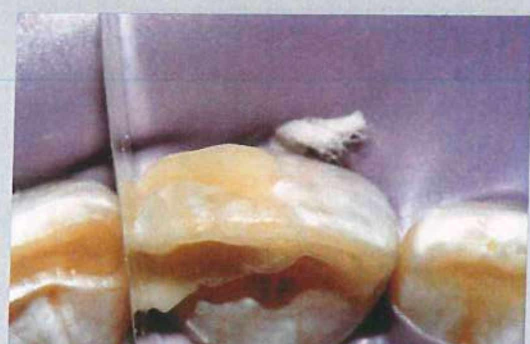


3-25k



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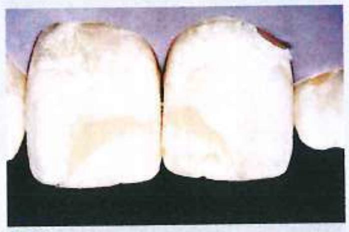
3-25m


3-25n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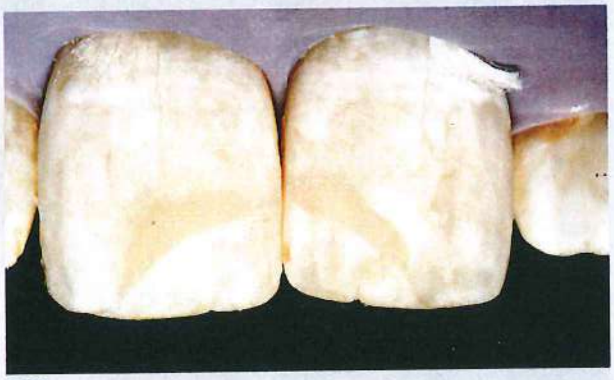
3-25p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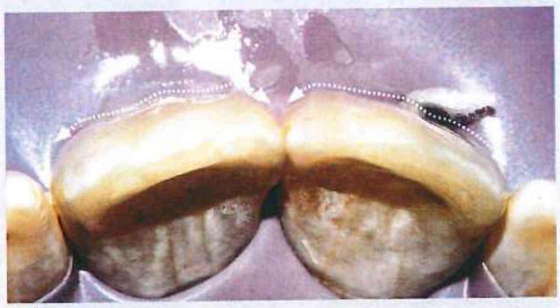
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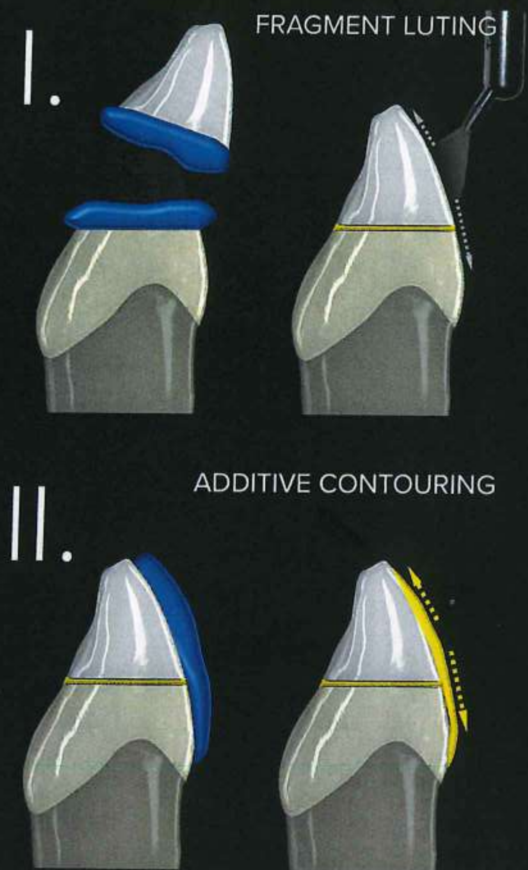
3-25w


3-25x

3-25y



3-25z

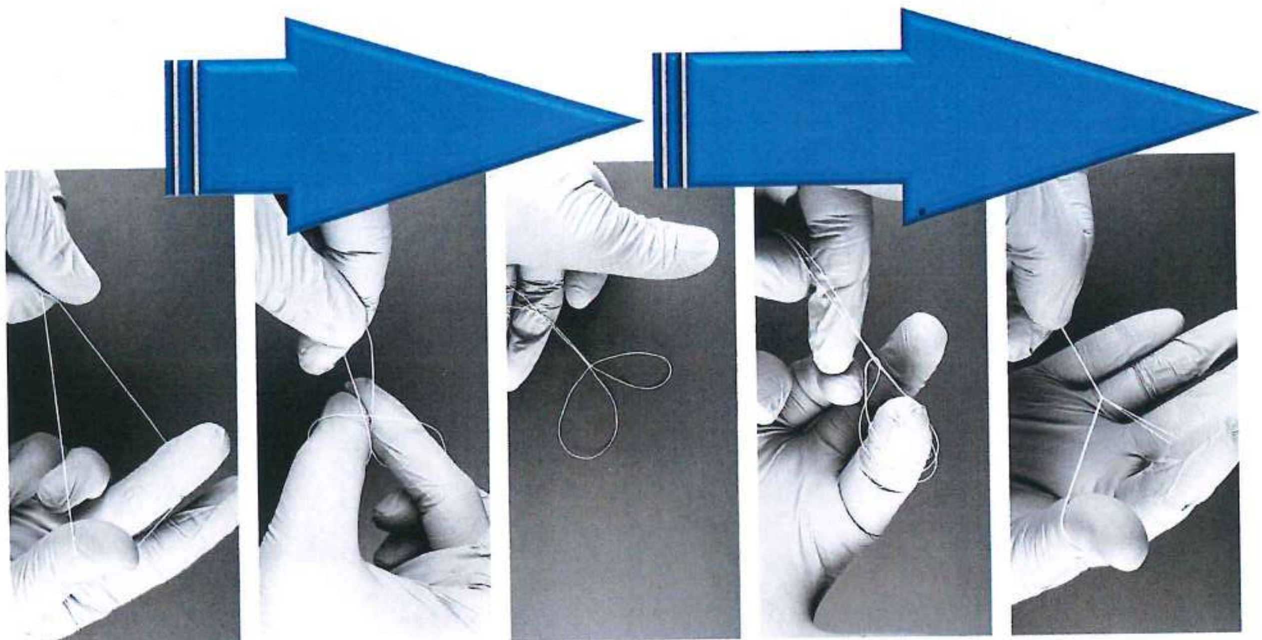
FIG 3-25 *(cont) (m and n)* Excesses of composite resin were removed before polymerization. *(o)* The exact same process was applied to the right central incisor. *(p to r)* The labial surface of both teeth was gently abraded with a diamond bur at 2,000 rpm, then etched before the application of adhesive resin and polymerization. *(s to u)* A thin layer of enamellike composite resin (White Bleach, Miris2, Coltène) was then strategically layered and polymerized, and glycerin gel was applied for surface polymerization. *(v)* Note the natural surface emulated by the additive reinforcement layer. *(w and x)* The lingual aspect of both teeth was treated similarly by surface roughening, etching, and placement of adhesive resin to perfectly seal the surface. *(y)* Postoperative view 2 weeks after the repair. *(z)* Summary of the fragment reattachment steps with labial reinforcement. The 11-year follow-up and maintenance of this case are presented in chapter 7, Fig 7-4.

3.7 ADHESIVE RESTORATIVE MATERIALS AND ARMAMENTARIUM

Placement of adhesive restorations requires the use of adequate materials and instruments. The process starts with strict isolation procedures. Proper tooth preparation should include the most conservative caries detection and removal techniques (described in Fig 3-54). In this section, special instruments will be discussed such as oscillating tips and composite resin placement instruments. Adequate bonding procedures to enamel and dentin and the selection of the most appropriate restorative materials will complete this section, which will end with basic considerations regarding light polymerization techniques.

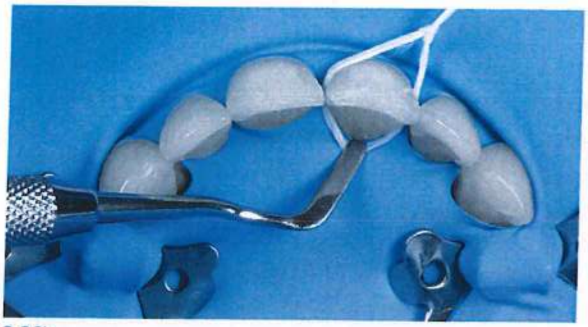
Isolation techniques

Rubber dam placement is undoubtedly the first choice for proper isolation because it will ensure both isolation and tissue displacement[94] and improve the restoration outcome.[95] In the maxillary anterior dentition, a double self-tightening ligature (Figs 3-26a to 3-26j) attached to the inverted metal frame (Figs 3-26k to 3-26m) will provide a comfortable access. Whenever possible, clamps can be used on top of rubber dam to improve grip and comfort for the patient and prevent stresses on the cervical enamel. In this regard, the SoftClamp (Kerr) may be the safest and most gentle alternative to a metal clamp (Fig 3-36n), but it exists only for molars. The second choice for isolation could be the Isovac mouthpiece (by Ziris) connected to the high-volume evacuator, which will provide proper isolation but will have to be combined with other tools (eg, retraction cords) for tissue displacement.



3-26a 3-26b 3-26c 3-26d 3-26e

FIG 3-26 Ligature and rubber dam application. *(a to j)* The double self-tightening ligature (concept courtesy of Dr Maxim Belograd) can be achieved with waxed floss. It is then applied to the teeth *(k)* and can be attached to the rubber dam frame to generate adequate deflection *(l and m)*. Note the clamps placed without perforations on the premolars. *(n)* The SoftClamp is an atraumatic alternative to metal clamps for molars.



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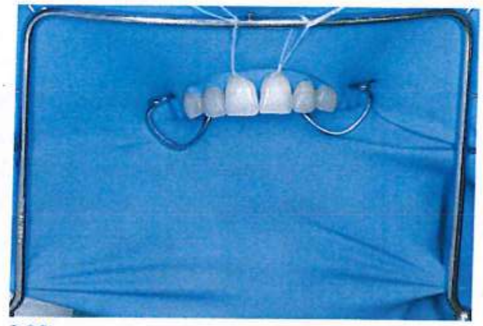

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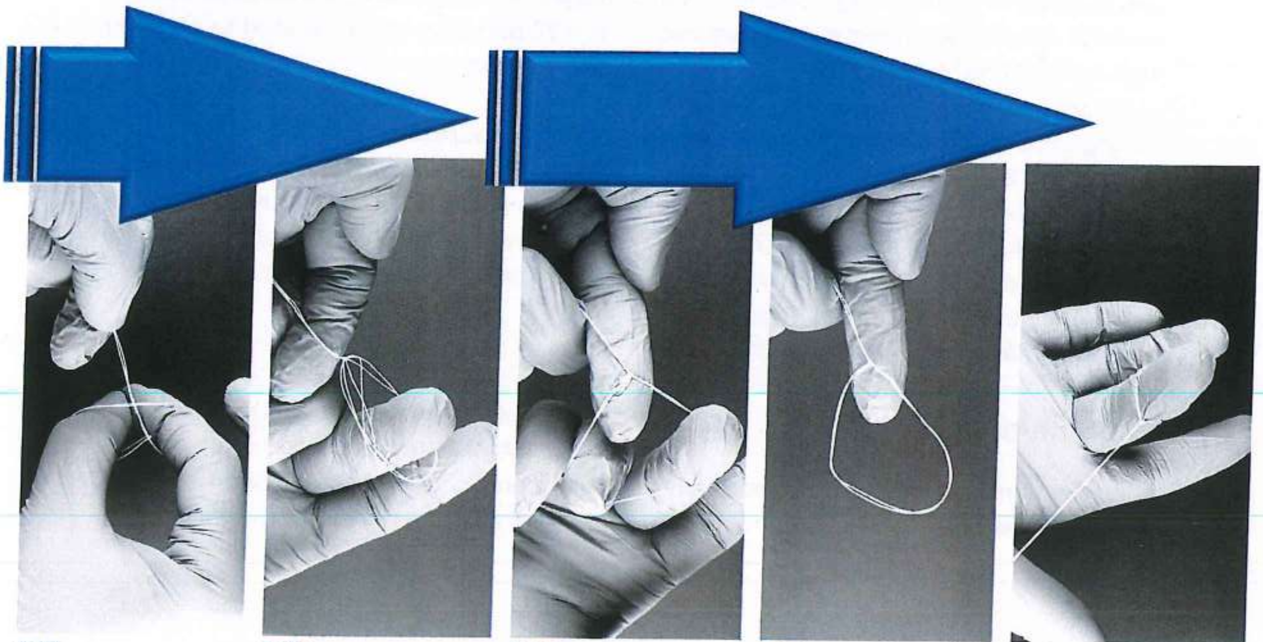


3-26f 3-26g 3-26h 3-26i 3-26j

Electric handpieces

Air-driven systems can be considered completely outdated today compared to electric handpieces, which have countless advantages: efficiency, quietness (high concentricity, less vibration, lower pitch, less irritating for the patient), and less aerosol production, among others.[96–99]

> Above all, it is the high torque of electric motors that stands out: The speed is maintained as the load on the bur increases.[96,97] This is especially significant at low speed, allowing extremely fine preparation of margins and smooth surfaces without stalling.

Some systems cover an ultrawide range of speed, from 100 to 40,000 rpm. Hence, one attachment (red-coded, 1:5 multiplication factor, friction grip) can cover all the needs (500 to 200,000 rpm), but because some tools are only available in latch grip (eg, some polishing systems), a second attachment might be required (blue-coded 1:1, no multiplication).

Existing air-driven handpiece systems can be upgraded in a flash with an external electric system (eg, NLZ by NSK, Electromatic by KaVo, iOptima by Bien-Air) by plugging the four-hole tubing into the control box (Fig 3-27a). Some brands propose lightweight titanium handpieces as well as outstanding four-jet irrigation and shadowless illumination (double LEDs).

Airborne-particle abrasion

A number of restorative and repair procedures require gentle cleaning with airborne-particle abrasion to make surfaces—tooth or restoration—more conducive to bonding or examination (eg, caries detection). The following elements must be considered when using air abrasion devices (Fig 3-27b)[100]:

Air pressure

No more than 60 psi/4atm (regular dental unit pressure) is required for surface cleaning, allowing the use of portable devices directly connected to the dental unit (eg, RONDOflex Plus 360, MicroEtcher by Danville). Pressures in excess of 100 psi/6.8atm and water are required for cutting, calling for larger self-operating systems/units (eg, PrepStart by Danville, AquaCare by Velopex, CrystalAir by Crystalmark Dental Systems).

Abrasive material

Most commonly, alumina particles with diameter 27 to 50 microns are used. Thin ceramic restorations, however, will be damaged and potentially crack after blasting with alumina particles, which have an irregular geometry and feature rough edges. Softer spheroidal glass beads (50 microns) at < 22 psi/1.5atm should be used for abrading thin ceramics.

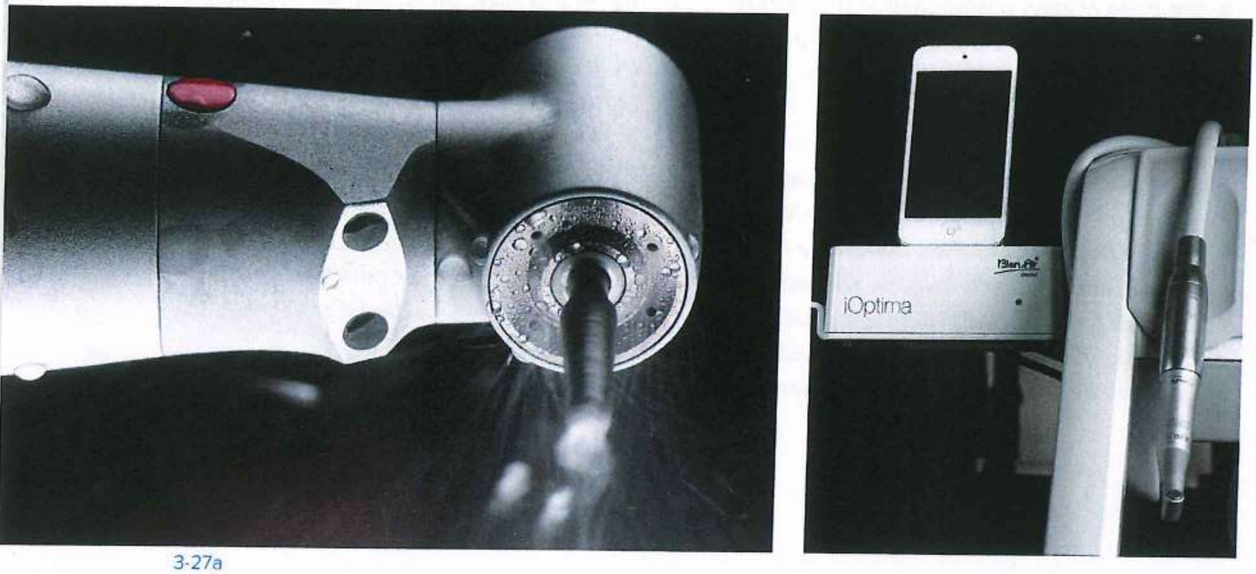
Specialty abrasive

Thirty-micron CoJet sand (3M) features silicoated alumina particles able to enrich the substrate surface with silica to improve silane efficiency for zirconia bonding or repairs (see chapter 7, Fig 7-3).

Safety

A high-volume evacuator suction should be used along with thorough protection of the patient's and operators' airways (rubber dam, masks, etc). Systems with water better confine the particles.

FIG 3-27 Armamentarium: Electric and air abrasion handpieces. *(a)* External electric motor system (images courtesy of Dr Marco Carvalho) with red-band friction-grip handpiece (*top and bottom left*, 1:5 multiplication). The native motor speed ranges from 100 to 40,000 rpm and can be intuitively controlled with a smart device or tablet via an app (*bottom right*, iOptima). Custom programs can be created for specific restorative procedures. *(b)* RONDOflex Plus 360 (KaVo) air abrasion device can be used with or without water. It conveniently connects to the four-hole tubing via a coupler (MULTIflex, KaVo, here customized with a pressure gauge).



3-27a

3-27b

Interdental preparation instruments

Damage to the adjacent dentition is a very common issue, especially in Class 2 (Fig 3-27c) preparations but also Class 3 preparations.[101–103] A first and easy preventive step is the placement of a barrier in the form of a sectional metal matrix and a wedge during preparation. The FenderWedge (Garrison) facilitates this process for posterior teeth (Fig 3-27d). A second measure is to limit the use of rotary instruments (burs) only to the main access preparation and switch to safer instruments for the preparation and finishing and especially beveling of the margins, when indicated.

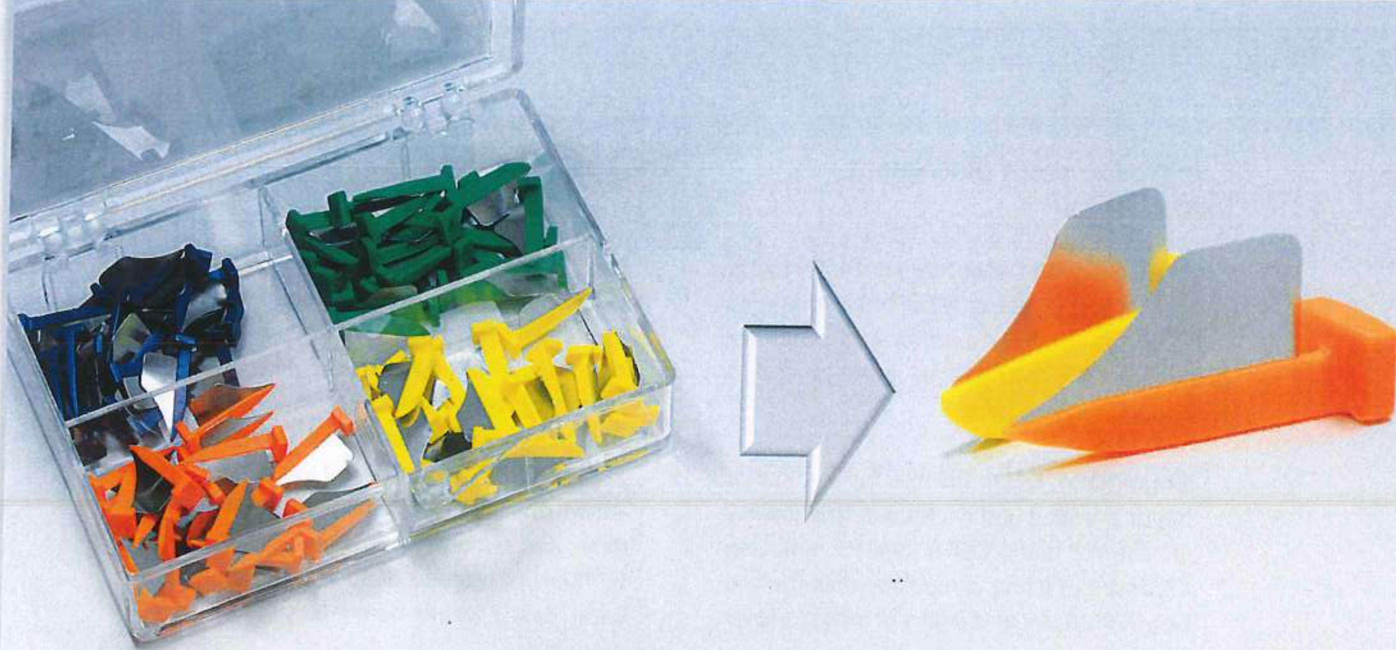
Single-sided oscillating diamond tips (SonicSys, KaVo) on an air scaler (eg, AS2000 by NSK in Fig 3-27e [top] or SonicFlex 2000N by KaVo) allow safe and minimally invasive shaping and finishing of proximal and proximogingival walls and can significantly reduce the risk of damage to adjacent dentition and soft tissues (see also Fig 3-51).

The air-scaler handpiece vibrates at a frequency of 6000–6500 Hz (max 3.5 bar). Five different tips (40-micron medium grit) can be used at pressure < 2 N (Fig 3-27e, *bottom*):

- **Half-torpedo (tip nos. 28 & 29):** Shaped like a blade with a chamfer design for cavosurface bevel of interproximal Class 2, 3, 4, and even veneer preparations (see chapter 6, Figs 6-30 and 6-31). It is ideal when facing a reduced maxillomandibular distance.
- **Bevel (tip nos. 58 & 59):** Conical shape (somewhat like a Chinese straw hat) with 45-degree bevel cut for cavosurface bevel of Class 2 (see Fig 3-51f) and Class 3 (Fig 3-27f) preparations.
- **Large (tip nos. 30 & 31) and small (tip nos. 32 & 33) hemispheres:** Shaped like hemisectioned round bur (diameter 1.5 or 2.2 mm) for Class 2 and 3 micropreparations and lateral access to small interdental caries (see Fig 3-52).
- **Prep Ceram (tip nos. 51 & 52):** Shaped like an inlay, specially developed for inlay/onlay preparations (see chapter 4, Fig 4-14) with optimum taper (laterally 60 degrees and cervically 75 degrees).

3-27c

FIG 3-27 *(cont)* **Oscillating preparation instruments.** *(c)* Amalgam restorations damaged during Class 2 preparation on the adjacent tooth. *(d)* The FenderWedge combines a plastic wedge and sectional metal band for fast placement and protection during preparation. *(e)* SonicFlex 2003 *(top)*. Five of the SonicSys tips *(bottom)*; each tip is available in two mirrored designs, one for mesial access and one for distal access. *(f)* Bevel tip no. 58 in action in a small Class 3 defect at the distal surface of this lateral incisor. The use of water is mandatory to cool the instruments and allow smooth action.



3-27d

3-27e

3-27f

Composite resin placement instruments

CompoSculp by Dr Didier Diestchi (Hu-Friedy) is an original and universal set of five instruments that can be used for anterior and posterior restorations (Fig 3-27g). They are color-coded for quick identification:

- **Green (DD1, DD2):** Pointed for fine sculpting of grooves and occlusal details (mainly in posterior teeth). DD1 is ideal for removing excesses of luting composite resin (before polymerization) at margins of inlays/onlays/veneers.
- **Yellow:** Round-ended condenser **(DD3)** and spatula **(DD4)** for inserting, condensing, and shaping the composite resin in small preparations (anterior and posterior teeth).
- **Red:** Round-ended condenser **(DD5)** and spatula **(DD6)** for inserting, condensing, and shaping the composite resin in large preparations (anterior and posterior teeth).
- **Blue (DD7, DD8) and gray (DD9, DD10):** Sharp ultrafine spatulas with various off-angles for shaping embrasures and marginal ridges. The sharpness of DD7–DD10 makes them also efficient to scrape flashes of polymerized resin from tooth surfaces.

LM-Arte set (LM-Dental) is another universal five-instrument set. Composite resin increments can also be carried into the preparation and condensed using a microbrush slightly humected with adhesive resin, which seems to decrease the risks of interlayer gaps and porosities.[104]

Enamel adhesives

Enamel/dentin adhesion is a very critical step of the restorative procedure. Operators should always keep in mind that the use of any form of peroxide (bleaching agents but also whitening mouthrinses, toothpastes, strips, etc) will affect the performance of the bond. Patient questionnaires should cover this topic, and patients should be advised to interrupt the use of such products for at least 3 weeks before restorative procedures.

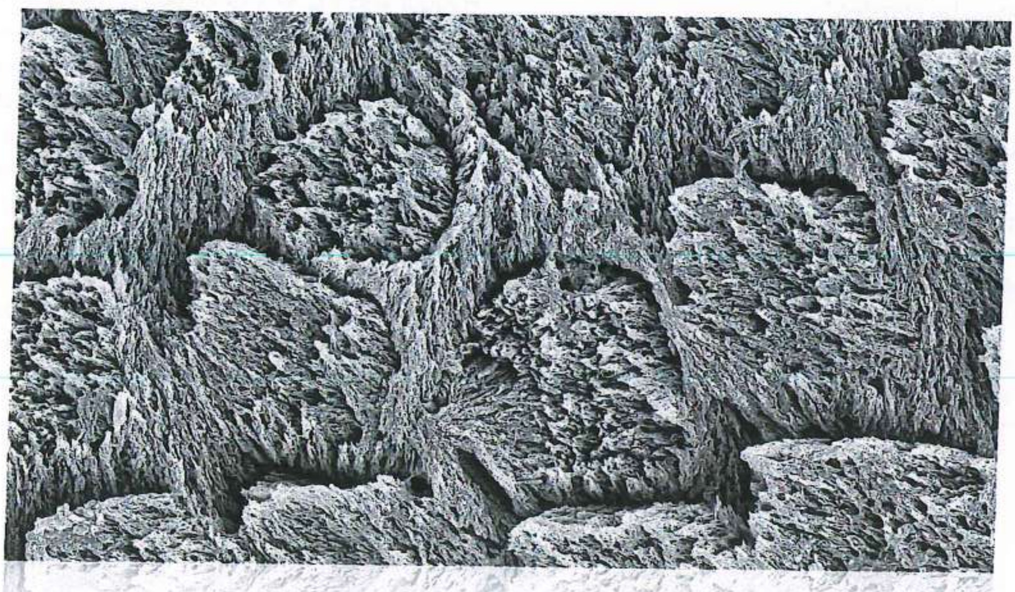
Successful execution of enamel bonding provides the major retentive feature of the restoration even in the absence of another type of mechanical retention or stabilization. The effectiveness of this procedure requires the use of 35% to 37% phosphoric acid for 20 to 30 seconds, followed by thorough rinsing and drying before the application of a low-viscosity adhesive resin (to form resin tags) and subsequent polymerization.[105]

Enamel is not isotropic, and hence the walls of the preparation should be contoured to give transverse sections of enamel prisms, which will provide significantly higher bond strength than longitudinal sections of enamel prisms (see Fig 3-51a).[106–108] The topography of the resin tags therefore vary with the location on a tooth and are dependent on the orientation of prepared cavity walls (see Fig 3-51a).

FIG 3-27 *(cont) (g)* **Sculpting instruments.** CompoSculp kit with five color-coded instruments that cover all needs for inserting, condensing, and shaping composite resin material.

FIG 3-28a Scanning electron micrograph (SEM) of etched enamel showing ideal honeycomb structure of etched enamel prisms with transverse section (prism width approximately 5 microns). This type III etching pattern is mixed dissolution of prism core (type I) and prism periphery (type II). The pattern is also very brittle, and gentle application of the adhesive is required to respect its integrity. (Image courtesy of Prof Jorge Perdigão, University of Minnesota.)

3-27g



3-28a

ETCHED ENAMEL

Tooth preparations modified to incorporate a cavosurface bevel on enamel, when possible, are recommended, especially for interdental margins.[109] ***Hence, the use of oscillating tips is the safest recommended approach (see Fig 3-27f).***[103]

Note that a prismless or aprismatic enamel layer (averaging 30 microns) may be found at the surface of newly erupted permanent teeth and is always found at the surface of newly erupted primary teeth.[110] This layer is typically found at cervical surfaces and within the fissure system. It is more mineralized (absence of organic prism boundaries) and will not yield good bond strength unless slightly ground (with a diamond bur) or etched more heavily. Even though aprismatic enamel can be viewed as a natural acid-resistant barrier to caries, its removal is recommended for improved bonding.[111,112]

Another important tip is to avoid rubbing the etched enamel (Fig 3-28) during the application of the adhesive resin or even while priming the dentin.[113] While the contamination of enamel with the priming resins does not decrease the bond strength, rubbing the etched enamel surface while massaging the dentin with microbrushes should be avoided.[113]

Dentin adhesives

The dentin substrate is much more complex than enamel, so numerous considerations require attention during dentin bonding.

DEJ as the gold standard

The ultimate goal of dentin bonding is the emulation of the ideal biologic "bond" between enamel and dentin at the dentinoenamel junction (DEJ). The strength of this natural assembly was evaluated at approximately 51.5 MPa in a microtensile bond test.[114] It can be explained in part by the structure of the DEJ and its rough and multiscalloped nature (see chapter 1, Fig 1-10).[115]

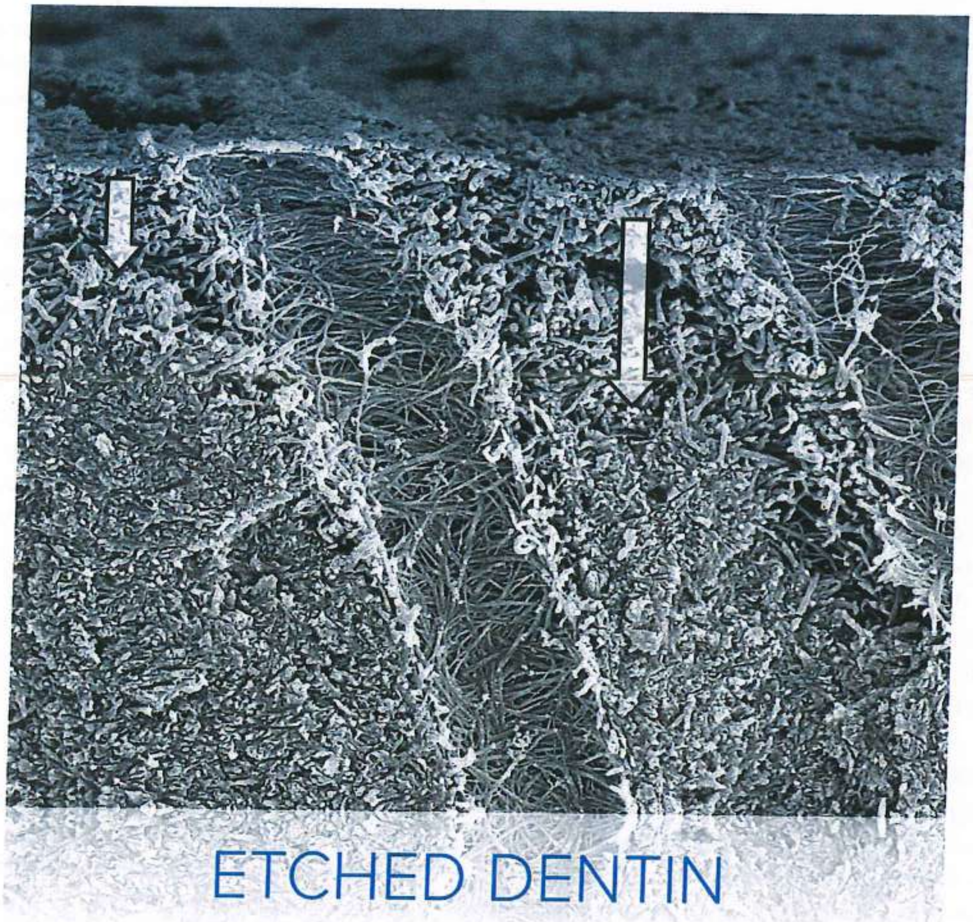
Hence, it seems advisable to mimic the roughness of the DEJ when preparing the dentin for bonding. Carbide burs can only produce smooth surfaces. Instead, systematic use of coarse diamonds for dentin preparation is recommended prior to dentin bonding,[116,117] and even more so when bonding to biocorroded ("eroded") dentin.[118]

Following preparation, the dentin is covered with a smear layer (debris of collagen and minerals), which impedes the bonding process. The two approaches available to remove the smear layer define the main families of modern dentin bonding systems: the total-etch approach and the self-etch approach.

Historical perspective

Table 3-2 lists the adhesive milestones and generations of dentin bonding systems in chronologic order.[119–124] Swiss chemist Oskar Hagger was the first to introduce a functional adhesive monomer in 1951—glycerphosphate dimethacrylate (GPDM)—which was able to penetrate the dentin surface and form an intermediate layer (later known as the *hybrid layer*) as shown by Kramer and McLean in 1952.[121] This likely made GPDM the first self-etching monomer, which is still used today in very popular products such as the OptiBond family (Kerr). In addition to introducing enamel etching in 1955,[105] Buonocore and his team also tried to bond to etched dentin as early as 1956.[122] Unfortunately, this procedure

FIG 3-28b SEM of etched dentin (cross-sectional view). The demineralization depth of the intertubular dentin is approximately 2–4 microns *(arrows)*. (Image courtesy of Prof Jorge Perdigão, University of Minnesota.)



3-28b

TABLE 3-2 Chronologic adhesive milestones and generations of dentin bonding systems

1951	First adhesive monomer: glycerophosphate dimethacrylate (GPDM) by Hagger (Switzerland)
1952	First-generation adhesive with GPDM (Sevriton, Kramer, and McLean, UK)[121]
1955	Enamel etching (Buonocore, USA)[105]
1956	Dentin etching with 85% phosphoric acid for 30 seconds (Buonocore)[122]
1960s	Concentration of acid reduced to 35% for 20–30 seconds
1970s–1980s	Second-generation, smear layer maintained but poor results (5–6 MPa)
1979	Removing the smear layer (Fusayama et al, Japan)[123]
1980s	Third-generation, modified or completely removed smear layer
1982	Hybrid layer (Nakabayashi et al, Japan)[124]
Late 1980s	Fourth-generation, three-step (etch-and-rinse)
Early 1990s	Fifth-generation, two-step (etch-and-rinse)
Late 1990s	Sixth-generation, two-step (self-etch) and one-step (with mixing)
2000s	Seventh-generation, one-step (without mixing)
2010s	Eighth-generation, multimode universal adhesives (etch-and-rinse or self-etch) with 10-MDP

10-MDP, 10-methacryloyloxydecyl dihydrogen phosphate.

met with very limited success, due to the poor wetting of dentin by the former hydrophobic resins. Researchers and manufacturers tried to develop chemical dentin bonding agents to be placed on top of the smear layer because etching of dentin (in order to obtain a micromechanical bond) was suspected of potential harmful effects to the pulp. This first generation of dentin adhesives resulted in poor performance, mainly from the weak adhesion of the smear layer to the underlying dentin.[125] The development of different treatments of the smear layer resulted in an improved but still insufficient dentin bond.[126] This second generation of adhesives was quickly followed by the third- and fourth-generation systems, which relied on the complete removal of the smear layer and partial decalcification of the dentin by an acid treatment.[123,127] This historical turning point in dentin bonding was initiated by Fusayama in 1982.[123]

The golden standard 3+1 STEPS (Fig 3-28c)

The demineralization resulting from the acid treatment (STEP 1, etch-and-rinse) exposes collagen fibers on the dentin surface that can then be impregnated with a "cocktail" of resin monomers with affinity for collagen, calcium, and water. This is the primer (STEP 2), for which an ethanol/water-based solvent is used as a carrier for the monomer cocktail. Gentle air-drying is necessary to promote evaporation of the solvent. This results in a resin-infiltrated collagen network, originally called the *hybrid layer* by Nakabayashi et al in 1982, also known as the *interdiffusion zone*.[124,128] The next step is the application of a more hydrophobic resin coating or adhesive resin (STEP 3) and its subsequent light polymerization (STEP 4). Along with the adherence and diffusion into the hybrid layer, the adhesive resin forms resin tags into the open dentinal tubules, resulting in a strong micromechanical interlocking. This fourth step (light polymerization) is often not mentioned but proves critical to the successful completion of the bond, as will be explained later when presenting the immediate dentin sealing technique (see chapter 4, section 4.4).

A certain thickness of adhesive resin is required (> 40 microns) in order to properly polymerize the adhesive and avoid oxygen inhibition of the hybrid layer.

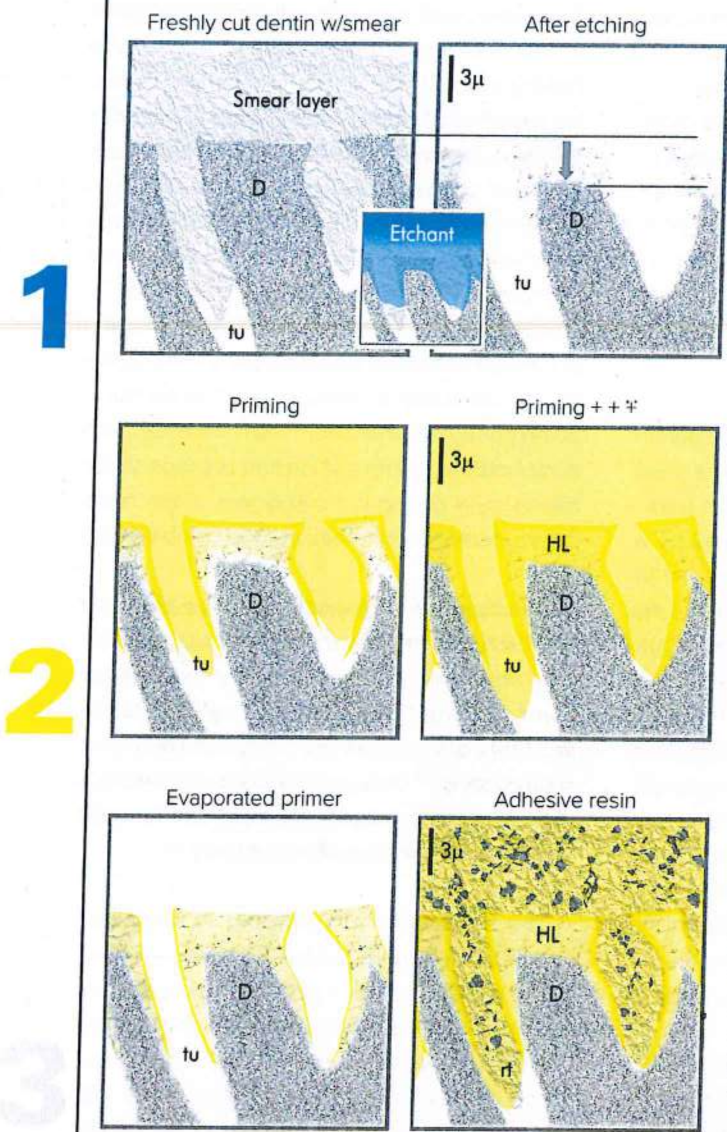
The rationale that lies behind the fourth generation is to obtain simultaneous bonding and sealing of the dentin, and thus theoretically prevent bacterial leakage, which is presumed to be the cause of most biologic failures encountered with adhesive restorations.[129] Using 30% to 40% phosphoric acid, etching is no longer regarded as harmful, which makes fourth-generation adhesives the first ones able to fully develop the fundamental mechanisms of adhesion (surface wetting, microretention, and chemical interaction).

Further developments of fifth, sixth, and seventh generations—The simplification era

The 1990s and early 2000s were marked by a strong desire from both clinicians and manufacturers to develop simplified adhesive systems (Fig 3-29a).[119,130] Despite this tendency, studies repeatedly confirmed that conventional three-step etch-and-rinse adhesives still perform most favorably and are most reliable in the long term.[119,130]

When primers are mixed with adhesives (fifth generation, etch-and-rinse two-step), the adhesives are more permeable and hence absorb more water over time than previous generations of adhesives. The most recent self-etch one-step adhesives are even more hydrophilic and more permeable to water derived from the underlying bonded dentin. This permeability can lead to a wide variety of problems, including accelerated degradation of resin-dentin bonds.[131] In addition, self-etching systems are not able to etch enamel properly. One-bottle systems (sixth and seventh generations) also show a more pronounced fatigue behavior compared to multistep systems,[132] and two-step self-etch adhesives (fifth generation) are less resistant to fatigue than three-step etch-and-rinse adhesives (fourth generation).[133] For this reason, simplified universal adhesives should rather be used in self-etch mode (first light cured) and protected by an additional layer of hydrophobic adhesive.[134]

Gold standard
Dentin bonding STEPS
Always start with freshly cut dentin!



→ Etching
(Phosphoric acid 35%–37.5%)

10–15 sec + Abundant rinsing and gentle air-drying.

→ Smear layer removed + 2–4 microns of dentin demineralized.

→ Priming
(Functional, hydrophilic monomers with water/alcohol solvents)

Scrubbing motion for 15 sec (repeat 2–3×), gentle air-drying (surface should look shiny but without liquid film).

→ Infusion of hydrophilic and functional monomers → Hybrid layer.

3 → Bonding
(Hydrophilic/hydrophobic monomers, *radiopaque* fillers 48% w)

Light scrubbing motion for 15 sec, gently remove excess from occlusal margins (gentle blow or dry brush).

→ Protection of the hybrid layer.

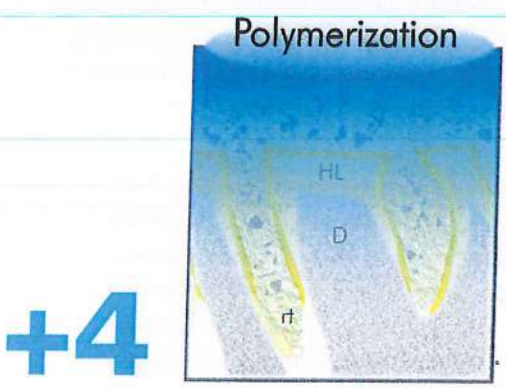


FIG 3-28c Schematic transmission electron microscopic views of dentin bonding steps. *Gray arrow,* demineralized dentin; D, dentin; tu, dentinal tubule; HL, hybrid layer; rt, resin tag. Note: Smear layer thicknesses may vary significantly based on dentin cutting technique (diamond vs carbide burs). Three different mechanisms of adhesion are established: surface wetting, microretention, and chemical interaction. Functional monomers (GPDM or 10-MDP*) are acidic molecules that may act as etchant (partially dissolving the smear layer and demineralizing hydroxyapatite), enhancing monomer penetration and allowing for the potential for chemical interactions with dental substrates. *10-MDP is a thinner molecule than GPDM and is the preferred monomer for self-etching adhesives.

A newest eighth generation of universal adhesives has been defined, as they can be applied in three different modes.[120] They include the functional monomer 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), which is more adapted to the self-etch approach compared to GPDM (thicker molecule). The eighth generation of adhesives remain vulnerable to a number of problems inherent to simplified adhesives as discussed above.

Healthy structural dentin bonding technique

In this context, use of a fourth-generation dentin bonding agent (DBA) can still be recommended. The unjustified commercial plethora of adhesive systems was demonstrated in 2012 by a meta-analysis of the parameters involved in dentinal adhesion.[135] The study revealed the list of the 10 most tested adhesive systems. OptiBond FL (Kerr), an etch-and-rinse three-step, and SE Bond (Kuraray), a self-etch two-step, were the two systems at the top of the list with the highest immediate and predicted 1-year bond strength. Marketed in 1992 (first version with dual polymerization) and then in 1994 in its still-current version, OptiBond FL remains the undisputed benchmark with an adhesion force of 50 MPa—able to mimic the DEJ[114]—and the lowest degradation rate with a 94% retention rate of nonretentive class V restoration after 13 years.[136]

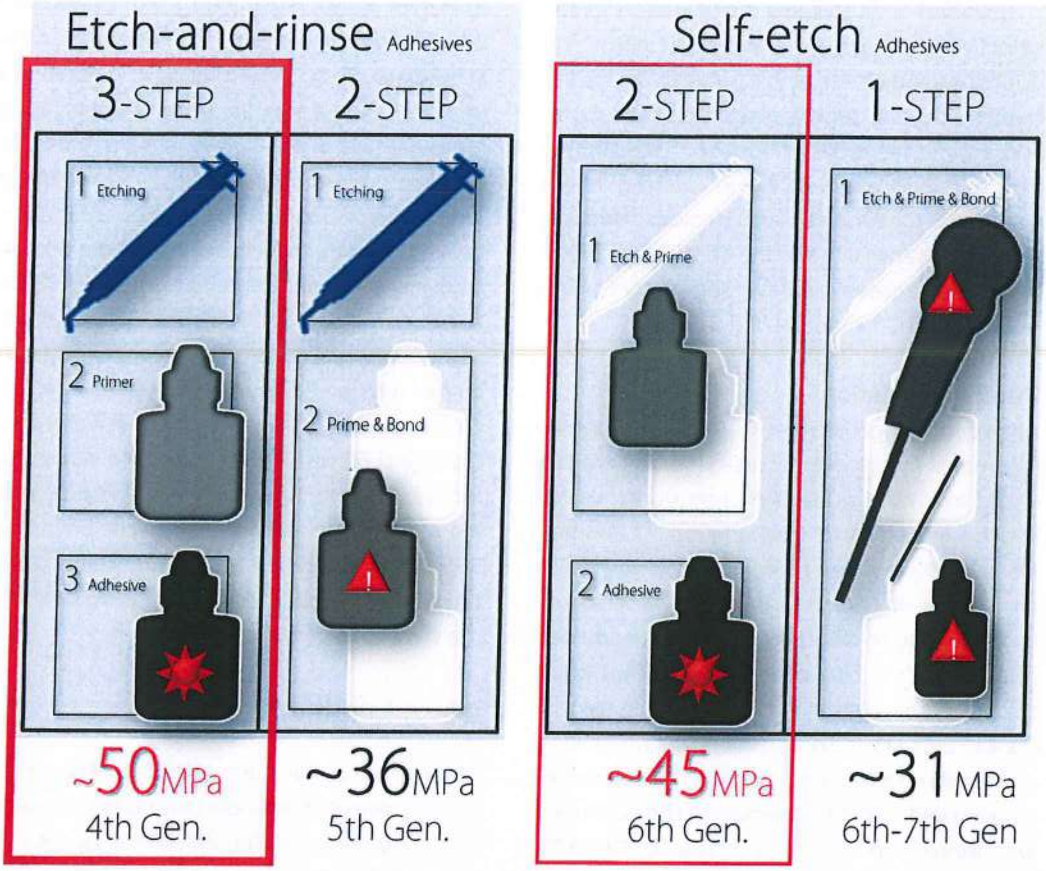
The adhesive resin of OptiBond FL is also radiopaque, a significant clinical advantage to detect interdental excesses and resin flashes on the radiographs. Another essential element is the method of application of the adhesive. The hybrid layer remains extremely thin: between 1 and 3 microns depending on the system. Adequate polymerization of the adhesive is essential to protect the hybrid layer.[137] As such, it is essential to recognize the inhibitory effect of oxygen on the polymerization of resins,[138] which can easily reach a depth of 40 microns and influence the quality of adhesion to dentin.[139]

As a result, perfect polymerization of the adhesive interphase requires an adhesive resin layer of about 60 to 80 microns. A filled adhesive system such as OptiBond FL therefore represents a certain advantage because of the viscosity of the adhesive resin, which contains about 48% of fillers in weight, including substantially radiopaque fillers. As such, this adhesive behaves also as a flowable composite (liner) and thus allows structural adhesion with the restoration. One study recommends a thick layer (double application) of adhesive resin to improve the adaptation of the restoration.[140] It is important to understand this structural aspect of dentinal adhesion. An extremely thin adhesive (eg, as in one-step systems) always has the risk of being poorly polymerized,[137] with all the resulting complications (compression and damage to the hybrid layer during the placement of the restoration, increased permeability and solubility, etc).

In summary, the etch-and-rinse three-step and self-etch two-step systems demonstrate not only improved performance but also better bond stability,[135] which can be related to the fact that both systems use a separate adhesive resin coating.[141] They proved to increase the survival of ceramic inlay/onlay restorations when compared to the simplified systems.[142]

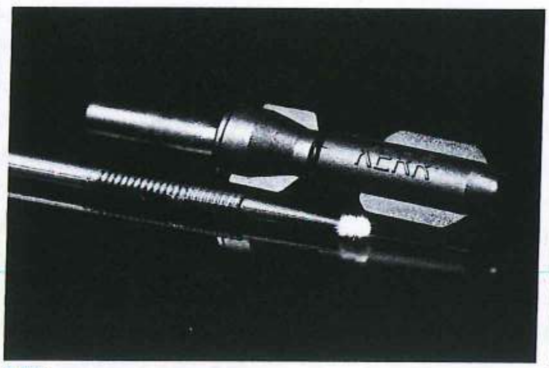
The superiority of OptiBond FL might be explained by its unique filled adhesive resin and by the fact that self-etch systems do not remove the smear layer but instead modify and incorporate that debris into the hybrid layer. Total impregnation of the demineralized collagen fibrils with "cocktails" of resin monomers from the primer is paramount to performance of etch-and-rinse adhesives. Because there are solvents in primers, bottle systems are subjected to evaporation each time the bottle is opened.

The use of single-dose systems (Figs 3-29b to 3-29d) can prevent solvent evaporation as well as the sedimentation of the filler in the adhesive bottle. The single doses can also be preheated for 15 minutes to improve the performance of the adhesive.



3-29a

3-29b



3-29c

3-29d

FIG 3-29 Contemporary dentin bonding systems. *(a)* The etch-and-rinse three-step (eg, OptiBond FL) and self-etch two-step (eg, SE Bond) systems present a separate adhesive resin coating (mostly hydrophobic). The etch-and-rinse two-step (eg, Prime & Bond NT, Dentsply) and self-etch one-step (eg, Adper Prompt L-Pop, 3M) systems present a more hydrophilic adhesive resin. The numbers at the bottom of each column represent the microtensile bond strength of the aforementioned products as predicted by Artificial Neural Network.[135] (Modified from Van Meerbeek et al.[119]) OptiBond FL is available in bottles or unidose systems. The unidose system presents two sealed rockets: yellow with the primer *(b)* and black with the adhesive resin *(c)*. Note the high viscosity and uniform density of the radiopaque filled adhesive resin *(d)*. (Photography courtesy of Dr Mehrdad Razaghy.)

Etch-and-rinse systems not only allow for the selective etching of enamel but also permit the operator to adapt the etching time to the type of dentin. Sclerotic dentin presents closed tubules and a hypermineralized surface,[143] resulting in thinner hybrid layers unless the etching time is doubled.[144] OptiBond FL also demonstrated low technique sensitivity and the ability to withstand shrinkage stresses in unfavorable cavity configurations (high C-factor; see Fig 3-36).[145,146]

Bond degradation

It has been suggested that host-derived enzymes (eg, matrix metalloproteinsases [MMPs]) are activated following adhesive procedures, which explain in part bond degradation.[147] Chlorhexidine (CHX) and benzalkonium chloride (BAC) are known inhibitors of MMPs and were shown to reduce bond degradation of etch-and-rinse adhesives.[148,149] Use of a BAC-modified phosphoric acid or pretreatment of etched dentin with 0.2% to 2% CHX are possible options when using etch-and-rinse two-step systems. The necessity of using MMP inhibitors remains to be confirmed with three-step systems such as OptiBond FL. The proven clinical performance of this robust adhesive may not justify this additional step.

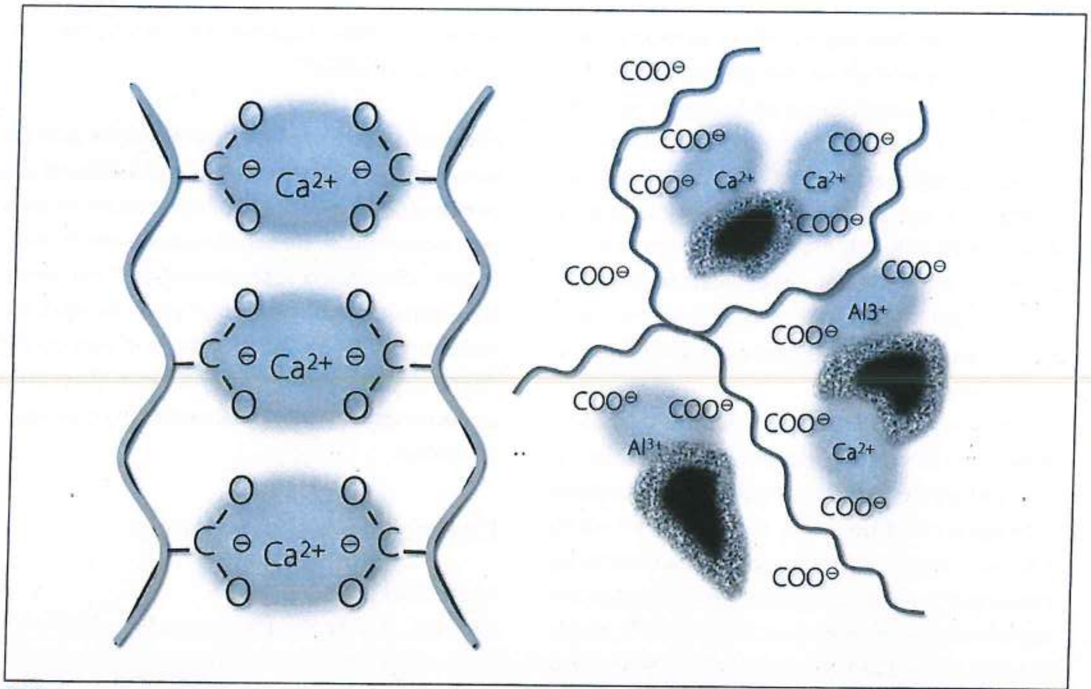
In any case, etching/priming/bonding should be always be preceded by dentin decontamination with low-speed bur cutting under abundant water spray to always start the bonding procedure on a freshly diamond-cut dentin.

Immediate dentin sealing (see chapter 4, section 4.4)

Because the structural dentin bond uses space (aforementioned thickness of about 60–80 microns), it is essential that this layer be included during the impression for semi-(in)direct or indirect restorations, whether analog or digital. Hence the need to apply the adhesive system to dentin immediately after tooth preparation, before impression-making. This approach, called *immediate dentin sealing (IDS)*,[150] in addition to demonstrating a superior bond strength, allows for a multitude of protective functions during and after the provisional phase to avoid anesthesia for the final restoration try-in and possibly during delivery, as well as facilitate immediate occlusal adjustments. A methodical application of IDS has been described,[151] and more than 20 advantages of the technique have been enumerated by the author with over 25 years of experience (see chapter 4, Table 4-4). A filled adhesive such as OptiBond FL represents a definite advantage for the IDS technique due to its ability to generate a consistent layer of resin, while an unfilled resin may generate insufficient thicknesses for adequate polymerization in the convex areas of the dental preparation.[152]

Glass-ionomer cements

Introduced in the early 1970s by Wilson and Kent,[153] conventional glass-ionomer cements (GICs; eg, Ketac-Molar, 3M or Fuji IX, GC) are obtained by mixing water, acidic polymers (polyalkenoic acids), and a reactive glass powder (calcium-fluoro-alumino-silicate glass). They set by acid-base reaction (chemical reaction, -COOH groups attacking the glass particles), forming a gel interphase (polycarboxylate matrix) between the glass particles (Fig 3-30). GICs can be considered both as a self-adhesive cement and as a self-adhesive restorative material. The clinical use of GICs was particularly significant in the 1980s and early 1990s because of the poor dentin bonding performance of resin bonding systems. Fluoride release from the glass particles, self-adhesive properties, and minor shrinkage on setting (see Fig 3-31) provided decent clinical service in situations where composite resin restorations would typically fail due to shrinkage and insufficient bonding (eg, Class 5 restorations).[75]



3-30a

3-30b

FIG 3-30a Simplified schematic of glass-ionomer setting. (Modified from ESPE product dossier.[154]) Upon mixing powder and aqueous acidic solution, carboxylate ions (COO^-) and H^+ ions are released. The surface of the glass particles is attacked by the positive ions and releases Ca^{2+} ions that cross-link with the polyacrylic acid chains to form the polycarboxylate gel *(left)*. Additional Al^{3+} ions are then released from the glass and contribute to the Ca-Al-carboxylate gel *(right)*. Note the black areas corresponding to the unreacted core of the glass particles embedded in the gel matrix.

FIG 3-30b Automix conventional GIC. Automix dispensing capsules have reduced time and technique sensitivity when using GIC (eg, Ketac Quick Molar Aplicap, 3M). The capsule is activated for a minimum of 2 seconds and then mixed for 10 seconds in a high-frequency mixer (only 8 seconds in RotoMix mixer by 3M).

The setting and stability of conventional GICs is highly dependent on the presence of water. They bond decently to dentin by interaction with the calcium in dentin following the removal of the smear layer with a mild acid (to avoid demineralization; eg, 20% to 25% polyacrylic acid for 10 seconds[155] or 5% NaOCl or 20 seconds[74,75]). Dentin should not be dehydrated before GIC application because the desiccated dentin would in turn alter the water balance of the GIC during early setting.[156]

Clinically, GIC used alone would ultimately suffer from deficient fracture and wear resistance and surface degradation (Fig 3-31).[157] Those disadvantages could be easily avoided when using GIC as a base material (a sort of "nonshrinking megafiller") under composite resin restorations, the so-called *sandwich techniques*,[158,159] which are still relevant today (see Fig 3-61). Alternatively, deficiencies of GICs led to the development of resin-modified GICs (RMGICs) and polyacid-modified composite resins (compomers) by the progressive change of the acid-base chemistry to resin polymerization chemistry (Fig 3-31). Interestingly, compomers present virtually no advantages over composite resins. RMGICs, on the other hand, present some advantages over GICs such as the photopolymerization and better resistance to desiccation, which come at the cost of decreased fluoride release, shrinkage on setting (resin type polymerization), followed by significant water sorption (swelling). Indeed, RMGICs contain hydrophilic monomers (eg, HEMA) to replace the water component of the conventional GICs, which also causes significant hygroscopic expansion.[160,161] Hence, conventional GICs remain a gold standard among polyalkenoate cements. Even though they do not photopolymerize, it can be still recommended to apply the polymerization light during the setting of a GIC to accelerate the setting. LED lights will produce enough heat (yet will be unable to damage the pulp because of the low thermal conductivity of the GIC),[162] which is known to improve the mechanical characteristics.[163] The surface of the GIC can be covered with adhesive resin to prevent desiccation during light application (see super-closed sandwich technique in Fig 3-62).[164]

The main uses of GICs and RMGICs can be summarized as follows: (1) as a provisional restoration; (2) as a dentin replacement (nonshrinkage base) under direct composite resin restorations (sandwich restorations, see Fig 3-60); (3) in nonvital teeth as a liner/barrier to separate endodontic filling materials from solvents during dentin bonding (see chapter 4, Fig 4-15); and (4) as cements for endodontic posts and crowns, if indicated.

Composite resin materials

Historical perspective[165]

Unfilled polymethyl methacrylate or PMMA is used today in powder/liquid form as a provisional material (see chapter 6, Fig 6-49), for example for mock-ups and as a bone cement in orthopedics. Its first use, however, was as a dental esthetic filling material in the 1950s. The first composite resins used in the 1950s were in fact glass-filled PMMA resins. The next development led to the use of amine-cured epoxy resins due to their adhesiveness to hard tissues.

A compromise between epoxy and methacrylate resins was conceived in 1956, and in 1962 Ralph L. Bowen patented a new large nonvolatile monomer, bisphenol A diglycidyl methacrylate or bis-GMA,[166] which was able to polymerize not only more rapidly but with less polymerization shrinkage, namely a third of that of methyl methacrylate.

Bis-GMA is not to be confused with bisphenol A (BPA), which is present as an impurity in some bis-GMA resins or as a degradation product (hydrolysis) from other resins (bisphenol A dimethacrylate, or bis-DMA used in sealants).[167] In the 1970s and 1980s, composite resin restorations were used only if the tooth would not have to bear significant functional loads, such as the anterior dentition. Following the work of Bowen[166] and Buonocore,[105] the physicochemical

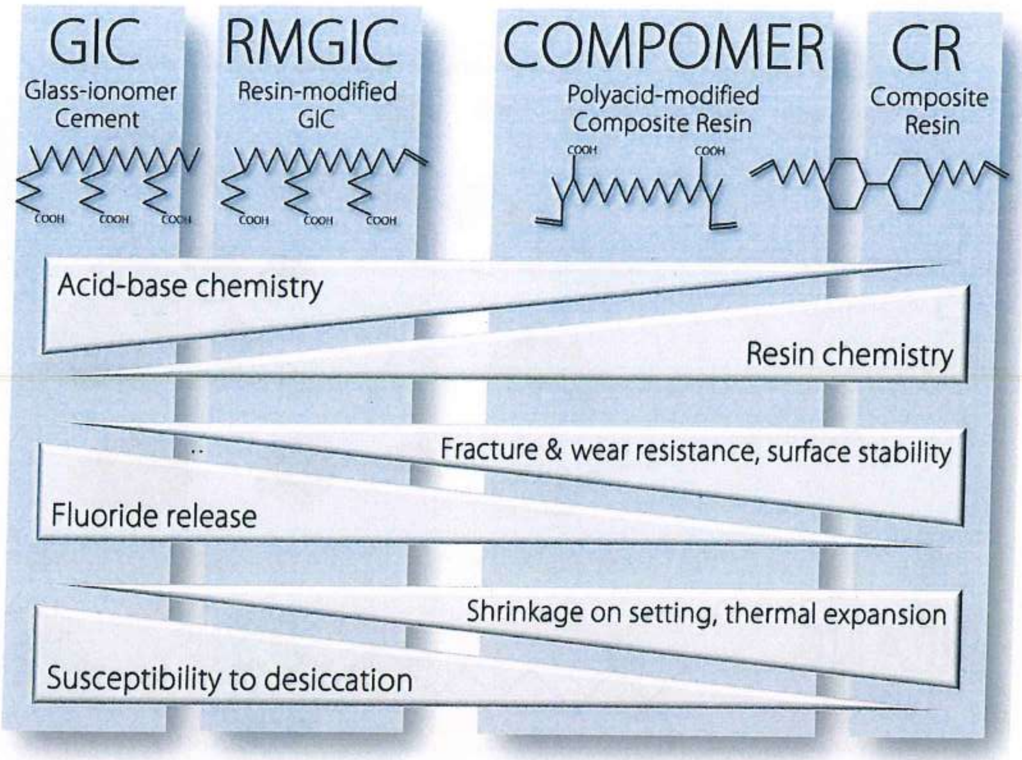


FIG 3-31 Tooth-colored restoratives from conventional GIC to composite resin. Note the progressive change in the chemistry from the acid-base (COOH groups, *left*, GIC) to resin chemistry (C=C dimethacrylate groups, *right*, composite resin). (Modified with permission from Albers.[157])

and esthetic properties of composite resins have been significantly improved by increasing the inorganic filler content while decreasing the individual size of the filler particles (Fig 3-32 and Table 3-3).[168–171] Macrofilled materials with particles far exceeding 1 micron (ground quartz and radiopaque glasses) were difficult to polish. For this reason, they were soon replaced with homogeneous microfilled materials made of 0.04-micron (ie, 40 nanometers) amorphous spheroidal silica obtained by pyrolysis. They were in fact nanofilled composite resins because nanotechnology includes the 1- to 100-nm size range. With a higher total filler-matrix interface (compared to macrofilled), the microfilled composites exhibited higher viscosity, which limited significantly their filler content (45% in weight). This was resolved by incorporating larger highly filled prepolymerized resin complexes, the so-called *inhomogeneous microfilled*. Bis-GMA resin matrix viscosity had also to be modified with a proportion of less viscous monomers such as urethane dimethacrylate (UDMA) or lower molecular weight monomers like triethylene glycol dimethacrylate (TEGDMA).[172] Those molecules also helped to improve the cross-linking of the polymer chains.

The first hybrid composite resins (also called* coarse hybrids*) were obtained by mixing the macroparticles and microparticles (bimodal). A turning point was the introduction of the fine hybrid family in the 1980s (Herculite, Kerr), the macroparticles of which were further ground not to exceed 1 micron (microparticles). Also called* submicron *or* microhybrids, *they featured an optimized blend of polishabilty and strength for anterior and posterior use. Herculite XRV has remained a landmark microhybrid material until today.

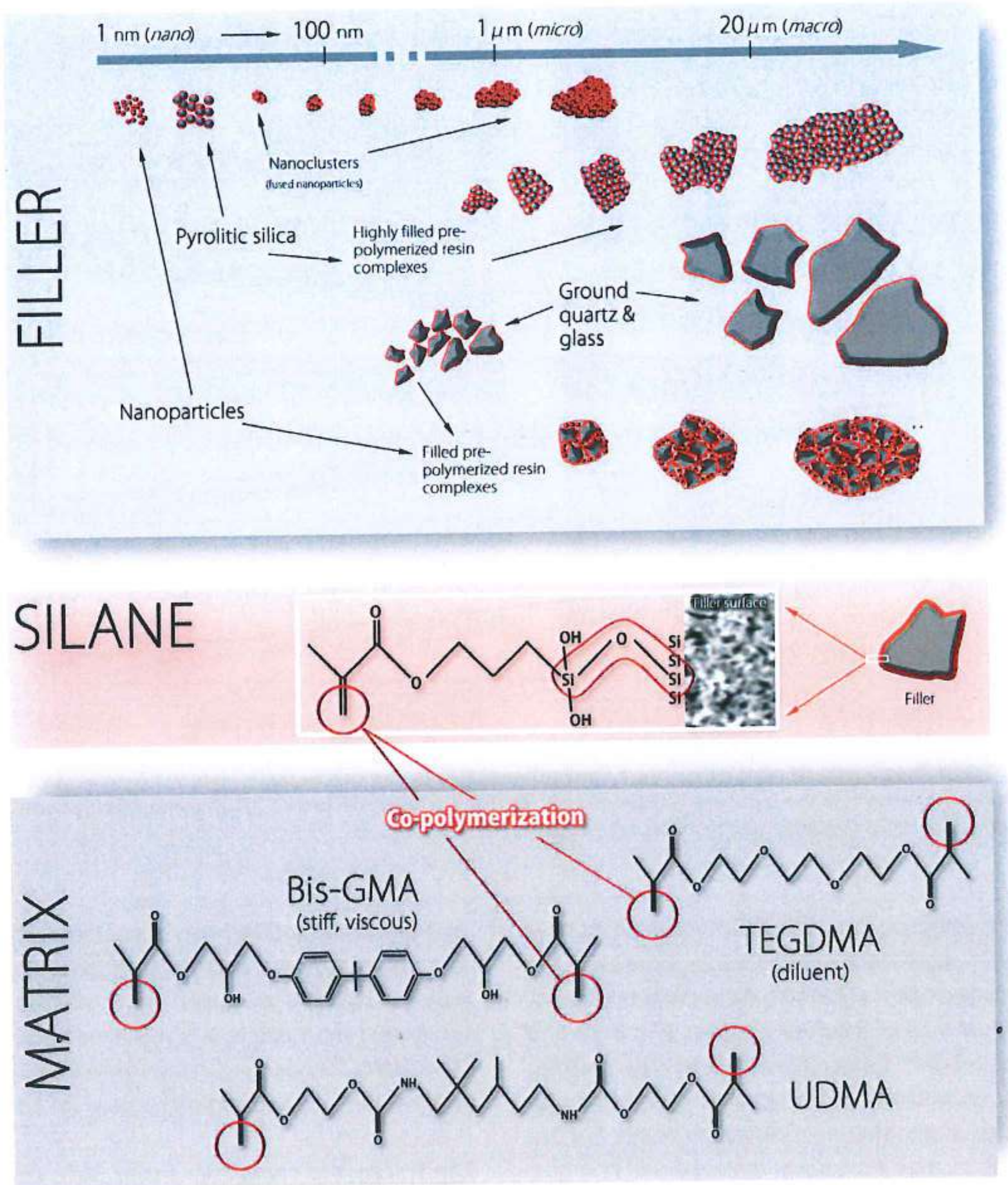


FIG 3-32 Possible components of composite resin systems. Ceramic **FILLER** technology includes a wide range of particle types (*top*, not all types illustrated). Fillers are silanated to ensure continuity and homogeneous distribution within the resin matrix. The **SILANE** molecule is bipolar: The hydrophilic side forms a covalent bond called *siloxane* (-Si-O-Si) with the silicium in the filler, and the hydrophobic side copolymerizes with the resin **MATRIX** (more information about silane chemistry is found in chapter 6, Fig 6-76). Urethane dimethacrylate (UDMA) is also used as a base for the resin matrix, but it has a higher concentration of double bonds than bis-GMA, yielding a higher degree of conversion and cross-linking. UDMA is less viscous than bis-GMA and does not necessarily require the addition of triethylene glycol dimethacrylate (TEGDMA) as a diluent.[169] TEGDMA has the highest concentration of double bonds, and when mixed with bis-GMA it increases the degree of conversion and cross-linking[169] but at the expense of increased polymerization shrinkage.[170]

TABLE 3-3 Historical classification and evolution of composite resin materials based on filler composition

Period and composite resin type	Filler type	Filler content (% weight)	Average particle size (μm)	Particle distribution (μm)	Examples of brand names
1970s					
Macrofilled (conventional)	Monomodal: Milled, edge-shaped macroparticles	60–80	> 5	1–40	Estilux Posterior (Kulzer) (initial formulation) Concise (3M)
LATE 1970s					
Homogeneous microfilled ("nanofilled")	Monomodal: Pyrolytic silica	35–45	0.04	–	Dual Cement (Ivoclar Vivadent)
Inhomogeneous microfilled ("nanofilled")	Monomodal: Pyrolytic silica Prepolymerized resin complexes (PPRC)	45–79	0.04	– 1–200 (PPRC)	Silux Plus (3M) Heliomolar (Ivoclar Vivadent) Durafill (Kulzer) Filtek A110 (3M)
EARLY 1980s					
Hybrid (Coarse)	Bimodal: Milled, edge-shaped macroparticles Pyrolytic silica	70–80	2–15 0.04	–	Occlusin (Coe Lab) FulFil (Caulk/Dentsply) Pekafill (Bayer Dental) Dicor MGC (luting) (Dentsply)
LATE 1980s					
Fine hybrid (submicron, microhybrid)	Bimodal: Microparticles Pyrolytic silica	70–80	0.5–1 0.04	0.1–10	Herculite XRV (Kerr) Tetric (Ivoclar Vivadent) Vit-l-escence (Ultradent) Enamel Plus HRi (dentin) (Micerium) Prisma APH, TPH (Dentsply) Clearfil AP-X (Kuraray) Variolink (luting)
1990s					
Small-particle spheroidal (3M)	Monomodal: Patented milled spheroidal zirconia-silica particles	78–85	0.6	0.01–3.5	Z100 (3M) Paradigm MZ100 (CAD/CAM) (3M) Filtek Z250 (3M) Filtek P60 (3M) Filtek Bulk Fill (3M)
Inhomogeneous small-particle spheroidal	Monomodal: Silica-zirconia Prepolymerized resin complexes	82	0.2	– 1–80 (PPRC)	Palfique Estelite (Tokuyama) Estelite Sigma (Tokuyama)
Fiber-reinforced condensable*	Trimodal: Chopped glass fibers Micro- or macro-particles Pyrolitic silica	83–85	0.04	60–80 (fiber length) 80–120 (fiber length)	Alert (Jeneric/Pentron) Restolux (Lee Pharmaceutical)
> 2000					
Nanofilled	Bimodal: Nanomeric - Silica Nanocluster (NC) • NC1 (SiZr) • NC2 (Silica)	78.5	0.02 + 0.075 0.005–0.02 0.075	– 0.6–1.4 (NC) 0.6–1.4 (NC)	Filtek Supreme Ultra (3M) Lava Ultimate (CAD/CAM) (3M)
Nanohybrid Homogeneous Inhomogeneous	Bimodal or trimodal: Radiopaque glass filler Silica nanofillers Prepolymerized resin complexes	~80	0.4 0.02 0.4 + 0.02	– – – 1–40 (PPRC)	Inspiro (Edelweiss DR) Essentia (GC) Cerasmart (CAD/CAM) (GC) Herculite Ultra (Kerr) Miris2 (Coltène) Enamel Plus HRi (enamel) (Micerium) Tetric EvoCeram (Ivoclar Vivadent)
2012					
Short fiber-reinforced*	Bimodal: E-glass fibers	77	17 (fiber diameter)	300–1,900 (fiber length)	everX Posterior (GC)
2019		70	7/140 (fiber diameter/length)	100–300 (fiber length)	everX Flow (GC)
	Barium silicate		0.7		

Modified/updated from Dietschi and Spreafico.[171]
Note the progressive decrease in filler size from > 40 microns to the nanoscale particles. As was the case for the microfilled materials, the higher total filler-matrix interface of nanofilled materials causes them to have higher viscosity (homogeneous nanohybrids). To increase the filler content, larger particles made of nanoclusters (fused nanoparticles) and highly filled prepolymerized resin complexes had to be added, hence the so-called *inhomogeneous nanohybrids*.
*Fiber-reinforced materials all have the same disadvantage that they cannot be polished smooth or maintain a smooth surface in the mouth; hence, coverage by a regular composite resin is needed.

A product with a unique filler technology, Z100 (3M) was released in 1992 and sold until 2019. It was a class of its own with a single type of filler (monomodal): a spheroidal zirconia-silica filler averaging 0.6 microns with a wide range of 0.01 to 3.5 microns. This allowed Z100 and the subsequent product, Z250, to reach unmatched filler content (85% in weight) and elastic modulus, while keeping excellent rheologic properties due to the spheroidal fillers.

Another unique material from the 1990s with exclusively spheroidal filler is the inhomogeneous microfilled (bimodal) Palfique Estelite (Tokuyama) with 0.2-micron silica-zirconia, including 1- to 80-micron prepolymerized resin complexes. Finally, the late 1990s and further were also marked by the simplification of the systems regarding esthetic layering (eg, Enamel Plus HFO, Mycerium; Miris, Coltène), allowing direct anterior restorations to be achieved with better predictability of success and startling illusions.[173–177]

When preheated to 130°F to 155°F (54°C to 68°C), microhybrid (eg, Enamel Plus HRi Dentin by Micerium; Herculite XRV Enamel by Kerr) and small-particle spheroidal (Z100) composite resins gain enough flow to become ideal luting materials for inlays, onlays, and veneers (see chapter 6, section 6.13).[178,179]

The "nanofilled" era

Since the 2000s, the focus has been toward further reduction of particle size in the nanofilled range as well as the development of low-shrinking monomers. In spite of this evolution, modern dental composite materials have still the same basic composition. In fact, microhybrids are also nanohybrids because of the nanoscale size of their original fumed silica particles. Therefore, the new nanofilled and nanohybrid materials have not proved to exceed the clinical performance of the microhybrids.[180] Both microhybrids and nanohybrids, when associated with the appropriate enamel/dentin adhesion, have allowed a significant widening of the indications to large restorations in both anterior and posterior teeth.[168,181]

The "bulk-fill" era

Bulk-fill versions of existing materials have been developed in order to simplify and accelerate the clinical procedures. Bulk-fills can be placed in a large or single increment. They are characterized by their increased depth of polymerization primarily due to their larger fillers and increased translucency[182]: Larger fillers produce a lower total filler-matrix interface, improving blue light transmittance through reduced light scattering. Some products use new photoinitiator systems to enhance the polymerization (Surefil SDR, Dentsply; Tetric EvoCeram Bulk Fill). Laboratory results are encouraging as bulk-fills seem to be able to reduce the cusp deformation, post-gel shrinkage, and shrinkage stress and increase the fracture resistance in posterior restorations.[183] Flowable versions of the bulk-fills have lower mechanical properties (less filler load) and usually require coverage with a regular composite to ensure the functional stability.[182]

Fiber-reinforced composite (FRC) resins

everX Posterior (GC) is a unique bulk-fill dentin-replacement hybrid composite resin containing E-glass fibers that are 1 to 2 mm in length. Other FRC materials (Alert by Jeneric Pentron and Restolux by Lee Pharmaceuticals) preceded everX by many years and were offered as condensable composite resins with increased fracture toughness.[184] The glass fibers, however, were chopped to a very short size (60–120 microns long), and the mechanical properties were only slightly better than those of most conventional composites with traditional fillers.[185,186]

Fiber fillers require a critical fiber length (in the millimeter scale) and aspect ratio of at least 70 (length/diameter) in order to significantly influence the overall mechanical properties. This was the goal of everX, which is recommended for high stress-bearing areas[187–190] (Fig 3-33). It presents a higher fracture toughness (2.6 MPa $m^{1/2}$) and flexural modulus within the family of bulk-fill materials but can be used easily in 4-mm-deep increments and can potentially match the toughness of dentin.[191,192] Like most FRC materials, it cannot be polished well and can only be used as an internal buildup or base to be covered with a regular composite resin (microhybrid or nanohybrid). everX Posterior proved to be worthy of consideration when restoring large defects[193] that would normally require a semi-direct or indirect approach but for which a direct technique is the only option due to financial limitations. As such, it is able to match the performance of CAD/CAM semi-direct inlays.[188] everX Posterior could be regarded as a possible substitute of the GIC in the sandwich approach, provided that it is covered with a sufficiently bright material to compensate for its excessive translucency. A potentially improved version (everX Flow, GC) was subsequently introduced with increased fracture toughness (2.8 MPa $m^{1/2}$) and eased placement due to its smaller fibers (micrometer-scale and aspect ratio of 20) and flowable consistency.[194] ***The future of FRC might lie in the combination millimeter- and micrometer-scale fibers, with aspect ratios of 20–70, the so-called "hybrid FRC."***

Flowable composite resins

Flowable materials were first proposed for laboratory use in the 1980s and early 1990s as an alternative to ceramic inlays/onlays and as veneering material on fiber-reinforced frameworks. Their low viscosity would allow the technician to use them with a paintbrush alike ceramics. Flowables have been used clinically since the mid 1990s and were obtained either by decreasing the filler load or/and increasing the fraction of diluent resins.[168,195] As such, they may exhibit variable properties, shrinkage on setting, as well as impaired wear resistance and mechanical properties. Therefore, like flowable bulk-fills,[181] they should be covered with a regular composite resin (microhybrid or nanohybrid) to develop the morphology and functional stability of the restoration.

Luting composite resins

A number of luting composite resins for crowns, veneers, inlays, and onlays also belong to the family of flowable materials, but they are able to polymerize both chemically and with light activation. When tertiary aromatic amines are included to induce self-polymerization, their oxidation may present an aggravating factor for the color stability of those materials. Their use should be limited to extremely thick or opaque restorations with limited penetration for the light. But even such a situation could be debated due to the high technique sensitivity and residual need of dual-cure cements for light activation (see next section, "Basics of photopolymerization and light-curing units"). In addition, Gregor et al found no difference in degree of cure between a dual-cure cement and a light-polymerized restorative used as a cement polymerized through 7.5 mm of restorative material (endocrowns).[196] Hence, preheated light-activated conventional microhybrids should be used as luting agents due to their superior mechanical properties[178] and wear resistance.[197] Even though they might be included in the same class, there are large differences in the viscosity of restorative composite resins.[198]

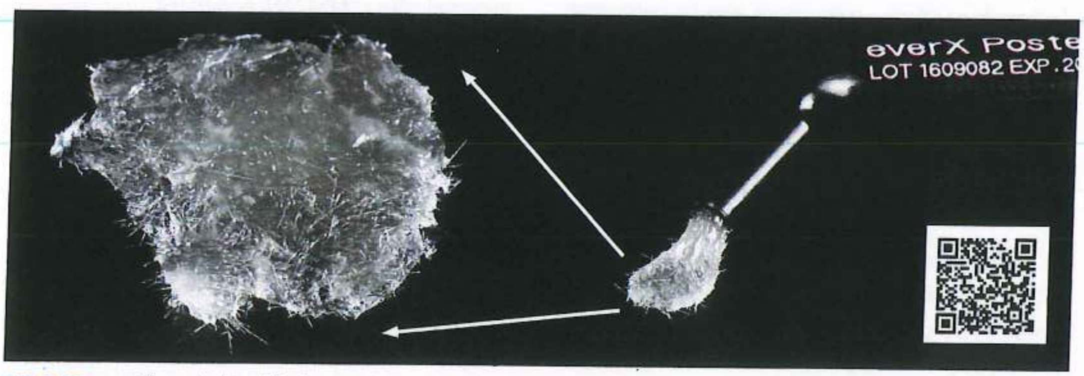


FIG 3-33 everX posterior. This innovative material, with its short E-glass fibers, presents a high potential as a bulk dentin replacement for bases and buildups.[187,188] It should always be covered with a regular veneering material.

FIG 3-34 Introduced in 2000, Paradigm MZ100 for Cerec was the first composite resin CAD/CAM block. (Photography courtesy of Dr Mehrdad Razaghy.)

The viscosity of the composite resin decreases as temperature increases (see chapter 5, "Thermomodified luting"). However, each brand reacts in a different way with a decrease ranging from 40% to 92%.[199] Some brands might even start to polymerize when stored more than 15 minutes in the heating device.

Caution: ***Many restorative composite resins are not appropriate for luting as their viscosity is not optimized even after preheating.[200]***

Composite resins for the dental laboratory and CAD/CAM blocks

Flowable materials, originally appreciated by laboratory technicians for their handling properties, should be avoided because they do not present appropriate physical and wear properties. Composite resins for the laboratory (indirect techniques) should not differ from those recommended for direct clinical use (ie, highly filled micro- and nanohybrids).

Laboratory-made restorations can be subjected to a postcure heat treatment at 212°F to 257°F (100°C to 125°C) for 10 minutes. This will optimize their conversion rate and physical properties as well as reduce the amount of residual leachable unreacted monomer.[201–205]

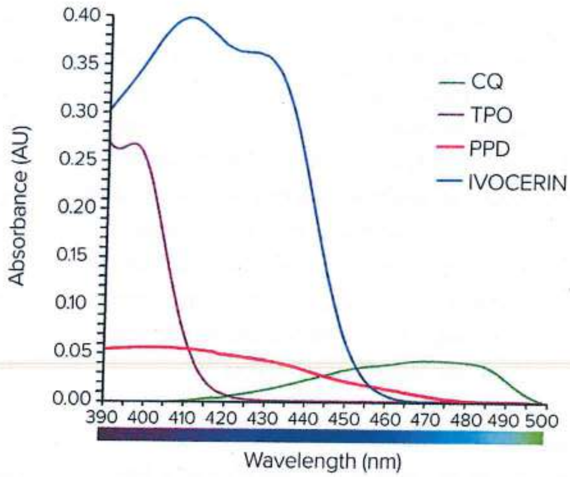
Some materials exclusively developed for the laboratory (eg, Premise Indirect, Kerr) include benzoyl peroxide (BPO), which is a heat initiator promoting chemopolymerization. Heat treatment and a 24-hour delay before delivery were demonstrated to benefit the degree of cure of Premise Indirect.[206] A sophisticated trimodal post-polymerization in a special device (light, heat, and pressure) was also developed to improve the resin conversion rate and physical properties (Premise Indirect Curing Unit, Kerr).

CAD/CAM systems have progressively replaced the artisanal indirect techniques discussed above. The first polymer block, Paradigm MZ100 (3M), was introduced in 2000 (Fig 3-34).[207] There is today a multitude of blocks based on the micro- and nanohybrid composite resin formulations. Their mechanical properties can potentially exceed those of their clinical and laboratory counterparts because CAD/CAM blocks can be manufactured under highly optimized conditions (somewhat similar to the trimodal post-polymerization),[208] resulting in higher degrees of conversion and increased filler content and decreased use and leaching of toxic monomer. UDMA usually replaces bis-GMA in those new blocks. In addition, the layering of direct and laboratory restorations always results in porosities and interlayer gaps, which can be avoided with CAD/CAM polymers.

In view of all the above, the acronym HPP for **high-performance polymers** ***seems appropriate for CAD/CAM composite resins.***

Composite resin blocks are also better suited to the milling process (faster milling, millability in thinner layers, and minimized marginal chipping) compared to ceramic blocks[209] and can be subject to simple but efficient esthetic optimization techniques (see chapter 4, section 4.8).[210]

FIG 3-35a Spectral absorption profiles of photoinitiators (at similar molar concentration). Note the high absolute absorbance of Ivocerin and TPO. (Reproduced with permission from Rueggeberg et al.[212])



Basics of photopolymerization and light-curing units[211,212]

Photopolymerization basics

Resin polymerization begins when free radicals are produced and cause the opening of the C=C double bonds of the monomers (initiation phase). This is followed by the elongation of the polymer (propagation phase) until two growing radical ends collide (termination phase). Free radicals come from photoinitiators, which are molecules capable of becoming reactive (ie, free radicals) when exposed to a given wavelength of light. The camphorquinone (CQ)/amine initiator system is most widely used in dental materials (absorption range 440–490 nm, peak at 468 nm). CQ, unfortunately, is bright yellow, which limits the amount that can be used without affecting the color of the restoration. In the 1990s, in part due to the popularity of bleaching techniques, other "clear" photoinitiators (eg, Lucirin TPO, absorption range 350–430 nm, and phenylpropanedione or PPD, 390–460 nm) had to be used and even combined with CQ/amine to alleviate this color problem.

Because of the difference in absorption ranges, light units that focus on the spectrum for the CQ/amine system (blue light) will not work for materials using TPO, which is more toward the ultraviolet range (Fig 3-35a).[212]

Ivocerin (Tetric EvoCeram Bulk Fill) is a new patented initiator with a broad spectrum (390–445 nm) and high absolute absorbance, particularly useful when considering bulk-fill techniques.

Self- and dual-polymerization

In self-cure systems, two pastes have to be mixed, one containing the **catalyst** (usually BPO) and one containing the **base** (or accelerator, a tertiary aromatic amine). Free radicals are produced by the reaction of BPO and the tertiary aromatic amine. In dual-cure materials, the base usually also includes the CQ/amine photoinitiator system, which means the base paste can also be photopolymerized alone if desired.

In addition to the potential color instability caused by the tertiary aromatic amine, dual-cure cements are extremely unstable due to the combination of antagonistic ingredients (BPO and bis-GMA). Light activation of dual-cure materials then becomes critical for adequate polymerization. Finally, simplified dentin bonding systems, because of their acidic monomers, may be incompatible with dual-cure materials,[213] which can be resolved by using IDS and resin coating techniques (see chapter 4, section 4.4).

Oxygen inhibition

Oxygen in the air can inhibit chain propagation by reacting with free radicals. This will produce an oxygen-inhibited layer (OIL) of about 10 to 20 microns,[214] but it can reach up to 40 microns.[138,215] This layer still has the potential for partial polymerization if oxygen is eliminated from the surface ("air-blocking") or if free radicals are supplied and diffused into the OIL by the addition of new material. The presence of this OIL should not affect interlayer cohesiveness.[138,214]

Light-curing units

Quartz-tungsten-halogen (QTH) lights have a broad spectral output (380–520 nm) with a spectral emission peak facing the absorbance peak of CQ. But the QTH spectrum is broad enough to initiate the polymerization of all materials available today (TPO-, PPD-, Ivocerin-, and CQ/amine-based) at relatively high power density (700–1200 mW/cm^2). Blue light–emitting diode (LED) lights were not available before the 1990s, and the first LED dental lights were introduced in 2001. They provide a longer life span (no filament), consistent output, and lower power consumption. First-generation LED lights were limited to a very narrow-band spectral output in the 440–490 nm range, highly effective for CQ/amine-based composites and adhesives. Today, multispectrum LED lights (eg, Bluephase, Ivoclar Vivadent; VALO, Ultradent) include several LEDs with different radiation output (Fig 3-35b), allowing them to target all current photoinitiators (385–515 nm range). However, single-spectrum LED lights targeting only CQ are still on the market and might not work with materials using, for instance, TPO. Plasma-arc curing (PAC) lights also cover most initiator systems but, like new-generations LED lights, they can produce a very high intensity output (1500–2500 mW/cm^2), generating also more heat. They were developed to reduce polymerization time to only 1 to 5 seconds, which may not be adequate for today's materials to the anticipated depth.[216]

It is agreed that high intensities not only increase the risk of thermal damage to the pulp and soft tissues but also cause more shrinkage stresses. Higher irradiance in a shorter time interval also may compromise the mechanical behavior of composite resins.[217] For these reasons, the upper limit should not exceed 1200 mW/cm^2 and 20 seconds.[218,219]

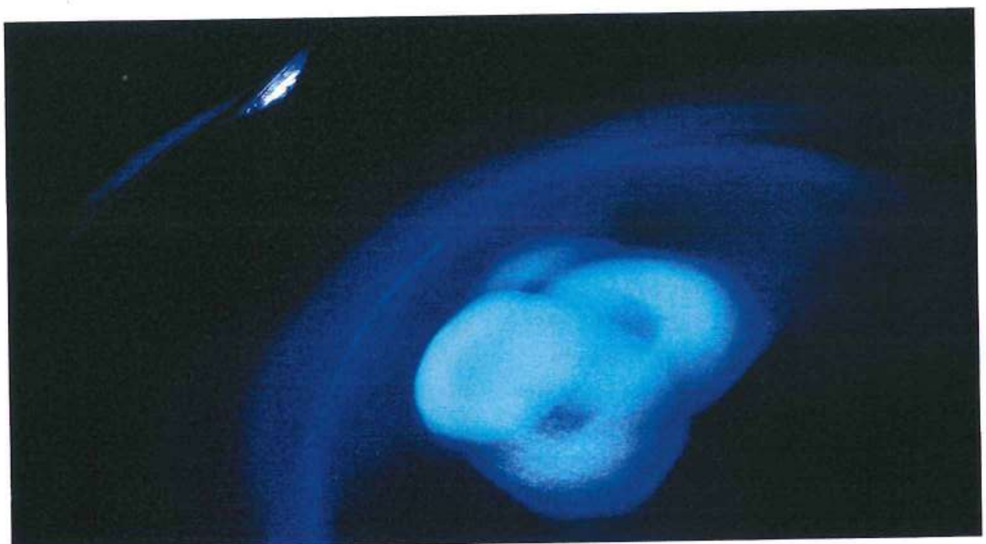


FIG 3-35b Multispectrum LED. Valo (Ultradent) is a broadband (multiwavelength) LED with a collimated beam and convenient glass lens (no light guide) for easy access and positioning, covering a 10-mm surface. It offers three intensity modes, but only the standard mode is recommended (1000 mW) because the other modes exceed the 1200-mW limit (1400 and 3200 mW). When holding the light away from a white background, four different LEDs become visible. (Photography courtesy of Dr Mehrdad Razaghy.)

Practical guidelines for light-curing units[216]

First and foremost, light units must be regularly cleaned and monitored for changes in irradiance value using a suitable radiometer. However, a proper light will still not be efficient if the operator is holding the tip at an angle and/or if the appropriate light-tip-to-restoration distance is not respected (an 8-mm distance can result in a 75% loss of irradiance). Deep gingival margins may require extended irradiance time up to 40 seconds at > 600 mW/cm^2.[220] The output will also be reduced if the seam of infection-control barriers crosses the light tip. Use of "blue blocking" shields/glasses to protect both the operator and dental assistant is paramount to ensure *(1)* protection from the "blue light hazard" (retinal aging and degeneration) and *(2)* that the operator can look at the light for its proper centering on the restoration. Improper positioning of the light for fear of watching is a common problem. Finally, air-cooling is a good way of limiting the risk of thermal damage to the pulp (especially when polymerizing adhesives in deep dentin) and soft tissues.

Irradiance will be attenuated in many other situations such as when more opaque and chromatic resins are used or when polymerizing through the restoration (indirect techniques). In those instances, higher output (1000–1200 mw/cm^2) and an extended irradiance time should be applied as needed for compensation; eg, up to 60 seconds per restored surface (restoration thickness 3–5 mm) and up to 90 seconds in the case of extremely thick restorations (5–7.5 mm).[196] Those extended times should always be segmented in maximum 20-second increments before moving to the next surface (applying three to four cycles around the tooth) to avoid focal temperature increases.

Polymerization kinetics and irradiance modes

Polymerization causes composite resins to shrink. The direction and intensity of this shrinkage are influenced by multiple factors,[221] including the preparation shape, the adhesive performance, the incremental placement technique, and the volume of material, among others. High light irradiance modes are known to increase temperature and shrinkage stresses,[218,219] so low-intensity regimens have been proposed to slow down the polymerization process and possibly delay the vitrification point of the resin.

Vitrification occurs when the polymer transforms from a gel into a solid and develops an elastic modulus. Before the vitrification point, the material is already shrinking but is still too soft and rubbery, unable to generate shrinkage stresses. Beyond the vitrification point, the shrinkage is accompanied by strain and stress due to the bond to the cavity walls. This happens when the polymer reaches a sufficient molecular weight and cross-link density.

Post-vitrification shrinkage will in turn cause the tooth structure to deform (and possibly crack, especially enamel) and/or force the adhesive interface to fail. It has been hypothesized that increasing the duration of the previtrification phase would allow more shrinkage to happen without stress by taking advantage of the material flow. Several low-intensity polymerization modes have been proposed to achieve that goal, such as the so-called *slow-start* (eg, < 300 mW/cm^2 for 5 to 10 seconds followed by > 500 mW/cm^2 for 40 seconds), and *pulse-delay* modes (eg, 200 mW/cm^2 for 3 seconds followed by 3- to 5-minute delay and then > 500 mW/cm^2 for 60 seconds). Unfortunately, the data is not fully conclusive on the efficiency of those techniques to reduce shrinkage stresses and marginal leakage compared to the conventional continuous 20-second polymerization at > 700 mW/cm^2.[222,223]

Composite resins keep shrinking after the light is turned off because a majority of the shrinkage stress happens during and after the vitrification stage.[224] This explains why postbonding enamel cracks are often not seen immediately after restoration placement but only > 24 hours later. It appears that extremely low intensities that would allow a clinically relevant stress relaxation (previtrification) would not allow a clinically relevant conversion rate of the material.[224]

C-factor or "V-factor"?

Polymerization shrinkage was originally thought to be directed toward the light source, which gave rise to various layering techniques and tools to "attract" the material against the cavity margins (eg, interproximal translucent wedges and matrices). It is now established that composite resins do not shrink toward the light but toward the surfaces to which they are bonded.[221] It has been suggested that the ratio between the bonded and unbonded surfaces, or the C-factor, could be an indicator of the shrinkage stresses to be expected in a clinically relevant situation.[225] Free unbonded surfaces allow for stress-relieving flow (deformation), which is not possible at restricted interfaces (bonded to the cavity walls). While this may be true, several elements need to be added to this concept:

1. Not only the free surface of the restoration but also the elastic deformation of the surrounding cavity walls (especially thin cusps) contribute to alleviate the shrinkage stresses. Strong adhesive systems can resist shrinkage stress despite high C-factors.[145] As such, they are able to transfer strain and stresses to the surrounding structures (eg, cusps), inducing hard tissue fractures (Fig 3-36).[146]
2. No matter how much compensation is provided, residual shrinkage stresses remain, the amount of which can be related to the volume of the restoration—the "V-factor,"[11] which will increase with the distance between the most distant points of the cavity. Even when compensation techniques are used (sophisticated layering, irradiation modes, etc), a large restoration will still generate major deformation. Factors influencing stress development are extremely complex (conversion, shrinkage, modulus, shape, boundary conditions), and reducing polymerization shrinkage is not a warrant of decrease of stress effects.[226] The context that generates stresses should be always considered, including volume and size.
3. Because of the V-factor, reduction of the volume of polymerizing composite resin is a valid approach. It can be achieved by introducing nonshrinking components ("megafillers"), eg, conventional GIC in the sandwich technique,[163] inserts,[227,228] or using semi-(in)direct and indirect techniques (inlays, onlays, veneers; see chapter 4, section 4.1).[229,230]
4. While the practical advantages of using semi-(in)direct or indirect techniques is widely accepted (morphology, contacts, occlusion, etc), the clinical significance of polymerization shrinkage has not been clearly established, and large direct composite resin restorations have demonstrated surprisingly good longevity.[181,231] A possible explanation is the hygroscopic expansion; even though it takes about 4 weeks, composite resins ultimately recover their original size by slowly absorbing water.[160,232]

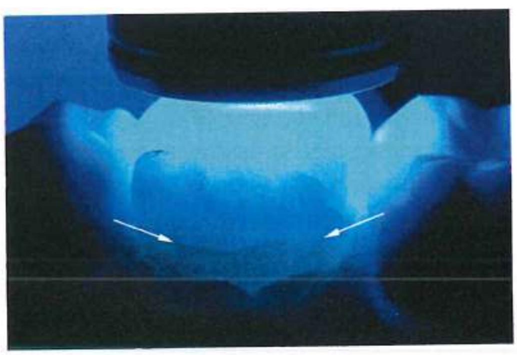


FIG 3-36 Direct large mesio-occlusodistal (MOD) restoration. (Reproduced with permission from Magne et al.[146]) The microtensile bond strength of OptiBond FL is not affected by the C-factor.[146] As a consequence, the large V-factor induced the cracks at the lingual cusp base *(arrows)* consecutive to shrinkage. The clinical relevance of those cracks is still debated.

TABLE 3-4 Resolution chart[233–236]

Magnification	Resolution (microns)
Unaided human eye	200
2.5× loupes	100
4× loupes	50
Sharp explorer	35–50
8× loupes/microscope*	25
10× loupes/microscope	20
14× microscope	14.3
20× microscope	10

*To distinguish structures of 25-micron size and below, a minimum of 8× magnification is required.

Magnification instruments

Biomimetic restorative dentistry implies that utmost attention is given to avoid the removal of intact tooth structure. Many tools will facilitate microinvasive approaches such as electric handpieces, oscillating instruments, etc. Improving visual acuity with magnifying aids, however, remains one of the most important prerequisites when using these tools. There is a wide range of dental loupes available, from low (2.5× to 4.5×) to high resolution (5.0× to 10.0×). While low-magnification loupes mainly aid with posture, high-resolution instruments (loupes and microscope) will significantly enhance both acuity (Table 3-4)[233–236] and body mechanics. Low-resolution loupes are simple lightweight magnifying lenses (usually three lenses, Galilean systems). High-resolution telescopes are heavier and more expensive because they use a series of lenses and incorporate prisms to upright the image (Keplerian/prismatic systems). Important parameters to consider are the following:

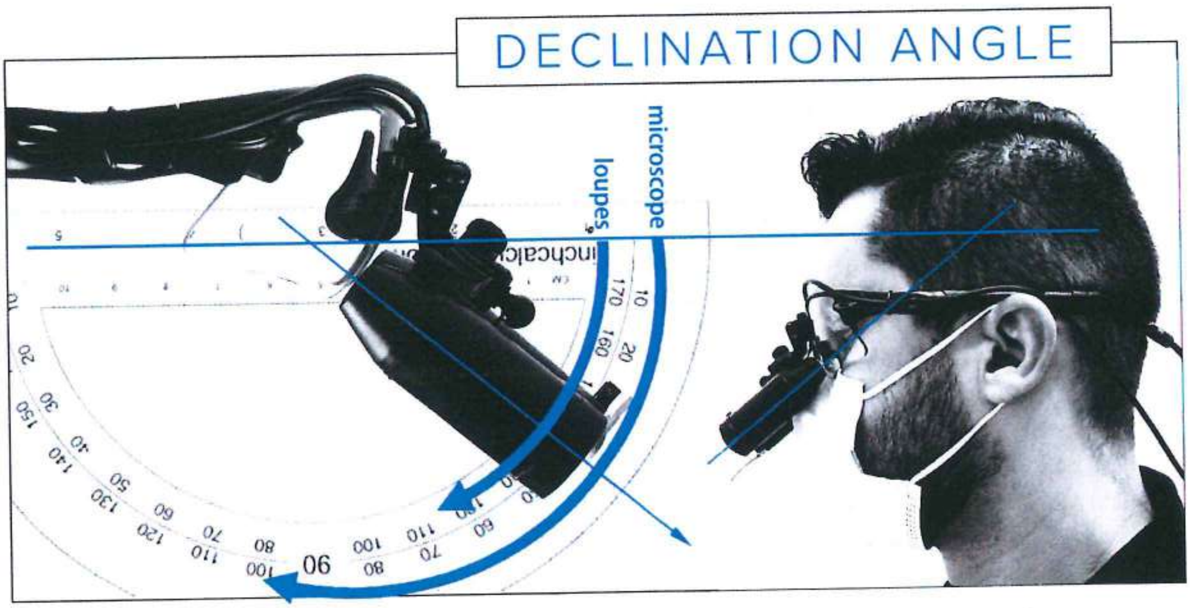
- **Working distance.** Appropriate working distance should allow the operator's back and neck to stay upright while the forearms are parallel to the floor. Note that increased working distance results in decreased magnification for a given loupe system.
- **Declination angle.** Appropriate viewing angle should allow the operator to keep his or her head tilted forward at no more than a 15-degree angle (Fig 3-37). Excessive head tilt must be avoided.
- **Field of view and depth of field.** High magnification and resolution logically come at the cost of a smaller viewable area and depth of field, even though prismatic systems can limit significantly this loss.

There are two type of telescope mounts:

1. **Through the lens (TTL):** The telescopes are glued to the lenses of the glasses. They are closer to the eyes, resulting in increased field of view. The main limitation of TTL is the declination angle (approximately 25–30 degrees) and the fact that changes in prescription lenses sometimes require return of the loupes to the manufacturer.
2. **Front lens mounted (FLM):** The telescopes are mounted with a hinge. They allow for adjustable and high declination view angles (up to 45–50 degrees).

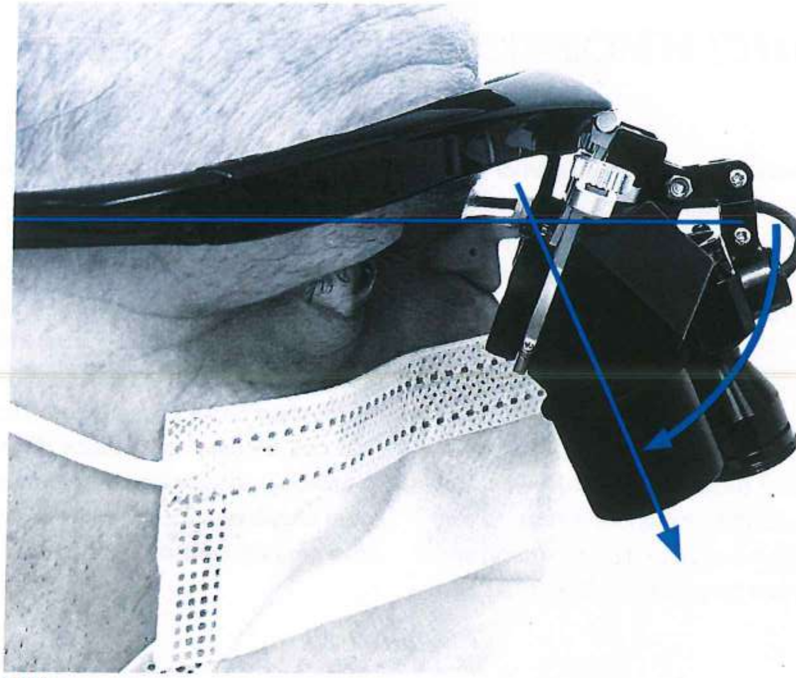
In view of the above, prismatic loupes with magnification 6.5× to 8.0× and FLM with minimum 40-degree declination angle can be recommended (Fig 3-37a). A wide nose seat is desirable to compensate for the weight of the telescopes. This level of magnification requires an integrated high-intensity LED light system with a "blue-blocking" filter for use during placement of composite resins.

The next step in magnification instrumentation is the use of an operatory microscope. This has long been considered the standard of care in endodontics. While it provides less flexibility and mobility than portable telescopes, the microscope will allow the operator to reach unmatched levels of magnification (see Table 3-4) and declination angles (> 90 degrees; Fig 3-37a). While it involves a substantial learning curve, this can be significantly reduced with intense training.



3-37a

FIG 3-37 High-magnification prismatic telescopes. *(a)* This lightweight frame with curved protection lenses allows a 40-degree declination view angle and up to 8.0× magnification (EVK 800, SurgiTel). *(b)* This other prismatic system with max 5.0× magnification allows for the most extreme declination of approximately 65 degrees by incorporating deflection prisms (Prismvue NF2, Pentax/Hoya Technosurgical). Another option for high-declination angle loupes is the ErgoPrism 5.0X by LumaDent. *(c)* The author's loupes have a native 8.0× magnification combined to short working distance 10-inch close-up caps (*) and close-up reading magnification in the glass lenses (**). This combination allows the author to raise the magnification to > 10.0×.



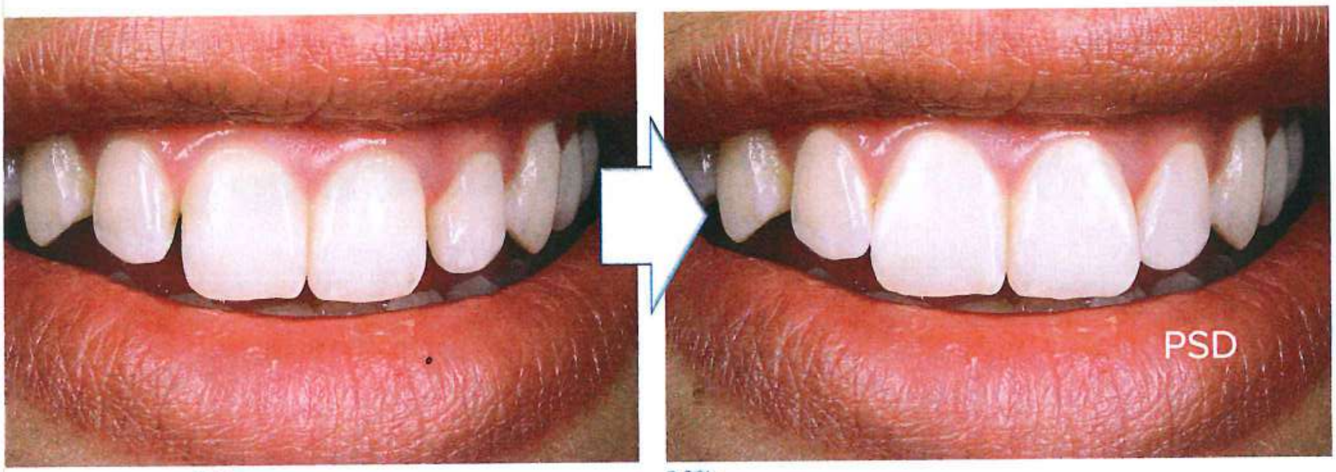
3-37b

3-37c

3.8 DIRECT RESTORATIONS IN ANTERIOR TEETH

Direct conservative esthetic restoration of anterior teeth is a daily routine. According to the biomimetic principle, localized missing tooth substance is not an indication for bonded ceramic restorations. Direct composite resins can be used instead, rather than partial ceramic restorations, also known as *ceramic fragments* or *partial veneers*. The latter have gained popularity through the so-called "no-prep" approach. Some significant drawbacks, however, can be expected due to the inherent brittleness of the ultrathin porcelain margins (difficult handling and maintenance; see chapter 6, Fig 6-22)[237] as well as the justification for their significantly higher cost (compared to the direct approach).

A classic example is the situation of diastema closure. Small direct composite resin additions are very simple to carry out, cost-effective, and provide outstanding results (Fig 3-38). The PSD (Photoshop Smile Design; see chapter 5, Fig 5-2) can be used as a quick diagnostic tool to motivate the patient, determining the ideal tooth shape and the need for minor prerestorative gingival corrections.

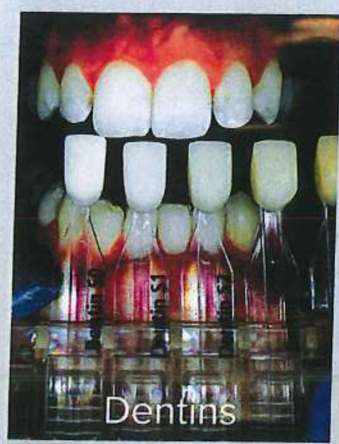


3-38a

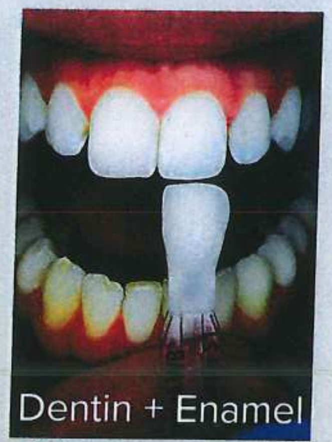
3-38b

FIG 3-38 Small direct composite resin additions for diastemata closure. *(a)* This patient presented with several gaps between her anterior teeth. PSD (see step-by-step process in chapter 5, Fig 5-2) was used to successfully motivate the patient and explore the effect of the composite resin additions as well as slight recontouring of the gingival contour *(b)*. *(c to e)* Following healing of the minor gingival corrections, the tooth color was selected using a cross-polarized light source (Smile Lite by Smile Line; see explanations for cross-polarization in chapter 5, Fig 5-34) along with a bilaminar shade guide (see Fig 3-47 for additional information about this process). *(f)* Strict isolation was obtained using rubber dam and additional shielding of the patient's face and airways with a wet paper towel during cleaning (airborne-particle abrasion) of the enamel surfaces. First, the central incisors will be enhanced at their distal outline. Although the composite resin additions involve mainly the distal surface, half of the labial enamel was also etched *(g)* in order to extend and optimally blend the restorations (universal principle of "additive contour"; see also Figs 3-42 and 3-43). *(h and i)* Dentinlike flowable composite resin was used first because of its ease of application (*arrows* showing distal contour enhancement), polymerized, and then covered with enamellike composite resin. Upon finishing of the central incisors, Teflon tape was used to wrap and protect those teeth while cleaning, etching, and restoring the mesial aspect of the lateral incisors *(shown on next page)*.

3-38c



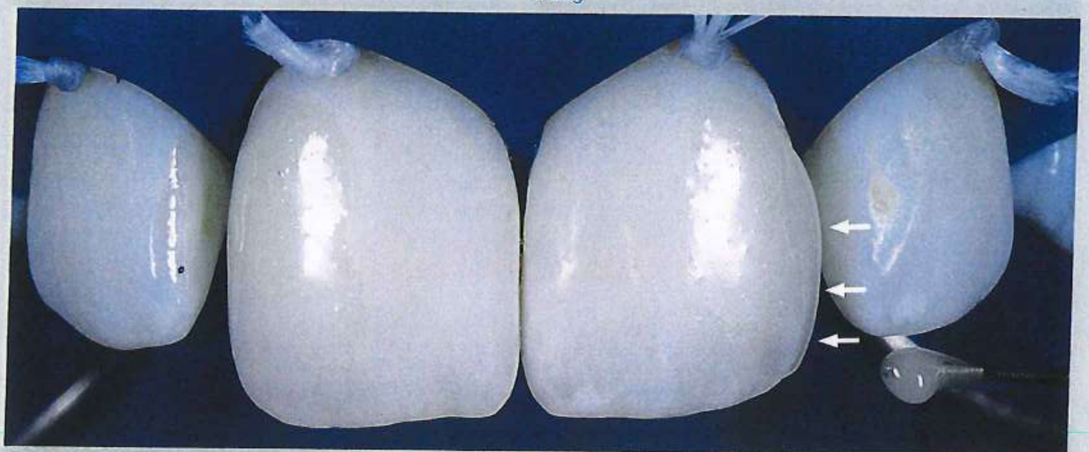
3-38d

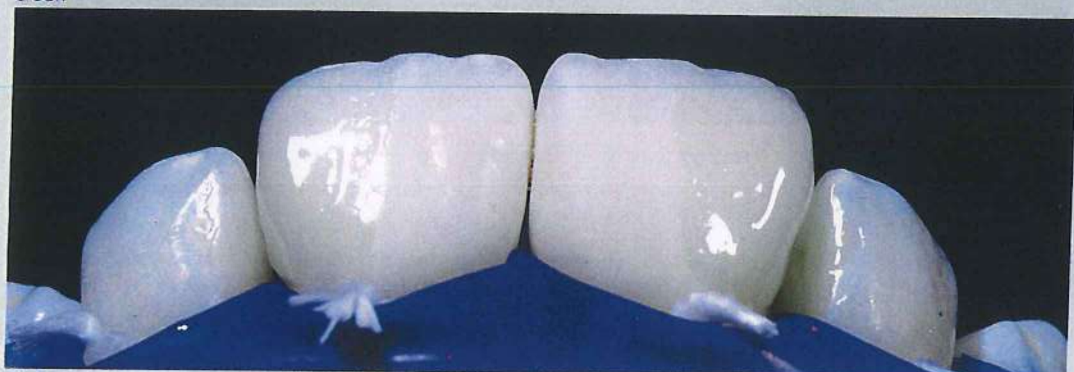


3-38e


3-38f

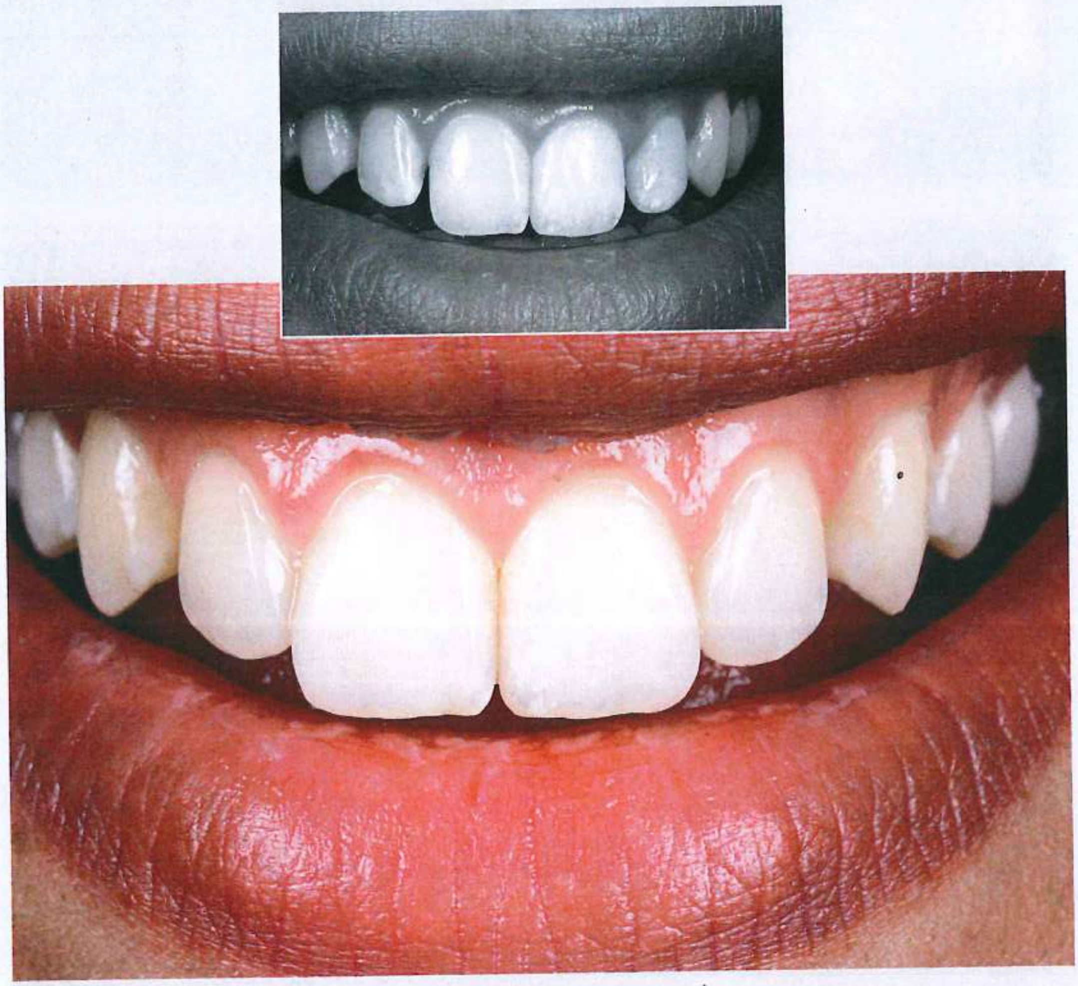

3-38g


3-38h


3-38i

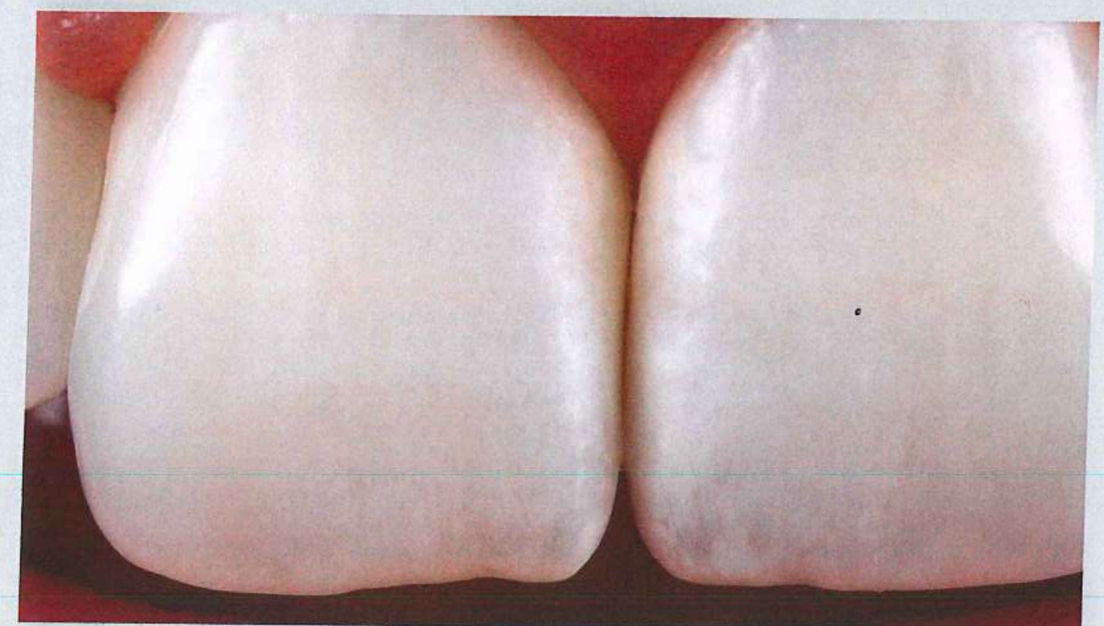
3-38j

3-38k



3-38l

3-38m



3-38n

FIG 3-38 *(cont)* No matrices were needed for the closure of the interdental contact. *(j)* The dentinlike flowable composite resin was laid directly against the neighboring tooth surface, polymerized, and completed with the enamellike layer. *(k)* Note the marked mesial line angle and the fact that the restoration extends onto more than half the labial surface for optimal blending; note also the intact etched surface of enamel *(arrows)* as the adhesion should always be shy of the unetched enamel. *(l to n)* The final results demonstrate outstanding color matching, perfect blending, and invisible margins (several light sources; preoperative overlay photograph in *l*), which is in contrast with the margins of partial veneers (or fragments; see chapter 6, Fig 6-22).

Since the 1990s, optimization of the optical characteristic of microhybrid and, later, nanohybrid composite resins has allowed direct anterior restorations to be delivered with a variety of layering techniques.[173–177,238–243]

> There are two main approaches to apply the restorative material: the classic **freehand** method or the more contemporary **guided** method.

Freehand placement method

In the early 1990s, direct composites had limitations due to the fact that they were applied with the freehand method; ie, without any help or guide for the shape of the layers. They offered adequate treatment outcomes for children but were possible in adults only when the volume, extension, or number of restorations was limited. Today the freehand method is appropriate for Class 3 and Class 5 restorations. Diastema closures and Class 4 restorations can also be performed freehand, especially when intact neighboring or contralateral teeth can be used as a guide (Fig 3-39; see also Fig 3-41), and even more so when no significant alterations of form or incisal length are desired (see Figs 3-43 and 3-45). The most popular esthetic composite resins for freehand application are multihue systems: They are available in almost all hues (A, B, C, D) of the original VITA classical shade guide. Herculite XRV remains a landmark material in this regard (Fig 3-40a), with both the enamel and dentin opacities available each in 16 of the VITA classical shades. Contemporary multihue systems include an even broader choice of shades (eg, Filtek Supreme Ultra by 3M with four opacities and 36 shades), making the selection process even more sophisticated.

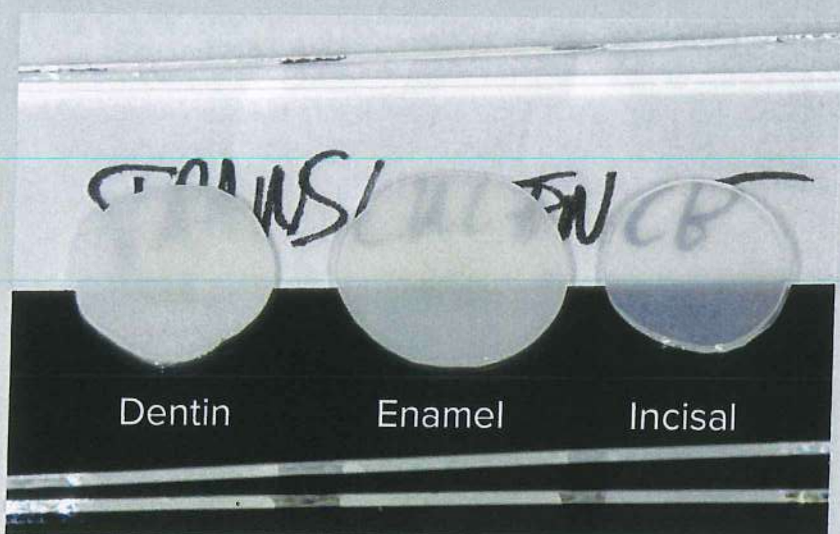
FIG 3-39 Single-tooth treatment with freehand application of composite resins. *(a)* This malformed and rotated lateral incisor is ideal for the freehand method. *(b)* Correction of shape and position can be easily handled with a direct technique. Furthermore, the restorative material is fully supported by intact underlying enamel, and this tooth will not be subjected to significant functional loads, resulting in successful clinical service for over 10 years *(c)*. Note the enamel chipping of the distal incisal edge of the natural unrestored central incisor.

FIG 3-40 Rapid evaluation of composite translucency. *(a)* Pressing small amounts of material between two glass slides and then light curing provides quick evaluation of materials: Herculite XRV Dentin *(left)*, Herculite XRV Enamel *(center)*, and Herculite XRV Incisal LT *(right)*. These three grades of opacity are well suited for freehand composite layering. The opalescence (blue and yellow reflections) of the Incisal LT material is remarkably close to the natural effect found in real teeth (see also Fig 3-44d).


3-39a

3-39b

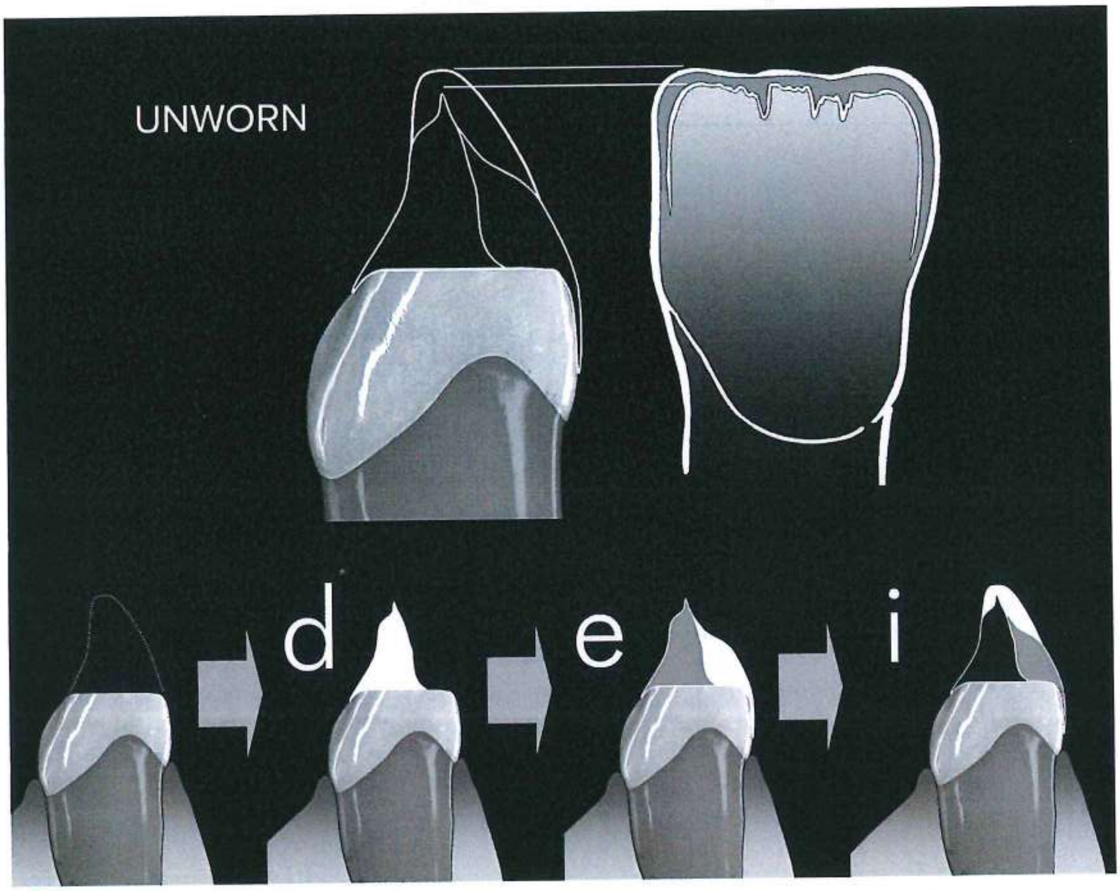
3-39c



3-40a

Three-increment method

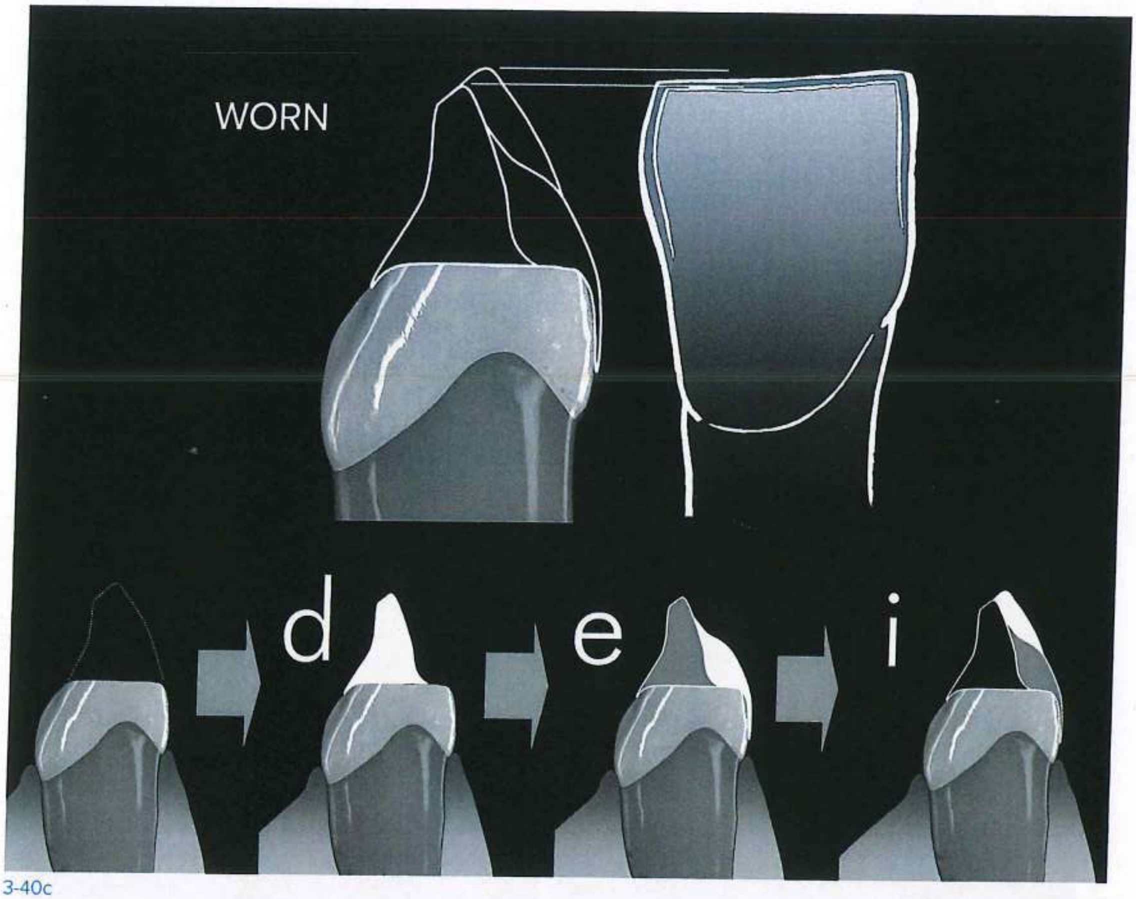
The freehand method can be easily applied in a simplified three-increment technique (dentin-enamel-incisal, or DEI; Fig 3-40).[174] An anatomical dentinlike core (Herculite XRV Dentin; or Enamel HRi dentin) is covered with translucent enamellike composite that extends onto the beveled enamel. Incisally, the dentin core is covered with transparent/translucent enamels (eg, Herculite XRV Incisal LT) or more opalescent incisal materials (eg, Enamel HRi). The incisal shape of the dentin core must be adapted according to the age of the tooth: sharp-edged for young unworn teeth (Fig 3-40b; see also Figs 3-43 and 3-45), flat and thicker for worn teeth (Fig 3-40c), or a combination thereof (Fig 3-41). As is the case for fragment rebonding (see Figs 3-24 and 3-25), the esthetic and mechanical outcome of anterior direct composite resins can be greatly enhanced by augmenting the bulk of the restoration to simulate the transition line angles at the facial and proximal aspects of the tooth (see Figs 3-42 and 3-43), the so-called *additive approach*.



3-40b

FIG 3-40 *(cont)* **Simplified three-increment stratification technique.** Unworn *(b)* and worn *(c)* teeth differ by the incisal shape of the dentin core (d) and the amount of incisal shade (i). The enamellike composite (e) always covers the facial bevel and progressively thins onto the incisal dentin. Differential halo effects are created by the shape and architecture of the incisal edge (illustrated in Fig 3-44).

FIG 3-41 **Small freehand Class 4 restoration.** *(a and b)* Preoperative and postoperative views of a Class 4 restoration on the left central incisor. The step-by-step restoration technique is illustrated in the following pages.



3-40c


3-41a


3-41b

3-41c

3-41d

3-41e

3-41f

3-41g

3-41h

3-41i

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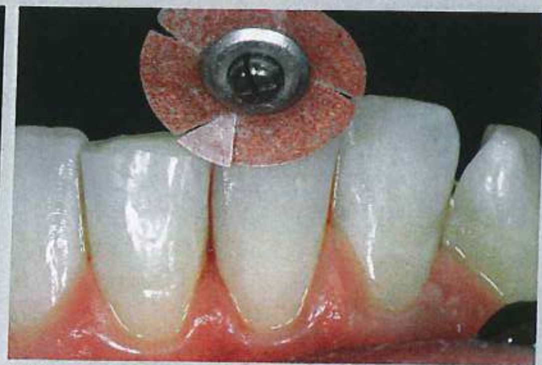
3-41l

3-41m



3-41n

3-41o

3-41p

3-41q

FIG 3-41 *(cont) (c)* VITA-based shade selection (dentin A3 and enamel A2). *(d)* The existing restoration was removed with a combination of rotary and oscillating instruments (SonicSys small hemisphere). *(e)* Residuals of resin can be eliminated noninvasively at low speed with a multifluted carbide bur. *(f)* The enamel margins and the labial surface were gently softened with an abrasive disk (eg, Sof-Lex, 3M). *(g)* Final preparation. *(h)* Standard adhesive procedures were applied, and the adhesive resin was polymerized. *(i)* The A3 dentinlike increment was shaped as in an unworn case but was extended all the way to the incisal edge surface. *(j)* Enamellike material was applied to the labial surface and translucent incisal material on each side (buccal and lingual) of the incisal dentin increment. *(k)* A slight incisal depression was created with a bur to simulate dentin wear, and *(l to o)* the final shape was refined with abrasive disks and strips. Note the notches created in the disk to make it more flexible and avoid excessive flattening of the surfaces. *(p and q)* Final polishing was carried out with an abrasive prophylaxis paste and silicon bristle brush.

3-41r

3-41s

3-41t

FIG 3-41 *(cont) (r and s)* Final restoration after rehydration of the teeth (incisal and labial views). *(t)* Note the anatomical details of the incisal edge perfectly reproducing the adjacent intact central incisor and the good stability at 3 years.

Universal additive principle

The additive approach was originally described for porcelain veneers as a redefinition of labioincisal morphology to recover the original enamel volume and shape (see chapter 5, section 5.5).[244]

> In the case of direct restorations, the additive principle implies extending the adhesive surface beyond the defect (additive etching and bonding) and using this additional surface to blend and reinforce the restoration (Figs 3-42 and 3-43).

Strong line angles strengthen the restorations because the buccofacial bulk is increased. This will help to prevent chipping of the incisal edge that could occur because of the limited elastic modulus and fracture toughness of the composite resin. ***It is also by virtue of the same additive principle that reattached fragments can be supplemented (blending and reinforcement) with composite resin. When designed properly, a direct composite resin restoration additively extending on intact enamel will not only be stronger and more anatomical but will also blend better and show improved color matching even upon aging of the underlying tooth structure (dentin sclerosis).***

3-42a

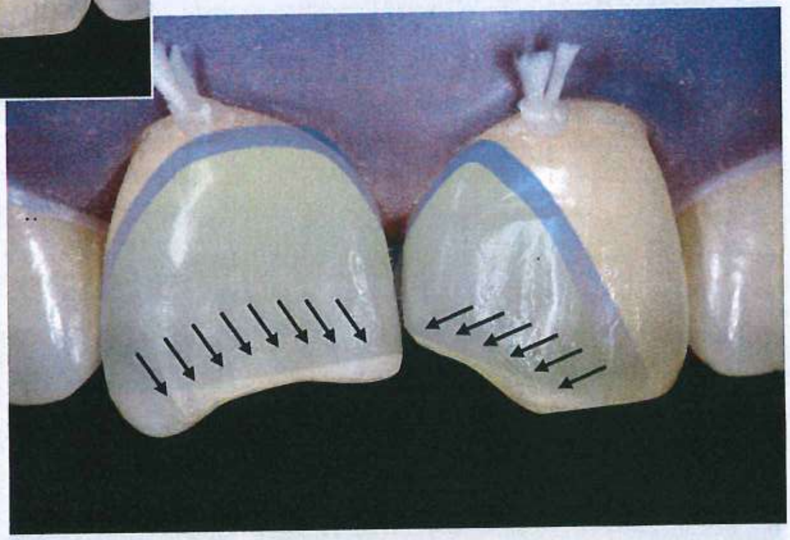
3-42b

3-42c

FIG 3-42 Small restoration with large additive contour. *(a)* Small enamel edge fractures are difficult to repair. The tooth could be restored without preparation, but the additive principle was applied. *(b)* The tooth was etched and bonded and restored far beyond the fracture line (*arrows*, image taken soon after rubber dam removal). *(c)* Following rehydration, the color integration and blending of the restoration are seamless.

3-43a

ADDITIVE PRINCIPLE



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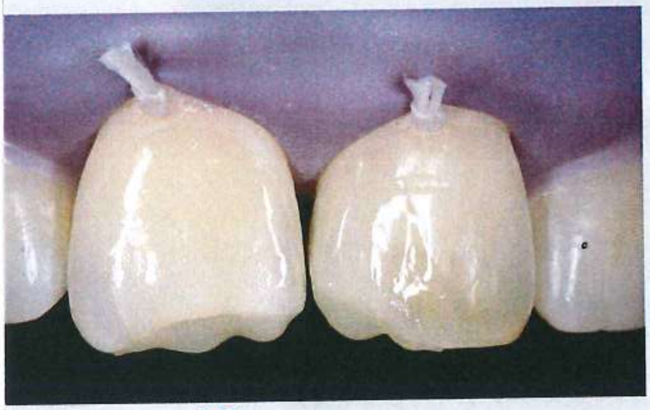

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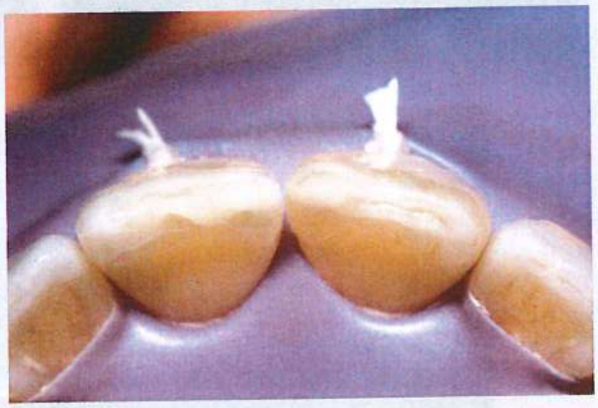
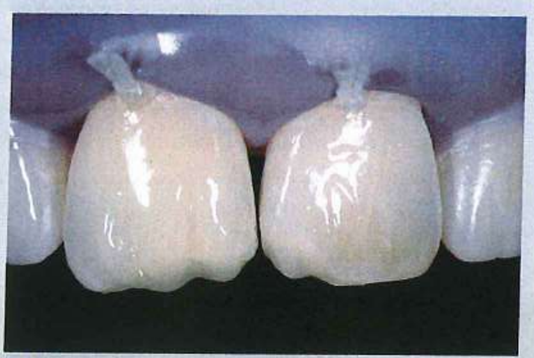
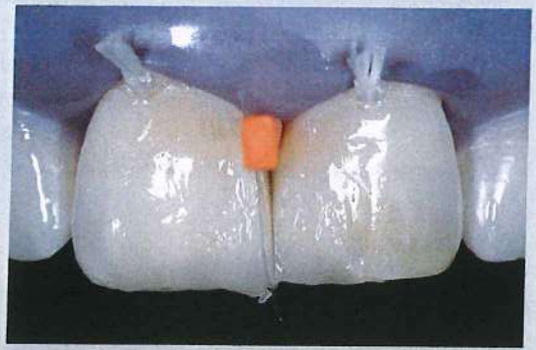


3-43d

FIG 3-43 Freehand three-increment technique with additive principle. The old discolored restorations *(a)* were removed, rubber dam was placed, and a soft convex bevel was created *(b)* using flexible disks. Note that the etching (blue) and bonding agent (yellow) surfaces were extended far beyond the bevel line *(arrows in b)*. Dentinlike lobes were placed and polymerized first *(c and d)*, followed by the enamel increment covering the bevel area (e, barely visible). Finally, the most translucent shade was used to restore the incisal edge *(f)*. This last increment is used to create a marked transition line angle (see *h, arrowheads*). *(g)* Clinical result following finishing procedures. *(h)* Note the incisal translucency and marked mesial ridge on the facial surface of both central incisors (flash reflections), which enhances the tooth morphology and favors the optical transition between tooth and restoration. *(i)* The result is totally stable after 3 years. The guided placement method (see Fig 3-48) could have been used in this case but would have required a silicon index of the existing restorations or of a wax-up. The freehand method was still applicable especially because no alterations of the incisal edge length were planned.

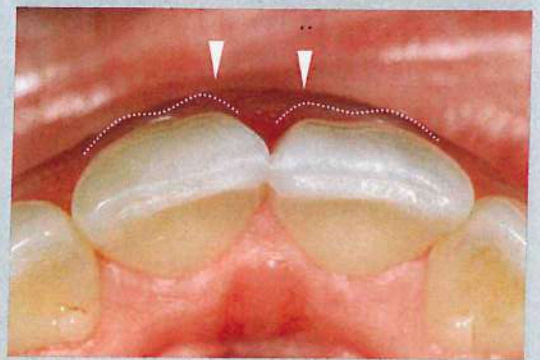


3-43e



3-43f

3-43g

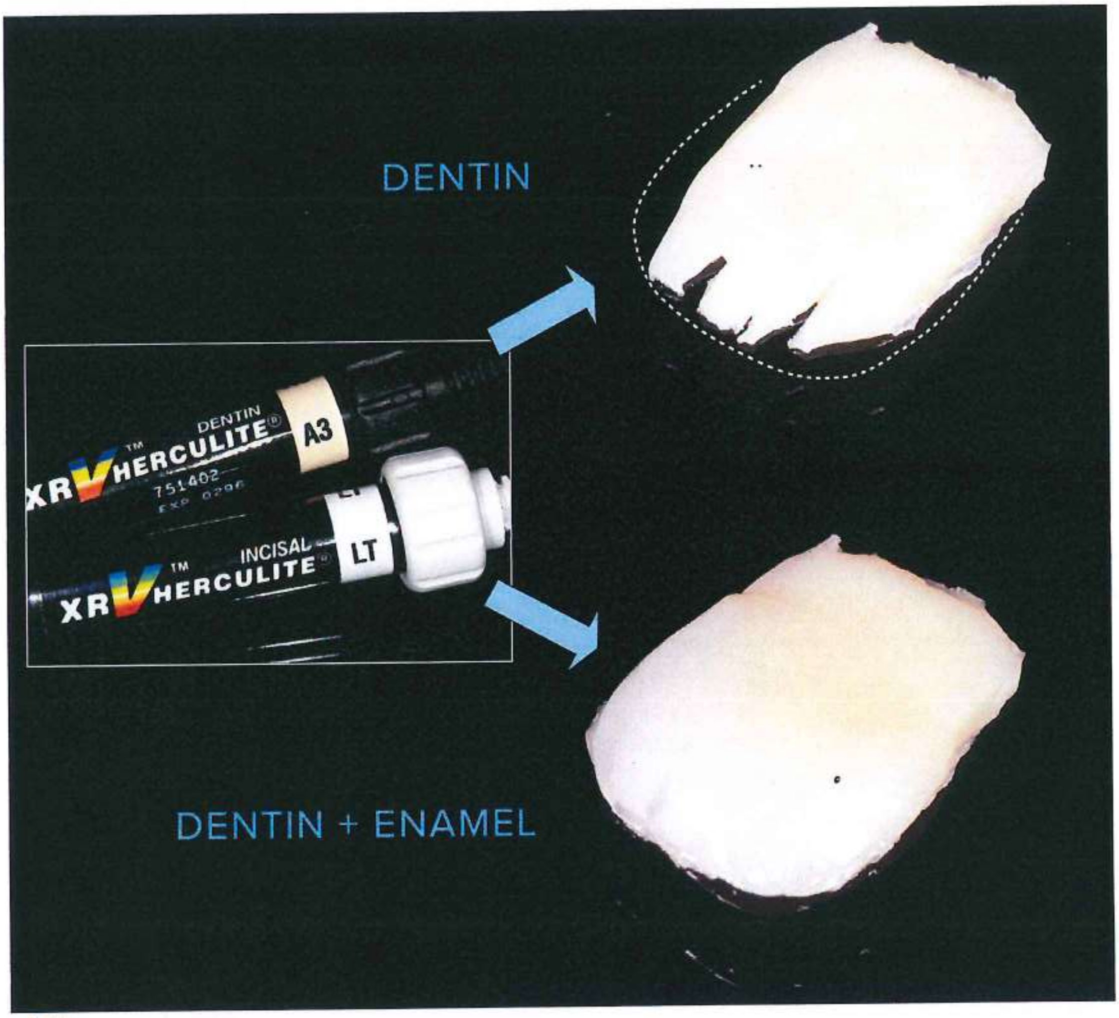


3-43h

3-43i

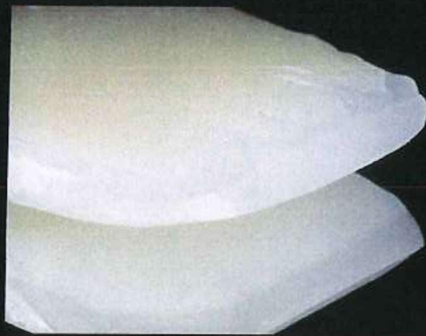
Simplified approach to incisal effects

The contrast of opacities between the dentin and incisal enamel is the key element to the natural effects in the tooth (see chapter 2, Fig 2-8g). It is possible to reproduce those effects with only two masses (Fig 3-44). By playing with the relative thicknesses of those two layers and their respective shape, a multitude of incisal effects can be replicated, from unworn to worn styles (Fig 3-45).[174]



3-44a

FIG 3-44 Anatomical shaping and differential opacity of composites. *(a)* These layered samples demonstrate that the esthetic potential of composite resins lies in the optimal combination of anatomical dentinlike cores covered by translucent incisal material. A key element is the modeling of the incisal edge: ground flat for a large white halo effect *(b and d, left)* or anatomically carved to follow the morphology of underlying dentin in younger teeth *(c and d, right)*. No effect resins have been used. *(e to g)* Clinical case (small Class 4 fracture) restored with similar characteristics obtained by the contrast between dentin and incisal masses. (Parts *a* and *d* reproduced from Magne and Holz.[174])



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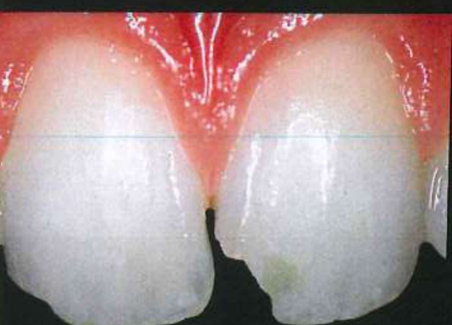
3-44c

3-44d



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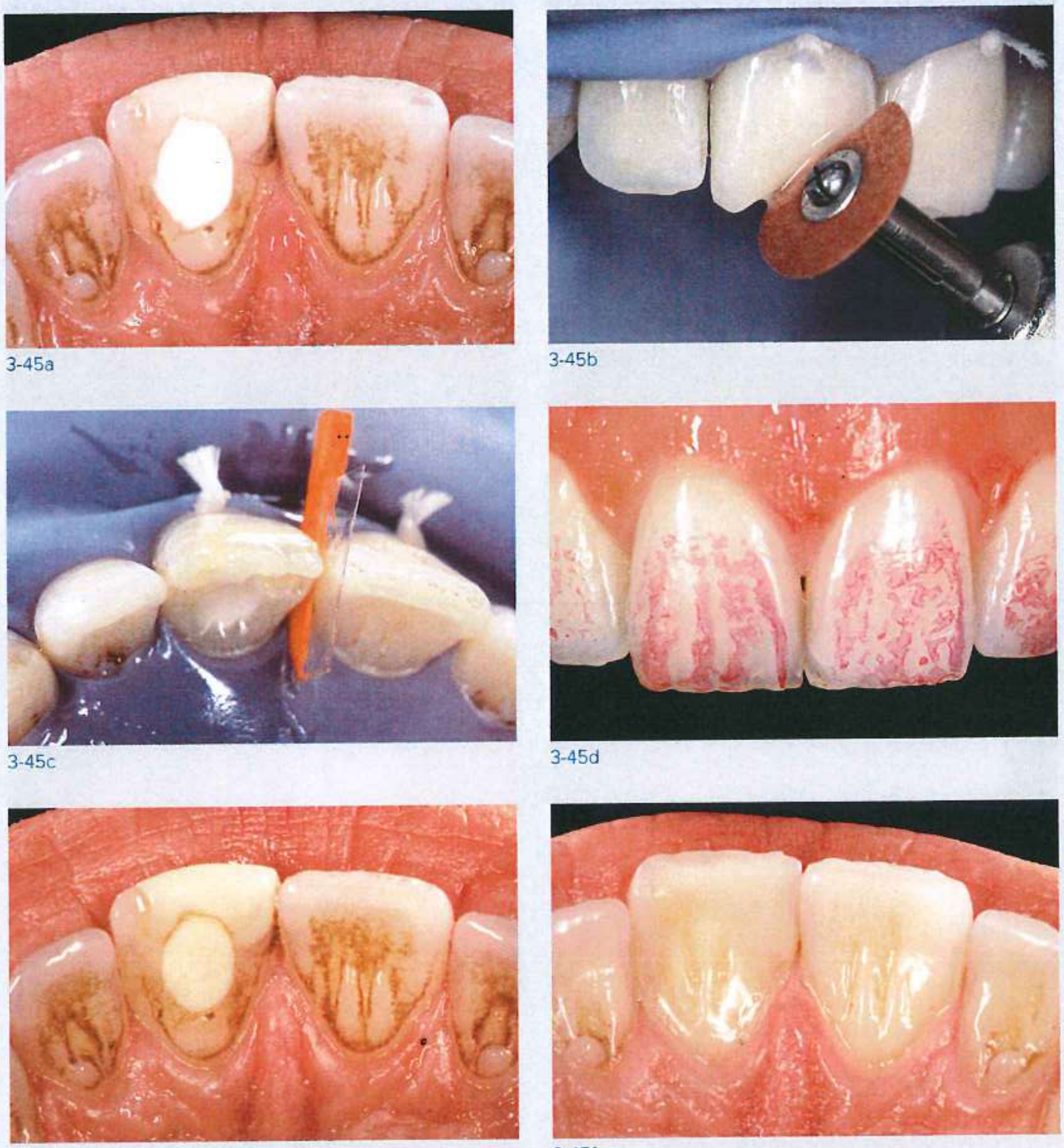


3-45a 3-45b 3-45c 3-45d 3-45e 3-45f

FIG 3-45 Extreme freehand Class 4 restoration after internal bleaching. *(a)* Palatal view of right central incisor after WBT was used and the tooth was sealed with GIC. A delay of 4 weeks with the GIC in place should be applied before replacement of the old restorations. *(b)* Tooth preparation was completed with abrasive disks to soften enamel margins and the labial surface. *(c)* Incisal view after bonding procedures and placement of the dentin increment. Note that the GIC was left as a dentin replacement for the endodontic access preparation (as explained in Fig 3-20). *(d)* Final restoration during surface texture adjustments using articulating paper rubbed onto the surface. *(e)* The restoration matches the contralateral reference tooth. *(e and f)* Palatal view before bleaching and after freehand restoration, respectively. *(g and h)* Comparative views before (onlay image) and after treatment. Note the natural incisal halo obtained without effect resins. (Parts *e* and *f* reproduced from Magne.[19])

3-45g

3-45h

"Sandwich" layering

Some particularly difficult cases can be addressed in a two-stage approach using the so-called *sandwich layering technique*.[174] This technique is particularly useful to reproduce complex subsurface effects. The tooth is first restored with the freehand method using only dentin and enamel increments. The focus of this first session is to match appropriate color and shape. Following rehydration of the tooth and confirmation of shade and anatomy, a slight cutback of the restoration is carried out to place effect colors and cover them with translucent material (Fig 3-46). Because the colorants are embedded into the restoration, there will be no effect of the surface wear on the stability of the result (Fig 3-46q).

3-46a

3-46b

3-46c

3-46d

FIG 3-46 Small incisal freehand sandwich layering: 24-year follow-up. *(a)* This incisal fracture of the left central incisor was restored to match the white spots on the intact contralateral tooth (postoperative view, overlay image with preoperative situation). *(b and c)* Enamel margins and the labial surface were softened with an abrasive disk. *(d)* Following bonding procedures, a freehand dentin/enamel buildup with additive principle was obtained (two increments). *(e)* The patient returned after tooth rehydration for confirmation of shade and form. *(f and g)* A 0.5-mm uniform layer of labioincisal enamel was removed, and small indentations were carved with a diamond bur to create recipient sites for the white resin effects. *(h and i)* The surface was cleaned with alcohol before the placement and polymerization of the white effect resin into the depressions. A photograph on the hydrated reference tooth (right central incisor) was used to gauge the amount of white effect needed (overlay image in *i*). *(j)* The surface was then covered with translucent composite resin. *(k to p)* The corrective restoration was then polished mechanically with abrasive disks and paste. Articulating paper rubbed onto the surface was used to confirm that the vertical and horizontal details match those of the intact reference tooth. *(q)* At 24 years later, the tooth is slightly discolored but the effects and length have been preserved with only minor maintenance. (Part *a* reproduced from Magne.[10])


3-46e


3-46f


3-46g


3-46h


3-46i


3-46j


3-46k


3-46l


3-46m


3-46n


3-46o


3-46p

3-46q

From multihue to single-hue composite resins and bilaminar shade guides

A turning point in the late 1990s and early 2000s was the introduction of single-hue composite resins along with more natural or "tooth-like" layering techniques, also called "anatomical build-up technique,"[175] "trendy 3-layer concept,"[238] or "natural layering concept" (see Fig 3-48).[241] Multihue systems have many shades for either enamel and dentin (many A, B, C, D VITA-based shades). Nevertheless, they fail to cover some of the extreme chromatic ranges found in patients (Figs 3-47a and 3-47b). In addition to their wide chromatic range, simple-hue systems (eg, ENA HRi by Micerium, Miris2 by Coltène, Inspiro by Edelweiss DR), in combination with the natural layering concept, proved to have superior color integration than multihue systems.[245] The shade guide is also a critical element in the process. Shade selection is more difficult when the shade guide is not made with the same material and thickness as the restoration.[246,247] Another challenge is that many shade guides do not represent the full spectrum of color found in natural teeth because of their limited color space.[248–254] Some guides have individual tabs for enamel and dentin, while others have tabs made with single monolithic (bulk) shades for both enamel and dentin or a single combination of enamel/dentin layers. More accurate layered custom guides can be produced with the material itself using prefabricated silicon molds, which uses material and is rather time-consuming. A prefabricated anatomical dual-laminate shade guide was first offered with Miris2 (Figs 3-47a and 3-47b). The selected enamel tab is "nested" over the dentin sample. The combination of different shades of enamel and dentin can be instantly compared with the tooth structure (enamel sample, dentin sample, and the enamel/dentin combination in a single observation). It is necessary to blend the enamel/dentin tabs with glycerin gel or water, which have a refractive index close to that of composite resins.[255] A more recent composite resin system, Inspiro, also offers a bilaminar shade guide (Figs 3-47c to 3-47f).

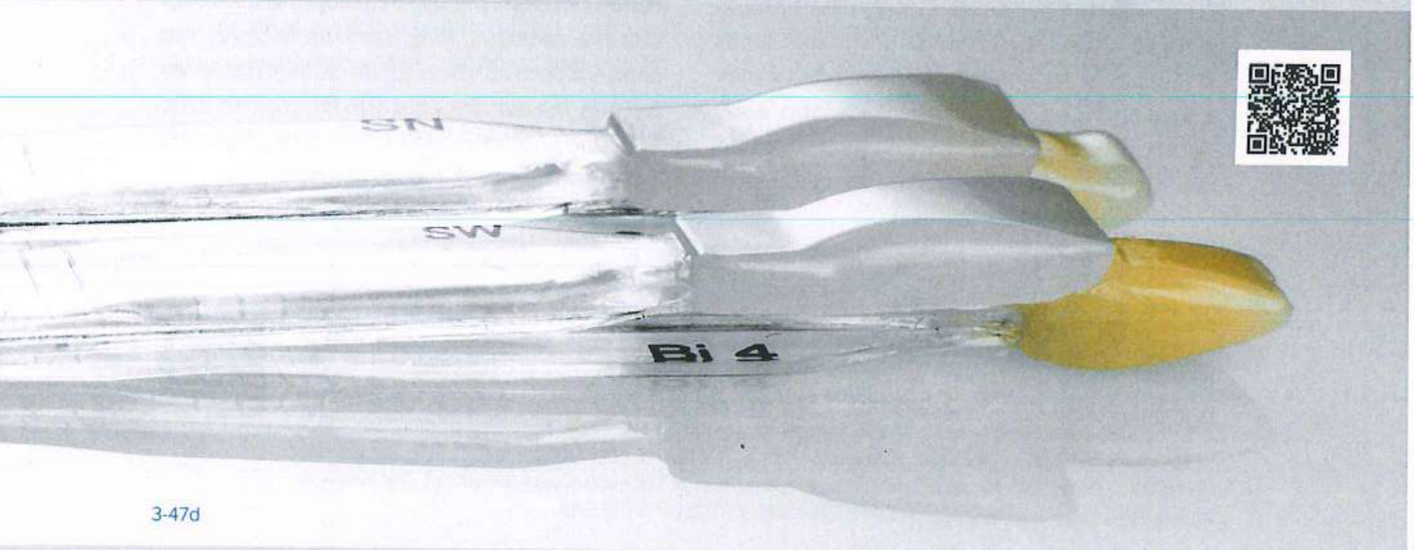
Those systems represent a dramatic simplification also because dentin is chosen from a single hue with up to 8 grades of chroma. The analysis of natural teeth has proven that an ideal dentin replacement can have a single universal hue and opacity but requires a large chroma scale.[241] Enamel works as filter, which can be high value (usually called "white" or "bleached"), neutral ("regular"), or low value ("Transpa" or "Ivory").[255] A highly chromatic dentin, for example level 3 (eg, Miris2 S3, matching VITA A3) can be filtered down to an A1 by the intense value of a bleached enamel (eg, Miris2 White Bleach). By the same token, a regular enamel (eg, Miris2 Neutral Regular) will usually maintain the chroma of the underlying dentin or tooth structure.[255]

FIG 3-47 Single-hue bilaminar shade guide. The Miris2 shade guide is not only bilaminar but also offers an ultrawide chromatic scale for dentin from 0 to 7 (instead of 1 to 4 when using multihue systems). *(a)* This specific case would require a level 4 or 5. *(b)* This other patient even reaches levels 6 and 7. Exact shade determination would require cross-polarized photography and software analysis (see *g*). *(c)* The Inspiro shade guide is designed similarly to Miris2 with 8 levels of dentin (body BiO to Bi7). Enamels are in the order of value filtering: high value for younger or bleached teeth (skin SB, SW), neutral (skin SN), and low value for older mature teeth (skin SI and ST). *(d)* Bilaminar dentin/enamel assembly.

3-47a

3-47b

3-47c



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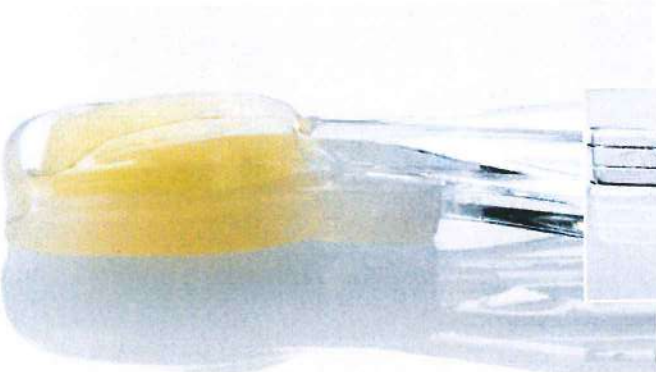
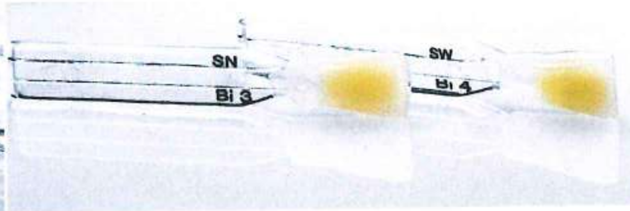


3-47e



3-47f

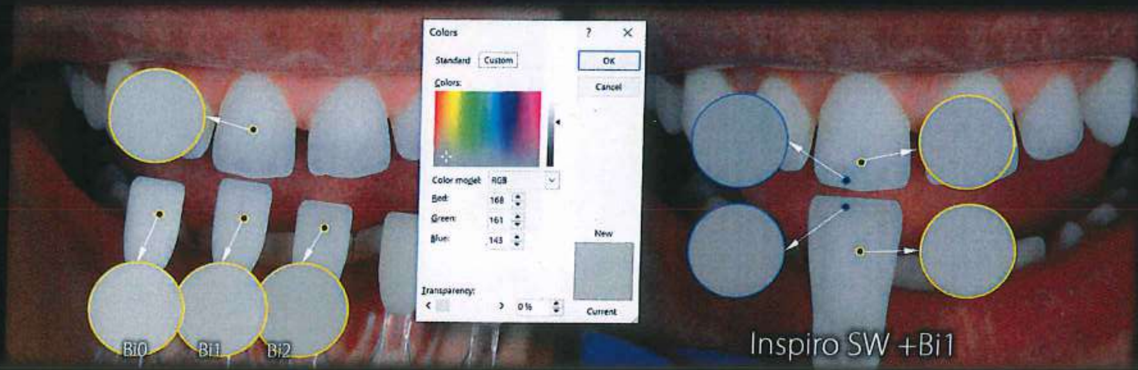
Bilaminar shade guides allow the dentin tab to be partially pushed out of the enamel veneer (see Fig 3-47d), providing a comprehensive view of the color with dentin alone, the dentin/enamel combination, and the enamel alone all visible at once next to the reference tooth. Exact shade selection requires a deeper analysis including shade mapping and digital photography with shade tabs[256,257] and a cross-polarization filter (see chapter 5, Figs 5-34 and 5-35).[258,259] The digital color picking tool available in most presentation software can also be used to generate color disks for a more visual comparison (Fig 3-47g).

Guided placement technique

It is difficult to simultaneously master marginal adaptation, form, and shade on several adjacent Class 4 restorations when using the freehand method, especially when planning alterations of the incisal edge length. As mentioned earlier, a turning point in the late 1990s and early 2000s was the use of more natural or "toothlike" layering techniques. The common goal of these methods is to mimic more accurately the natural morphology of enamel and dentin compared to the freehand approach. They are inspired from the realm of dental porcelain. The procedure is facilitated by the use of a silicon matrix. This stent can be obtained from previous casts of the patient, an existing restoration with appropriate shape and length, or from a wax-up/mock-up of the fractured/worn teeth. The silicon matrix allows the precise placement and polymerization of an enamellike shell of restorative material on the palatal aspect, which in turn will give support and guidance while developing the natural shape of dentin and facial-incisal enamel shell (Fig 3-48).

When a significant alteration of incisal length is planned, as is often the case when treating two central incisors, the use of a diagnostic wax-up and the corresponding mock-up is highly recommended to confirm that the patient approves not only the esthetics but also the comfort, function, and phonetics of the restoration (Fig 3-49; see also chapter 5, Figs 5-10 and 5-15).

FIG 3-47 *(cont) (e and f)* It is mandatory to place glycerin or water in between enamel and dentin to ensure continuity of light refraction during shade matching. *(g)* Cross-polarization photographs of reference teeth edge-to-edge with shade tabs can be imported in a presentation software. Shade disks are created and filled by picking the color (with the built-in Color Picking tool) of the reference area (tooth), dentin shade tab, and dentin/enamel combinations. The larger area and uniform color of the disks facilitate comparison. The exact color profile (in this case RGB) of each circle can also be compared numerically by accessing the properties ("format") of each shape *(windows)*. The mock-up and restoration of this specific case are presented in chapter 5, Fig 5-15.



3-47g

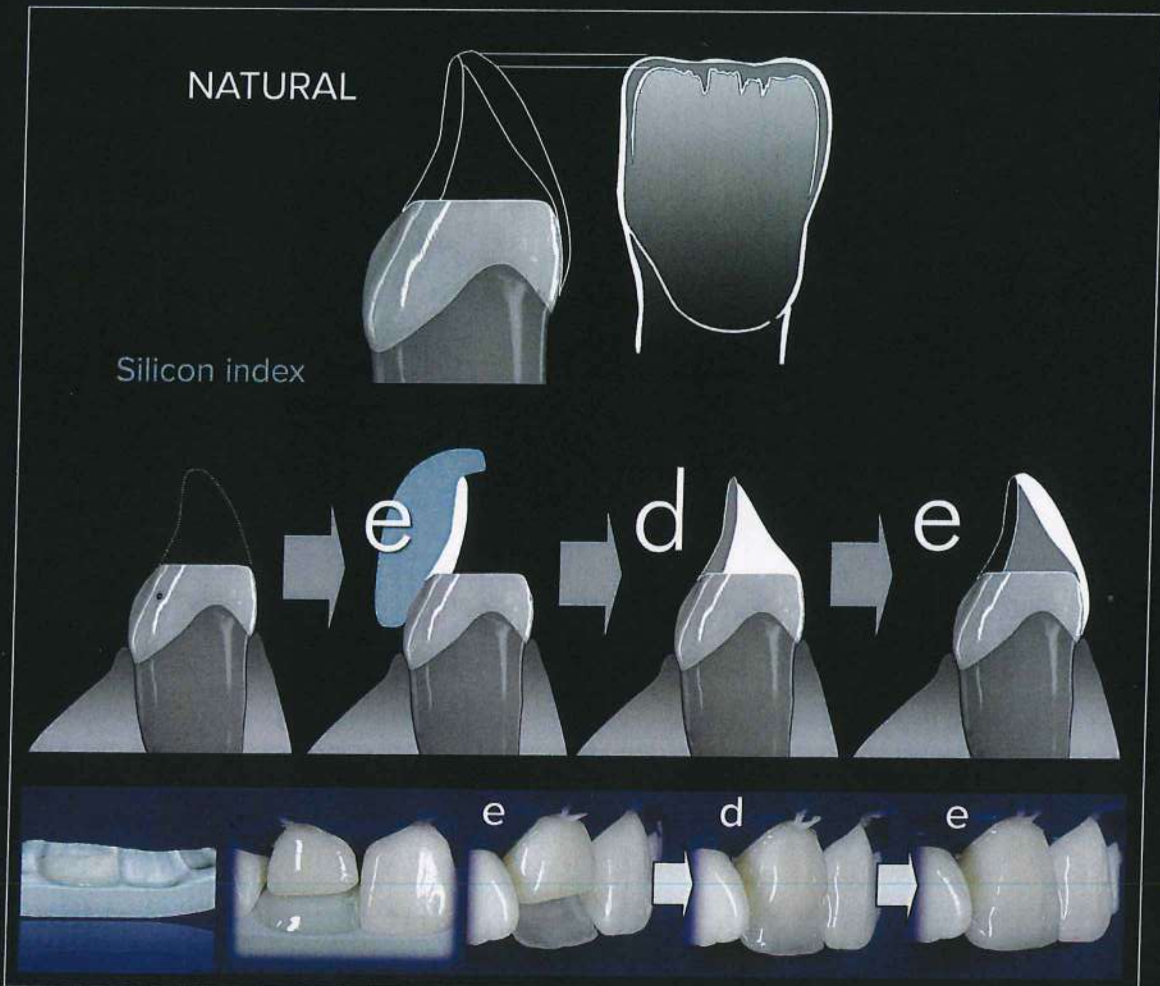


FIG 3-48 Natural guided stratification technique. A lingual shell of enamellike material is formed by a silicon index. Dentinlike increments are placed to reproduce the original location of natural dentin. Effect resins can be placed onto the incisal dentin if needed. The last increment is the labial enamel. As is the case in the freehand method, unworn and worn teeth differ by the extension of the dentin core (short of the incisal edge for unworn, exposed at the incisal edge for worn). Note that the dentin should be extended labially to the area of the enamel bevel, especially in the presence of underlying sclerotic dentin (masking purpose).

3-49a

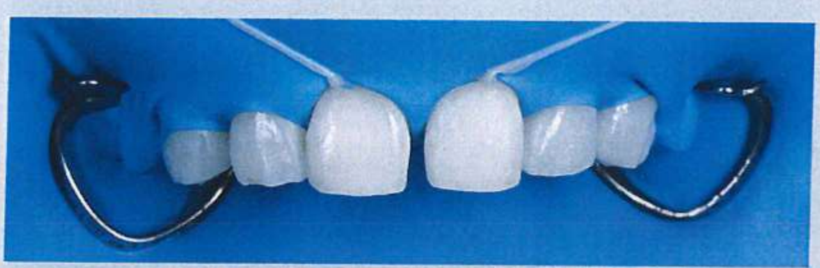
3-49b

3-49c

3-49d

3-49e

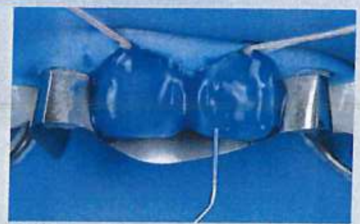
FIG 3-49 Step-by-step natural guided stratification case. *(a)* The patient desires to close the diastema between the central incisors. *(b)* Old residual resin restorations were removed followed by vital bleaching. A wax-up *(c)* and the corresponding mock-up *(d and e)* were used to explore the possibility of elongating the central incisors and revealed that the patient desired slightly shorter and more uniform incisal edges. Following removal of the mock-up and appropriate rubber dam placement *(f)*, the fit of the silicon index was tested first, then a metal matrix was used to protect the neighboring teeth during airborne-particle abrasion and etching *(h and i)*. Following abundant rinsing and drying, the adhesive resin was applied, thinned by high-speed suction *(j and k)*, and polymerized. The lingual enamel shells were then pressed firmly onto the incisal edge with the silicon index and polymerized *(l and m)*. The strong pressure allowed the silicon index to seat deeper than normal and achieve the shorter length desired by the patient. Note the small gap intentionally left between the shells to indicate the exact midline. A higher-chroma dentin was used first to close the diastema (*n*, teeth are kept separated with a small piece of metal matrix, no wedge used), followed by the application of the labioincisal dentin increment *(o)* and final labial enamel increment (*p*; the use of a wide flat brush facilitates the natural shaping). No internal effect masses were used because no effects were found on the adjacent intact teeth.



3-49f

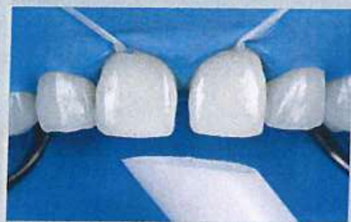
3-49g

3-49h



3-49i

3-49j



3-49k

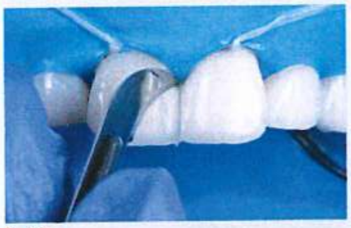
3-49l

3-49m

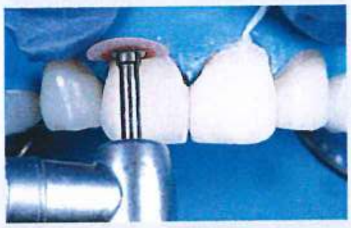
3-49n

3-49o

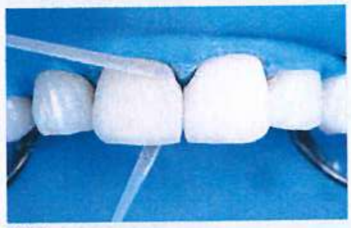
3-49p



3-49q



3-49r



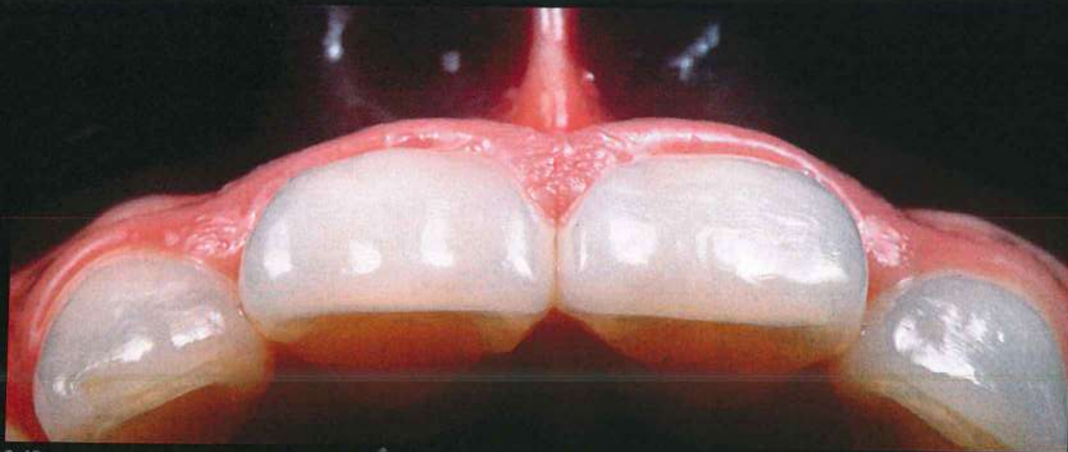
3-49s

3-49t

3-49u

3-49v

FIG 3-49 *(cont) (q to s)* Following final polymerization of the labial enamel (with additional polymerization through glycerin gel), a no. 12 blade and abrasive disks and strips were used to remove resin flashes. *(t)* Surface texture was developed with articulating paper, burs, disks, and polishing pastes (see all steps in Fig 3-50). *(u and v)* The final results achieved the patient's expectations. Note the rebound of the interdental papilla and tight fit with the restorations' interdental miniwings. *(w to y)* Angulated views outline the details of labial lobes and surface texture, which match those found on the lateral incisors. (Case treated in collaboration with Dr Jacqueline Younesi.)



3-49w

3-49x

3-49y

Surface texture

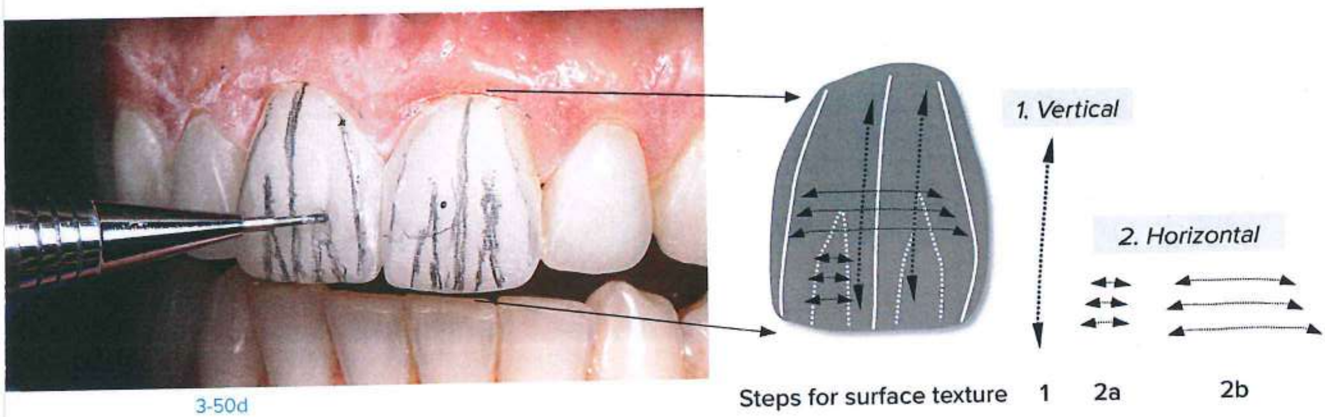
Whether it is with ceramics or composite resins, the development of surface texture must always follow two consecutive steps (Fig 3-50) in order to mimic the natural tooth architecture (see chapter 2, Figs 2-5, 2-6, and 2-10): ***(1) the vertical texture formed by the three labial developmental lobes, and (2) the horizontal texture between and across the lobes. The specific architecture of each tooth (central incisor vs lateral incisor vs canine) must be emulated accordingly.***

A regular diamond bur at low speed is recommended because the diamond grain will simulate the growth lines (perikymata) during the second step (gentle horizontal strikes). The polishing is initiated with silicon points (eg, Jiffy by Ultradent), and final gloss can be obtained with successive pastes (diamond and aluminum oxide, eg, ENA Shiny by Micerium) and brushes. It is generally recommended to exaggerate the texture in anticipation of the loss of texture that will occur during polishing and gloss. Surface polishing and gloss can also be obtained in two steps using universal diamond-impregnated polishers (eg, Feather Lite, Brasseler; see Figs 3-50t and 3-50u).

3-50a

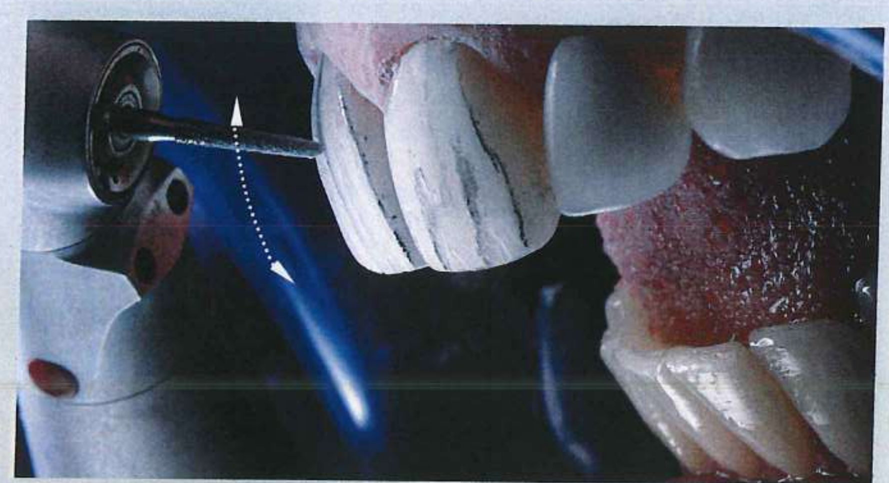
3-50b

3-50c



3-50d

FIG 3-50 Surface texture. The two maxillary central incisors (*a*, preoperative view; note existing porcelain veneers on the lateral incisors) were restored additively ("no-prep") with the guided technique (*b and c*; see this case in chapter 5, Figs 5-8 and 5-10 for detailed wax-up and mock-up procedures). Following removal of resin flashes and softening of the surface with abrasive disks, pencil marks are used to outline the major elements (*d*, mesial and distal line angles, central lobe, and V-shape concavities in between; see chapter 2, Fig 2-5g). A regular diamond can be used at low speed, starting with vertical movements (step 1) to deepen the space between the lobes *(e and f)*. Gentle horizontal movements are then carried out, first in between the lobes (step 2a) and then all across the surface (step 2b) to reproduce the perikymata. Articulating paper rubbed onto the surface allows visualization of the intensity of detail of the texture *(h and i)*, which can be modulated with abrasive disks at low speed *(j)*. Embrasures can be refined with thinner abrasive disks or strips while holding the contact point open with dental floss *(k and l)*.



3-50e

3-50f

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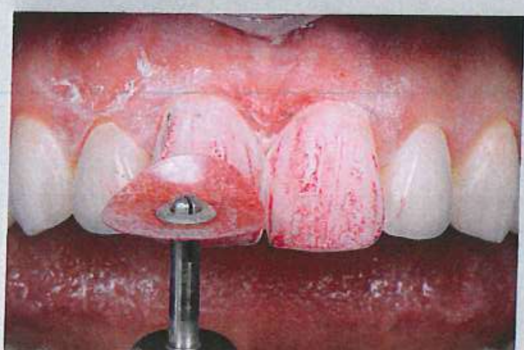

3-50j

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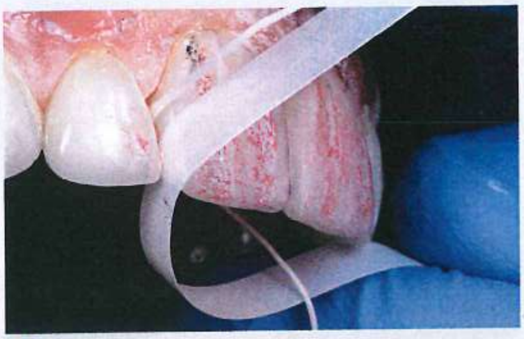


3-50l

3-50m

3-50n

3-50o

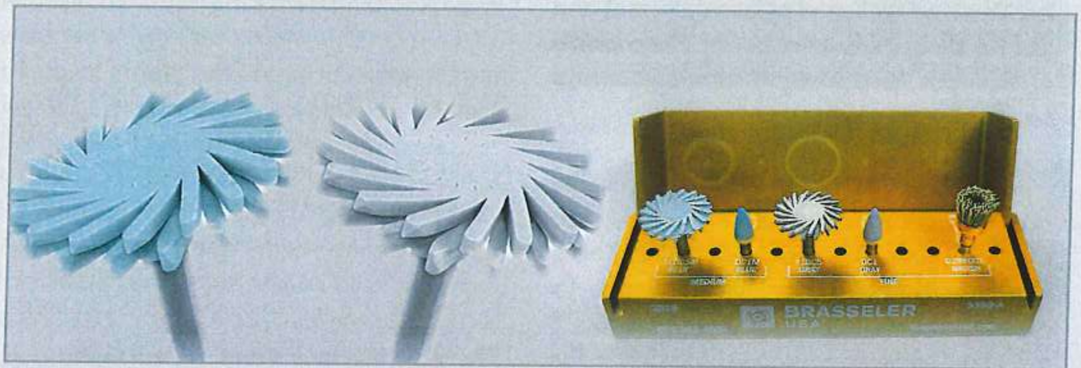
3-50p

3-50q

3-50r

FIG 3-50 *(cont)* Silicon points (eg, Jiffy) are used with the same vertical and horizontal sequence *(m and n)*. A semigloss can be obtained with a silicon bristle brush, but high gloss requires the use of 3-micron diamond paste *(o*, ENA Shiny, Paste A), 1-micron diamond paste (ENA Shiny Paste B, not illustrated), and aluminum oxide paste *(p and q*, ENA Shiny Paste C). *(r to t)* Postoperative views demonstrate pleasant integration within the smile, clean finish, and high gloss →

3-50s



3-50t

3-50u

with textured surfaces (preoperative overlay image in *s*). (Case treated in collaboration with Dr Dennis Sourvanos.) The Feather Lite polishing kit (Brasseler) is a simplified two-step system including points and spiral brushes *(t)*. It is used directly after texturing with diamond burs (blue medium and fine gray). *(u)* Note the detailed texture and outstanding gloss obtained in this other case of central and left lateral incisors.

3.9 CONSIDERATIONS FOR DIRECT RESTORATIONS IN POSTERIOR TEETH

Beyond the choice of the restorative material itself, there are significant clinical considerations that will influence the performance of direct posterior restorations.

Tooth preparation

Outline form of adhesive preparations should be essentially driven by the extent of the caries, demineralization of adjacent enamel, and discoloration of enamel or dentin. The principle of maximum tissue preservation should always be respected.

Marginal ridges, oblique ridges, and sound occlusal surfaces can be preserved even where enamel is not completely supported by dentin. The "adhesive preparation" should consist of a conservative round or ovoid internal shape,[260] including beveling of enamel margins.[103] For existing restoration replacement, the general cavity design should be limited to the removal of the restoration and damaged tissues followed by the beveling of enamel margins. The proximal bevel should have a 45-degree angle because prism direction is at right angles to the cavosurface. Safe interdental preparation is facilitated by the use of single-sided oscillating diamond tips (Fig 3-51; see also Figs 3-27e and 3-27f). The prism direction in the zone of the central fossa is inclined toward the fossa. Parallel occlusal walls (or even slightly convergent) still allow a transverse cut across the prism's long axis, thereby achieving more efficient etching. Nevertheless, occlusal margins can still be smoothed (minibevel) with a fine diamond bur to remove possible weakened enamel and to enhance the esthetic blending of the composite resin. Extensions of proximal walls can be kept as minimal as possible and can be placed in contact areas. No "extension for prevention" is needed.

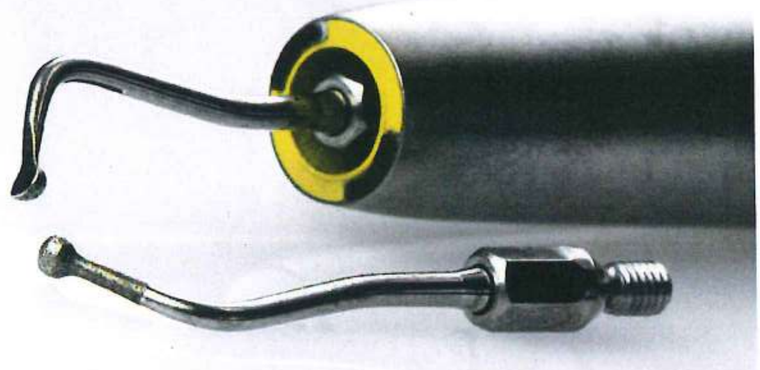
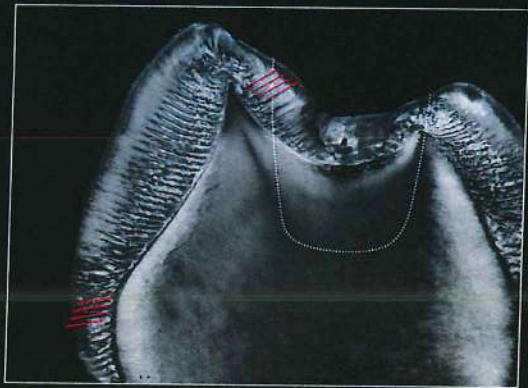


FIG 3-51 Safe interdental tooth preparation. Oscillating device (SonicSys and large hemisphere tips by KaVo) used for interdental preparation *(above)*. *(a)* Cross section of a posterior tooth (cross-polarization photography courtesy of Prof Luis N. Baratieri) showing the general prism orientation *(red arrows)*. Note the transverse section of occlusal enamel with occlusal margins while cervical enamel requires beveling to avoid longitudinal section. *(b and c)* Mesiodistal cross section showing safe accessing of interproximal caries carried out with a small spherical diamond bur, with the risk of damaging the neighboring tooth. *(d)* In lieu of or in addition to using a separation FenderWedge (see Fig 3-27d), retaining a small enamel wall during the access can be recommended as a "safety net." *(e and f)* The oscillating tools can then easily be applied—first the hemisphere to eliminate the unsupported enamel, then the bevel tip to apply the 45-degree bevel both at the gingival and axial margins of the proximal box. *(g to j)* Corresponding clinical sequence with hemisphere and bevel tips.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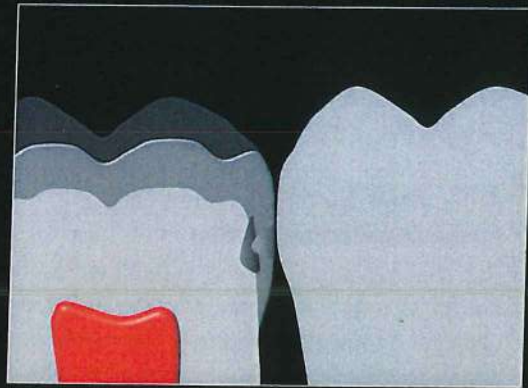
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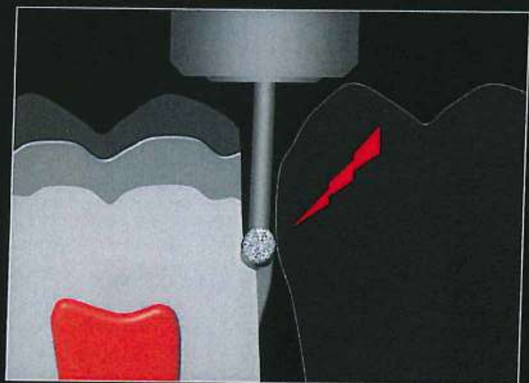
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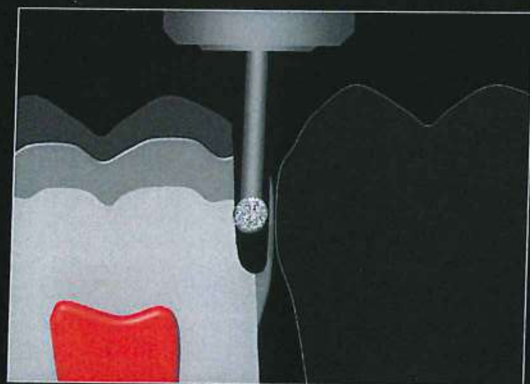
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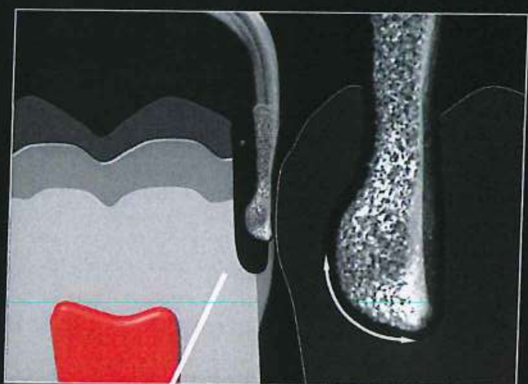
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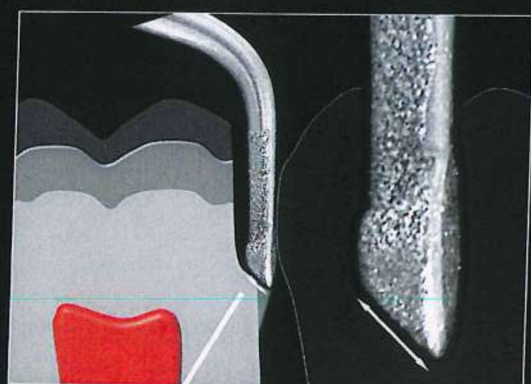

3-51f


3-51g


3-51h


3-51i


3-51j

OSCILLATING TIPS

Small interproximal lesions can sometimes be accessed laterally instead of opening an intact marginal ridge. In this situation, the small oscillating hemisphere can be used as a single tool to open access, clean the lesion, and finish the margins (Fig 3-52).

From initial opening to deep caries removal endpoints (CREs)

For shallow lesions in the superficial dentin, complete removal of caries by the traditional visual and tactile technique is recommended. The use of fiberoptic transillumination (FOTI) can be of significant help to locate the exact entry point through the marginal ridge (Fig 3-53). The ultimate approach to transillumination is the NIR (near-infrared) DIAGNOcam device (KaVo), allowing the operator to take digital occlusal images while transilluminating the tooth from both buccal and lingual aspects. The results suggest that NIR transillumination may substitute the use of bitewing radiographs in everyday clinical practice.[261,262] For deeper lesions, the main challenge is to determine the ideal caries removal endpoints. More sophisticated techniques are required than traditional visual and tactile techniques.

Clinicians may struggle to remove infection without exposing the pulp.[263] Detailed knowledge of 3D dental anatomy, histology, microbiology, and adhesive dental science should be combined. Visual dye staining in particular can be of significant help to guide the clinician in deep caries diagnosis and removal.[264]

3-52a

3-52b

3-52c

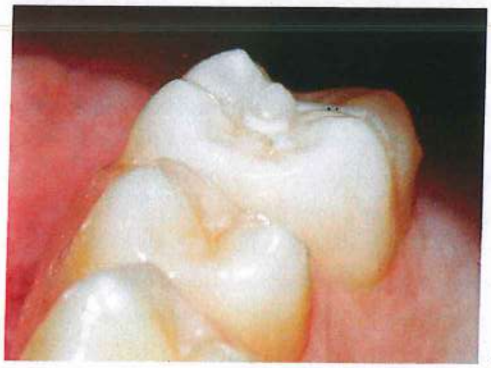
FIG 3-52 Lateral access to small interdental lesion. *(a to c)* Hemisphere oscillating tips could be used alone to prepare and clean this small caries lesion. *(d to g)* Similar situation using the oscillating tip and allowing the mesial marginal ridge of this first molar to remain intact. Teflon tape was used to wrap the neighboring tooth while performing adhesive procedures and placing the restoration. (Case treated in collaboration with Dr Mariely Márquez Lorenzo.)

FIG 3-53 Fiberoptic transillumination. *(a and b)* Microlux 2 transilluminator (AdDent) can be used for anterior and posterior teeth to detect caries but can also be used to visualize cracks and root canal orifices. The light guide is placed as close as possible to the interdental contact to reveal the exact extent of the lesion and facilitate the centering of the bur for initial access. Two devices can also be used simultaneously from buccal and lingual sides to enhance visualization. *(c)* K-Lite by Smile Line is a similar device that features a dual LED: white (6,000 K) for transillumination and visualization of opalescence, crack lines, and fractures, and violet (UV-A 395) that makes it easier to detect composite resins or adhesives with fluorescent components, calculus, or plaque. *(d)* The UV component emphasizes a fluorescent filling, and the white light reveals cracks (two devices used simultaneously). (Photography courtesy of Dr Katherine Losada.)

3-52d

3-52e

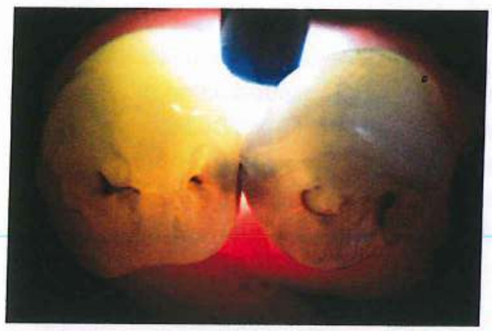
3-52f



3-52g

FOTI: FIBER-OPTIC TRANSILLUMINATION

3-53a



3-53b

3-53c

3-53d

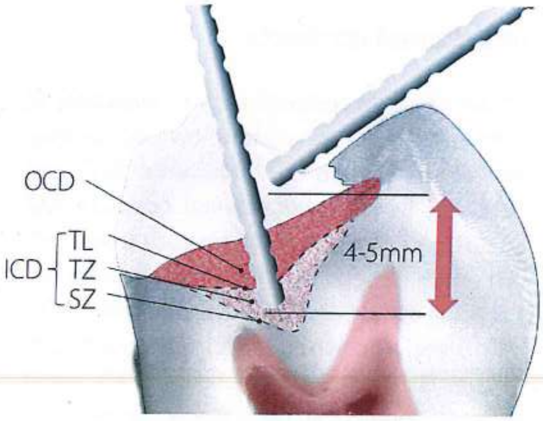
For teeth with a positive pulpal vitality test, CRE determination aims at the absolute avoidance of pulpal exposure while creating a peripheral seal zone (PSZ), which acts like a highly bonded restorative "moat"[264]: A bond strength of approximately 45 MPa can be generated by a PSZ that is 2 to 3 mm wide consisting of totally clean superficial dentin (1–2 mm), DEJ, and enamel (1–1.5 mm). There are two layers in the caries lesion (Fig 3-54a).[265] The outer carious dentin (OCD, caries-infected dentin) is highly acidic, infected, and presents denatured collagen fibrils, irreversibly damaged and demineralized. The inner carious dentin (ICD, caries-affected dentin) is partially demineralized and slightly infected, but collagen fibrils have retained their structure and integrity. In ICD, whitlockite crystals (calcium phosphate precipitates from dissolved hydroxyapatite in the transparent zone) fill the enlarged tubule lumens,[266] and there is a chance for this layer to be remineralized from the surrounding dentin if the pH is neutralized.[267] Removing the OCD only and saving the ICD for remineralization is a concept from the 1960s.[268] It is difficult, however, to clinically distinguish between these two layers. By using only visual and tactile methods for deep caries removal, the pulp may be exposed because the ICD, the normal deep dentin, and reparative dentin are all softer than superficial and intermediate dentin. Significant progress was made with the introduction of propylene-glycol solutions (eg, Caries Detector by Kuraray). It is important, however, to know that caries dye will produce a darkly stained OCD, while the ICD should remain lightly stained (pink haze).[264]

The ultimate goal of CREs and PSZ can be summarized as follows (Figs 3-54b to 3-54g):

1. Bonding to as much sound dentin as possible (superficial dentin) and formation of a strong PSZ free of any red stain (clean superficial dentin, DEJ, and enamel).
2. Removal of highly infected OCD inside the PSZ (leave the ICD pink haze) without exposing the pulp. In extremely deep lesions, small areas of circumpulpal OCD can be left to prevent pulp exposure.
3. Use of adhesive restorative techniques that will maximize the bond strength of the PSZ and ICD (see Fig 3-29 for dentin adhesives).

There is strong clinical evidence supporting the leaving behind of infected dentin, the removal of which would put the pulp at risk of exposure. Once isolated from their source of nutrition by a restoration of sufficient integrity, cariogenic bacteria will either die or remain dormant. This poses no risk to the health of the dentition.[269] An estimated 93% to 96% survival rate at 3 years was obtained after incomplete excavation of deep caries (leaving OCD at the center of the cavity) and restoring with GIC liner and composite resin.[270] In younger patients, this will also permit complete root formation.

FIG 3-54 Caries removal endpoints. *(a)* Deep caries lesions are made of the outer carious dentin (OCD) and inner carious dentin (ICD), with its three layers: turbid layer (interphase with OCD), transparent zone (tubule lumens filled with whitlockite), and subtransparent zone (normal sensitive dentin). A periodontal probe should be used to assess when the excavation reaches the circumpulpal area (4–5 mm from the occlusal developmental groove). *(b)* In such a situation, total removal of OCD and ICD may lead to unnecessary pulp exposure. *(c)* In even deeper lesions with OCD (staining dark red) extending to the circumpulpal area, the goal of CRE is primarily to create the PSZ *(yellow arrows)*. *(d)* Pulpal exposure should be avoided even if it means leaving a small amount of OCD on top of the ICD. *(e to g)* Common clinical situation with complete OCD removal but ICD (pink haze) left in the circumpulpal area. (Reproduced with permission from Alleman and Magne.[264])



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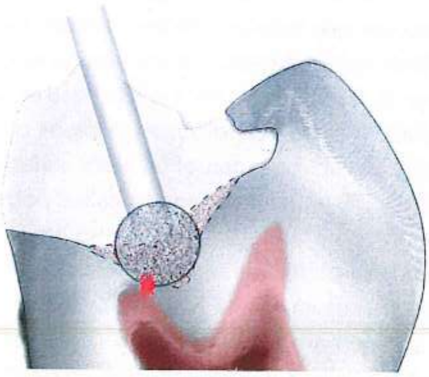

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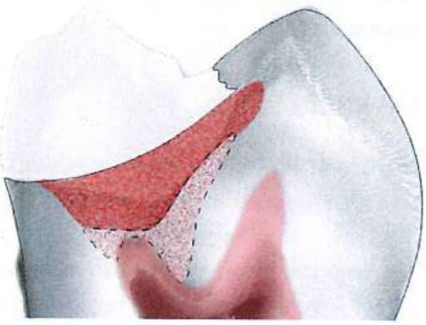

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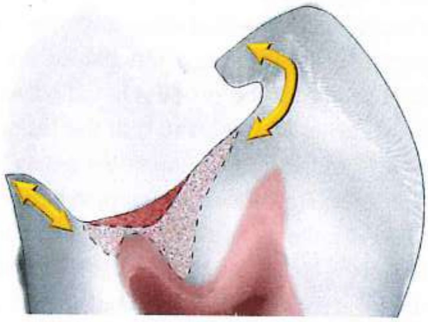
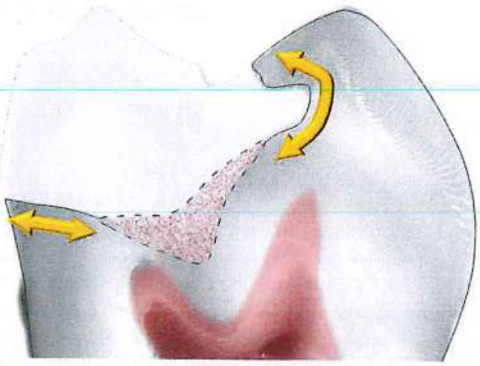


3-54d

PERIPHERAL SEAL CONCEPT

3-54e



3-54f

3-54g

Whether or not to open deep occlusal grooves and fissures is another clinical challenge. While caries detection dyes can be good indicators, laser fluorescence (LF) proved extremely efficient as a second option in cases of doubt after visual inspection of occlusal surfaces (Fig 3-55).[271] Bacteria metabolites called *porphyrins* fluoresce when irradiated at 655 nm, and the intensity correlates with the lesion depth. Thorough cleaning of the tooth surface with gentle airborne-particle abrasion is necessary to avoid false positives. The device (DIAGNOdent, KaVo) is calibrated with a fluorescent disk and a zero baseline (area of the tooth with sound enamel). The probe is then placed perpendicular to the occlusal surface and rotated sideways to seek for the highest numerical value displayed on the device LCD screen (peak). Mechanical intervention (opening of the groove) is indicated with values above 30, meaning that the lesion has passed into the DEJ. For numbers below 14, no action is required; for values ranging between 14 to 29, the patient should be advised to use fluoride and the lesion can be monitored for changes at the next recall visit. Because of its high sensitivity (few false negatives), LF is a perfect complement to the high specificity (no false positives) of visual examination and bitewing radiographs.[272] DIAGNOdent, however, tends to overscore discolored surfaces (brown or dark).[273]

Interdental contacts

Unlike amalgam restorations, the packability of composite resins, no matter how viscous they are, does not help to obtain better proximal contacts. Securing interdental contacts and contours of direct restorations may prove difficult and is dependant on the use of contoured sectional metal bands, special separation rings (Fig 3-56), and wedges (eg, Composi-Tight system, Garrison).[274] When used properly, good proximal contact can be achieved consistently and predictably. In addition, the use of metallic bands improves polymerization by light reflection.[275] ***Various interdental clearances also call for sectional bands with various curvatures and emergences.***

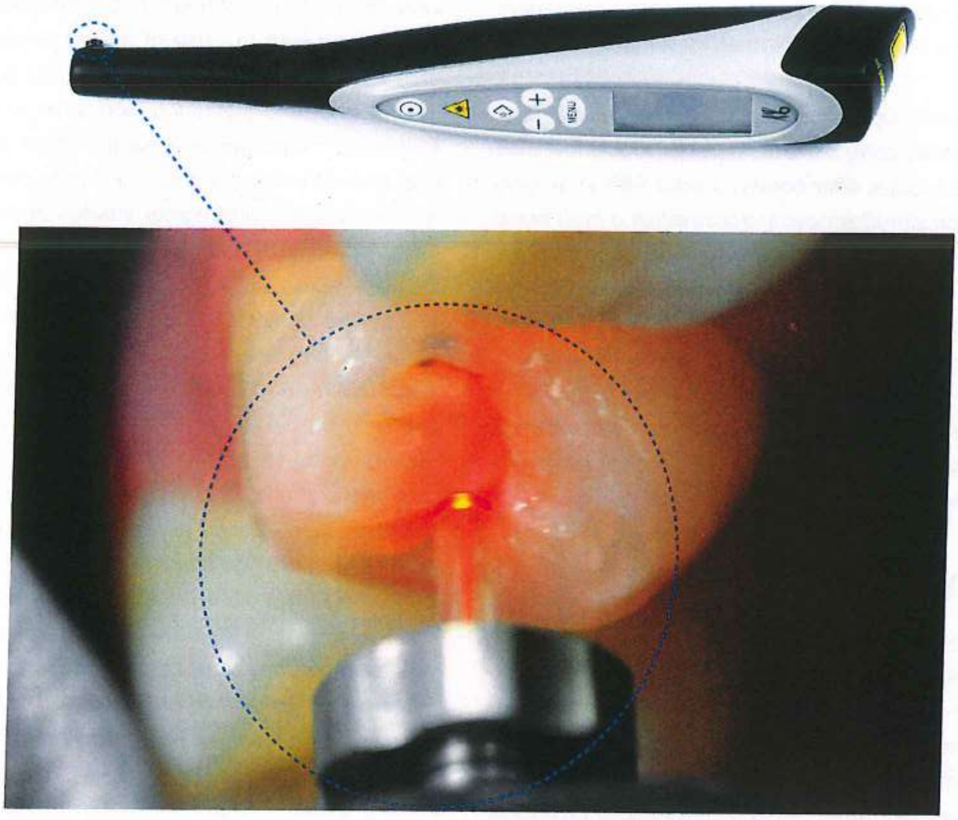
Flowable liners

The use of flowable liners as an elastic layer has been suggested to reduce the effect of polymerization shrinkage. It is based on the assumption that the lower the elastic modulus of the composite resin material, the lower the effects of the contraction stress will be. The results, however, have been inconclusive,[276] with some studies even demonstrating more microleakage and shrinkage stresses when using this technique.[277,278] The explanation may be that flowable liners also present increased polymerization shrinkage due to their composition (lower filler content and presence of more diluent resins).

FIG 3-55 Laser fluorescence—DIAGNOdent pen. As the laser is applied to the site, some degree of fluorescence is reflected, which is proportionate to the depth of the caries. The tooth surface must be cleaned (eg, airborne-particle abrasion) to avoid false positives (organic stains, plaque, and calculus are highly fluorescent). After calibration, the device will start emitting a sound when exposed to a positive fluorescent substrate. The pitch of the sound increases with the amount of fluorescence detected, which is metered through a number on the LCD screen: 0–10 for healthy structure, 11–20 for outer half enamel caries, 21–30 for inner half enamel caries, > 30 for dentin caries.

FIG 3-56 Separation rings. The Composi-Tight system is a popular product and is available with various shapes of grip and soft pads (orange original, blue for short clinical crowns, green for wide boxes). (Photography courtesy of Dr Mehrdad Razaghy.) Various interdental clearances also call for sectional bands with various curvatures and emergences.

LASER FLUORESCENCE



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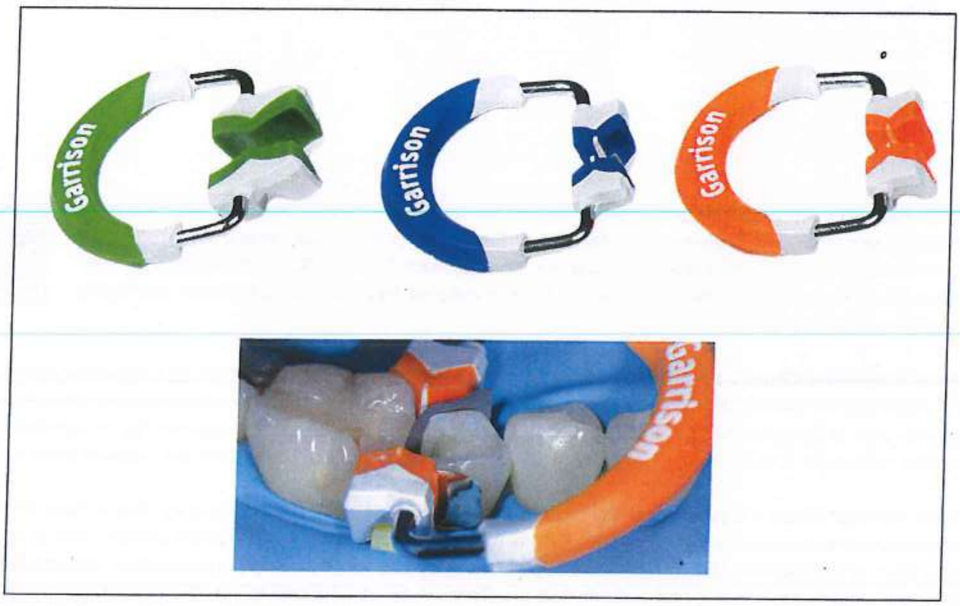


3-56

From a practical standpoint, however, the use of a flowable liner to smooth the preparation surface will certainly help to improve the internal adaptation and avoid gaps during the placement of the first composite resin increment (Fig 3-57).

Because OptiBond FL adhesive resin is a kind of flowable composite resin (radiopaque, low elastic modulus, filler content about 48% in weight), it can simultaneously accomplish a high bond strength and smooth the preparation surface for optimal adaptation, while showing some positive effects on the adaptation of the restoration in dentin when used as a thick liner.[140] Contraction stresses seem relieved by the application of an increasing thickness (> 100 microns) of low-stiffness adhesive.[279] Occlusal margins should be avoided to limit wear.

Layering techniques

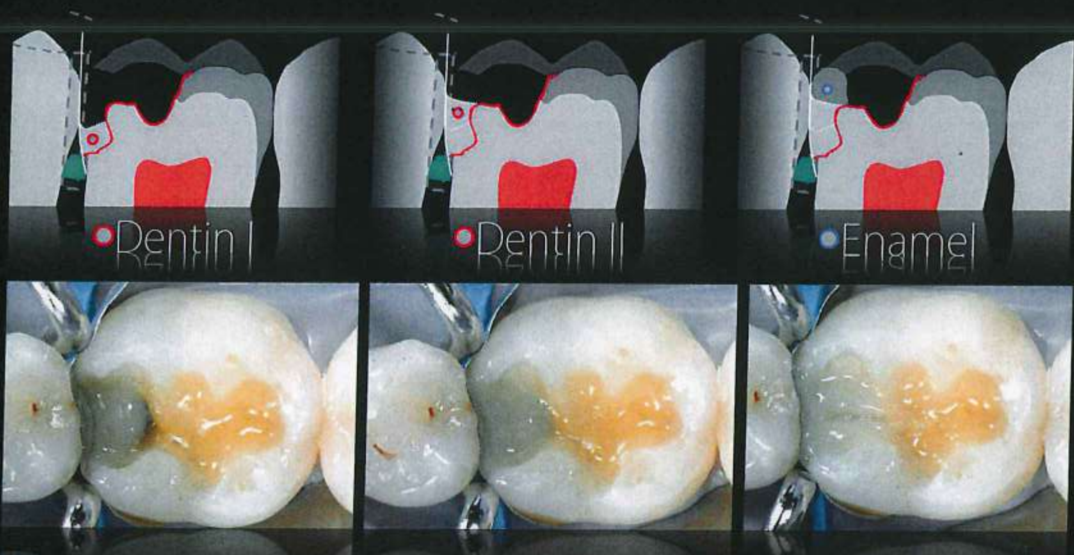
The first step in the restoration is to ensure optimal enamel-dentin bonding followed by the use of incremental layers of composite.[280] Numerous techniques have been proposed to limit the effect of shrinkage stresses. A number of studies have demystified various protocols by showing that layering does not necessarily decrease shrinkage stresses[281,282] but might even make them worse compared to bulk filling.[283] The very simple horizontal layering technique (Fig 3-58) along with the use of a filled three-step etch-and-rinse adhesive (OptiBond FL) proved its efficiency in maintaining high bond strength to dentin.[284] Opaque and warm shades (dentin-like) should be applied first and then covered with translucent and lighter shades at the top. Effect coloring resins can be applied either on the restoration surface or preferably under the enamellike composite layer to provide a more natural appearance (Fig 3-59).[174,285] Polymerization shrinkage in direct restorations, however, can only be partially compensated, no matter what layering technique is used. For large-volume restorations, only semi-direct and indirect inlays can potentially eliminate the problems related to shrinkage (especially enamel cracks) by limiting the volume of shrinking material to the luting layer.[286] ***Sandwich techniques (see next section) may represent a good, affordable alternative to semi-(in)direct/indirect techniques when dealing with large restorations in low-income patients.***

FIG 3-57 Flowable liner and irregular cavity floor. It can be challenging to apply viscous composite resin restoratives to uneven preparation surfaces *(left)*. Placement of a flowable resin liner on top of the adhesive reduces the risk of interlayer gaps and porosities *(center)*. Slight wetting with a filled adhesive resin and use of a microbrush to pack the composite resin material also facilitates placement, especially in interproximal boxes *(right)*.

FIG 3-58 Simplified Class 2 layering. A horizontal layering in two to four increments (~1.5 mm thickness) can be used in most cases and should always start with several dentinlike increments to establish an opaque base, especially in the presence of darkly stained underlying dentin. The area of the marginal ridge can then be completed with an enamellike increment. The separation ring and matrix can then be removed to complete the restoration as a Class 1.

FIG 3-59 Natural Class 1 layering. *(a)* Occlusal layering is similar to interdental layering. The surface of the last dentin increment should be concave to mimic natural dentin. A fine spatula or an explorer can be used to draw the exact location of developmental grooves in the unpolymerized material. Following polymerization, dark brown effect resin is applied to those grooves and polymerized too. This serves as a "roadmap" for the accurate application and polymerization of each enamel cusp, one by one.

3-57



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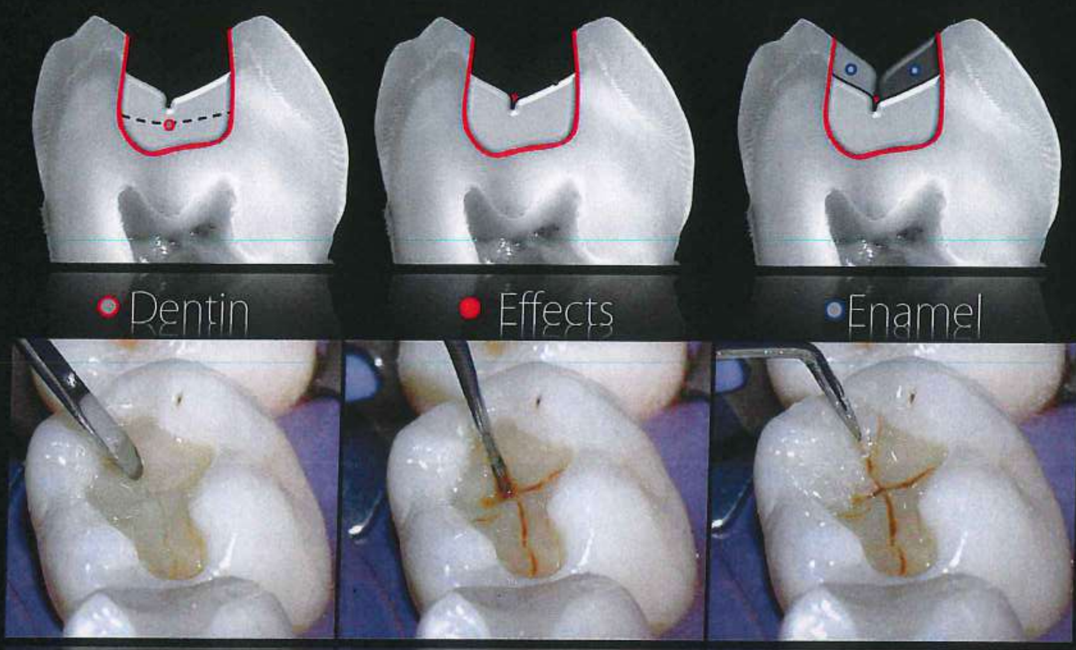

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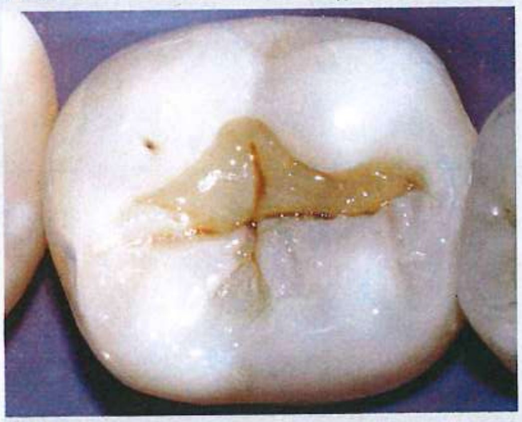
3-59c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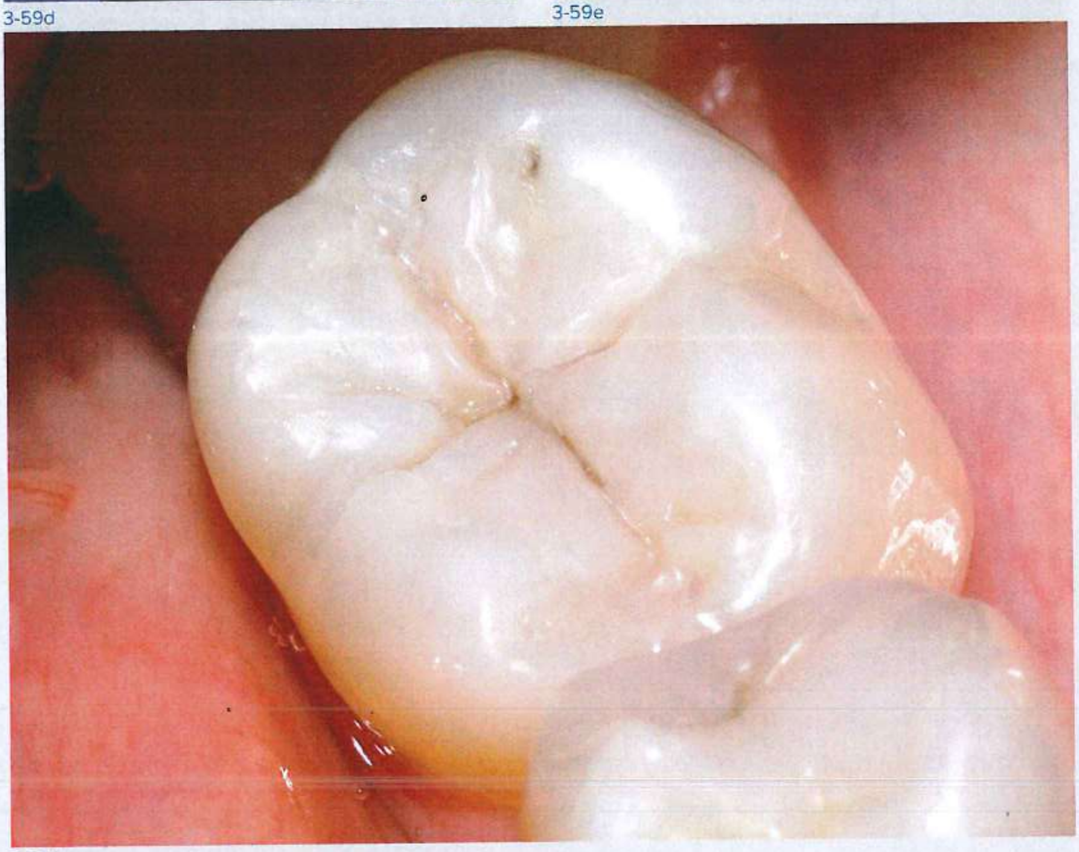
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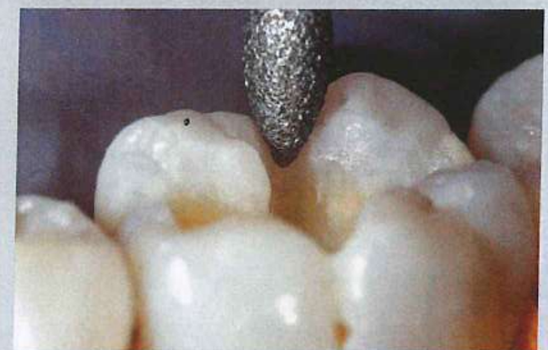

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3-59k

FIG 3-59 *(cont) (b to f)* Complete sequence from the occlusal view, dentin increment with "roadmap" grooves *(b)*, effect resin inside groves *(c)*, enamel increments one by one *(d and e)*, and final restoration after tooth rehydration *(f)*. The 14-year follow-up of this restoration can be seen in chapter 1, Fig 1-24c. (Reproduced with permission from Magne.[285]) *(g)* Proximal ridges are intact on this mandibular first molar, which represents the ideal size and indication for a direct composite resin restoration. *(h and i)* Tooth preparation after caries removal and occlusal bevel. The restoration was layered using the same "sandwich technique" as the previous case,[174] which comprises a characterized base *(j and k)* covered with more translucent masses polymerized one lobe/cusp at a time *(l to o; see next page)*, allowing the elaboration of a sophisticated morphology and functional masticatory surface.

3-59l

3-59m

3-59n

3-59o

3-59p

3-59q

3-59r

FIG 3-59 *(cont) (p to r)* Due to the careful sequential placement of each lobe and elimination of excesses before each polymerization, finishing of the restoration is significantly simplified; the final contours and luster are easily obtained with "homemade" notched Sof-Lex disks.

Large sandwich restorations

Polymerization contraction stress is the result of complex interactions between polymerization shrinkage, elastic modulus, conversion degree, and cavity configuration, among other factors. McLean first introduced the sandwich restoration (SR) in the 1970s[287,288] as a valid solution to address the problem of shrinkage and poor dentin bond strength of earlier composite resin and adhesive formulations. Composite resin is only used as an "enamel" and combined with GIC as a dentin replacement. In this way, the volume of shrinking resin can be reduced, thus increasing cuspal stability[289] by limiting the residual stress and contributing to better marginal sealing and interfacial adaptation.[287–291]

Open sandwich

The GIC can be used as a proximal margin elevation base and left exposed at the cervical margins, the so-called "open SR" (Fig 3-60, left). In this specific location (dentin margin), the GIC has the capacity to release fluoride and inhibit dentin demineralization lesions.[292] While this technique was particularly useful during the 1980s due to the poor efficiency of dentin adhesives, some authors advised against this type of treatment. Low success rates were found in clinical studies investigating open SRs with traditional GIC,[293,294] which suffered from dissolution and progressive volume loss. Many fractures were found in the open SR group[294] because of their low flexural strength compared to composite resin materials. The replacement of GIC with RMGIC improved the performance of SRs, yielding similar results to direct composite restorations after up to 9 years of evaluation.[295]

Closed sandwich

In the closed SR, the GIC/RMGIC base is totally covered by composite resin and does not extend to the margins (Fig 3-60, center, and Fig 3-61).[296] When using a conventional GIC, closed SRs proved significantly superior to open SRs, which needed replacement in 75% of the cases after 6 years.[294] This configuration, when used with RMGIC, also demonstrated less microleakage compared to composite resin restoration alone.[295] From a clinical standpoint, cracking of the conventional GIC and internal gaps may develop as a consequence of dehydration before bonding procedures (see Fig 3-61e). Enamel etching can be performed prior to the application of RMGIC, but enamel can be contaminated by the conditioner or primer of the RMGIC. It was proposed that using a single adhesive system for both restorative materials would make the sandwich technique less complicated.[297,298] The increased viscosity of the GIC/RMGICs (eg, compared to resin bonding agents) may also result in voids and gaps.

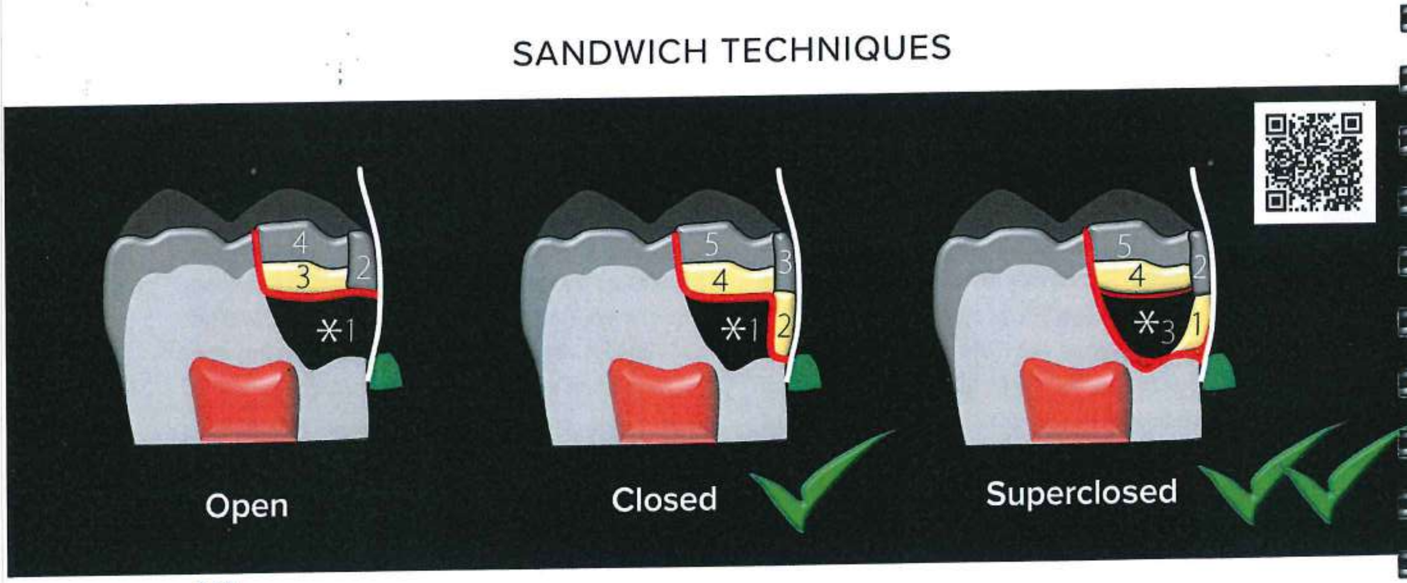
Superclosed sandwich

In view of the above, use of a resin adhesive before the placement of the GIC/RMGIC was suggested.[299,300] This corresponds to the logical evolution of the closed SR technique and was presented as the "superclosed SR."[301] In this case, the low-shrinkage and low–thermal expansion GIC/RMGIC base is applied after sealing the tooth with an enamel/dentin bonding agent (Fig 3-60, right, and Fig 3-62). In other words, the appropriate enamel-dentin bonding procedure is first applied to the isolated preparation before inserting the dentin-replacing GIC or RMGIC.

For Class 2 superclosed SRs, the layering technique must be adapted to facilitate the insertion of the GIC/RMGIC. It is advisable to start building the proximal walls of the defect with a thin layer of composite resin (converting the Class 2 defect into a Class 1), which will define a confined volume for the application of the GIC/RMGIC (see sequence in Fig 3-60, right). At least 2 to 2.5 mm of occlusal clearance must be kept for the overlaying composite resin. Lack of occlusal thickness of composite resin may affect the overall performance of SRs.

Inclusion of GIC/RMGIC bases under large direct superclosed SRs does not affect their fatigue strength but tends to decrease the shrinkage-induced crack propensity.[301] In the same study,[301] however, it was found that a CAD/CAM composite resin inlay (Paradigm MZ100) stands as an undisputable reference regarding not only its strength but also its ability to prevent shrinkage-induced cracks in the cusps (see chapter 4, Figs 4-10 and 4-11). It is a fact, though, that despite their outstanding performance, luted indirect restorations often must give way to more convenient and more affordable solutions such as sandwich techniques.

New short fiber-reinforced materials (eg, everX Posterior and everX Flow by GC) might represent the next evolution of the superclosed SRs to replace the GIC/RMGIC for high-stress bearing areas.[189,190] With its higher fracture toughness and flexural modulus within the family of bulk-fill materials, SFR composite resin can be used easily in 4-mm-deep increments and can potentially match the toughness of dentin.[191,192]



3-60

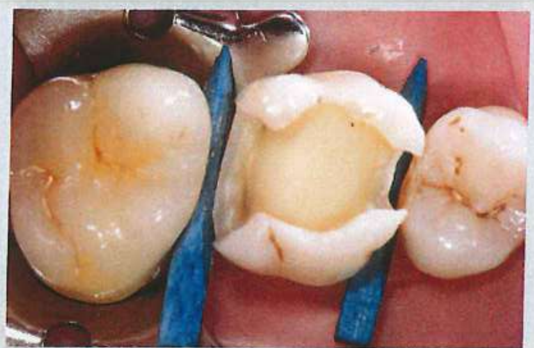
FIG 3-60 Sequence of the three different sandwich restorations. In the open SR *(left)*, RMGIC should be used (*) and is placed first and fills the entire base of the preparation, all the way to the proximal margin (*red:* enamel-dentin bonding). Similarly, in the closed SR *(center)*, the GIC/RMGIC precedes enamel-dentin bonding but is absent from the margin. In the superclosed SR *(right)*, enamel-dentin bonding is the first step, followed by the vertical layering of the proximal wall. The GIC/RMGIC is then placed in the main dentin volume, followed by occlusal layering (~1.5 mm of dentinlike and 1 mm of enamellike material).

FIG 3-61 Large closed SR—long-term follow-up. (Images reproduced from Magne.[296]) *(a)* This compromised first molar is without distobuccal root (extracted for periodontal reasons). *(b)* The large MOD defect will be restored with a direct technique due to the reserved prognosis of this tooth. *(c)* In the early 1990s, it was suggested to close the apical portion of the tooth with amalgam due to the opening left by the missing root. The main dentin volume was then filled with GIC *(d)* followed by the placement of composite resin *(e to g)*. Note the desiccation and cracking of the GIC during enamel etching.

3-61a

3-61b

3-61c



3-61d

3-61e

3-61f

3-61g

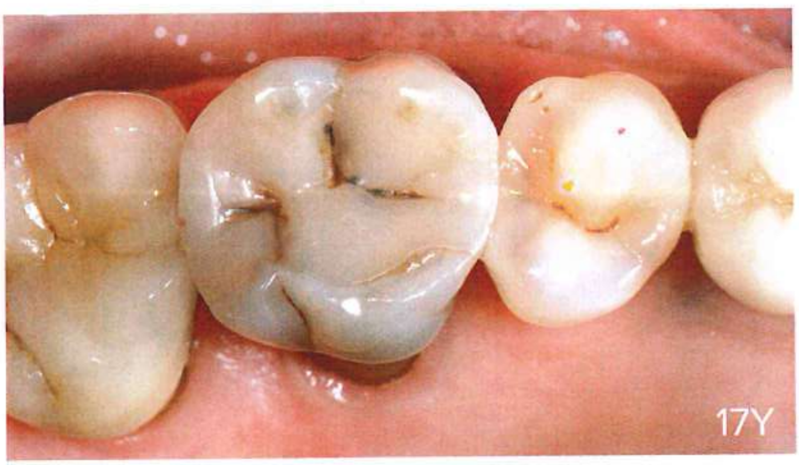
As such, direct restorations with everX replacing dentin were able to match the performance of CAD/CAM semi-direct inlays (Cerasmart, GC) while generating only minor shrinkage-induced cracks.[188] Its manipulation remains a challenge, and it needs to be covered with a sufficiently bright material to compensate for its excessive translucency. Those problems are avoided when using GIC/RMGIC SRs.

Polishing and finishing

Polishing and finishing of direct posterior composite restorations follow the same steps and instruments described for anterior teeth. Following occlusal adjustments, silicon points and disks (eg, Jiffy) are used with the same sequence (see Figs 3-50m and 3-50n), finishing with a silicon-bristle brush. ***Surface polishing and gloss can be obtained in only two steps using universal diamond-impregnated points and spiral brushes (eg, Feather Lite blue and gray, Brasseler; see Figs 3-50t and 3-50u).***

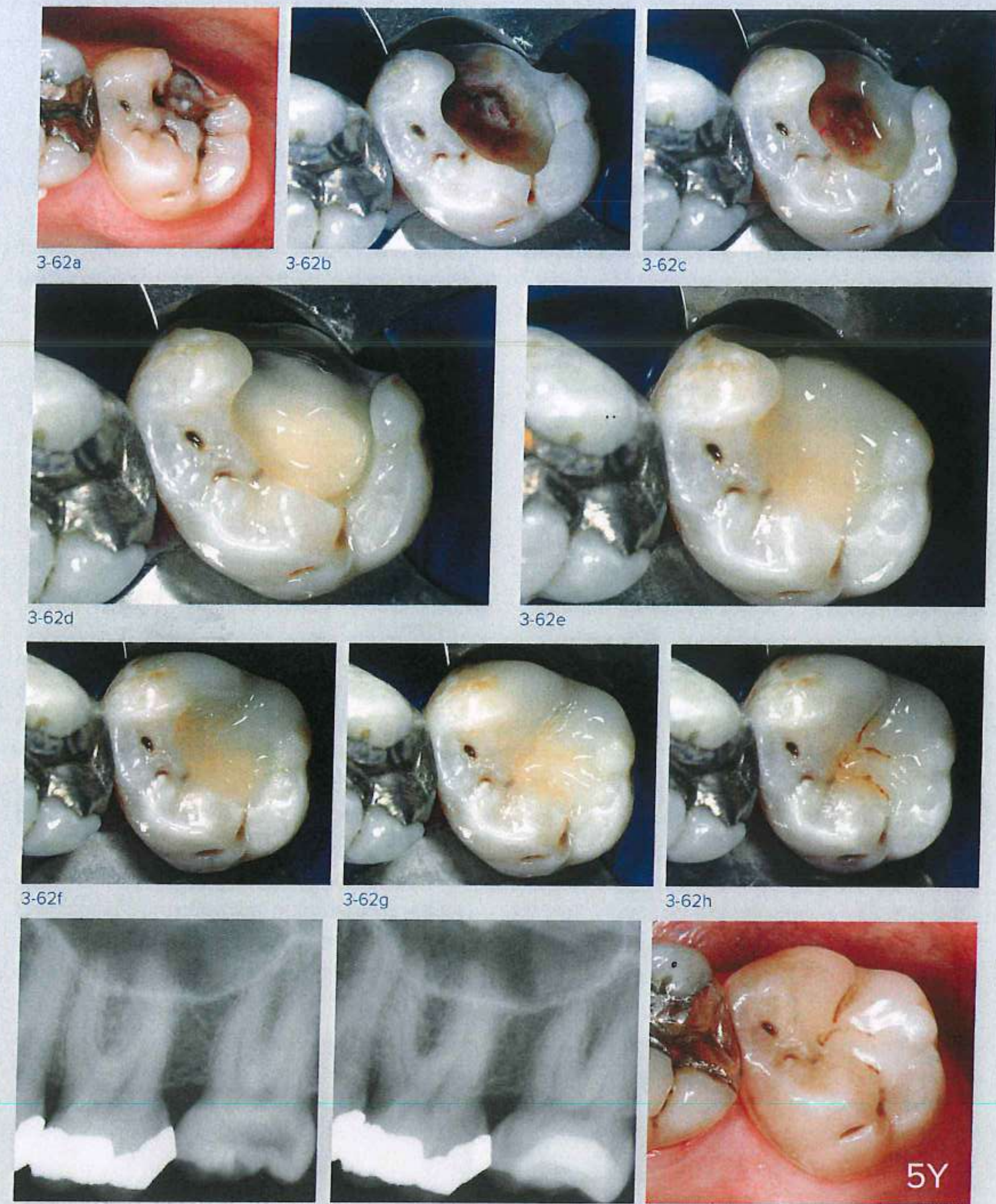
3-61h

3-61i



3-61j

FIG 3-61 *(cont) (h)* Seven-year postoperative bitewing radiograph. Note that the antagonists are porcelain-fused-to-metal restorations. *(i)* Despite color changes, there are no mechanical failures or enamel cracks found after 17 years of clinical service. *(j)* Antagonist ceramic restorations have caused significant wear of the mesiopalatal cusp with exposure of dentin.



3-62a 3-62b 3-62c 3-62d 3-62e 3-62f 3-62g 3-62h 3-62i 3-62j

FIG 3-62 Superclosed sandwich technique step by step. *(a)* There is a large and deep occlusal caries lesion on this second molar, and the buccal enamel has collapsed. Following partial CRE and enamel finishing *(b)*, enamel-dentin bonding was applied and polymerized *(c)*. *(d)* About 50% of the preparation volume was filled with conventional GIC, leaving 2 to 2.5 mm of occlusal clearance for the composite resin. Note the adhesive resin that was immediately placed to cover the GIC (while shaping it with a microbrush) and polymerized. The heat from the light accelerates the setting of the GIC and may also improve the mechanical characteristics.[162] Composite resin was first placed and polymerized in the buccal area to define the occlusal perimeter *(e and f)* before starting the occlusal layering *(g)* and coloring *(h)*. *(i)* Preoperative and postoperative radiographs. *(j)* Clinical view after 5 years of successful clinical service. No functional or shrinkage-induced cracks are visible despite the large volume of restorative material.

3.10 DEEP MARGIN ELEVATION TECHNIQUE

Localized subgingival margins can complicate the placement of both direct and indirect adhesive restorations (isolation, impression, delivery) and subsequently affect their durability and effect on the periodontium.

A technique is proposed in which a modified tofflemire matrix is placed, followed by IDS and coronal elevation of the deep margin (to a supragingival position) using a base of direct-bonded composite resin.[302] For practical and socioeconomic reasons, deep margin elevation may be a useful noninvasive alternative to surgical crown lengthening. The technique might also facilitate the placement of large direct composite resin restorations.

Subgingival interdental margins may be encountered when replacing large Class 2 restorations. Such situations generate significant technical operative challenges, such as the difficulty in isolating the operatory field by means of the rubber dam, placing wedges and sectional matrices in case of direct techniques, impression-making (whether traditional or digital), and adhesive luting in the case of semi-direct and indirect techniques. When not achieved properly, these procedures may affect the longevity of the restoration and its relationship with marginal periodontal tissues.

There are various clinical approaches to this dilemma.[303–323] Gingival margins can be surgically exposed by apical displacement of supporting tissues.[305,314,320] This may be, however, at the expense of attachment loss and possible anatomical complications such as the proximity of root concavities and furcations. Once exposed to the oral environment, those areas can be problematic to maintain and may generate additional challenges.

Another approach, presented for the first time by Dietschi and Spreafico in 1998,[303] is to place a base of composite resin in order to displace, in a coronal position, the proximal margins underneath indirect-bonded restorations (Fig 3-63).

Deep margin elevation (DME),[302,311,321,322] also called *cervical margin relocation*[311,313,320,323] or *proximal box elevation*,[309] is best performed under rubber dam isolation, following the placement of a modified circumferential matrix.[302] Today, the DME concept can be used in synergy with the

3-63a

3-63b

FIG 3-63 Radiographic control after deep margin elevation. Clinical case before *(a)* and after *(b)* placement of a composite resin base that seals the dentin and elevates the distal margin of the mandibular first molar. Following the elevation, the margin was easily accessible for final optical impression and allowed the safe delivery of the final restoration under rubber dam.

IDS technique (see chapter 4) to improve the bond and marginal seal of indirect adhesive restorations.[150–152,324–327] In addition to the supragingival elevation of the margin, the adhesive composite resin base allows sealing of the dentin, reinforcement of the undermined cusps, and filling of the undercuts and provides the necessary geometry for the inlay/onlay restoration.

Fundamentals of the DME concept

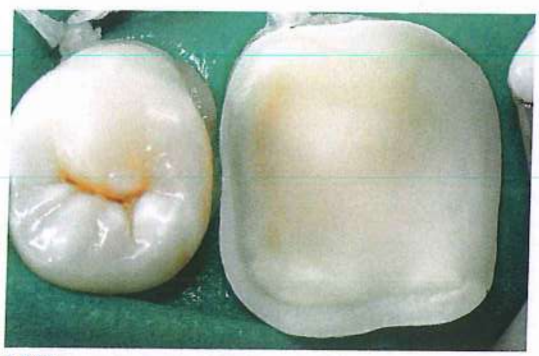
The DME concept applies to preparations for direct restorations and semi-direct and indirect adhesive inlays and onlays (especially those generated by optical impression and CAD/CAM) when gingival margins cannot be isolated by means of rubber dam alone. During inlay/onlay delivery, excess luting composite resin needs to be eliminated prior to curing, which, in the presence of subgingival margins, causes a substantial risk of hemorrhaging or breaking the seal necessary for proper isolation (even under rubber dam). This problem is usually nonexistent when cementing conventional full-crown restorations because excess cement (GIC, zinc phosphate, polycarboxylate, etc) can be easily removed after setting. In the case of inlays/onlays, one can eliminate that difficulty by first attempting DME. Surgical crown lengthening can always be performed later in case of unsuccessful DME (eg, persistent bleeding during and after DME or lack of marginal adaptation as seen on radiography).

Once again, one must always carefully take into consideration the risks of involving a furcation or a root concavity before planning surgical crown lengthening and therefore prioritize DME when this risk is present.

DME is achieved by placing a direct composite using a modified "supercurved" circumferencial matrix (eg, Greater Curve by Greater Curve, ReelMatrix Margin Elevation by Garrison) to bring the gingival margin to a level where it can be sealed with rubber dam during the delivery of the inlay/onlay. This allows proper removal of excess luting composite resin before curing. DME should always be achieved directly after IDS, under rubber dam, and only if the margin can be isolated properly with the modified matrix. It is absolutely contraindicated otherwise. It is recommended to make a bitewing radiograph (Fig 3-63b) and evaluate the proper adaptation of the composite resin in the gingival area (absence of gaps or overhangs) before proceeding with the final impression. A careful follow-up of the case will determine soft tissue health and the potential necessity for surgical intervention (in case of periodontal alteration and adverse effect on the biologic attachment).

Whenever possible, it is recommended to proceed to DME before endodontic treatment in order to benefit from the improved isolation during root canal therapy (Fig 3-64).

3-64a



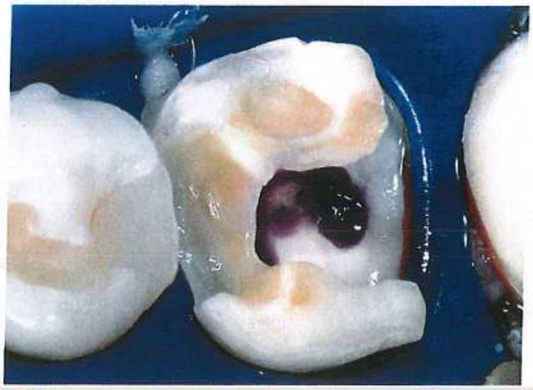
3-64b

FIG 3-64 DME preceding endodontic treatment. *(a)* The distal margin was elevated to facilitate endodontic retreatment. The final onlay preparation was obtained after placement of a GIC barrier at the canal entrance and composite resin to restore the pulp chamber ceiling. *(b)* Clinical view just before adhesive luting of the indirect ceramic onlay, showing perfect isolation and ideal conditions for delivery.

A typical clinical example where DME can be attempted is presented in Fig 3-65. The following elements are fundamental for successful DME:

1. **A curved matrix should be favored.** A traditional matrix may allow the isolation and elevation of margins located above the CEJ. In the case of margins located in the area of the CEJ, a traditional matrix will usually generate insufficient gingival emergence profile and contour.
2. **Sufficient buccal and lingual walls of residual tooth structure must be present to support the matrix.** Localized elevation is possible, but extended elevation in the buccal and lingual direction will usually be limited due to matrix instability and collapse.
3. **Matrix height should be reduced to 2 to 3 mm only** (slightly higher than the desired elevation). The narrowness of the matrix will allow it to slide subgingivally and seal the margin more efficiently (see Figs 3-65e to 3-65h). Wedging is often not possible or even necessary.
4. **After placing the matrix, carefully check that the gingival margin is sealed by the matrix.** Isolation is paramount for DME. No gingival tissue or rubber dam should remain between the margin and the matrix. If necessary, Teflon tape (twisted to form a "floss") can be packed in the gingival sulcus to generate compression and limit the production of gingival fluid. The matrix-in-a-matrix technique (see point 11), may appear salutary when other ways of isolation seem impossible. In the case of unsuccessful isolation, a surgical approach may be used along DME,[320] knowing that it could lead to further anatomical challenges by exposing root concavities and furcations.
5. **Before starting bonding procedures, the margin should be gently reprepared using a fine diamond bur or oscillating tips.** The Hemisphere or Prep Ceram tips (KaVo) are used with abundant water spray (see Figs 3-65k and 3-65l). This will ensure the elimination of debris and other contamination (saliva, blood) of the dentin that may have occurred during matrix placement. Oscillating tips should be preferred over burs because the inner surface of the elevation matrix should not be damaged or scratched during this process. An undamaged matrix will generate a smooth elevation composite resin surface and limit the need for polishing.
6. **For endodontically treated teeth, one must ensure that appropriate root canal therapy has been achieved and place a GIC barrier to cover the access to the canals.** The GIC barrier will prevent any interactions between the endodontic sealants and the solvent in the primer of the dentin bonding agent. As mentioned before, DME can also be used prior to root canal therapy to facilitate proper isolation during RCT (see Figs 3-64 and 3-67).

FIG 3-65 Proper isolation of a subgingival margin. *(a and b)* Typical clinical situation demonstrating the difficulty in isolating the deep distal margin on this mandibular first molar due to saliva and blood leakage as well as rubber dam slipping over the margin. This situation is ideal to attempt DME, which will be facilitated by the natural convex outline of mandibular molars. *(c)* The curved matrix (Greater Curve) on the matrix holder allows convergence and tight subgingival fit. *(d)* A post-elevation radiograph of another case shows the mesial margin of the mandibular left second molar elevated with a curved matrix while the distal margin of the left first molar was elevated with a regular matrix. Note the difference in emergence profile.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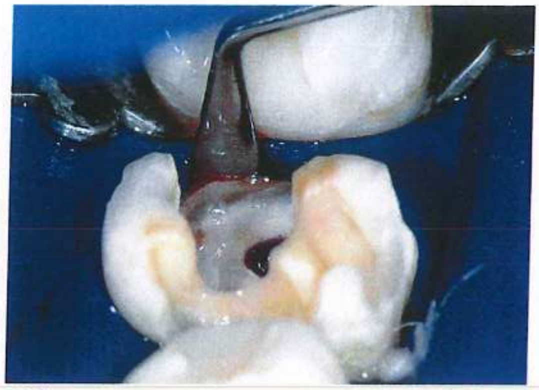
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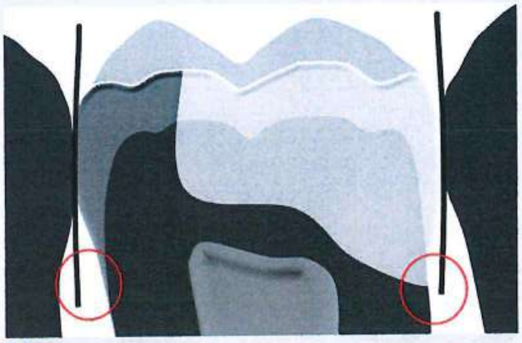

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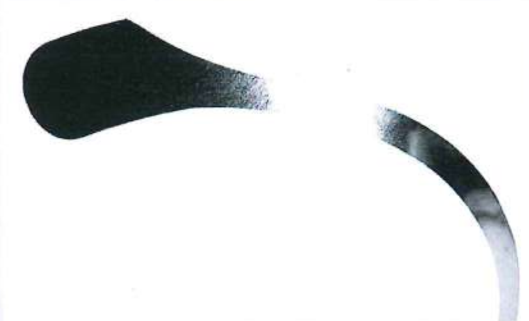

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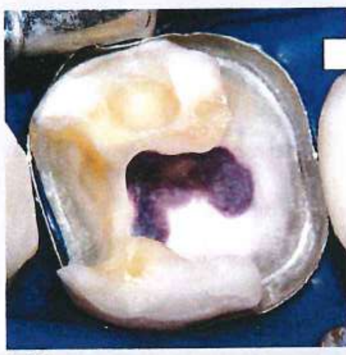


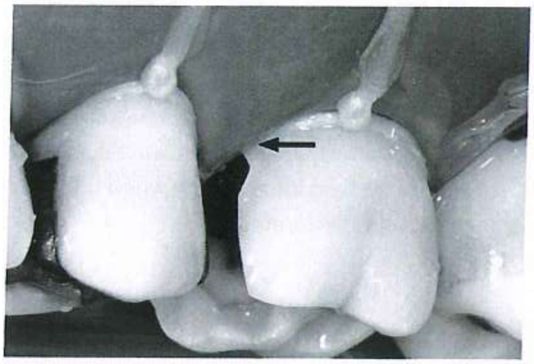
3-65j

3-65k

3-65l

3-65m

7. **IDS**,[327] preferably using a three-step etch-and-rinse dentin adhesive such as Opti-Bond FL, is applied to the preparation in the presence of the matrix and followed by the placement of a composite resin base that will relocate the margin about 1.5 to 3 mm (in one to three increments). This part of the procedure is similar to that of a direct composite resin restoration.
8. **Various types of composite resins can be used for the elevation (traditional restorative or flowable).**[304,313,316] One to three 1- to 1.5-mm horizontal increments can be used depending on the elevation required.[305–307] When highly filled microhybrid or nanohybrid restoratives are used, it is recommended to preheat the material to 130°F/55°C (eg, using the Calset unit, AdDent) to facilitate the placement and minimize the risk for interlayer gaps. Final polymerization through a layer of glycerin gel (air-blocking) is recommended. The margin relocation also permits the removal of severe undercuts (eg, from an existing amalgam preparation), allowing for a more conservative inlay preparation (Fig 3-66).



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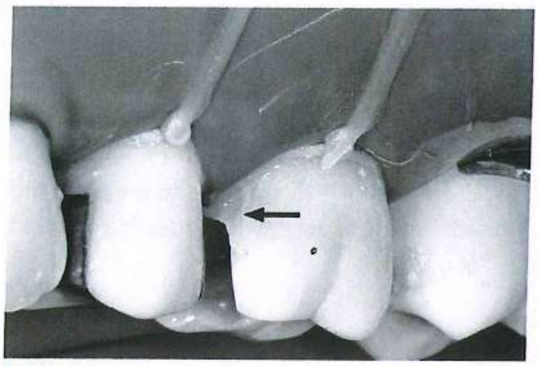


3-66b

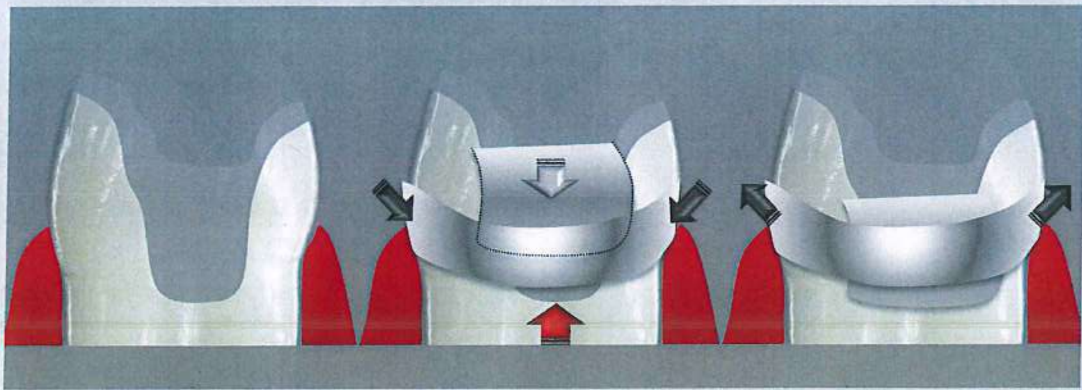
FIG 3-65 *(cont) (e)* Mesiodistal cross-sectional view of the traditional matrix in full height; note the deficient gingival seal due to the lack of occlusal divergence. The high contour (equator) of the clinical crown is limiting the fit. *(f and g)* This can be resolved by using the curved matrix and reducing the height of the matrix to about 3 mm (or slightly higher than the desired elevation). Once tightened, the modified curved matrix can adapt to the tooth contour by sliding more apically. *(h)* Hence, the marginal seal is secured. *(i to k)* Clinical situation before *(i)* and after *(j)* matrix placement and during margin refinishing (*k*; Prep Ceram tip illustrated); note that the root canals are already sealed by the endodontist with a dentin adhesive and purple flowable composite resin. *(l)* Cross-sectional view during margin refinishing (in this case, with the Hemisphere tip). *(m)* IDS and base applied.

FIG 3-66 DME and removal of undercuts. *(a)* Existing caries or old amalgam removal may generate a deep margin undercut. *(b)* The undercut was suppressed by DME, allowing for a more conservative inlay preparation.

9. **Once the elevation is completed, finishing procedures are applied as required for a direct restoration.** This involves carefully eliminating excesses and resin flashes around the tooth using a no. 12 blade or a sickle scaler. Interdental flossing is used to check for the absence of overhangs and flashes. Unwaxed floss is recommended for this step as it will more easily shred to reveal excesses. It is also recommended to reprepare all enamel margins in order to remove eventual excess of adhesive resin. Oscillating tips can also be used to refinish the elevated margin.
10. **Finally, a bitewing radiograph is taken to ensure that no excesses or gaps are present** before proceeding to final preparation and impression as a normal case. It is interesting to note that the presence of a deep subgingival adhesive margin might not affect the periodontal status and health of the restored tooth (see biologic considerations in next section).
11. **The "matrix-in-a-matrix" technique is a last option in case of extremely deep and localized lesions** (Fig 3-67). It consists of sliding a sectioned fragment of a metal matrix between the margin and the existing matrix, as well as packing a "ball" of Teflon tape between the two matrices to enhance the adaptation, especially when dealing with root concavities.
12. **Delivery of the restoration on an elevated margin requires careful cleaning of the existing composite resin base using airborne-particle abrasion**, as is the case when using the IDS technique, followed by etching/rinsing (enamel) and application of adhesive resin.[327] It was demonstrated by Gresnigt et al that placement of an indirect restoration on an existing and even aged composite resin restoration does not affect the longevity.[328]
13. **DME can be used also for direct composite resin restorations.** Even though the DME technique is originally intended for semi-direct (including CAD/CAM) or indirect restorations, it may also represent a useful tool as a preliminary step before placing a large direct composite resin restoration, which will further facilitate the positioning of separation rings and generate improved contours and tight proximal contacts. Due to the socioeconomic context, three-, four-, and five-surface direct composite resin restorations are increasingly used.[181] The use of IDS and DME in combination with a delayed restoration technique[329] might even improve the quality and performance of those large direct restorations. As always, patient, operator, and material factors are to be taken into account when the restorations are performed.[330]

FIG 3-67 DME with matrix-in-a-matrix technique. *(a)* Extremely deep but localized lesions *(left)* may not be reached by the curved circumferential matrix alone. After slightly loosening it, a sectioned rectangular piece of metal matrix can be inserted between the margin and the circumferential matrix *(center)* in order to reach further into the subgingival area. The circumferential matrix is then secured again *(right)*. *(b)* Bitewing radiograph showing a perforating caries lesion at the distal of the first premolar. *(c)* The patient had to be seen in emergency for pulp extirpation and placement of a provisional restoration. Before final endodontic therapy, the restorability of the tooth was assessed through the process of margin elevation. *(d)* The modified matrix was used. *(e)* The circumferential matrix facilitates the caries cleanout by protecting soft tissues and keeping rubber dam from being caught in the bur (debris from the provisional restoration is still visible). *(f)* Oscillating tips are used to clean the margin, but there is still a gap with the matrix *(g)*. *(h and i)* A sectional fragment of a regular matrix is inserted between the margins and the first matrix. A small "ball" of Teflon tape is inserted between the two matrices *(j)* and condensed apically (using a periodontal probe) as near as possible to the margin and concavity *(k to m)*.

MATRIX-IN-A-MATRIX



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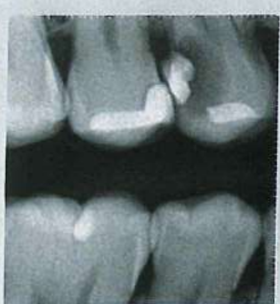

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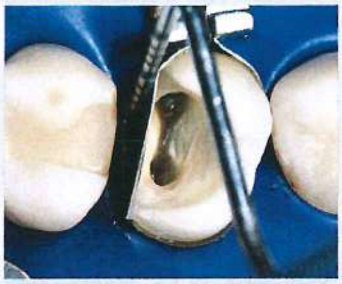

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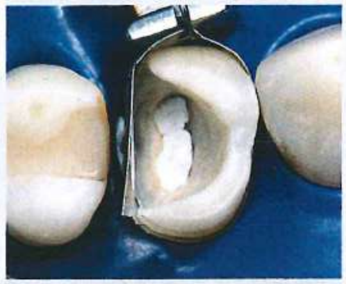

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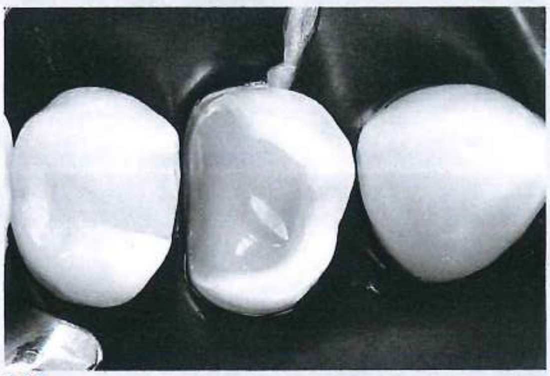


3-67s

FIG 3-67 *(cont)* Teflon tape was used to temporarily close the canals during this pre-endodontic IDS (also called IPDS, or immediate pre-endodontic dentin sealing; see chapter 4, Table 4-4, point 18). The margin was then sealed (along with the rest of the dentin) with OptiBond FL *(n)* and elevated with several increments of regular composite resin material (Z100, *o and p*). *(q and r)* Pre- and post-elevation radiographs show successful elevation. The patient was then sent for final root canal therapy, which was facilitated by the new margin location. The margin was then reprepared and lowered to the level of the gingiva (to provide optimal emergence for the future onlay), and more composite resin was added to close the endodontic access and restore the pulp "ceiling" *(s)*.

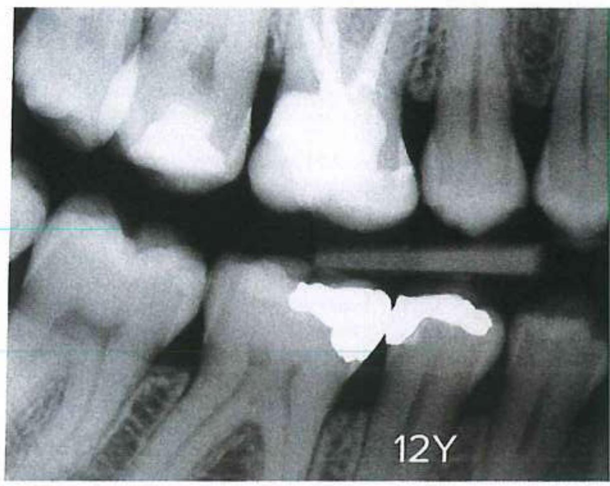
Biologic considerations

***The elevation composite resin seems to be well tolerated by the surrounding periodontium (clinically and histologically),*[318,321–323] *which is corroborated by observations about crown fragments reattached within the biologic width.*[331]** In the first and unparalleled clinical and histologic study in humans, Bertoldi et al[321] demonstrated that subgingival restorations were compatible with gingival health, with levels similar to that of untreated root surfaces, hence confirming that the DME procedure produces favorable clinical and histologic outcomes allowing a routine utilization in reconstructive dentistry.

Nonadhesively cemented restorations seem to behave differently than adhesive margins with regard to colonization by microorganisms and accumulation of plaque.[331] As previously mentioned, a careful follow-up of the case will determine the soft tissue health and the potential necessity for surgical intervention (in case of periodontal alteration and adverse effect on the biologic attachment). A clinical study revealed no evidence of bone loss or pathologic interproximal periodontal probing depth after 12 months.[315] In deep situations, bleeding on probing is possible in 53% of cases,[315] in which case a surgical approach would still be feasible to address this problem. For the other 47% of cases, the successful outcome justifies attempting the procedure. The relocation technique presented in this section, as well as the operator's experience, can further improve the success of DME. Survival rates up to 97% for adhesive partial lithium disilicate restorations and 94% for composite resin restorations are reported at 12 years.[322] Both materials even performed better when compared to indirect restorations without DME.

Even though more clinical research is needed to validate this approach, preliminary long-term results are very encouraging.[302,319,322] ***Meanwhile, DME not only represents a very useful, achievable option for patients who cannot afford more invasive procedures that might include full-coverage crowns, endodontic treatment, and surgery, but it also addresses the main goal of restorative dentistry, that is, the conservation of tooth structure.*** A major impact on digital dentistry is expected due to its facilitation of optical impression of previously subgingival margins. A long-term follow-up of a case is presented in Fig 3-68.

3-68a



3-68b

FIG 3-68 Long-term follow-up of an elevated restoration. *(a and b)* Postoperative clinical view and corresponding radiograph 12 years after treatment with DME and a composite resin onlay on this endodontically treated maxillary first molar. (Clinical case courtesy of Dr Roberto Spreafico, Busto Arsizio, Italy.) Note that the mesiolingual cusp was not overlapped.

Acknowledgments

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4 SEMI-(IN)DIRECT APPROACHES IN POSTERIOR AND ANTERIOR TEETH

As illustrated in the previous chapter, utmost respect of intact hard tissues and valuable clinical service characterize direct composite resin restorations. The cost-effectiveness and minimally invasive approach of resin-based materials is also gaining popularity for CAD/CAM use, especially in the posterior dentition. Semi-(in)direct CAD/CAM composite resin inlays/onlays may be considered when direct techniques are challenging to apply (eg, large shrinking volume with cervical margins in dentin) and when indirect technique costs are not justified or simply not affordable by the patient. For the same reason, some anterior cases that would normally be resolved with either direct composite resin or indirect porcelain veneers can now be treated using novel semi-indirect CAD/CAM techniques, characterized by their noninvasiveness and simplicity. Bilaminar anterior restorations consist of a customized histoanatomical CAD/CAM dentin base with an incisoproximal or occlusal cutback covered by a generic enamel skin. With both anterior and posterior semi-(in)direct techniques, the patients can be treated either in a single clinical session—semi-directly—or in two clinical sessions—semi-indirectly. The purpose of this chapter is to present another tool of the restorative armamentarium to bridge the gap between direct and indirect techniques.

4.1 HISTORICAL PERSPECTIVE AND CLASSIFICATION

During the 1980s and early 1990s, the restorative options were mainly direct composite resin restorations or full-coverage cemented crowns. At that time, the dental community became aware of the possibility to bridge this gap using indirect bonded restorations (veneers, inlays, and onlays) as an intermediate step, which made sense from both an economical standpoint and from a tissue-conservation standpoint.[1,2] An additional possibility to bridge a gap, this time between direct and indirect adhesive approaches, was provided through simplified *semi-direct* (in one clinical session) or *semi-indirect* (two clinical sessions) restorations (Table 4-1).[3] These new options included a number of extraoral steps that were accomplished within the dental office ("in house"). The semi-indirect restorations are luted, as is the case with indirect restorations, but the latter always implies at least two appointments and the collaboration of a dental laboratory. While direct and semi-direct restorations are made entirely chairside within a single session, semi-indirect and indirect restorations require the use of provisional restorations and two clinical sessions. ***Semi-(in)direct techniques are those that combine aspects of the semi-direct and semi-indirect techniques and are recommended when direct techniques are challenging to apply (eg, large shrinking volume with cervical margins in dentin) and when indirect technique costs are not justified (or simply not affordable by the patient).***[4] Large Class 1 and Class 2 preparations involving a limited number of teeth, ideally premolars and first molars, with favorable intraoral access show outstanding long-term results (Fig 4-1).[5]

Extraoral steps also facilitate the development of optimal occlusal and interdental anatomy compared to direct techniques. The original semi-direct approach was first developed for the posterior dentition through various intraoral or extraoral inlay techniques using composite resins[4–9] and was also used in the anterior dentition for veneers (the so-called "direct-indirect technique" by Newton Fahl).[10,11] Early CAD/CAM systems were also used for semi-direct restorations, but they focused mainly on generating ceramic inlays and onlays in a single session.[12] Totally new perspectives with CAD/CAM technology appeared in 2001 with the advent of CAD/CAM composite resin blocks.[13]

TABLE 4-1 Classification of restorative techniques

DIRECT composite resins	**SEMI-DIRECT** composite resins or ceramics	**SEMI-INDIRECT** composite resins or ceramics	**INDIRECT** composite resins or ceramics
One clinical session	(Direct intraoral, extraoral, CAD/CAM) One clinical session + extraoral step ("in house")	(Extraoral or CAD/CAM) Two clinical sessions + extraoral step ("in house")	(Layered, pressed, CAD/CAM, etc) Two clinical sessions One laboratory step (external)
One step	**One step**	**Step 1**	**Step 1**
Tooth preparation and restoration	Preparation ⇩ Impression ⇩ Restoration fabrication (in-office) ⇩ Delivery (luting)	Preparation ⇩ Impression ⇩ Provisional restoration	Preparation ⇩ Impression ⇩ Provisional restoration
–		**Step 2**	**Step 2**
		Restoration fabrication (in-office)	External laboratory ⇩ Restoration fabrication
	–	**Step 3**	
		Delivery (luting)	
		–	**Step 3**
			Delivery (luting)

The four restorative approaches and their sequential description.[3]
Each box represents a clinical session or laboratory step. For all four approaches, when dealing with major morphologic modification of anterior teeth, it is recommended to proceed first with a wax-up and a mock-up before the restorative phase itself (see section 4.8).
Impression refers to either analog or digital techniques.

The direct intraoral inlay

Also called the *direct-indirect technique*,[14] this semi-direct approach consists of a bulk or layered buildup light polymerized directly inside the isolated nonretentive tooth preparation (Fig 4-1).[6] Simple, smooth, and perfectly tapered preparations are mandatory to allow the retrieval of the polymerized inlay from the tooth. The total shrinkage (dimensional stability) and final monomer conversion is accelerated via photothermic postcuring in a special oven. The DI-500 Oven by Coltène/Whaledent was originally designed for this purpose (7 minutes at 120°C/248°F). Other composite resin laboratory ovens such as the Premise Indirect Curing Unit by Kerr can be used. Dry heat can also be obtained from a simple sandwich toaster, as long as temperature calibration is achieved with an oven thermometer.

As is the case for any of the semi-(in)direct extraoral and indirect layered techniques, the recommended restorative composite resin materials should not be different from those used in direct applications (microhybrids/nanohybrids).

Subjecting the inlay/onlay to the postcure dry heat treatment at 100°C–125°C (212°F–257°F) for 7 to 10 minutes will not only optimize the conversion rate and physical properties but also reduce the amount of residual leachable unreacted monomer.[15–19]

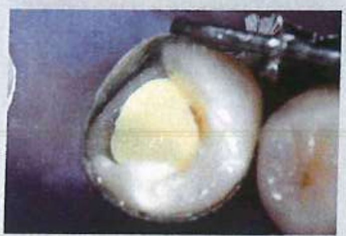
Even though the original idea of direct inlays dates from the 1980s,[6] some clinicians still advocate them today.[20] Complex preparations such as mesio-occlusodistal (MOD) with buccal and lingual extensions must be avoided because the intraoral shrinkage might lock the restoration and render retrieval problematic or impossible. An additional contemporary challenge of this technique is represented by the immediate dentin sealing (IDS) layer, which can potentially be adhered to during the fabrication of the inlay. A thick isolation of the preparation with a silicon film (eg, Rubber Sep, Kerr) was suggested to resolve some of those issues.[20] However, during the early 1990s, another solution was provided in the form of extraoral inlay systems (eg, AP.H-Inlay System by Dentsply Caulk).[21]

FIG 4-1 Direct inlay: long-term follow-up. *(a and b)* This mandibular second premolar presents a large occlusodistal defect. The mesial marginal ridge is intact, but remaining cusps are undermined and thin. A glass-ionomer cement (GIC) sandwich technique could have been used, but this case was treated in the early 1990s and a zinc phosphate base was used to seal dentin and fill the undercuts *(c)*. Following isolation with petroleum jelly and a regular circumferential matrix *(d)*, dentinlike and enamellike composite resins were layered *(e and f)*. The light-polymerized inlay was easily retrieved with a scaler *(g and h)* and subjected to postcure heat treatment (7 minutes at 120°C/248°F). *(i)* Try-in and surface conditioning (see delivery steps in section 4.7) were performed before delivery with a regular light-activated microhybrid restorative material. *(k to m)* Postoperative views showing proper morphology and color and after 20 years of successful clinical service *(n)*. Note the neighboring second molar with a 14-year-old occlusal composite resin (same tooth shown in chapter 3, Fig 3-59). This tooth was moved orthodontically from its original position to close the gap left by the missing first molar.


4-1a


4-1b

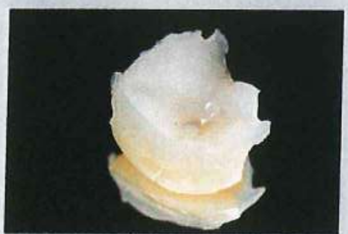

4-1c


4-1d


4-1e


4-1f


4-1g


4-1h


4-1i


4-1j


4-1k


4-1l


4-1m

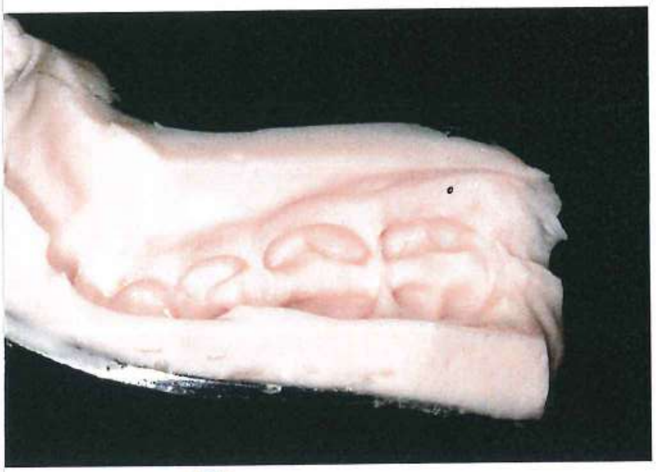
4-1n

The extraoral inlay

Because in the extraoral approach the composite resin inlay/onlay is fabricated extraorally on a quick-set silicon die,[4,21–23] a more sophisticated layering technique allows for improved esthetics and morphology (Fig 4-2). Only a quadrant alginate or silicon impression is needed, making it usable for moderate to large cavity preparations with or without ideal access (eg, second molars). Fast-setting silicone model materials were originally developed for this technique (previously Mass model by DeTrey-Dentsply, EOS by Vivadent). Mach-2 and Blu-Mousse by Parkell as well as the GrandioSO Inlay System by Voco are two extraoral systems available as a low-cost alternative to the sophisticated and expensive CAD/CAM systems. The model can be fabricated at minimum cost in 5 to 6 minutes. As is the case for the direct intraoral inlay, the regular postcure dry heat treatment at 100°C–125°C (212°F–257°F) for 10 minutes should be applied to the polymerized restoration before the intraoral delivery.

For both intraoral and extraoral techniques, the main challenge is the occlusion (missing antagonist dentition), which can result in substantial adjustments upon restoration delivery. Hence, the occlusal relationships and existing occlusal surfaces must be carefully observed before tooth preparation.

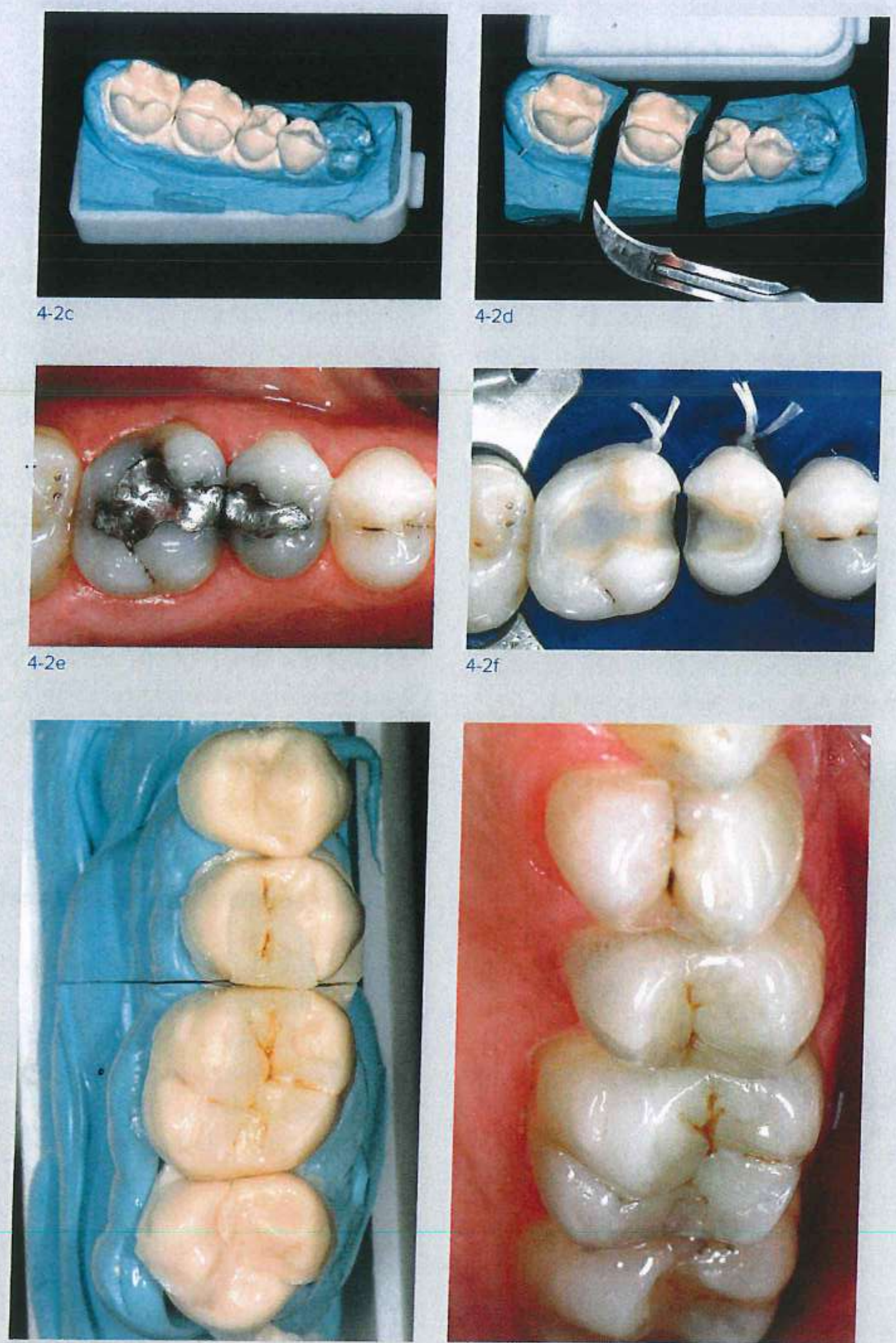
The control of occlusion makes CAD/CAM systems the prime choice over other semi-(in)direct techniques because they include antagonist teeth and occlusal contacts in the scanning/designing process. Nevertheless, like dental technicians who still favor "handmade" refractory die porcelain veneers (fully layered), some skilled practitioners still appreciate the artisanal aspect of the extraoral inlay/onlay, allowing them to generate a "laboratory-looking" restorations (Fig 4-2g) at minimal cost. Some others also use this technique to fabricate semi-direct provisional restorations.



4-2a

4-2b

FIG 4-2 Semi-indirect extraoral inlay. *(a)* A simple alginate can be used to fabricate the fast-setting silicon model. A silicon impression can be used too but should be first coated with a silicon-to-silicon separating agent (eg, GI-Mask Universal Separator, Coltène/Whaledent). *(b)* The silicon model is a two-phase system: Mach is an automix fluid material injected directly into the occlusal aspect of the impression (mainly the teeth) and then immediately covered with the more viscous Blu-Mousse, which serves as a rigid base (gingival portion of the impression). Plastic base formers are supplied with the system. Minutes later, the sectional model in its base is ready *(c)*. A scalpel blade can be used to separate the teeth and facilitate interdental adaptation and contour of the restorations *(d)*. The separated dies can be easily fitted back together into the base former (see part *g*).



4-2c 4-2d 4-2e 4-2f 4-2g 4-2h

FIG 4-2 *(cont) (e)* This classic example of amalgam replacement is a good indication for this technique. The undercuts left by the old restorations were closed "additively" using the IDS technique and composite resin (see steps in section 4.4), followed by gentle enamel margins repreparation to obtain clean finish lines. Rubber dam can be maintained during impression-making *(f)*. Dentin and enamel layers were applied directly to the model (*g*, no isolation and no die spacer used). Inlays were easily retrieved from the flexible model and slightly adjusted by gently reducing the fitting surface with a diamond bur (to compensate for the absence of a die spacer). *(h)* Final fit after adhesive delivery with a preheated restorative microhybrid composite resin. (Parts *a*, *c*, and *d* reproduced with permission from Magne.[22])

4.2 THE CHAIRSIDE CAD/CAM AGE

Historical perspective

CAD/CAM systems were pioneered during the 1980s. The initial milestone was accomplished by French dentist and inventor Dr François Duret, who conceived the first optical impression system.[24] The famous dentist/engineer team Werner Mörmann and Marco Brandestini developed the first chairside system in 1984 in Zurich, Switzerland, which they named CEREC.[25] The acronym stands for **CE**ramic **REC**onstruction, because their original focus was form-grinding ceramic inlays in a single clinical session.[26] The first concept was a small compact mobile unit including all components, computer, acquisition camera (Fig 4-3), and machining device.

FIG 4-3 Young Dr Magne (with hair) using the original CEREC 1 camera during a continuing education course at the University of Geneva in 1990.

A single grinding wheel was originally used, which seriously limited the shape of the restoration (eg, flat occlusal surface), also resulting in more invasive preparation principles in order to allow for the manufacturing. By the third generation (CEREC 3 by Sirona Dental Systems), the machining unit was separated from the acquisition unit and refined with a more precise two-bur system and the ability to roughly shape the occlusal morphology. With increasing computer performance and manufacturing technology, additional systems appeared, which now cover all types of restorations with mesmerizing progresses in accuracy (including occlusion), speed of acquisition, and real tridimensional design.

Current aspects and system choice

Today it is possible to acquire and design a single restoration in a matter of minutes. It is beyond the scope of this work to review the ever-changing marketplace of intraoral scanners; instead this section analyzes the new possibilities provided by this novel tool.[27]

New possibilities of intraoral scanners

1. Optical impressions reduce stress and discomfort.
2. Accuracy is equal to conventional impressions for single restorations up to three to four elements (quadrants). This aspect is constantly evolving and improving and will allow similar accuracy for full-arch digital impressions in the near future.
3. The process is simpler and more efficient than the analog workflow.
4. Digital data saves space (no physical storage of casts, etc) and facilitates communication with both the patient and the dental laboratory.

Subgingival margins remain a challenge, which can be partially overcome with the deep margin elevation (DME) technique (see chapter 3, section 3.10) or by scanning a regular impression. Purchasing and managing costs are also to be considered in the equation. In summary, system selection should be performed only after careful analysis of the following factors:

- **Ergonomics of the intraoral camera.** Systems vary in size, which will affect handling and access to the most posterior areas of the mouth.
- **Powder (titanium dioxide) vs powderless systems.** Powder-free systems are logically the most convenient and popular, but accuracy may still be best when using the antireflective powder coating.[28,29]
- **Simple, efficient, and intuitive design software.** Like most technology in everyday life, some devices are more intuitive, leaving little space for customization, while others will allow sophisticated editing with a larger number of tools. There are advantages and shortcomings to both sides. While a sophisticated design software will provide more advanced editing, it might also have a much steeper learning curve, requiring a highly trained staff person (representing an additional investment).
- **Libraries of natural anterior tooth shapes.** Most systems are able to generate restoration proposals with adequate posterior tooth shapes, either using existing libraries or calculated from complex mathematical models based on hundreds of natural teeth.[30] Anterior tooth proposals can be more problematic and may require major editing to provide satisfactory results. In this regard, the possibility to copy a pretreatment situation (eg, wax-up or mock-up; see Figs 4-27 to 4-29) is a substantial advantage (eg, Biogeneric Copy mode in CEREC by Sirona, or PreOp mode in PlanScan by Planmeca).
- **Type of digital workflow.** There are mainly two types of digital workflows: *(1)* 100% in-office or *(2)* in-office acquisition combined with remote design and manufacturing. In the first case, the operator (dentist or staff) acquires the data and then designs and manufactures the restoration, resulting in complete autonomy and efficient production (usually ideal for single-unit restorations). However, it is also a much larger investment that some practitioners are not ready to undertake, leading them instead to invest only in an acquisition system (intraoral scanner) and outsource the design and manufacturing to a dental laboratory. This second approach is indicated when dealing with multiple-unit works and complex rehabilitations. It may also require a system with a more open platform for data exchange. Both approaches are appropriate and can be combined and/or sometimes correspond to different practice models serving different patients' needs.
- **Reliability, stability, and support.** Systems that have just been launched on the market may be prone to more troubleshooting problems compared to systems that have been available for several years. Companies also have very different market penetration in different countries, which will also influence the type of support available. Once the digital workflow is adopted by an office, the lack of immediate support might have disastrous consequences when facing troubleshooting problems.

4.3 POSTERIOR CAD/CAM RESTORATIONS

The CAD/CAM system itself should only be considered as a tool to be mastered like any other tool, which should ease the selection process using the six aforementioned factors (see previous page). Subject to more debate is the choice of the CAD/CAM restorative material and the various esthetic individualization techniques. Original CAD/CAM blocks for chairside systems were only available in feldspathic porcelain (Fig 4-4) or glass-ceramics. Long-term clinical performance of those original inlays and onlays proved highly acceptable[31] with unrivaled survival probability estimated at 87.5% after 27 years.[32] It was only in 2001 that the first composite resin block for CEREC was introduced to the market by 3M in the form of Paradigm MZ100, a microhybrid spheroidal composite resin with zirconia and silica fillers.[12] Today the spectrum of esthetic CAD/CAM materials ranges from the strongest ceramics (zirconia-based) to lithium disilicate, lithium silicate and leucite-reinforced glass-ceramics, feldspathic porcelain, polymer-infused ceramics (also called *hybrid ceramics*), a wide variety of composite resins, and even polymethyl methacrylate (PMMA)-based polymers.[33]

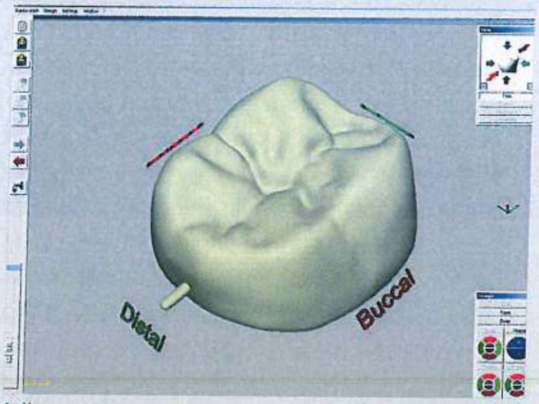
Composite resins vs ceramics

The original goal of composite resin blocks was to overcome the brittleness and abrasiveness inherent to ceramic materials. The original Paradigm Z100 composite resin block demonstrated obvious advantages over porcelain ones,[34–40] including millability in thin layers (more conservative and preventing marginal chipping), more efficient milling (much faster and with less wear of the milling burs), favorable mechanical resistance, enamel-friendly wear, minimal risks of precementation fracture, and ease of delivery and reparability. All of these advantages also prompted the use of composite resin blocks in the anterior dentition (see section 4.8).[3] With similar fracture toughness,[41] Paradigm Z100 proved its clinical performance to be similar to the original feldspathic ceramic blocks with a significant advantage for color matching.[42] In vitro, it demonstrated superior resistance to fatigue in the form of onlays on endodontically treated molars (Fig 4-5)[37] or thin occlusal veneers on biocorrosion-simulated teeth (see also chapter 6, section 6.8).[38] These results are very encouraging, considering that even nonretentive feldspathic occlusal veneers (Mark II, VITA) already proved to perform well clinically with a survival probability of 99.3% at 93 months.[43]

FIG 4-4 Early monolithic porcelain overlay on an endodontically treated molar. *(a and b)* The CEREC 3 system was used along with a feldspathic porcelain block (Mark II, VITA) to design an overlay on this endodontically treated molar. Note the simplistic occlusal anatomy *(c*, try-in) compared to the mill preview *(b)* but also the uniform opacity and color *(d*, postoperative view).

FIG 4-5 Accelerated fatigue survival of early CAD/CAM materials.[37] The configuration of this experiment *(a)* mimics the clinical situation of Fig 4-4. Porcelain Mark II was compared to Paradigm MZ100 by progressively increasing occlusal loading (30,000 cycles for each 200 N increment). The percentage of intact specimens (vertical axis in *b*) starts decreasing after 800 N for the porcelain and 1,200 N for the composite resin. By the end of the test (1,400 N), none of the porcelain onlays survived, while 70% of the composite resin onlays were still intact. For comparison, maximum bite force in human ranges between 420 N and 630 N.[44] The IDS concept was applied, and a preheated light-polymerized restorative composite (Z100) was used as a luting agent. (Images reproduced with permission from Magne and Knezevic.[45])

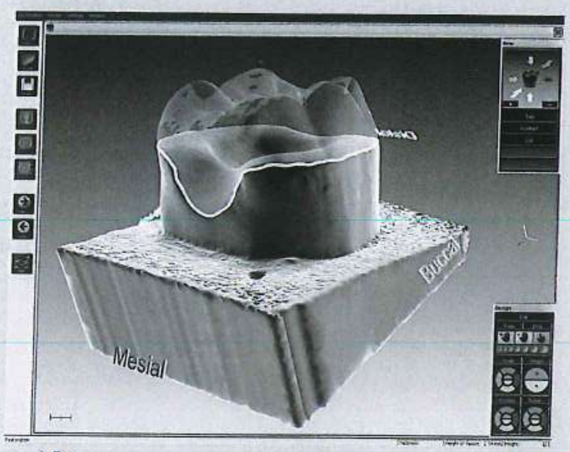
4-4a



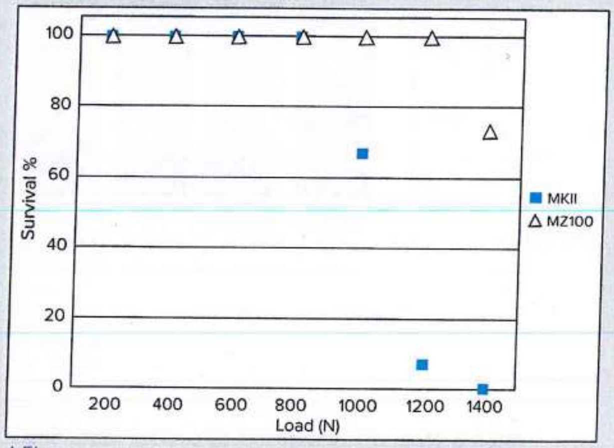
4-4b

4-4c

4-4d



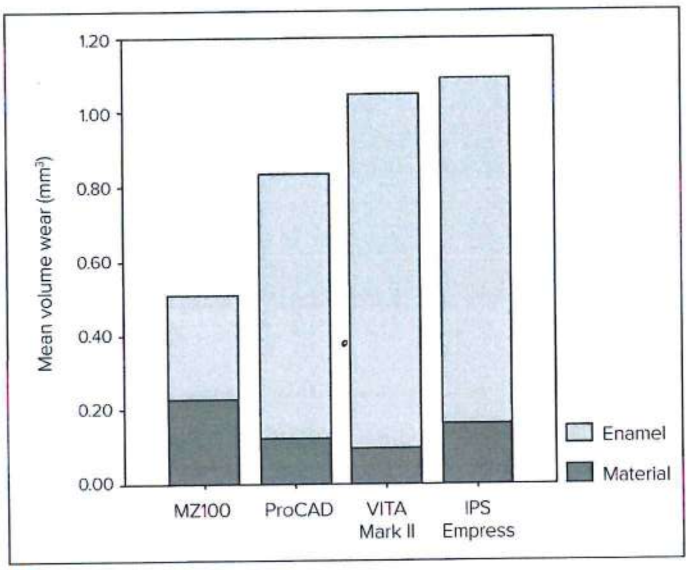
4-5a



4-5b

It seems also that the use of polymer-based materials, with their dentinlike elastic modulus, allows a more favorable distribution of stresses when considering those endodontically treated molars (Fig 4-6).[46,47] Enamellike wear properties of polymer-based material is another substantial factor to be considered when restoring posterior teeth.[48,49] Ceramic materials are known to be more wear-stable than composite resins, but they also produce more antagonistic enamel wear. Globally, the total wear (material itself plus antagonistic enamel) is more favorable for composite resins such as MZ100 (Fig 4-7).[48] Considering that both volume and height loss are affected, it might be preferable to choose polymer-based materials for patients with high occlusal activity. In the last decade, major dental manufacturers came to realize all the aforementioned advantages of composite resin blocks, allowing them to apply high temperature and high pressure polymerization modes as well as increased filler content. The resulting materials are far more homogenous and have fewer flaws than hand-layered "artisanal" ones, hence the acronym HPP (high-performance polymers).

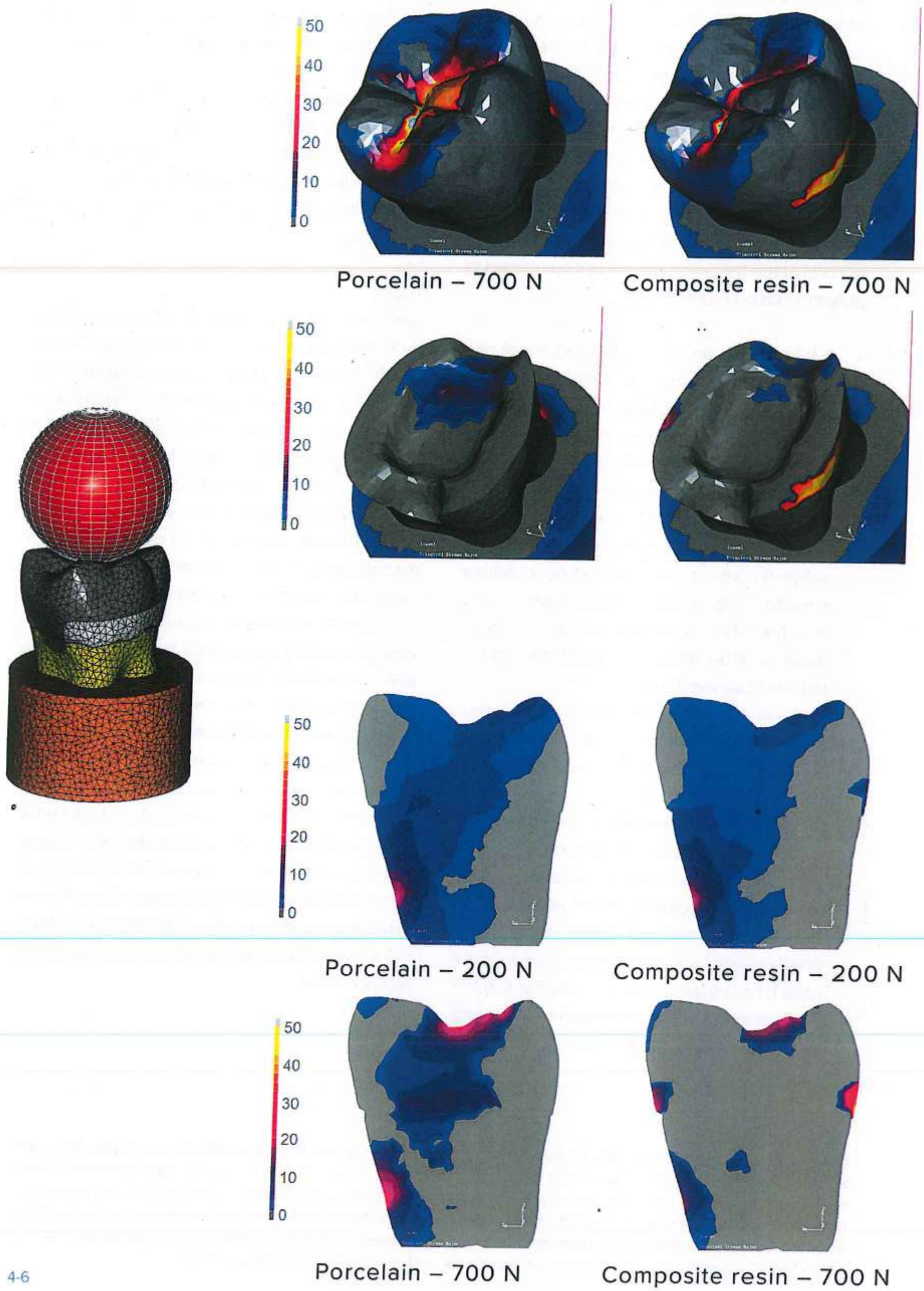
Despite the excellent clinical results of the original "low-strength" Mark II porcelain and attractive stress-absorbing behavior of HPPs, ***the quest for ultimate ceramic strength led to the development of reinforced glass-ceramics, such as lithium disilicate. Finally, a true hybrid material was introduced in the form of a resin-infused glass-ceramic or PICN (polymer-infiltrated ceramic network) called Enamic by VITA.***



4-7

FIG 4-7 Volume wear of antagonist pairs. Note that the cumulated wear is the smallest for MZ100 compared to all three other ceramic materials. The composite resin shows the highest material wear, but it matches the amount of antagonist enamel wear. (Reproduced with permission from Kunzelmann et al.[48])

FIG 4-6 Numeric simulation of overlay materials. This virtual model was designed and tested with the finite element method. Like the experiment in Fig 4-5, occlusal loading was simulated with a spherical antagonist *(left)*. *(top)* Maximum principal stress (MPa) at 700 N occlusal loading. Note the different stress distribution with higher tensile stresses at the occlusal surface (especially the central groove) for the ceramic restoration and higher stresses at the buccal margin for the composite resin restoration. *(bottom)* Maximum principal stress (MPa) as seen in buccolingual cross sections across the distal root. Note the very similar stress distribution for both materials with 200 N occlusal loading compared to 700 N. More stress is transferred to the root with the ceramic at 700 N, which might explain the deeper fractures observed with the in vitro experiments.[37,45] (Reproduced with permission from Magne.[47])


50
40
30
20
10
0
Porcelain – 700 N
Composite resin – 700 N
Porcelain – 200 N
Composite resin – 200 N
Porcelain – 700 N
Composite resin – 700 N

4-6

Lithium disilicate blocks

Introduced in 2006, IPS e.max CAD lithium disilicate ceramic by Ivoclar comes prepared in a "blue" state (partially crystallized), which is easier to mill, and then becomes a fully crystallized glass-ceramic via heat treatment (20–25 minutes at about 800°C under vacuum). With its 360 MPa of flexural strength, it is the strongest ceramic among non-zirconia-based CAD/CAM materials. When using this type of material, one must be mindful of the following differences compared to polymer-based materials:

- It takes more time (crystallization firing) and more work to fabricate and is therefore more likely to be applied in a semi-indirect approach (also potentially costlier).
- Due to the inherent brittleness of ceramic,[50] the milling tends to damage the material (see Figs 4-26a and 4-26b),[51] causes more wear to the milling burs, and requires more marginal edge thickness and support (to produce smooth margins without fractures/chipping) and therefore more preparation of intact tooth structure (deeper chamfer/shoulder or thicker cusp overlaps).
- Bonding procedures require the use of hydrofluoric (HF) acid 5% for 20 seconds (followed by postetching cleaning and use of a silane; see section 4.7).
- Occlusal adjustments, when necessary, are more technique sensitive and require more polishing work with specific instrumentation (diamond-impregnated silicon wheels).
- Potentially less material wear but more antagonistic enamel wear can be expected, as is the case for all ceramic materials (see Fig 4-7).[48,49]
- The unrivaled material strength may exceed that of the natural tooth structure, which can be regarded either as an advantage (excellent restoration survival, Fig 4-8) or a shortcoming (more catastrophic failure modes).[52]

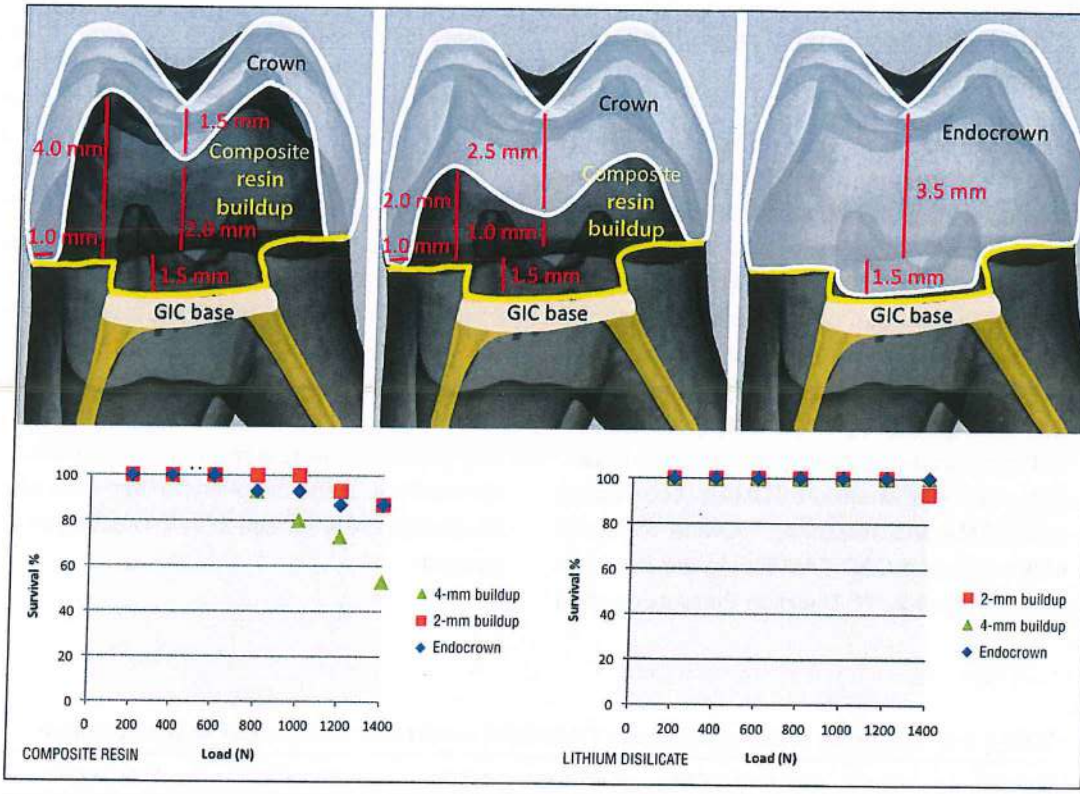
Subsequent blocks made of lithium silicate (Obsidian by Glidewell) and zirconia-reinforced lithium silicate glass-ceramics (eg, Suprinity by VITA, Celtra and Celtra Duo by Dentsply Sirona) have followed e.max CAD and are still under evaluation.[33]

PICN

Enamic (VITA) CAD/CAM blocks were obtained by infiltrating a partially presintered glass-ceramic scaffold with a UDMA/TEGMA mixture.[53] The original process was patented by Giordano in 1997.[54] Due to its true hybrid nature, this PICN has an intermediate elasticity (E-modulus 30 GPa) between that of dentin (14 GPa) and enamel (80 GPa) yet demonstrates a enamel-friendly wear behavior like HPPs[49] as well as excellent machinability.[33] The wear damage mode somehow simulates that of enamel (Fig 4-9) with the resin phase wearing first (similar to the interrod area of enamel) followed by the ceramic phase exfoliation (similar to the enamel rods themselves).[55] In view of the above, the ***PICN constitutes an excellent biomimetic candidate.***[56] Surface conditioning steps for bonding Enamic restorations, however, are similar to porcelain (HF-etch and silane, see Table 4-5). Like HPPs, esthetic customization is possible only through resin-based additions (surface staining or cutback/layering with composite resin). Future research should confirm whether PICN represents the most valid biomimetic dentinoenamel hybrid replacement.

FIG 4-8 In vitro accelerated fatigue survival of composite resin and lithium disilicate crowns/endocrowns without ferrule effect. This experiment follows similar conditions as in Figs 4-5 and 4-6. Endodontically treated molars with extensive loss of coronal structure and no ferrule effect survived loads significantly above physiologic level (800 N) with resin nanoceramic CAD/CAM endocrowns and crowns preferably with a short buildup *(left)*. Lithium disilicate crowns with or without buildup (endocrowns) also exceeded all expectations. See section 4.6 and Fig 4-19 for additional elements about endocrowns. (Reproduced with permission from Magne et al.[57])

4-8



4-9a

4-9b

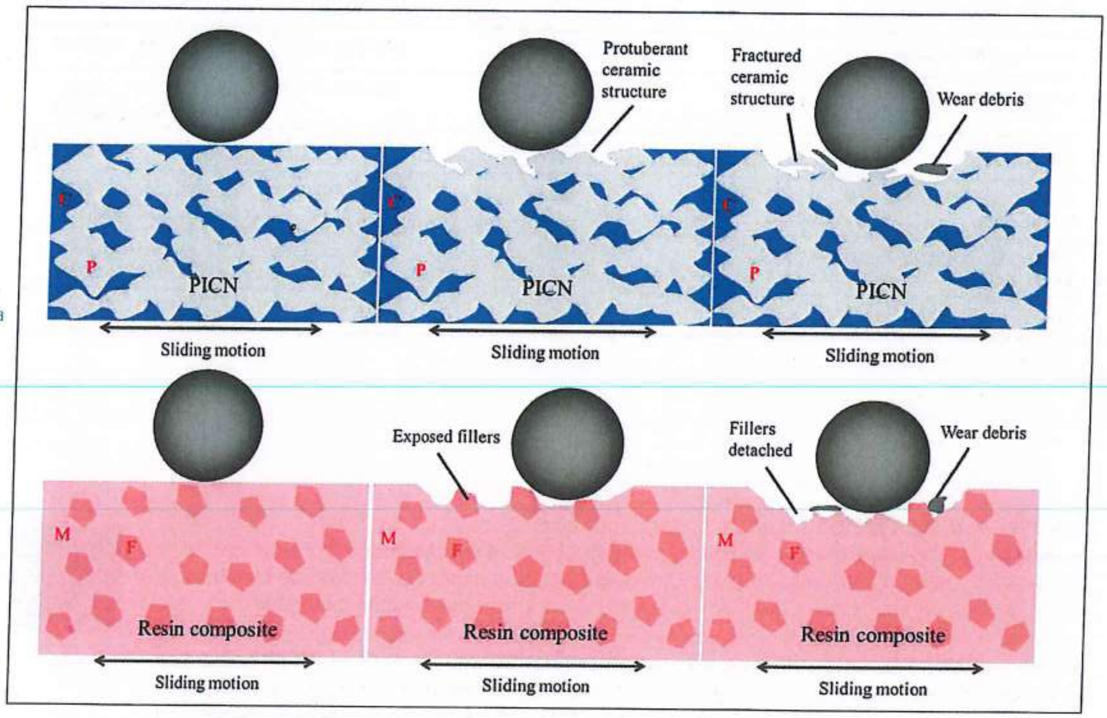


FIG 4-9 Wear damage of PICN and composite resin. Schematic representation of the wear and damage processes in *(a)* Enamic and *(b)* composite resin. C, ceramic phase; P, polymer matrix; F, fillers; M, resin matrix. (Reproduced with permission from Xu et al.[55])

CAD/CAM composite resin inlays/onlays

Hand-layered (artisanal) composite resin inlays/onlays are operator-dependent and can potentially present gaps and porosities and possibly suffer from inhomogeneity and limited degree of conversion (55%–67%). Their CAD/CAM counterparts, however, can be subjected to heat and pressure during the manufacturing of the blocks, with a significant impact on the physical properties through increased density (reduction of defects)[58] and conversion rates that can potentially reach 95% when pure UDMA is used (instead of bis-GMA and TEGDMA).[59] A wide variety of polymer-based CAD/CAM blocks are available today (Table 4-2).[60,61] The High Translucency (HT) shades are recommended for posterior restorations. Regarding adhesive delivery, HF acid etching is not recommended for most composite resins. Instead, airborne-particle abrasion and silane pretreatment is generally suggested to increase bond strength (see section 4.7).[62,63] CAD/CAM composite resin inlays/onlays can be applied with various customization techniques, from none (monolithic) to surface colored (with coloring and glazing resins; eg, Optiglaze by GC; Fig 4-10) or cutback and layered with enamellike material (see anterior case in Figs 4-26 to 4-31). The standard pretreatment (airborne-particle abrasion and silane or special primer) must also be applied to the surface to be characterized or layered.

TABLE 4-2 Examples of composite resin CAD/CAM blocks and their properties/composition

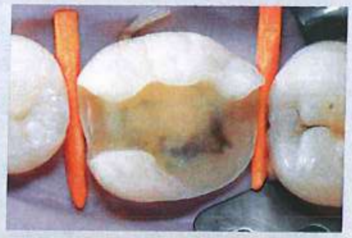
Material	E-modulus (GPa)	Flexural strength (MPa)	Filler (% weight)*	Resin matrix*
PICN - Enamic (VITA)	21[60]–34.5[61]	160*–202[60]	Sintered (86)	UDMA, TEGDMA
Grandio Blocs (Voco)	14.8[61]–18*	333*	Nanohybrid (86)	UDMA, DMA
Paradigm MZ100 (3M)	14.1[61]	190[60]	Microhybrid (85)	Bis-GMA, TEGDMA
Lava Ultimate (3M)	12.1[61]–12.8[60]*	204*–248[60]	Nanofilled (80)	Bis-GMA, UDMA, Bis-EMA, TEGDMA
Cerasmart (GC)	10.4[61]–12.1[60]	231*–234[60]	Microhybrid (71)	Bis-MEPP, UDMA, DMA
Brilliant Crios (Coltène/Whaledent)	10.3*–11[61]	198*	Microhybrid (70)	Bis-GMA, Bis-EMA, TEGDMA
Tetric CAD (Ivoclar Vivadent)	10.2*	274*	Nanohybrid (71)	Bis-GMA, UDMA, Bis-EMA, TEGDMA
Shofu Block HC (Shofu)	8.8[61]–9.6*	191*	Microhybrid (61)	UDMA, TEGMA

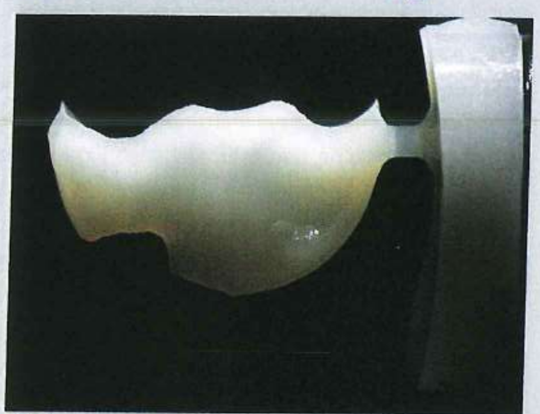
*Manufacturer information.

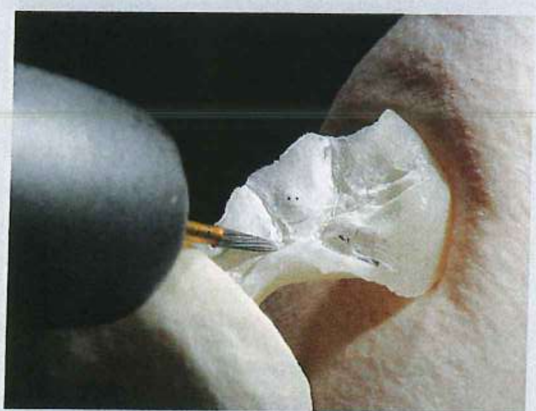
FIG 4-10 Paradigm MZ100 onlay. *(a)* Typical fatigue cusp fracture on a tooth with an old amalgam restoration. *(b)* Removal of the existing filling reveals abundant infiltration and corrosion products. *(c)* Following tooth cleanup and preparation, the entire exposed dentin was sealed with OptiBond FL (Kerr), and the undercuts were filled with composite resin. The corresponding CAD/CAM onlay was milled with Paradigm MZ100 *(d)*, which was further refined by hand for morphology (groove carving, e) and esthetics. Following airborne-particle abrasion (max 50 microns Al_2O_3 at 2 bar), application of a silane *(f)*, and subsequent heat-drying, developmental grooves were slightly characterized with intense brown color *(g and h)*. After polymerization of those effect resins, the onlay was glazed, and glycerin gel was applied for more polymerization *(i)*. *(j to l)* Preoperative and postoperative comparative views (onlay delivered with a preheated light-polymerized restorative material; see Fig 4-23 for step-by-step delivery procedures of composite resin inlay).

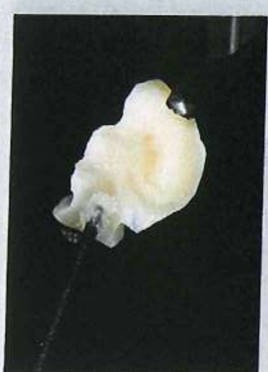

4-10a


4-10b


4-10c


4-10d


4-10e


4-10f

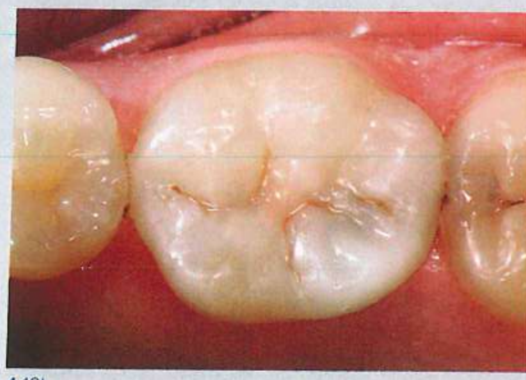

4-10g


4-10h


4-10i


4-10j


4-10k


4-10l

CAD/CAM composite resin inlays not only increase the fatigue resistance of large Class 2 MOD defects when compared to direct composite resin restorations (Fig 4-11), but they also eliminate the problem of shrinkage-induced enamel crack propensity by eliminating the V-factor (see chapter 3, page 304).[64,65]

Principles for adhesive tooth preparation

As is the case for direct restorations, the outline of the preparation initially depends on the extent of the decay, the level of demineralization of adjacent enamel, any discoloration of enamel or dentin that might have a negative effect on esthetics, and the geometry of the restoration to be replaced. The principle of maximum tissue preservation has to be respected, and marginal ridges, oblique ridges, and sound occlusal surfaces have to be preserved, even where enamel is not fully supported by dentin. When metallic restorations are replaced, the general cavity design is already determined, and the preparation only needs tapering of proximal margins after removal of any damaged tissues. Dentin undercuts resulting from the existing cavity design or caries removal do not need to be eliminated. These concavities will be removed "additively" by the application of IDS and composite resin (the "bio-base") before making the impression. Deep subgingival proximal margins may be elevated with a direct composite (see chapter 3, section 3.10). For optimal finishing and adaptation, occlusal and proximal butt margins are recommended. The proximal and occlusal extensions can be kept as minimal as possible and can be placed in contact areas. As usual, the use of oscillating techniques (Prep Ceram tip nos. 51 and 52 [KaVo]; see Fig 4-15) is recommended for optimizing and finishing proximal cavity shape without risking damage to the adjacent dentition.

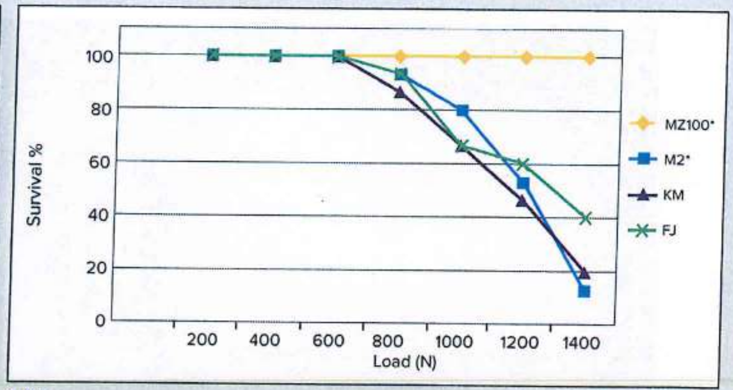
Cuspal coverage and cracked teeth

Thin, isolated remaining cusps (< 1.5 mm thick at the base or when the occlusal margin is located at the cusp tip) can be covered to ensure a 0.5- to 1-mm overlap of composite resin material (1.5 mm for ceramics); in this case, a hollow chamfer or various degrees of "veneerlay" design will ensure both an optimal marginal adaptation and esthetic blending (Fig 4-12; see also Figs 4-20a and 4-20b). Overlapping an undermined cusp is traditionally recommended in the case of cracked tooth syndrome.[66] Onlays promote extracoronal strengthening and protect against further crack propagation. On the other hand, adhesion alone has proven the potential to "reassemble" weakened cusps with or without cusp overlapping, as demonstrated by Opdam and Roeters.[67] They found no influence of cusp overlap in reducing the symptoms of cracked teeth. Yet other studies emphasize the strengthening effect of cuspal coverage.[68–71] Whether overlapping or not, a weakened cusp is always a challenge.

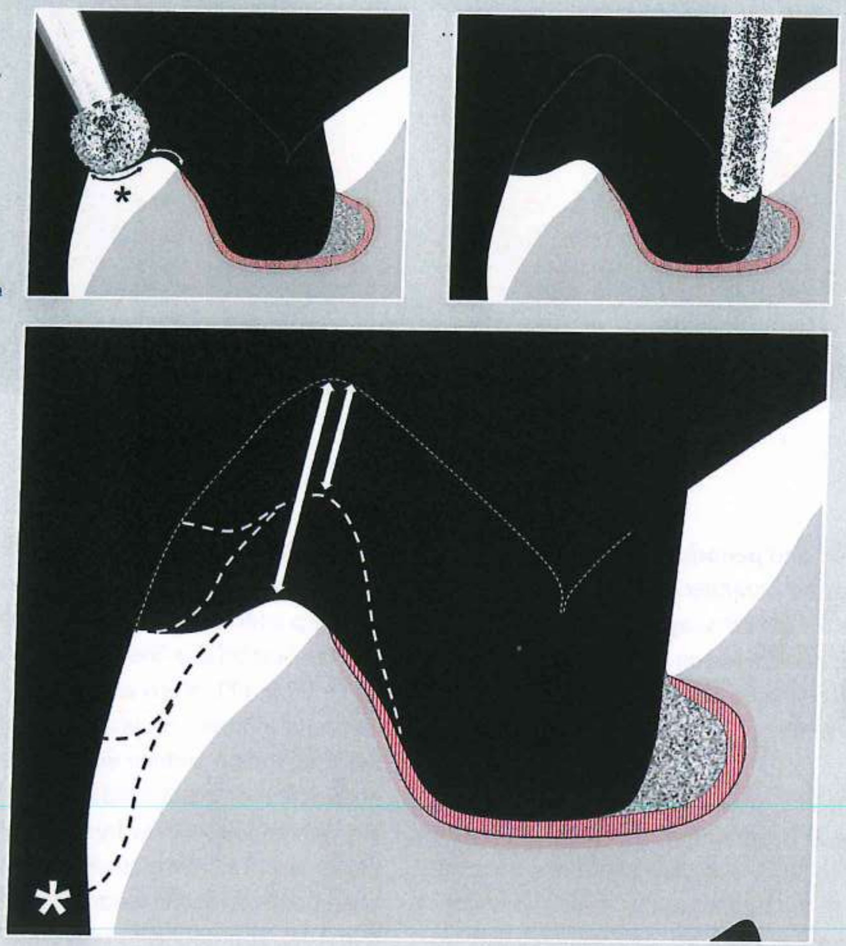
> Fennis et al[72] may have very well summarized the clinical dilemma of cusp overlapping by stating that removing cusps for adhesive restorations requires caution because it may increase the fatigue resistance of Class 2 restorations, whereas fractures of restorations with cuspal coverage led to more catastrophic failures, which are virtually impossible to repair. It seems that the motto "choose your poison" is appropriate in this situation.

FIG 4-11 Absolute survival of Paradigm MZ100 large MOD inlays vs direct restorations. Note the rounded internal line angles of the large MOD preparation *(left)*. These experiments[64,65] follow similar loading conditions as in Figs 4-5, 4-6, and 4-8. Various direct restorations (M2, fully layered with Miris2, Coltène/Whaledent; KM, superclosed sandwich technique with Ketac Molar, 3M; FJ, superclosed sandwich technique with Fuji II LC, GC) start failing at 800 N. Paradigm MZ100 CAD/CAM inlays survived the test 100% of the time.

4-11a



4-11b



4-12a

4-12b

4-12c

FIG 4-12 Adhesive onlay/veneerlay preparations with bio-base. Following the placement of the bio-base (IDS + composite resin to improve geometry and fill in undercuts), enamel margins are finished *(a and b)*. A hollow chamfer *(* in a)* can be used for both composite resin and ceramic materials and provides not only better bonding to enamel (transverse prism cutting) but also improved esthetic blending of the margin.[73,74] The amount of cusp overlap is material-dependent and ranges from 0.5 to 1.0 mm for composite resin and reinforced lithium-silicate ceramics *(short double arrow in c)* to 1.5 mm for regular porcelain *(long double arrow in c)*. Various degrees of esthetic blending are possible *(dotted buccal finish lines in c)* depending on the clinical situation and the need for masking or preventive masking (eg, nonvital teeth). The so-called "veneerlay" design *(* in c)* offers the most stable esthetic result with the margin following the contour of the gingiva *(d, see next page, maxillary first molar;* see also Figs 4-20a and 4-20b) and is especially convenient when dealing with short clinical crowns *(d)*.

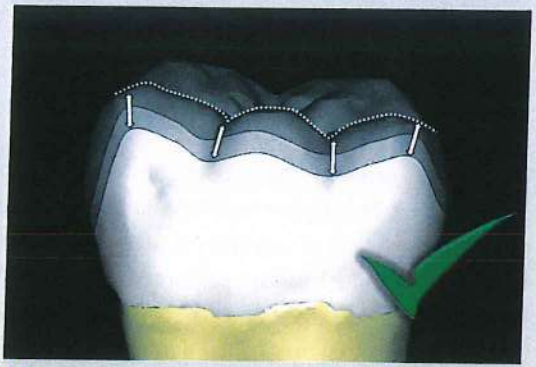
4-12d

Endodontic and periodontal status of cracked teeth must be carefully considered. The presence of a localized deep periodontal pocket (> 6 mm) is considered an important factor when deciding whether to preserve the cracked tooth or extract it.[75,76]

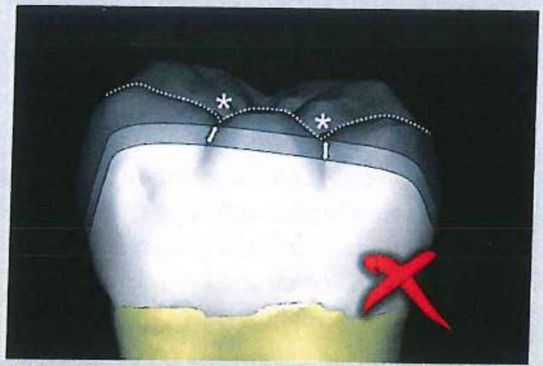
In case of protective conservative cuspal coverage, it is paramount to follow the tooth anatomy to allow sufficient clearance not only at the cusp tip but also at the level of developmental grooves (Fig 4-13). A preliminary wax-up and corresponding silicone guides are recommended to achieve this goal. More details about so-called "occlusal veneers" are found in chapter 6, section 6.8 (see Fig 6-20).

IDS—Bio-base

Posterior teeth will significantly benefit from IDS when CAD/CAM restorations are used (see later section on 20+ reasons for IDS).[77] The milling process does not allow for the reproduction of sharp internal line angles and irregularities. The application of a filled adhesive system such as OptiBond FL (Kerr) will not only ensure the immediate dentin protection but also smooth the preparation surface without need for more subtraction of intact hard tissues. When dealing with endodontically treated teeth (ETT), the placement of a 1-mm glass-ionomer cement (GIC) base/barrier is recommended before starting IDS (Fig 4-14). The goal is to prevent solvents from the priming resin of the adhesive from interacting with the root canal sealer and creating a contaminating smear layer on the dentin. Here again, additions of composite resin are used to improve the geometry and remove undercuts (Fig 4-15). ***IDS and composite resin additions form the so-called "bio-base"*** (term coined in 2005 by Drs Wendel Robertson and David Alleman).



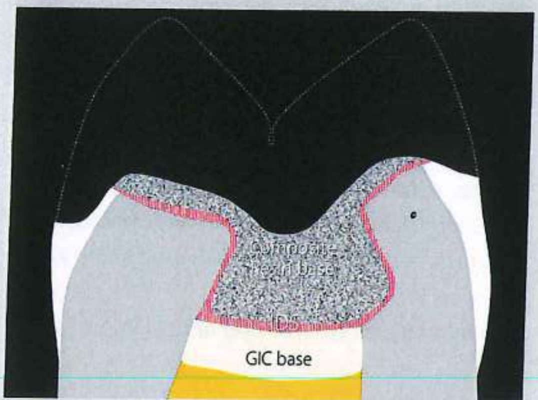
4-13a



4-13b

4-14a

4-14b



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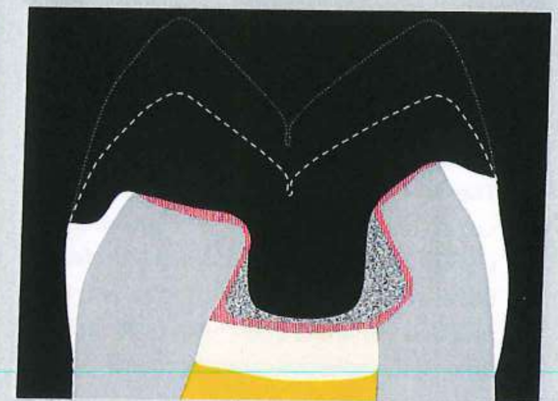


4-14d

FIG 4-13 Conservative cuspal coverage. *(a)* The primary morphology of the tooth must be followed when overlapping cusps. *(b)* Flat cuspal overlap leads to insufficient restorative material thickness at the level of the developmental grooves (*). Adequate clearance must be confirmed with a silicon index of the ideal morphology (wax-up). Buccal views have been used here, but the same concept would apply in a buccolingual cross section.

FIG 4-14 Bio-base or endocrown on endodontically treated posterior teeth (buccolingual cross sections). Once the dentin is cleaned and the root canal treatment is complete *(a*, gutta-percha in orange), a GIC barrier is placed *(b)*, followed by the application of the filled light-polymerized dentin bonding system (red liner in *c* and *d*). Composite resin additions complete this bio-base and can be shaped for an onlay/overlay-type preparation *(c*; see also Fig 4-15k) or for an endocrown-type preparation. The endocrown is particularly suited for short clinical crowns and in the case of limited interocclusal clearance in order to produce enough ceramic thickness *(d)*.

4.4 IMMEDIATE DENTIN SEALING

IDS is a universal concept whereby freshly cut dentin is sealed with an adhesive system immediately after preparation (before impression) for inlays/onlays/veneers and even crowns.

Fundamental steps for IDS

There are 10 fundamental steps to achieve successful IDS (Fig 4-15 and Table 4-3)[77]:

1. **For ETT, a GIC barrier must be placed** to isolate the endodontic sealer from the solvents in the adhesive primer. This step can be skipped for vital teeth.
2. **The dentin surface must be refreshed with a rough diamond bur (for total-etch adhesives)** or multifluted carbide bur (for self-etch adhesives). Diamond burs produce a rougher surface (increased surface area, somewhat similar to the roughness of the dentino-enamel junction) but also more smear layer, which is compatible with total-etch systems because they remove the smear layer. Self-etch adhesives, however, do not perform well in the presence of a thick smear layer.[78]
3. **The adhesive system is applied** to the freshly cut dentin according to the manufacturer's instructions. Filled adhesives are preferred because they can be radiopaque and they produce a more uniform resin coating.[79] Air-thinning the adhesive is not recommended for IDS in order to keep a consistent thickness of resin.[79] The thicker layer of adhesive resin is preferable in anticipation of airborne-particle abrasion just before restoration delivery.[80] When using simplified and unfilled adhesive systems (that are thin by nature), it is recommended to protect the bonding resin by using a flowable liner (see IDS reason #2 in the next section).
4. **Optional: Application and polymerization of composite resin additions** (regular micro- or nanohybrid restorative material) to improve preparation geometry, block out undercuts, reinforce remaining cusps, and possibly elevate deep margins (see DME in chapter 3, section 3.10).
5. **Air-blocking is performed.** Cover the entire preparation with glycerin gel and polymerize again to minimize the oxygen-inhibited layer.
6. **All enamel margins are refinished** (to eliminate possible excess adhesive resin). Interdental finishing for inlays is best achieved with the Prep Ceram oscillating tips (nos. 51 and 52).
7. **The preparation surface is gently pumiced** to remove debris and remnants of the oxygen-inhibited layer. If not removed, those remnants will interfere with the setting of silicon impression materials.[81,82] This step can be skipped when using optical impressions.

FIG 4-15 Step-by-step IDS on posterior ETT. *(a)* This mandibular molar received a successful endodontic therapy that was preceded by distal margin elevation. *(b and c)* After treating the dentin of the pulp chamber with NaOCl 5%, a GIC barrier was placed on top of the gutta-percha and root canal sealer. Canals can also be sealed individually (see Fig 4-17k, IDS reason #18). *(d to h)* The entire dentin was then refreshed with a diamond bur at low speed (not illustrated) and immediately followed by the application of the dentin adhesive system (OptiBond FL): etching for 15 seconds (not illustrated), priming twice for 20 seconds each *(d)*, air-drying *(e*, primed dentin must look shiny), and application of filled light-polymerized adhesive resin *(g and h)*. The adhesive resin was not air-thinned. Composite resin additions were placed to fill the pulp chamber *(i)* and restore the pulp ceiling *(j*; see also Fig 4-14c). Following the placement and polymerization of the bio-base *(l)*, further light polymerization was carried out through glycerin gel *(m)*. After rinsing and drying, all enamel margins were refreshed with diamond instruments before final impression: round bur for the hollow chamfer *(n)* and hemispheric oscillating tips for interdental margins *(o)*. *(p)* Alternatively, Prep Ceram tips nos. 51 and 52 can be used, especially for inlay preparations. *(q)* Composite resin onlay/overlay in situ.

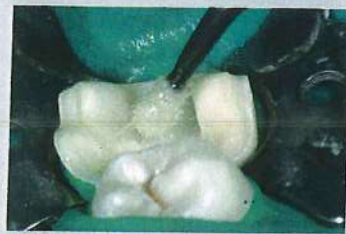

4-15a


4-15b


4-15c


4-15d


4-15e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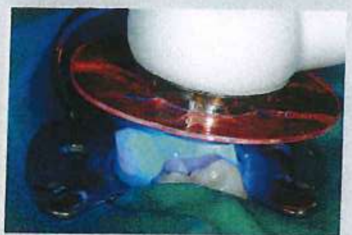
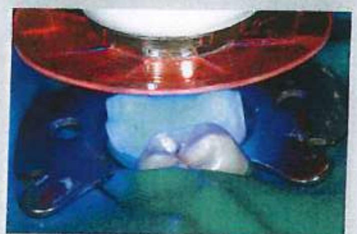
4-15g


4-15h


4-15i


4-15j


4-15k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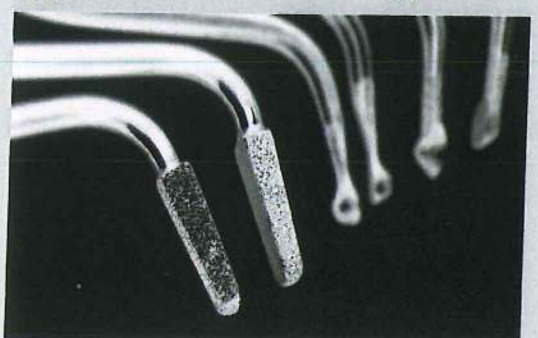
4-15m


4-15n


4-15o


4-15p


4-15q

8. **Final impression** using preferably polyvinyl siloxane (PVS) materials. Polyether materials should be avoided as they may adhere to the IDS layer (unless IDS is completely covered with composite resin, regular or flowable).[81–83]
9. **The tooth preparation is isolated with a thick layer of petroleum jelly** before resin-based provisional materials are applied (Fig 4-16). PMMA and soft resin materials (eg, Fermit, Ivoclar Vivadent) as well as resin-based provisional cements (eg, Temp-Bond Clear, Kerr) will strongly adhere to the IDS layer. Using a separating medium (eg, thick layer of petroleum jelly or single layer of Pro-V Coat by Bisco) will facilitate removal of provisional restorations when the patient returns for restoration delivery.
10. **Careful airborne-particle abrasion of the preparation surface** is performed just before restoration delivery (before enamel etching) in order to ensure a strong resin-to-resin bond.[84] Air abrasion is followed by enamel etching/rinsing/drying and application of adhesive resin to the entire preparation surface (no polymerization until the restoration is completely seated). No dentin primer is needed unless dentin has been omitted with the original IDS or re-exposed during cleaning of the preparation.

TABLE 4-3 Essential steps for successful IDS and their purpose

Step	Purpose
1. GIC barrier onto root canals (for ETT only)	Prevents formation of contaminants due to dissolution of endodontic sealer by solvents in dentin adhesive primer.
2. Freshly cut dentin	Cleans the dentin surface and increases surface area (rough diamond); for total-etch adhesives only. Use carbide bur for self-etch adhesives.
3. Apply filled dentin adhesive	Seals all exposed dentin with a consistent layer of adhesive resin (no air-thinning). **A flowable liner should be applied on unfilled adhesives or when polyether impression materials are used.**
4. Apply composite resin base (if needed)	Improves preparation geometry, fills undercuts, and reinforces remaining cusps, possibly elevating subgingival margins.
5. Apply glycerin and polymerize ("air blocking")	Minimizes the thickness of the oxygen-inhibited layer.
6. Refinish enamel margins	Eliminates excess adhesive resin and removes enamel undercuts. Use oscillating tips for interdental margins.
7. Pumice tooth preparation (not needed with optical impressions)	Eliminates debris and residues of oxygen inhibition and prevents interaction with PVS impression materials.
8. Final impression	Facilitates fabrication of the restoration, preferably polyvinyl siloxane (polyethers show adherences to IDS unless bio-base is applied).
9. Isolate preparation before provisionalization	Avoids adherence and locking of the provisional restoration.
10. Air-abrade preparation before luting restoration	Removes debris and cleans the IDS surface for optimal resin-to-resin bonding with the luting agent.

FIG 4-16 Type of posterior provisional restorations. *(a to c)* The inlay preparations are covered with a thick layer of petroleum jelly before the application of a soft resin (eg, Fermit). *(d)* The patient is asked to bite down to facilitate removal of the excess before polymerization of the material. *(e and f)* These onlay preparations are short and nonretentive. Silicon indexes of a wax-up *(g)* are used to check preparation clearances and to fabricate a PMMA provisional restoration *(h*, shown before trimming), the margins of which have been intentionally left with overhangs wrapping the lingual gingival enamel for improved stability *(i and j)*. The final restorations are featured in Fig 4-20. *(k)* Buccolingual cross-sectional view showing the overhangs beyond the provisional margins. Additions of flowable composite can also be used to lock the restoration. Temp-Bond Clear can be used for provisional cementation as long as a separating medium (Pro-V Coat or a thick layer of petroleum jelly) is applied to the preparations beforehand.


4-16a

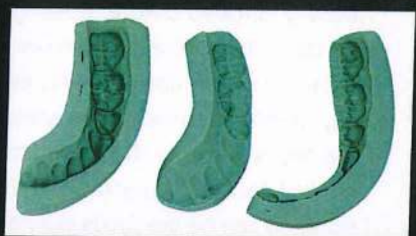

4-16b


4-16c


4-16d


4-16e


4-16f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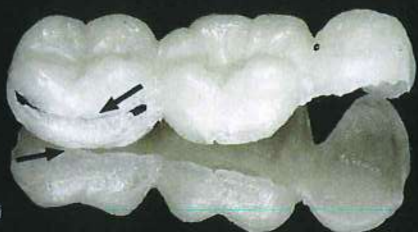
4-16h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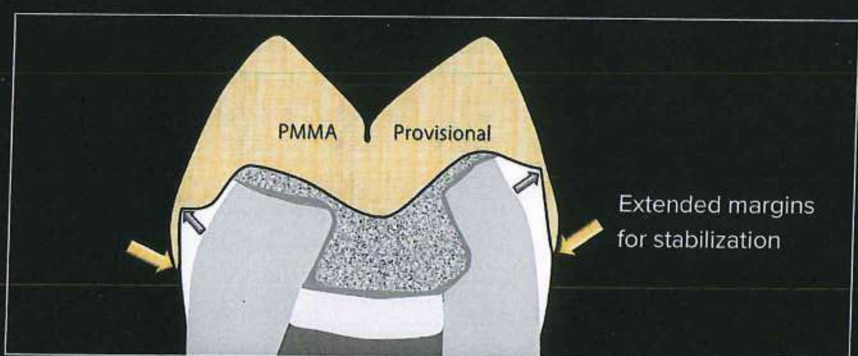
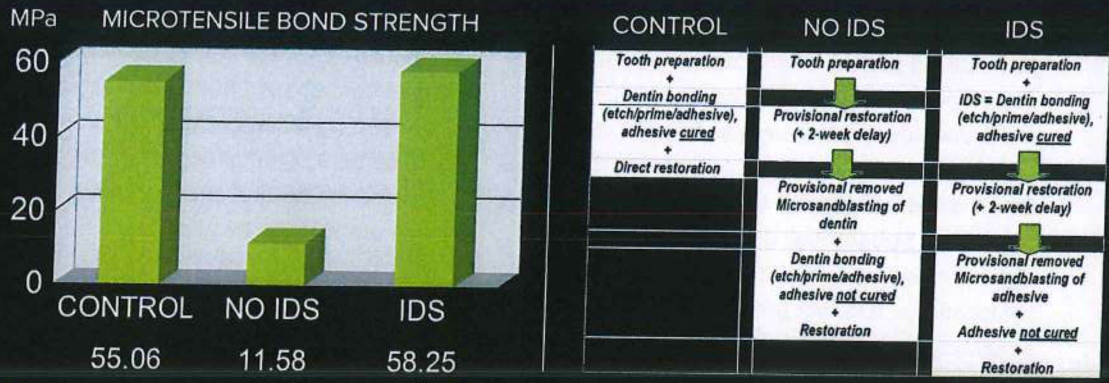


4-16k

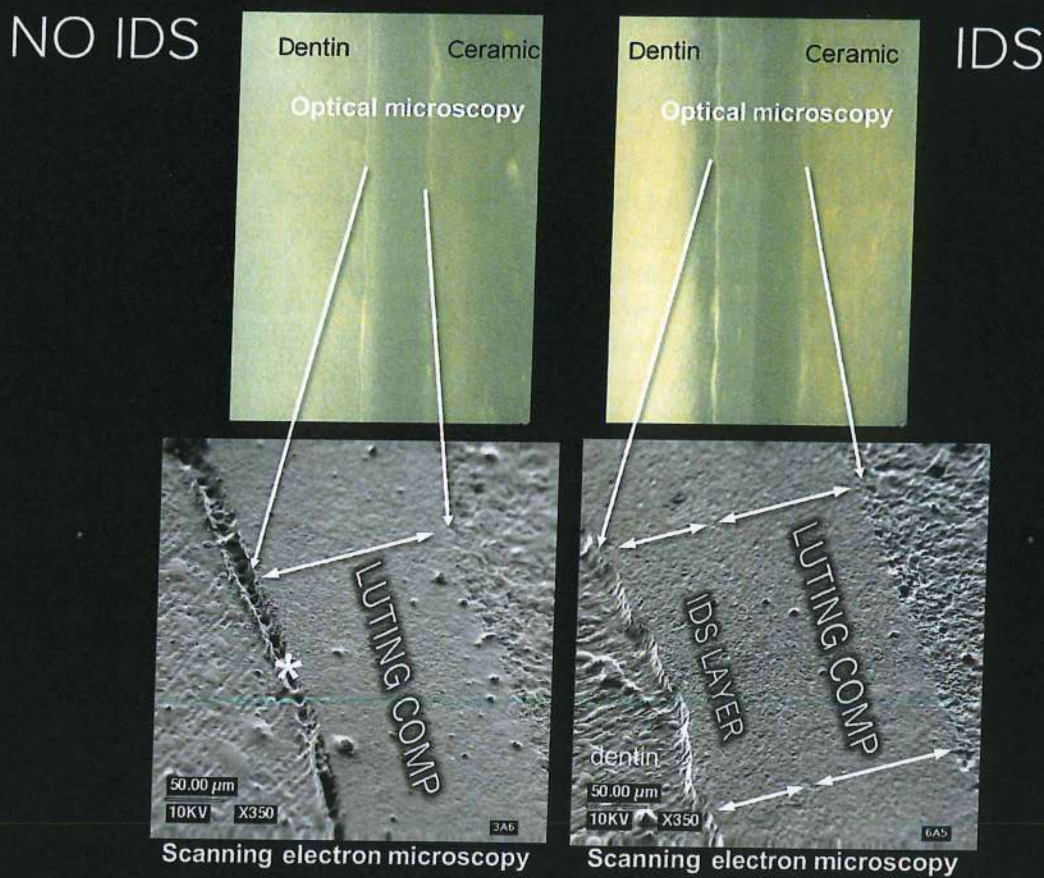
20+ reasons for IDS

The use of IDS has been documented since the early 1990s. When a significant area of dentin has been exposed during tooth preparation, it is strongly advised to immediately apply a low-viscosity adhesive resin to the freshly cut dentin according to the manufacturer's instructions. IDS is applied right before making an impression. It was first proposed by Ikonoshi[85] and Nikaido et al[86] under the name "resin coating technique" in 1992. Others have called this procedure "dentin sealing"[87] or "dual bonding."[88] Extensive literature reviews support IDS,[89,90] and there are at least 20 reasons to justify its use (Table 4-4):

1. **Bonding to freshly cut dentin.** The dentin can be deemed "clean" immediately following tooth preparation. Impression materials are able to penetrate and remain trapped inside the dentinal tubules during impression procedures.[91] For the same reason, contamination during provisionalization can reduce the potential for dentin bonding.[88,92,93] High-torque low-speed cutting with a diamond bur (for total-etch adhesive systems that remove the smear layer) or carbide bur (for self-etch systems) is recommended immediately before IDS.[78]
2. **Prepolymerization thickness and stabilization of the hybrid layer.** When dentin bonding is carried out during the final restoration delivery, the adhesive resin is left unpolymerized to allow the complete seating of the restoration. This leads to a collapse of the resin-collagen hybrid layer under the pressure created during seating of the restoration and causes a significant loss of bond strength (Figs 4-17a and 4-17b).[94–96] Some clinicians have suggested to air-thin and polymerize the adhesive resin at a thickness that would not prevent the restoration seating. As such, it is essential to recognize the inhibitory effect of oxygen on the polymerization of resins, which can easily reach up to a depth of 40 microns[97] (compared to 1–3 microns for the hybrid layer) and influence the quality of adhesion to dentin.[98] ***Thin adhesives will not polymerize well due to the oxygen-inhibition layer.[83] Hence the only way to obtain a thick and consistent resin coating and well-polymerized hybrid layer is to apply the dentin bonding agent before making the impression.*** A filled and radiopaque adhesive system, such as OptiBond FL, is the most appropriate to achieve the aforementioned goals (Fig 4-17b).[79,84,99] Other adhesive systems (less filled or unfilled) will perform better with IDS when covered with a flowable liner.[83,100–102] Higher bond strength and interdiffusion zone (hybrid layer) thicknesses are reported when using IDS.[103]
3. **Selective wet dentin bonding.** Enamel is usually air-dried before bonding, which can be difficult to achieve when dentin bonding is carried out simultaneously to enamel bonding (during restoration delivery). With IDS, the focus is solely the wet dentin bonding (stage I, tooth preparation), while dry enamel bonding can be the focus during restoration delivery (stage II).
4. **Delayed loading of the dentin bond.** When using indirect techniques, the sealed tooth preparation is provisionally restored without bonding. The IDS layer is therefore stress-free until the restoration delivery. This delay (minimum of 24 hours) allows the maturation of the dentin bond (potentially 15%–25% increase).[104] The postponed occlusal loading results also in improved restoration adaptation.[105] Restoration delivery can be postponed up to 12 weeks without compromising the resin-to-resin bonding to the existing IDS layer.[84]



4-17a

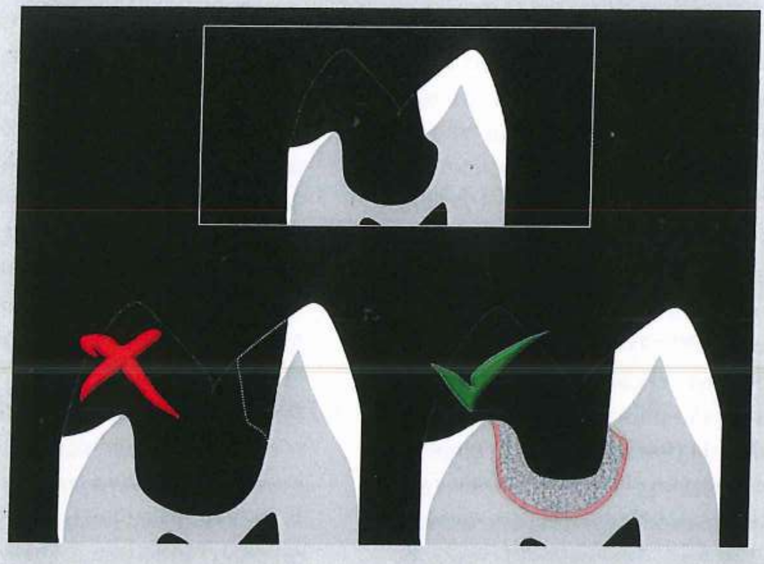


4-17b

FIG 4-17 Reasons for IDS. *(a and b)* Investigations reveal the detrimental effect of unpolymerized adhesive (no IDS group) on bond strength and internal adaptation.[84,95] OptiBond FL was used in this experiment. Note the consistent layer of the prepolymerized IDS resin coating (~80 microns) underlying the luting cement (~120 microns; *b, right*). On the other hand, the hybrid layer collapse is well visible when the adhesive is not prepolymerized, resulting in a significant gap *(* in b, bottom left)*. (SEM views reproduced with permission from Magne and Douglas.[95])

5. **Decreased bacterial leakage during the provisional phase.** There are no perfectly sealed provisional restorations. Unless IDS is used, open dentinal tubules can be colonized by bacteria.
6. **Decreased sensitivity during provisionalization.** Substantial discomfort can be experienced by patients with provisional restorations. IDS will prevent any type of sensitivity during that stage.
7. **Decreased postoperative sensitivity.** As previously explained under reason #2, without IDS, the unpolymerized hybrid layer will collapse and potentially leave a gap upon polymerization and contraction of the luting agent (see Fig 4-17b, left).[95] According to the hydrodynamic theory, outward fluid flow from the dentinal tubules into this gap is the potential cause of dentin sensitivity and will typically happen upon release of occlusal load.[106] The IDS technique not only provides superior internal adaptation,[107] but interfacial gap length is also reduced from 86% (no IDS) to only 7%.[108] A reduction of postcementation hypersensitivity by IDS was even observed when delivering fixed partial dentures.[109]
8. **Improved tooth preparation and restoration adaptation.** Along with the bio-base concept (see Fig 4-14), IDS allows for the creation of better geometry to smooth the floor and fill any undercuts in the tooth preparation (Fig 4-17c). IDS-rounded angles and smoother surfaces are preferred for either optical scanning or traditional laboratory work (eg, less die spacer required). Finishing instruments (eg, fine diamond bur) can be omitted because of the smoothness of the filled resin coating. Consequently, several studies demonstrated that the internal fit of CAD/ CAM restorations is improved by IDS application.[101,110]
9. **Reinforcement of remaining tooth structure.** Undermined cusps left after removing amalgam restorations can be additively reinforced by the bio-base (IDS plus composite resin). Soft resin provisional restorations could have a wedging effect on compromised cusps if not reinforced by the additive bonding of the bio-base. Cusps that would normally require overlapping may be preserved instead (Figs 4-17c to 4-17h).
10. **Tissue conservation—adhesion vs retention/ resistance form.** The IDS layer converts the preparation surface into an adhesive substrate. Any type of preparation shows improved bond strength, including crown preparations.[111] Because glass-ionomer and resin cements can potentially adhere to the IDS surface, the need for retention and resistance form is minimized. ***In the case of full-coverage crowns, IDS allows for shorter and more tapered preparations (substitution of mechanical retention by adhesion), preventing the placement of subgingival margins or the use of surgical crown lengthening and even the need for endodontics (to seek intraradicular retention).*** The resistance to dislodgement when using a resin coating is so high that it can exceed the strength of the tooth (cohesive dentin fracture; see chapter 1, Fig 1-17c).[112] IDS can even benefit monolithic zirconia restorations.[113]

FIG 4-17 *(cont) (c)* An undermined cusp *(top)* should be reinforced additively by the bio-base *(bottom right)*, and only the enamel margin should be tapered. Omitting the bio-base concept would result in a substantial loss of tissue, occlusal margins nearing the cusp tips, and possible need for cusp overlap (onlay). *(d to f)* This clinical case of amalgam removal and cleanup illustrates how the bio-base was used to fill severe undercuts. *(g and h)* Only the occlusoproximal enamel margins were tapered (small hollow bevel illustrated as well as stone replica of preparations). *(i)* Postoperative view of the composite resin inlays. (Part c reproduced with permission from Magne.[22])



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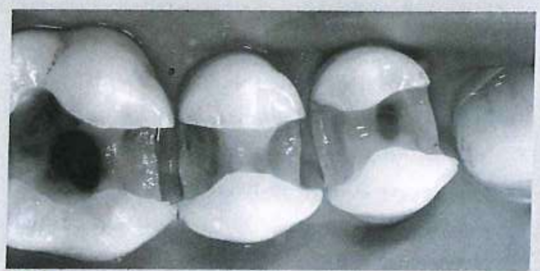
4-17d



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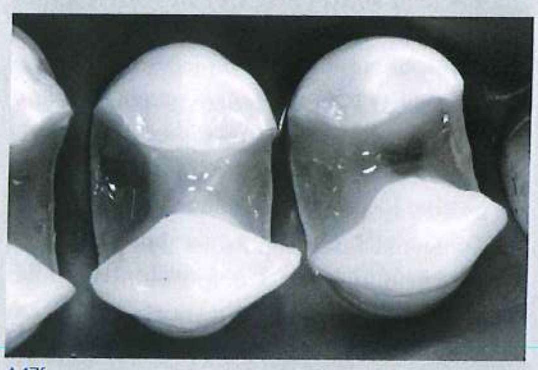

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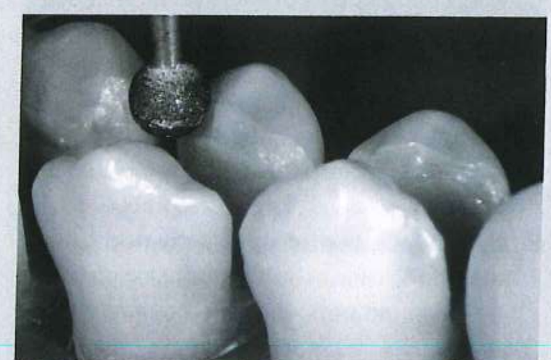

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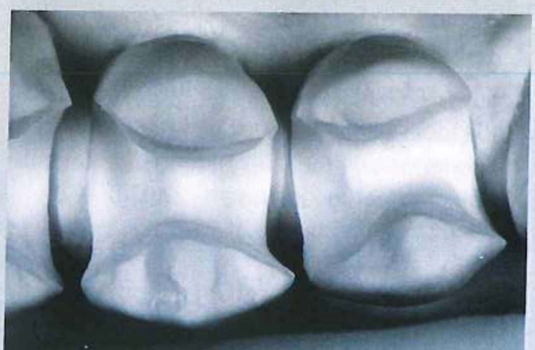


4-17h

4-17i

11. **Strengthening effect on ceramic crowns, onlays, and veneers.** The optimized adhesion obtained though appropriate IDS also increases the fracture strength of full ceramic crowns[100] and anterior and posterior veneers/onlays.[38,114–117] Here again, a sufficient IDS film thickness proves essential, which is why thin adhesives (simplified ones) have to be supplemented with a flowable liner to polymerize properly.[84,100] The concept works only because this layer is captured in the impression as part of the preparation.
12. **Facilitated try-in procedures.** The complete dentin desensitization effect of IDS allows the removal of provisional restorations without need for anesthesia. Integration of crowns or veneers can be assessed in relationship with the natural lip contours. Optimal proprioception for occlusal adjustments is also facilitated because studies have shown an increase in bite force under anesthesia.[118,119]
13. **Improved compatibility of adhesives and dual-cure cements.** When dentin bonding is carried out during restoration delivery, acidic components of some simplified adhesive systems (especially all-in-one) interact with the self-curing components of dual-cure luting agents.[120–122] Applying the adhesive and composite resin bio-base separately (before impression) potentially eliminates this interaction during delivery of the restoration.
14. **Systematic use of light-activated luting materials.** In the event that the luting composite resin did not polymerize optimally (eg, under thick restorations), the IDS layer acts as a well-polymerized barrier that prevents the leaching of unpolymerized monomers into the dentin. This potentially decreases the need for dual-cure cements. As for strength, thick restorations have increased structural intrinsic strength that compensates for the eventual incomplete polymerization of the light-activated luting material.
15. **Adherence of resin-based provisional materials.** Provisional restorations may be spot bonded to nonretentive tooth preparations such as posterior occlusal veneers. In addition to extending the provisional restoration beyond the preparation margins (see Fig 4-16k), a small area of the occlusal surface may be left uncovered with a separating medium (eg, Vaseline or Pro-V Coat), allowing for some adherence and extra stability to the exposed IDS layer.
16. **Possibility to omit provisional cements.** A convenient technique to fabricate provisional anterior veneers is to directly "shrink-fit" acrylic resin onto the preparations by pressing PMMA resin with a silicon index. The pressed veneers are locked by shrinkage and trimmed intraorally. As explained under reasons #5 and #6, in the case of large dentin exposures, no bacterial leakage and sensitivity are expected when IDS has been applied. In posterior teeth, soft resins (eg, Fermit) can be placed directly into the preparation.
17. **Optimal protection of direct pulp capping.** It is long known that the success of direct pulp capping seems to rely more on a perfect hermetic seal to prevent bacterial leakage rather than the biocompatibility of the capping materials.[123] In the past, zinc oxide–eugenol cements could achieve that goal but proved incompatible with composite resins. Dentin-resin bonding is the modern way of obtaining that seal. Composite resin polymerization shrinkage, however, can cause internal gaps. In this context, an optimal seal can be obtained by applying IDS immediately following the pulp capping itself (eg, CaOH or MTA cements covered with a glass-ionomer liner). A small bio-base can be placed, and the tooth can be restored with a nonshrinking interim material (eg, GIC) until the status of the pulp is deemed positive (Fig 4-17j).

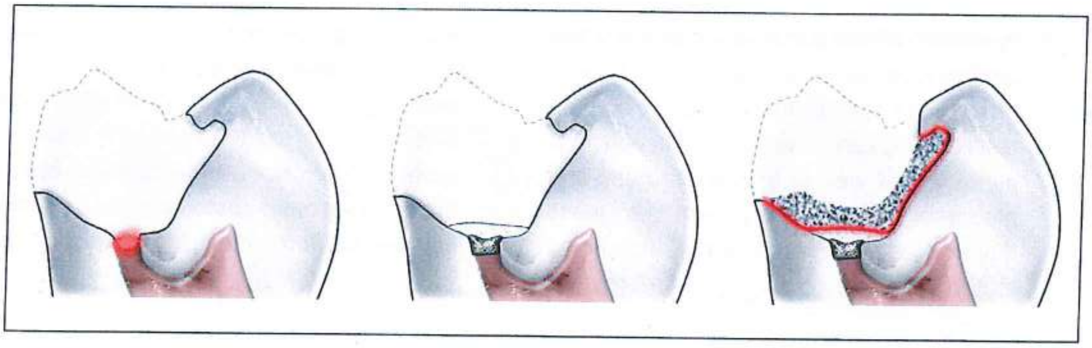


FIG 4-17j Direct pulp capping with compatible biomaterials and a GIC barrier *(center)* is complemented with a bio-base for hermetic sealing *(right)*. Any type of provisional material can be used until the pulp status is confirmed positive.

18. **Sealing of ETT.**[124,125] The same principles discussed under reason #17 apply here: Freshly sealed root canals must be immediately protected from bacterial recolonization (coronal seal). This is achieved by first placing a GIC barrier (as explained in Figs 4-14 and 4-15), cleaning/refreshing the exposed dentin with a bur, immediately followed by IDS. A purple flowable composite resin liner (PermaFlo Purple, Ultradent) can supplement IDS before placing a nonshrinking interim restoration (eg, GIC). The purple liner is convenient when the referring dentist proceeds to final restoration because it simplifies the location of the pulp chamber floor (Fig 4-17k). Above all, should the patient not be able to undergo definitive coronal restoration straight away, the root canal would remain sealed. ***Immediate pre-endodontic dentin sealing (IPDS) represents an even better approach in which IDS is performed before endodontic treatment[126] and possibly in combination with a bio-base (to reinforce weak cusps) and with DME (see Fig 3-67).*** The advantage of IPDS is that it is performed on dentin before it is exposed to endodontic irrigants such as NaOCl, which are known to damage the collagen of dentin and potentially affect the bond strength. Open canals can be temporarily sealed with Teflon tape during IPDS in order to avoid penetration of resin flashes (see Fig 3-67m). ***IPDS will not only optimize bond strength but also protect the ETT from fracture and bacterial infiltration until final restoration.***
19. **Contingency to the DME technique.** IDS (or even IPDS) should always precede DME as explained in chapter 3 (section 3.10, element #7). Elevating a deep gingival margin is a logical complement to IDS.
20. **Two-stage placement of direct composite resin restorations.** A clinician may be in a situation where time is running out because multiple teeth have been prepared for a direct restoration and caries cleanout took more time than originally planned. IDS and a bio-base can be applied to the clean dentin surfaces followed by a provisional restoration. When the patient returns for the next appointment, teeth will be desensitized by IDS, limiting the need for anesthesia. The operator can immediately proceed with enamel beveling and restoration. The dentin bond will benefit from the delayed loading principles discussed under reason #4.

21. **Protection of root surfaces and biocorroded dentin.** Root dentin is more susceptible to caries, and it appears that even a thin bonded resin coating can protect the tooth from root caries[127,128] as well as prevent bacteria and plaque adherence and growth.[129] It seems that the resin coating materials also resist toothbrush abrasion well.[130] This represents a promising indication for the elderly population (increasing number of root caries) but also as an immediate measure to prevent further loss of tooth structure in cases of severe biocorrosion. ***A flowable liner can be added to the resin-coated surface to further improve the durability of the protective film.***

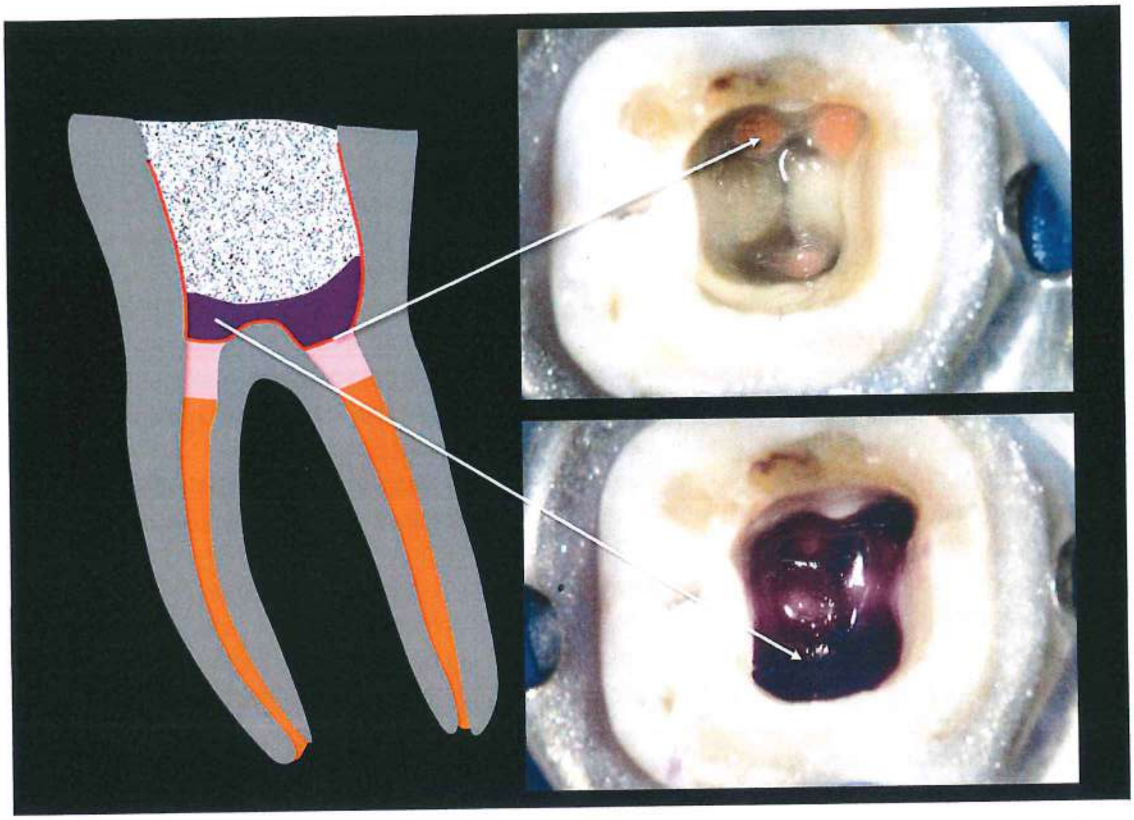


FIG 4-17k ETT can also benefit from IDS to prevent coronal leakage during the interim phase before final restoration. A pink GIC barrier is placed first (eg, Fuji Triage by GC), followed by IDS *(bottom right)* and the placement of a purple flowable composite resin (PermaFlo Purple, *top right*). The preferred approach, however, is immediate pre-endodontic dentin sealing (IPDS), in which IDS is applied before endodontic therapy as illustrated in Fig 3-67 (concomitantly with DME and the placement of a bio-base to elevate margins and reinforce weakened cusps, when necessary).

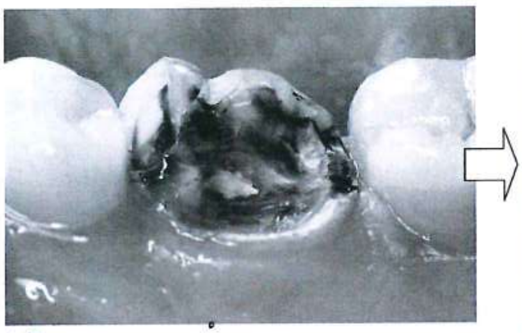
TABLE 4-4 The 20+ reasons for applying IDS

Reason	Explanation
1. Bonding to freshly cut dentin	Dentin contamination reduces the bond strength.
2. Proper polymerization and stabilization of the hybrid layer	The dentin adhesive needs to be thicker than the oxygen-inhibited layer. A thick adhesive will prevent seating of the restoration unless applied before impression-making.
3. Selective wet dentin bonding	Enamel requires dry bonding, and dentin bonding is a wet process. IDS focuses on wet dentin bonding immediately after tooth preparation (stage I). Enamel is bonded separately during restoration delivery (stage II).
4. Delayed loading of the dentin bond	Postponed restoration delivery allows for the maturation of the IDS dentin bond (15%–25% increase due to resin postpolymerization).
5. Decreased bacterial leakage	Provisional restorations always leak. IDS prevents bacteria from entering the dentinal tubules during provisionalization.
6. Decreased sensitivity during provisional stage	IDS acts as a dentin desensitizer. No other desensitizer is needed.
7. Decreased postoperative sensitivity	IDS prevents gap formation and the related hydrodynamic fluid movements causing pain.
8. Improved tooth preparation	IDS (and the bio-base) fills undercuts, produces a smoother surface, and improves geometry.
9. Reinforcement of remaining tooth structure	IDS and the composite resin additions (bio-base) support undermined/unsupported cusps that could have fractured during the provisional stage.
10. Substitution of retention/resistance form	IDS converts any type of preparation to a bondable substrate, which removes the need for specific geometry and stabilization (unless required for proper positioning).
11. Strengthening effect on crowns/onlays/veneers	The brittleness of ceramics is compensated by the underlying bond even in thin restorations like porcelain veneers.
12. Facilitated try-in procedures and occlusal adjustments	The desensitizing effect of IDS precludes the need for anesthesia, preserving lip dynamics and natural proprioception.
13. Compatibility of adhesives and luting cements	Simplified adhesives have acidic components that interact with self-curing cements. IDS and bio-base eliminate those interactions.
14. Use of light-activated products always possible	IDS is a barrier preventing the toxic leaching of unpolymerized monomers into dentin (in the case of a thick opaque restoration).
15. Spot bonding temporaries	Areas of IDS can be used for adherence of resin-based temporaries (by leaving small surfaces unisolated) in cases of totally nonretentive preparations.
16. Omission of provisional cements	No bacterial leakage or sensitivity is expected, and temporaries can be locked without cement (shrink-fit technique), especially for veneer cases.
17. Optimal protection of direct pulp capping	Preceded by direct pulp capping with CaOH or MTA (plus a GIC barrier), IDS is a perfect seal from bacterial leakage.
18. Sealing of ETT/IPDS	Preceded by isolation of the canals with a GIC barrier, IDS is a perfect seal from bacterial recolonization of the canals. IDS, however, should be preferably performed before endodontic treatment (IPDS) because endodontic irrigants and sealers contaminate the dentin and decrease the resin-dentin bonding potential.
19. DME complements IDS	IDS (or IPDS) always precedes DME; they complement each other.
20. Two-stage placement of direct restorations	IDS can be applied to multiple teeth (desensitization effect) when time constraints do not allow final restoration during the same session, limiting the need for anesthesia at the next appointment.
21. Protection of root surfaces and biocorroded dentin	The resin-coated surface is more resistant to demineralization, plaque adherence, and growth. Addition of a flowable liner to the IDS layer further improves the durability of the protective coating.

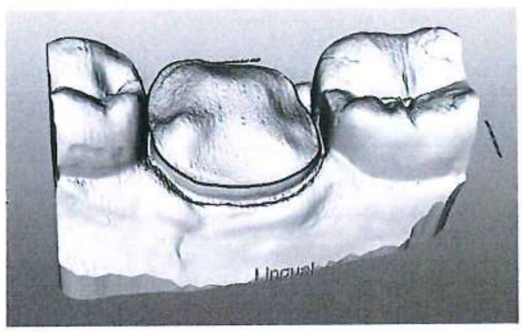
4.5 THE NATURAL CAD/CAM RESTORATION

This section describes the treatment and follow-up (through the 4th year of clinical service) of the restoration of a severely damaged vital molar using a unique approach proposed by Schlichting et al.[131,132] A third molar harvested from a donor (the daughter of the patient) was strategically positioned in a CAD/CAM block, allowing real human enamel and dentin to restore the tooth (Fig 4-18).

An old infiltrated restoration was removed and followed by a nonretentive onlay preparation including IDS. The extracted tooth was chosen among three donated third molars based on its compatible anatomy and dimensions with the tooth to be restored. The decoronated tooth was positioned in ideal occlusion within the patient's modified cast and scanned as a reference to be correlated with the dataset of the tooth preparation by the Biogeneric Copy module (CEREC). A first block was milled to generate a silicon index used to position the natural tooth crown ideally within another customized L-shaped block. Once attached to the new block, it was milled again using the existing design and delivered using standardized adhesive procedures described under section 4.7.



4-18a



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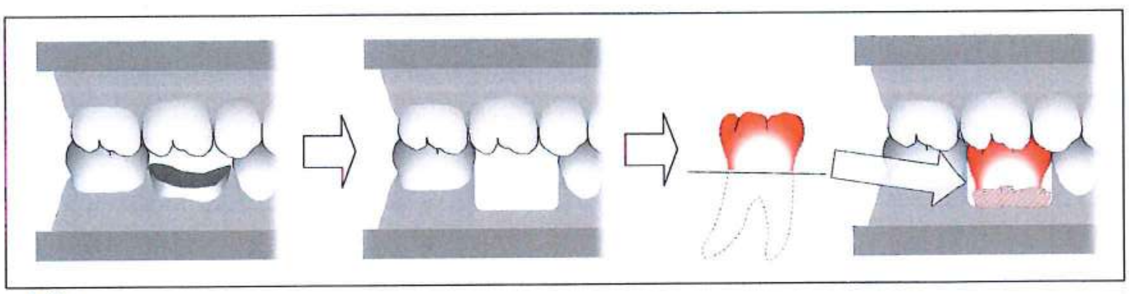
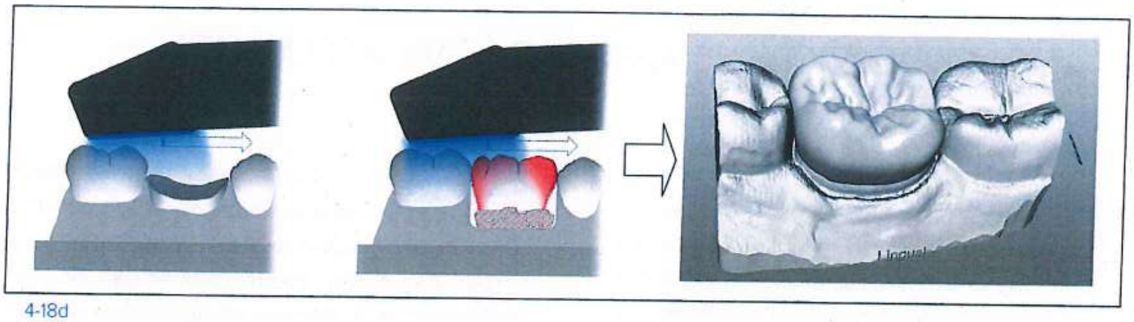


4-18c

FIG 4-18 Ultimate biomimetic CAD/CAM restoration. *(a)* This severely damaged molar was prepared for an onlay and subjected to the IDS technique. The patient and donor (patient's daughter) provided informed consent to have the treatment completed with the extracted tooth. *(b)* Both optical and analog impressions were used. *(c)* The mandibular full-arch stone cast *(left)* was modified by removing the prepared tooth and grinding a large slot *(center)*, where the decoronated tooth *(in red)* was positioned in ideal occlusion and stabilized with wax *(right)*.



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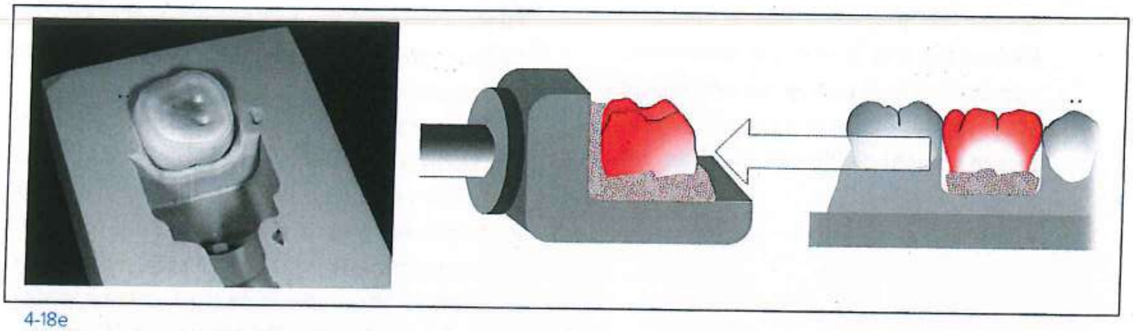

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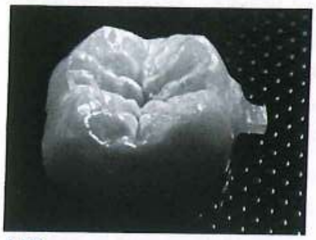
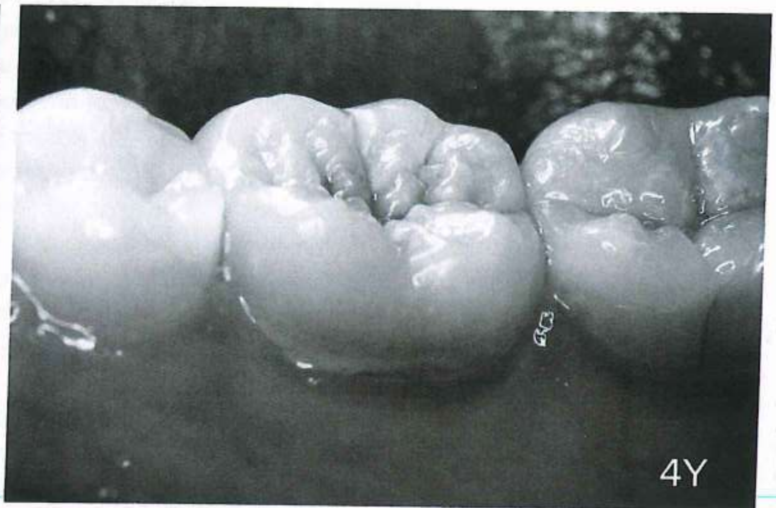


4-18f

4-18g



4-18h

FIG 4-18 *(cont) (d)* Two digital datasets were used: the tooth preparation *(left)* and the Biogeneric Copy using the stone cast with the ideally positioned extracted tooth *(center)*. Intact neighboring teeth allowed the fitting of both datasets, and the restorative design was calculated *(right)*. The restoration was milled with a first block, but the milling process was interrupted before the separation of the onlay from the block. A silicon putty captured the exact position of the onlay's occlusal surface. *(e)* The decoronated tooth was placed with the occlusal surface fitting in the silicon index *(left)*. A new L-shaped block was then seated in the silicon index with composite resin to attach the natural tooth (recovered from the model) in the exact indexed position *(center)*. *(f)* The same exact design was milled using the customized block (note that due to the indexed positioning, the milling burs did not alter the existing occlusal surface of enamel). *(g and h)* Radiographic and clinical views 4 years after the adhesive delivery. (Clinical case and photography courtesy of Dr Luis Henrique Schlichting; reproduced with permission from Magne and Schlichting.[132])

4.6 ENDOCROWNS AND CAD/CAM ASSEMBLIES

The adhesive restoration of severely broken-down posterior ETT remains a highly debated topic.[133] These teeth can be considered severely compromised unless coronal tooth structure is left to ensure the so-called "ferrule effect."[134] Hence, the first goal in the biomimetic approach is to preserve sound coronal tooth structure and prevent any further loss of coronal dentin that could reduce the ferrule effect.

"Internal ferrule" concept

There is widespread agreement that the ferrule (even partial) has a dominant effect[134–136] and that the use of radicular posts (either metallic or fiber-reinforced) cannot be justified.[136,137] The resulting strategies led to the original monobloc approach by Pissis,[138] later named "endocrown" by Bindl and Mörmann,[139] through which a new concept can be applied, the so-called "internal ferrule." In this concept, a reinforcement ring is formed by the structural bonding to the radicular dentin walls (Fig 4-19a). IDS is applied before the impression/fabrication of a polymer-based CAD/CAM endocrown, which can be left as is or used as a buildup to be complemented with an onlay or a crown. Clinically, the HPP endocrown can be used as an interim restoration and later supplemented with a ceramic onlay or a crown (Fig 4-19b). The restoration can also be fabricated as a bilaminar assembly (see chapter 1, Fig 1-32). Semi-direct core buildups made from HPPs improved the performance of glass-ceramic crowns compared with direct composite resin buildups.[140,141]

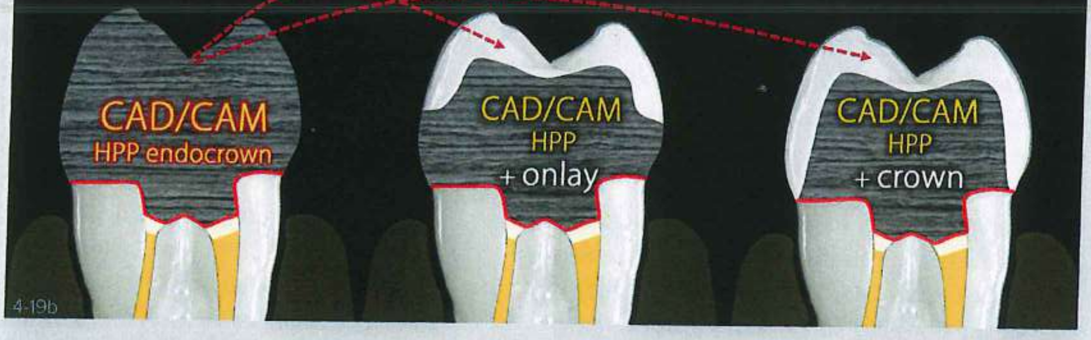
The ceramic endocrown, on the other hand, has been supported by 20 years of documentation. A 10-year prospective study confirmed that it constitutes a gold standard for the no-post, no-core approach, with an estimated survival rate of 98.8% for lithium-disilicate glass-ceramic endocrowns (including the IDS technique),[142] confirming previous in vitro results.[52] ***Endocrowns are minimally invasive, they reduce the risk of catastrophic failures, and they are easily performed.*** A case of anterior endocrown is presented in Fig 4-30. Recent in vitro research supports the no-post approach even in anterior ETT without ferrule (see chapter 6, Fig 6-18).[143] One questionable aspect of ceramic endocrowns is the difficulty to retrieve or reaccess the canal through the thick and strong glass-ceramics. The answer might come from advanced 3D guided endodontics (see chapter 3, Figs 3-16b to 3-16d) and the use of CBCT imaging to design a 3D-printed endodontic guide to drill minimally at the exact location and angulation.[144,145]

FIG 4-19 The internal ferrule concept and novel polymer-based CAD/CAM endocrown options. *(a)* Structural adhesion (using a filled light-polymerized adhesive system) can create a peripheral bonding ring that mimics the classic external ferrule effect *(left)*. When combined with CAD/CAM polymer buildups, the performance of glass-ceramic crowns can be enhanced *(right)*.[140,141] *(b)* HPP endocrowns can serve as an interim restoration *(left)* to be later complemented with a ceramic onlay or crown *(center and right)*.

FIG 4-20 Confirmation of appropriate try-in sequence. *(a and b)* These onlays (same case as in Figs 4-16e to 4-16j) feature the various degrees of cusp overlap explained in Fig 4-12c. *(c to g)* Two sequences of delivery are simulated on the stone cast and reveal that the premolar cannot be seated last but needs to be seated first or second, prior to the first molar.

INTERNAL FERRULE

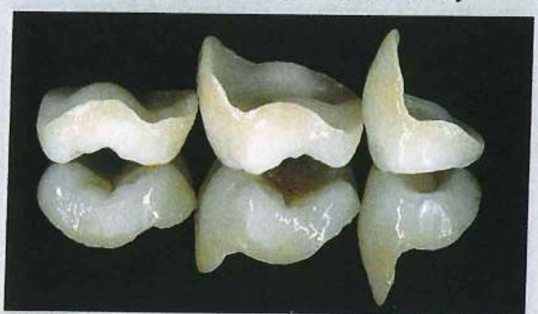
4-19a



4-19b

Onlay "Crownlay" "Veneerlay"


4-20a


4-20b

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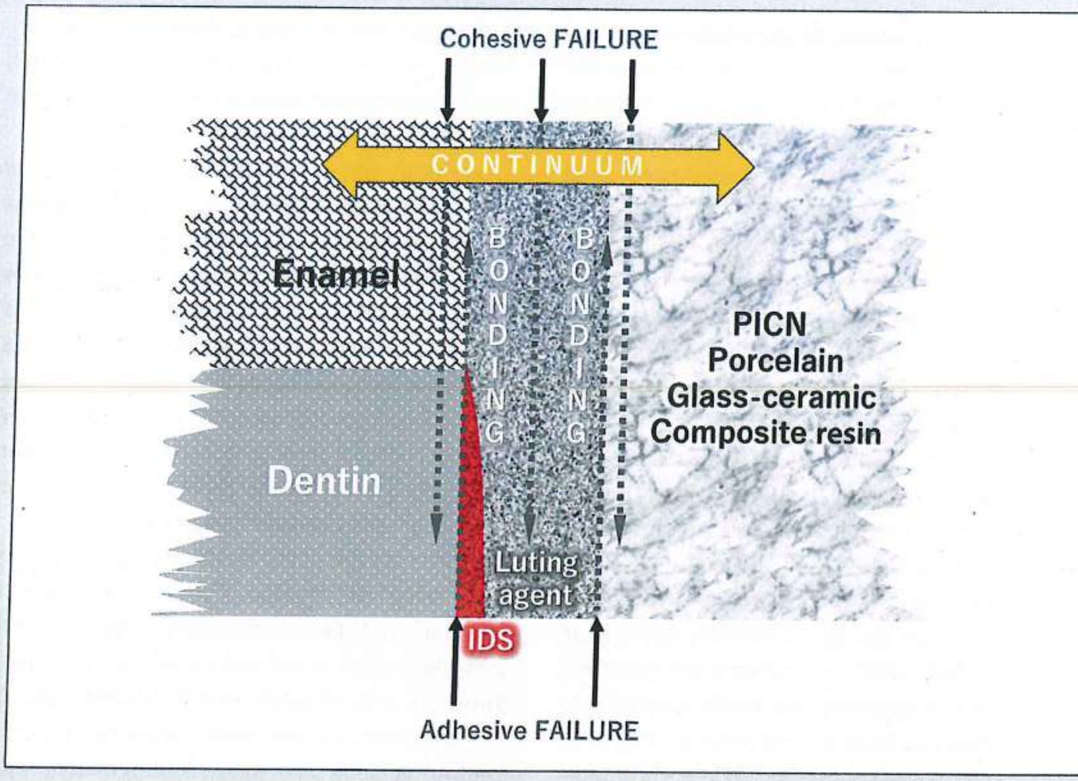
4-20g

4.7 LUTING PROCEDURES IN POSTERIOR TEETH

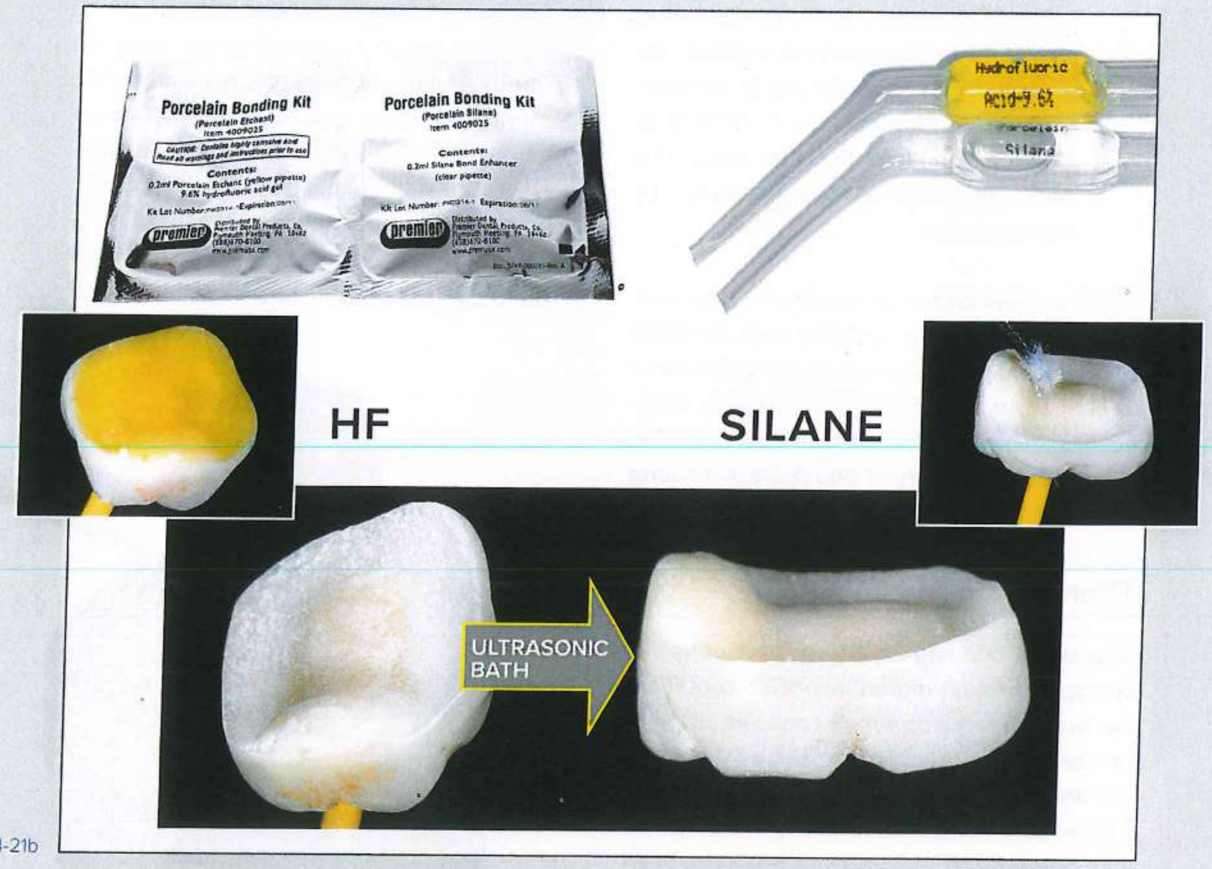
Luting procedures for posterior teeth follow the same principles as in the anterior dentition (see chapter 6, section 6.13). Delivery of semi-indirect restorations starts with try-in procedures to confirm appropriate seating and marginal adaptation of the restorations. When dealing with multiple units, it is paramount to confirm the insertion sequence on the stone cast (Fig 4-20). Successful adhesive delivery of semi-indirect restorations implies successful resin bonding at three different levels (Fig 4-21a):

1. **Resin bonding to enamel:** Resin bonding to enamel through acid etching has been explained in detail in chapter 3 (Fig 3-28a).
2. **Resin bonding to dentin:** Resin bonding to dentin is normally not performed at the stage of restoration delivery but should have been obtained before impression-making through the IDS technique (see section 4.4).[81,84] At delivery, the focus should be only on the resin-to-resin bonding between the luting agent and the IDS layer. This entails *(1)* airborne-particle abrasion (30–50 microns Al_2O_3 at 30 psi) of the enamel and the IDS layer (and/or bio-base) followed by *(2)* acid etching (to condition the enamel and clean the rest of the tooth surface) and abundant rinsing and drying. No dentin primer should be used unless exposed dentin (omitted by the IDS protocol or due to overly aggressive airborne-particle abrasion) is found. Finally, *(3)* the entire surface preparation is wet with adhesive resin but not polymerized until the restoration is seated.
3. **Resin bonding to restorative materials:** There are at least four classes of materials that will require different conditioning (Table 4-5):
   - **Feldspathic porcelain** (Fig 4-21) requires etching with 9% to 10% HF acid for 90 seconds, rinsing and cleaning in ultrasonic bath for 2 to 3 minutes (in distilled water or 90% ethanol),[146,147] drying and application of a silane solution for 20 to 30 seconds (1–2 coats), air-drying and heat-drying (1 minute at 100°C/212°F or 2 minutes with hair dryer on hot position),[148,149] and finally wetting with adhesive resin (no polymerization until restoration is seated). ***The silane application and drying should not leave the fitting surface of the restoration shiny. A shiny surface indicates that the silane has been applied in excess (too many coats and/or for too long).***
   - **Lithium disilicate glass-ceramic** requires etching with 5% HF acid for 20 seconds, rinsing and immersion in ultrasonic bath for 2 to 3 minutes (in distilled water or 90% ethanol), drying and application of a silane solution (1–2 coats), air-drying and heat-drying (1 minute at 100°C/212°F or 2 minutes with hair dryer on hot position), and finally wetting with adhesive resin but not polymerizing.

FIG 4-21 Continuity of the resin bond via porcelain etching, cleaning, and silanization. Successful resin bonding to the various substrates must be achieved in order to fulfill the biomimetic principle—that is, to obtain a long-term continuum between restoration and tooth. *(a)* Successful bonding to dentin requires IDS *(dark red)*. *(b)* Porcelain Bonding Kit by Premier is a sealed package including unidoses of HF acid and prehydrolyzed silane *(top)*. This porcelain restoration was etched with HF 9.6% for 90 seconds *(left inset)* and rinsed abundantly. Note the strong white residues (crystalline precipitates) that are not readily soluble in water *(bottom center-left)* but require removal by ultrasonic cleaning in distilled water or 90% ethanol.[146,147] Also note the clean sonicated surface *(bottom center-right)* ready for silane application and heat-drying *(right inset)*.


Cohesive FAILURE
CONTINUUM
Enamel
Dentin
BONDING
BONDING
Luting agent
IDS
PICN
Porcelain
Glass-ceramic
Composite resin
Adhesive FAILURE

4-21a


Porcelain Bonding Kit
Porcelain Bonding Kit
HF
SILANE
ULTRASONIC BATH

4-21b

- **PICN and leucite-reinforced glass-ceramics** require etching with 5% HF acid for 60 seconds, rinsing and immersion in ultrasonic bath for 2 to 3 minutes (in distilled water or 90% ethanol), drying and application of a silane solution (1–2 coats), air-drying and heat-drying (1 minute at 100°C/212°F or 2 minutes with hair dryer on hot position), and finally wetting with adhesive resin but not polymerizing.
- **Polymer-based materials** require surface roughening with a coarse diamond bur and airborne-particle abrasion (30–50 microns Al_2O_3 at 30 psi), immersion in ultrasonic bath for 1 minute (in distilled water or 90% ethanol), drying, and application of one of the following[150–153]: *(1)* a silane solution (1–2 coats), air-drying and heat-drying (1 minute at 100°C/212°F or 2 minutes with hair dryer on hot position), and finally wetting with adhesive resin but not polymerizing; or *(2)* alternatively for some CAD/CAM composite resins, a special resin primer containing methyl methacrylate and an organophosphate monomer like MDP (eg, Scotchbond Universal by 3M, One Coat 7 Universal by Coltène/Whaledent) can be used. This option is sometimes recommended by manufacturers.

The materials and most important luting principles are similar for anterior and posterior bonded porcelain restorations (semi-direct and indirect) and are presented in detail in chapter 6, section 6.13, for anterior bonded porcelain restorations ("Try-in and Adhesive Luting Procedures").

Thermomodified luting

Successful bonding implies optimal adhesive strength through material-specific conditioning but also requires strong cohesive strength of the luting materials themselves. Hence, a radiopaque-filled adhesive resin (wetting resin for the tooth and restoration) and preheated light-polymerized restorative material have been suggested as luting agents. Friedman[154] demonstrated the success of porcelain veneers bonded with a microhybrid restorative composite resin for over 15 years.

By 1995, Besek et al[155] had established that dual-curing resin offered no advantages compared to light curing only, and they may have been the first authors to propose the use of a restorative composite resin as a luting agent for ceramic inlays. The light-curing composite resin was judged to be easier to handle than the dual-cure material. Because the operator has more time for excess removal prior to polymerization, fewer luting composite overhangs are found with the solely light-polymerized composite.[156]

Concerns about the depth of polymerization have been demystified. The thickness of the restoration can be compensated for by extended polymerization times (up to 90 seconds per surface), and no effect of the polymerization mode (light vs dual) was found on the mechanical performance of thick (up to 7 mm) onlays and overlays.[156–159] In addition, wear resistance of restorative materials proves to be superior to methacrylate or phosphate-based resin cements.[160,161] Using light-curing restorative materials for luting tooth-colored inlay/onlays/overlays should therefore no longer be considered hazardous but rather beneficial.[162] Lastly, clinicians may be concerned by the possibility of incomplete restoration seating due to the

4-22

viscosity of the restorative material. Preheating the restorative composite resin through ultrasonic devices[163] or with a small composite heater at 68°C/155°F for 10 minutes (Fig 4-22)[164] has not only resolved this issue but also proven to have positive effects on marginal/internal adaptation and bond strength.[165–167]

Heated composite resins also polymerize better.[168–170] The aforementioned benefits are limited during luting procedures due to the rapid cooling of the material before it is light-polymerized.[164,165] ***Restorative materials with large fillers should be avoided** (eg, with macroparticles and/or large prepolymerized filler complexes; see chapter 3, Fig 3-32 and Table 3-3).*[171] Although microhybrid restorative composite resins might not present the lowest film thickness, inlays/onlays prove to seat more predictably with a preheated restorative material such as Z100 (3M) when compared to a dual-cure cement.[171] This may be explained by the additional clearance space for the luting agent that is created when air-abrading the fitting surface of composite resin inlays/onlays before bonding. Heated material can be reused because up to 20 cycles can be applied to the same syringe without affecting the mechanical properties or polymerization rate.[172,173]

Even though they might belong to the same class, different restorative composite resins may exhibit large differences in their viscosity.[174] In addition, each brand reacts in a different way to preheating, with a decrease ranging from 40% to 92%.[175] Some brands might even start to polymerize when stored more than 15 minutes in the heating device. ***Hence, many composite resins are not appropriate for luting because their viscosity is not optimized even after preheating.***[176]

TABLE 4-5 Surface conditioning according to material

Steps	Feldspathic porcelain	LiDi[a]	PICN and leucite[b]	Polymer
1. Airborne-particle abrasion with Al_2O_3 30–50 microns at 30 psi	No (but OK with glass beads at 22 psi)	No (but OK with glass beads at 22 psi)	No (but OK with glass beads at 22 psi)	Yes (preceded by roughening with coarse diamond bur)
2. HF etching	Yes 9%–10% HF for 90 seconds	Yes 5% HF for 20 seconds	Yes 5% HF for 60 seconds	No
3. Postetching cleaning in ultrasonic bath (water or 90% alcohol)	Yes	Yes	Yes	Yes
4. Silane application and heat-drying 1 minute at 100°C/212°F[d]	Yes	Yes	Yes	Yes [c]Or special primer
5. Wetting with adhesive resin (no polymerization)	Yes	Yes	Yes	Yes

[a]Lithium silicate, lithium disilicate, and zirconia-reinforced lithium silicate glass-ceramics.

[b]Leucite-reinforced ceramics.

[c]Depending on block manufacturer (primer with methyl methacrylate and MDP).

[d]More information about silane application methods is provided in chapter 6, Fig 6-76. Allowing the silane to react for 5 minutes is an alternate method to heat-drying for 1 minute.

FIG 4-22 Composite resin preheating device for thermomodified luting. The Calset device (AdDent) can be purchased with various trays. The Dispenser Tray can warm up compules and syringes up to 68°C/155°F and is also compatible with the Centrix and Venus dispensers.

A standard luting procedure is illustrated in Fig 4-23. Finishing of the restoration should be carried out first using hand instruments (scalpel #12 and sickle scaler) to remove small flashes and overhangs (Figs 4-24a to 4-24d). Large excesses of luting material or large overhangs and overcontours are too difficult to remove by hand. Such defects can be easily resolved with a reciprocating handpiece and single-sided diamond blades (Figs 4-24e to 4-24h).

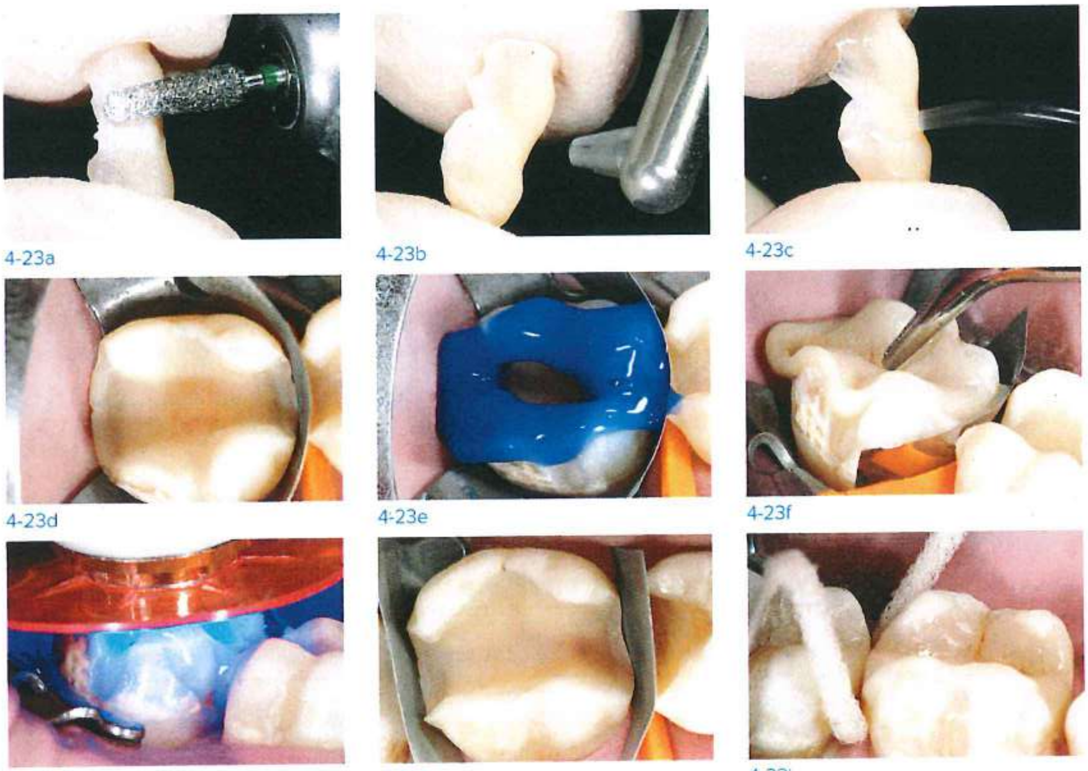


FIG 4-23 Conditioning and luting of composite resin inlay. *(a and b)* The fitting surface is roughened with a coarse diamond bur at low speed (note the safe distance to the margin) and air-abraded before cleaning in an ultrasonic bath (not shown). *(c)* The silane is applied, air-dried, and heat-dried. *(d and e)* The tooth is isolated and air-abraded, then etched (note that mainly the enamel is etched but not exclusively). Both fitting surfaces (tooth and inlay) are coated with a thin layer of adhesive resin (not shown). *(f)* The preheated restorative composite resin is injected in the tooth, and the inlay is gently seated. Note the sectional metal band preventing contamination of the neighboring tooth. *(g)* The polymerization light is applied (three times for 20 seconds per surface), and additional polymerization is achieved through the application of glycerin gel. *(h)* The whole process is repeated for the next tooth. Each time, all unpolymerized excess composite resin is carefully removed. *(i)* Super Floss (Oral-B) is perfect for wiping off interdental margins before polymerization. Note in this case that the small buccal extensions of the preparations on both molars were previously restored with a direct composite resin restoration to simplify the design of the inlays. The same case is featured in Figs 4-16a to 4-16d, illustrating the short-term provisionalization.

FIG 4-24 Interdental finishing tools. *(a and b)* Blade #12 can be bent with a hemostat plier after heating up the blade tip until red. **IMPORTANT:** Once bent, the blade must be reheated to red hot and cooled in water for annealing before use. Applying the annealing process is necessary for hardening the steel again. *(c and d)* The curvature of the blade allows deep interdental access for removal of resin flashes. *(e and f)* Profin reciprocating handpiece and Lamineer tips by Dentatus are ideal for large interproximal corrections. *(g and h)* The single-sided diamond blades (15 to 150 micron-grit) can be inserted horizontally to file the excesses and polish the adjusted surface. The postoperative radiographic image confirms the smooth margin.

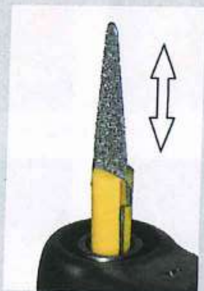

4-24a


4-24b

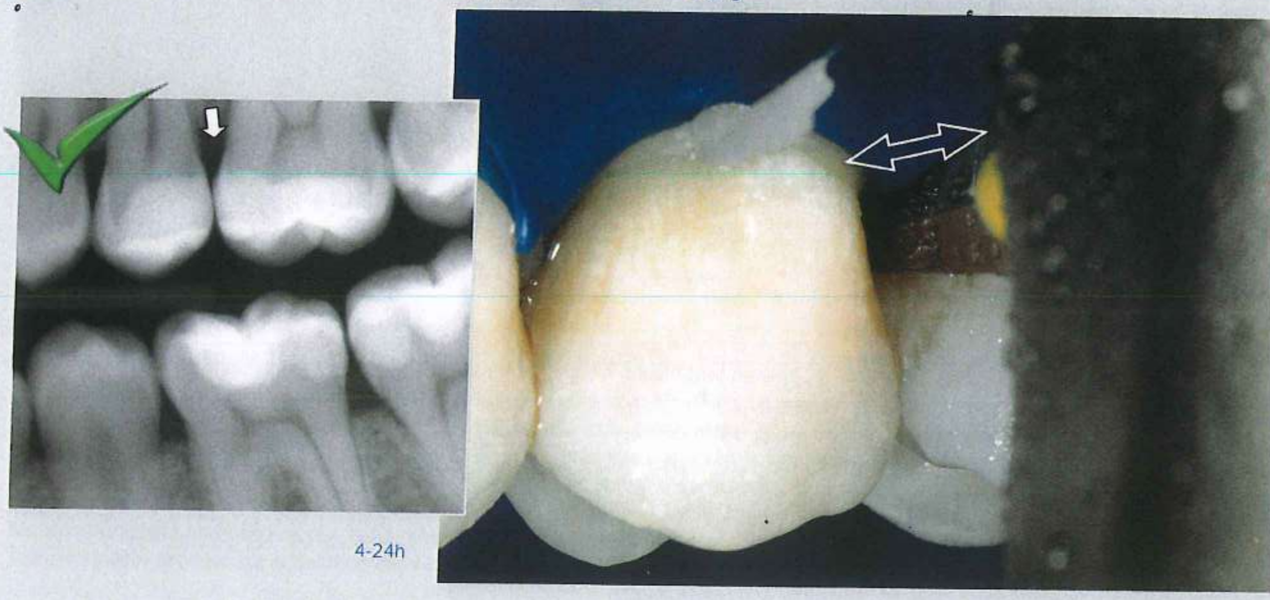

4-24c


4-24d


4-24e


4-24f


4-24g


4-24h

Additive luting

Marginal ridge (MR) integrity is the most critical factor in preserving the cuspal stiffness of posterior ETT.[177] When 1 to 2 mm of intact mesial and distal MR is present, composite resin restorations can be used alone to restore the access preparation. In that way, the fracture resistance can be preserved to the level of the intact tooth.[178] When endodontists preventively reduce intact cusp tips and marginal ridges (Fig 4-25a), however, the dilemma of cusp overlap arises. The option of additive luting may be the best way to preserve all the remaining hard tissues and restore proper occlusal morphology (Figs 4-25b to 4-25i). ***Because the luting agent is a regular restorative material, it can be used additively to extend beyond the inlay margins and restore the missing cusp and MR anatomy.***

4-25a

4-25b

4-25c

4-25d

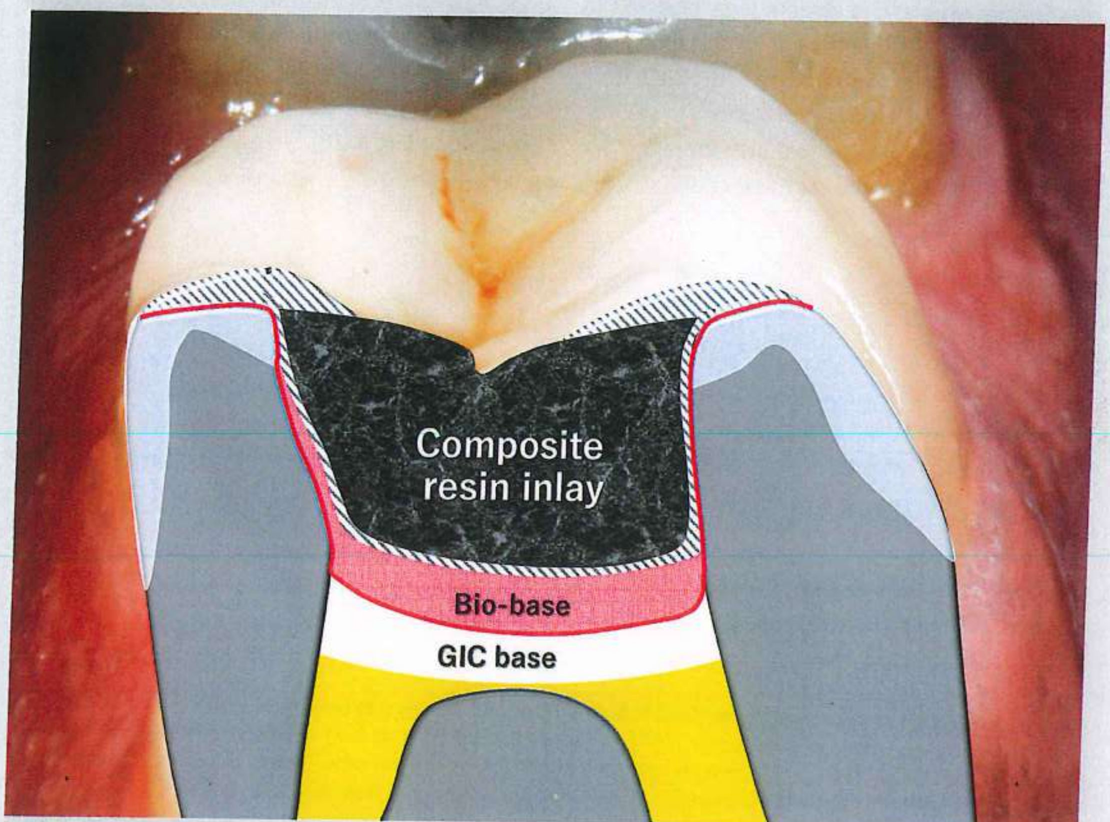
FIG 4-25 Additive luting. *(a)* This endodontically treated molar still has MRs, but the cusp tips and MRs have been slightly reduced by the endodontist. *(b)* The clinical crown is also very short. *(c)* After internal cleanup, a GIC barrier and a bio-base (IDS plus composite resin base) were placed. *(d to i)* An inlay was fabricated and delivered with an additive amount of luting composite (restorative material) to complete the missing cusp and MR anatomy. The occlusal enamel and occlusal surface of the inlay were conditioned accordingly to allow the adhesion of the luting composite resin *(dashed area in i,* cross-sectional view). Note the postoperative radiograph showing maximum preservation of mesial and distal volumes of enamel/dentin *(h)*. A classical approach with a full–crown coverage preparation would have required the sacrifice of a major amount of intact tissues and still have resulted in problematic retention/resistance form due to the limited clinical crown height.


4-25e


4-25f


4-25g


4-25h



4-25i

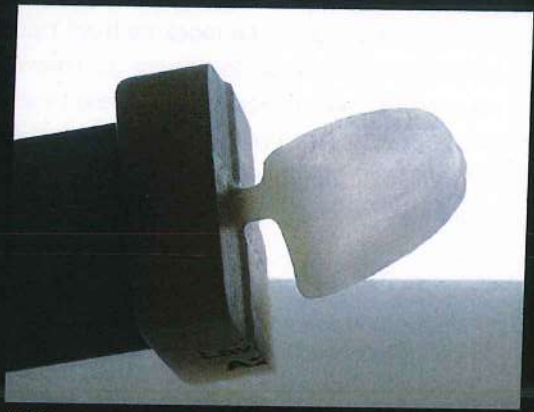
4.8 ANTERIOR CAD/CAM RESTORATIONS

Bridging the gap

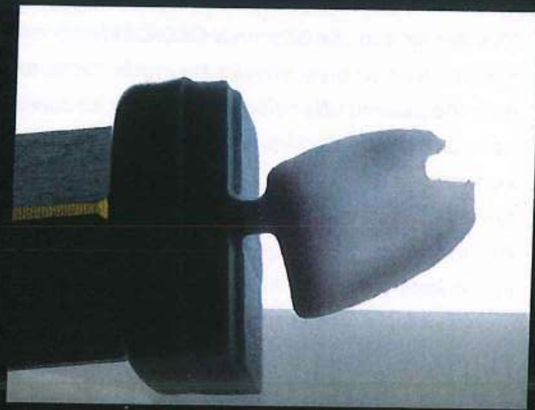
Direct restorations have been recognized for their cost-effectiveness, valuable clinical service, and respect of intact hard tissues (see chapter 3, section 3.8). Resin-based materials are also gaining popularity for CAD/CAM use in the anterior dentition. Traditionally, direct composite resin or indirect ceramic veneers are offered to the patient. Porcelain restorations provide unmatched long-term performance, their surface can be ideally polished in the laboratory, and they require minimal maintenance over the years (see chapter 7, Fig 7-1). Working with a "champion" dental ceramist, however, is mandatory due to the nonorganic nature of the material. To simulate the complex optical behavior of the natural tissues, the ceramist must diligently apply numerous layers and effects (see layering in chapter 6, Figs 6-65 and 6-66). Generating flush and properly finished margins requires a light marginal chamfer preparation along with smooth internal contours and minimum clearance for the porcelain (~0.4–0.6 mm; see chapter 6, Fig 6-26). If those principles and their related costs are agreed upon (tissue-wise and money-wise), long-term predictability can be achieved.[179–183]

Today, the gap between direct and indirect techniques can be bridged by a novel semi-indirect CAD/CAM approach.[3] ***It consists of a milled low-translucency dentin base customized by histoanatomical incisoproximal cutback and layering with a generic translucent enamel skin.*** Treatment can be performed in one clinical session—semi-directly—or two clinical sessions—semi-indirectly. Resin-based materials or PICN are preferred because of their millability in thin layers and simplicity of customization (using light-polymerizing colorants and composite resin additions) compared to ceramics. Effective resin-to-resin/PICN bonding is crucial to this technique (as per Table 4-5, last two columns), both before the application of the enamel skin to the cutback surface but also to the fitting surface of the restoration during its delivery. Sophisticated effects can be obtained despite the simplicity of this technique (Fig 4-26).

FIG 4-26 Polymer vs ceramic anterior CAD/CAM restorations. A minimally prepped anterior tooth was scanned, and a labioincisal veneer was designed. *(a)* The thin margins (~0.15–0.20 mm) were successfully milled using a composite resin block, but marginal defects are found when milling the exact same design in ceramics *(b)*. *(c to f)* Two central incisor veneers are made of customized CAD/CAM composite resin. Note the incisal edge effects obtained by the incisoproximal cutback, slight internal coloring (blue-lavender effects), and coverage with an enamellike composite resin skin. All customization steps are detailed in Fig 4-28. Specimens fabricated during a hands-on course.



4-26a



4-26b

4-26c

4-26d

4-26e

4-26f

The decision to use bilaminar CAD/CAM polymer restorations should always be made together with the patient after discussion about invasiveness and cost-effectiveness compared to direct composite resins and indirect ceramics and knowing that anterior indirect ceramic restorations always provide the best performance in the long term (see chapter 7, section 7.1).[183]

Digital/analog workflow

After collecting all the required data, the first step is always to generate a wax-up/mock-up (see chapter 5) based on the knowledge of tooth morphology, intuition, sensitivity, and a good perception of the patient's individual character. It consists of redefining the original coronal volume in harmony with the smile. This can be done using a digital workflow by scanning the dentition and using a design software (digital wax-up). The corresponding model is then printed to fabricate silicon indexes for the mock-up. In a hybrid digital/analog workflow, type IV white stone study casts (eg, Fujirock EP, GC) from a polyvinyl siloxane impressions are used. In the case of a "no-prep" approach (Table 4-6; see also Fig 4-30), this baseline cast can be digitized to generate a first dataset. The second dataset is obtained after the physical wax-up. Restorations can be generated by copying the design (eg, using the Biogeneric Copy mode in the CEREC system by Sirona), provided that a mock-up has been carried out and the design approved as is by the patient. When major editing and modifications of the mock-up have been carried out in the mouth (during the "test drive"), the second dataset should be generated using the mock-up instead of the wax-up (Table 4-6). The wax-up/mock-up workflow has long proven to generate precise and predictable results.[184–186]

Step-by-step process

The complete step-by-step process is illustrated with the restoration of two endodontically treated central incisors that were first bleached using the walking bleach technique (Figs 4-27a to 4-27c), followed by wax-up and mock-up (Figs 4-27d to 4-27m). Upon acceptance of the mock-up and a 4-week postbleaching delay, the teeth were microprepared (preparations guided by the mock-up; see technique in chapter 6, Figs 6-25 to 6-29) and the lingual surfaces restored with composite resin. Two low-translucency (LT blocks) composite resin CAD/CAM veneers were designed/milled by "Biocopy" (Biogeneric Copy in the CEREC/Sirona Software) of the wax-up (Figs 4-27n to 4-27s), customized, and delivered (Fig 4-28). The esthetic potential of this technique is also demonstrated in another case, this time with a "no-prep" approach due to the existing biocorrosion of the enamel (see Fig 4-29), and in additional cases in chapter 5 (eg, Fig 5-22, 6-year follow-up). The same workflow can be used to produce CAD/CAM ceramic veneers ("Biocopy," cutback, and customization) but requires slightly more tissue reduction and is also more laboratory-intensive (see chapter 6, Fig 6-57).

FIG 4-27 Wax-up/mock-up and Biocopy workflow. *(a to c)* These endodontically treated central incisors were first bleached internally. The baseline casts *(d and e)* were used to generate a rapid additive wax-up *(f and g)* and the corresponding silicon indexes for the mock-up. Note correction of the rotated right central incisor and the addition of wax over the gingiva at the mesial zenith *(arrows)* to match the gingival contour of the left central incisor.

TABLE 4-6 **Workflow and data acquisition for Biocopy mode**

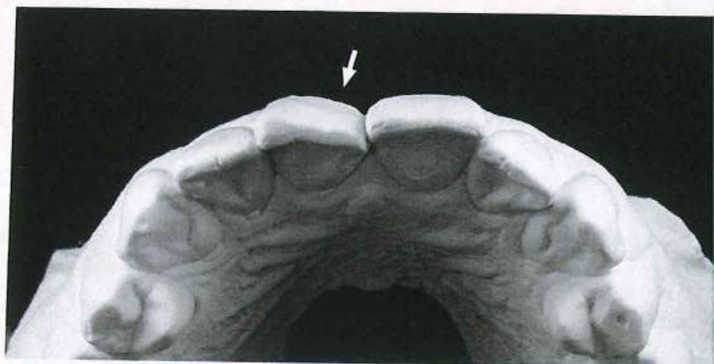
No-prep (Fig 4-29)	Prep (Figs 4-27 and 4-28)
1. Impression/scan preoperative teeth → **Dataset 1**	1. Impression/scan preoperative teeth
2. Digital or analog wax-up → Silicon indexes	2. Digital or analog wax-up → Silicon indexes
3. Intraoral mock-up → Two ways: Mock-up accepted (no changes) → Scan wax-up = **Dataset 2** Mock-up edited → Scan mock-up = **Dataset 2**	3. Intraoral mock-up → Two ways: Mock-up accepted → (no changes) Scan wax-up = **Dataset 2** Mock-up edited → Scan mock-up = **Dataset 2**
4. Design/mill restorations ("Biocopy") → **Subtract dataset 1 from dataset 2**	4. Mock-up–driven tooth micropreparations → Impression/ scan preparations = **Dataset 1**
–	5. Design/mill restorations ("Biocopy") → **Subtract dataset 1 from dataset 2**

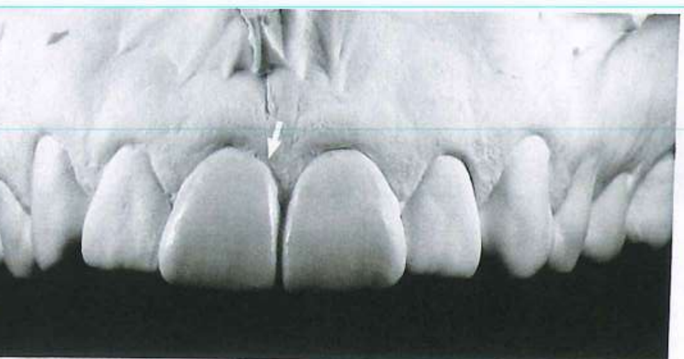

4-27a

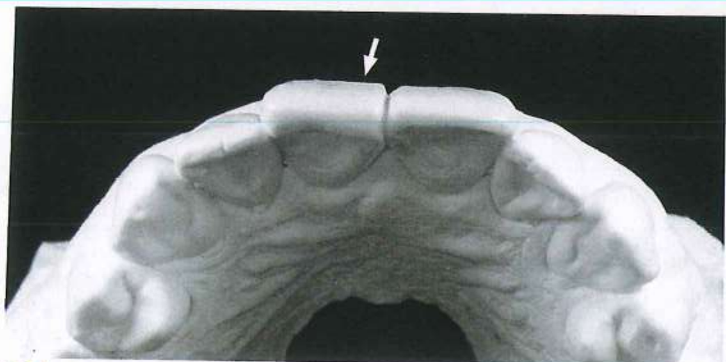

4-27b


4-27c


4-27d


4-27e


4-27f


4-27g

4-27h

4-27i

4-27j

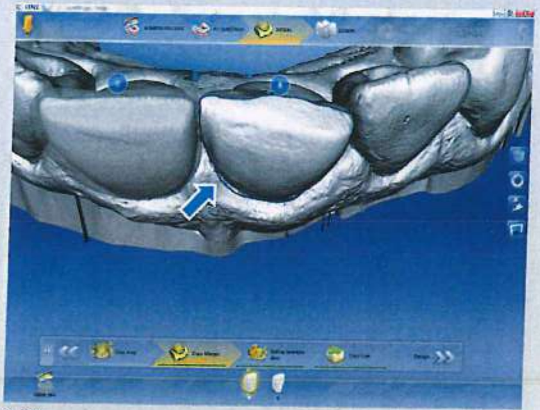
4-27k

4-27l

4-27m

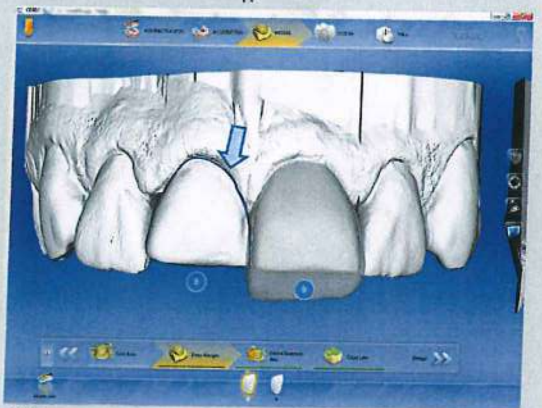
MOCK-UP

FIG 4-27 *(cont) (h)* The existing Class 4 restorations were carefully removed before fabricating the direct mock-up. PMMA resin was molded (through the silicon index) onto the spot-etched incisors *(i)*, trimmed, colored, and glazed for the test drive by the patient *(j to m)*. Note the faithfulness of the mock-up compared to the original wax-up (overlay in *m*). Upon patient acceptance of the esthetics and function of the new design, the mock-up was used as a guide for ultraconservative tooth preparations and final impression. A provisional restoration similar to the mock-up was fabricated (using the same silicon index, not illustrated).

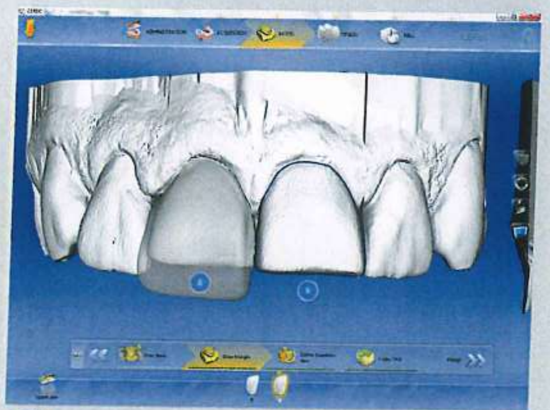


4-27n

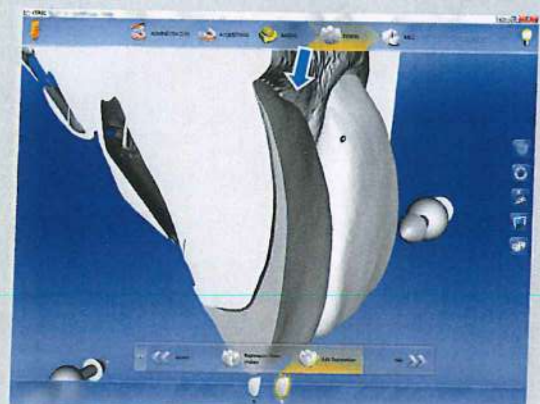
4-27o



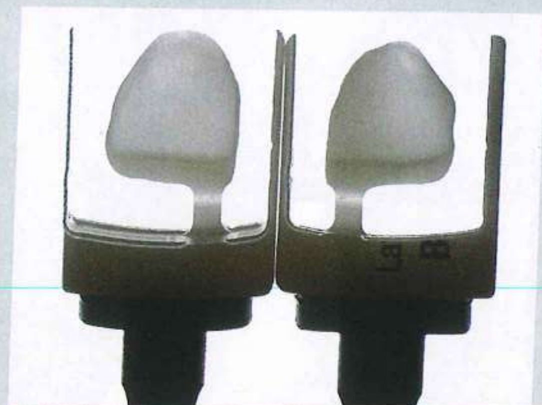
4-27p



4-27q



4-27r



4-27s

FIG 4-27 *(cont) (n to r)* The wax-up was powdered and scanned into the Biogeneric Copy folder of the CEREC software and automatically correlated to the scan of the preparations to generate the restorations. Note the mesial gingival margin of the right central incisor *(blue arrow in n, o, and p)*, which was intentionally drawn on the gingiva to support the mesial line-angle. This overhang *(arrow in r)* will be completed with a small addition of luting composite (during the delivery) to support the mesial gingival contour (as a compensation for the rotated base of the tooth) and match the contour of the gingiva on the contralateral tooth. *(s)* Milled composite resin restorations with LT blocks shade B1.

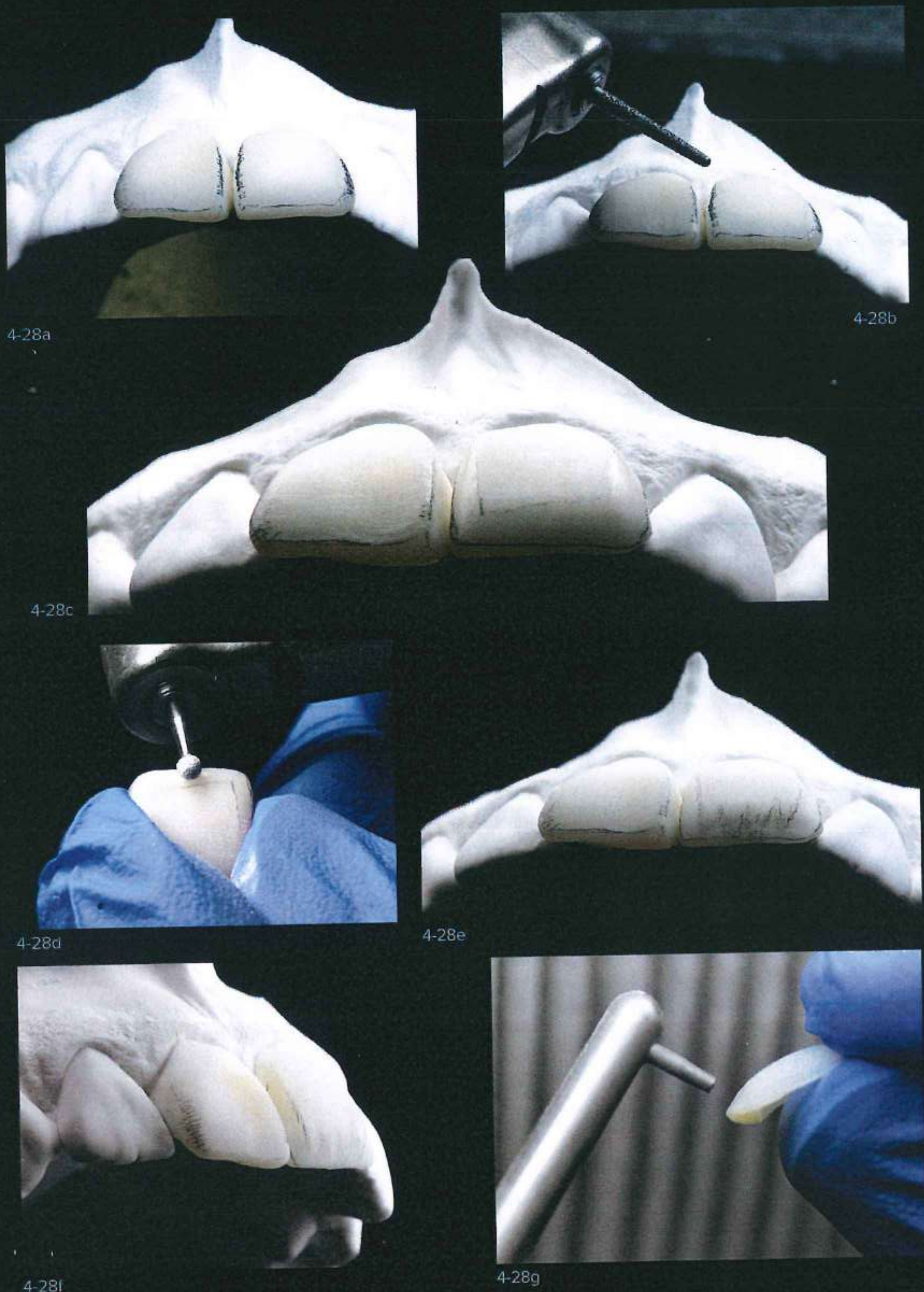
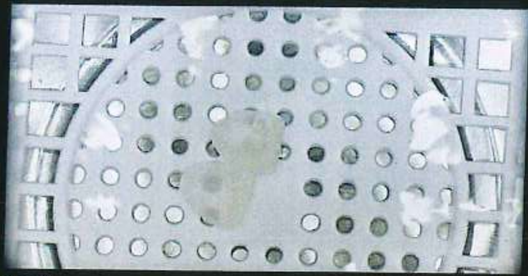
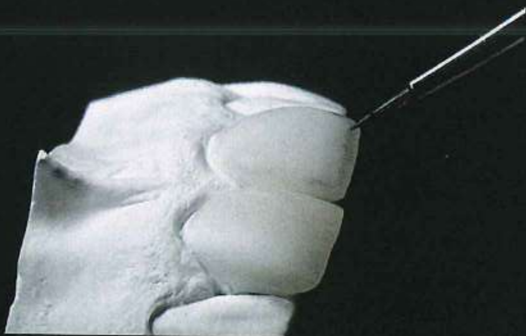


FIG 4-28 Incisoproximal cutback and internal effects (sandwich technique). *(a)* The labioincisal edge and mesial and distal line angles have been marked with a pencil. *(b and c)* A rough diamond bur is used to create a U-shaped flat surface (left central incisor). This is further reduced with a rough round diamond bur to create a concave surface *(d)* as well as dentin mamelons *(e and f)*. *(g)* The modified surface is air-abraded with 50-micron alumina at 30 psi.



4-28h

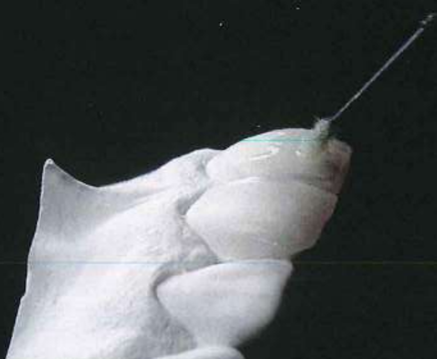
4-28i



4-28j

4-28k

4-28l



4-28m

4-28n

FIG 4-28 *(cont)* The restorations are cleaned in distilled water in the ultrasonic bath *(h)*, dried, silanated *(i)*, air-dried and heat-dried (not shown), and carefully repositioned on the stone cast for further application of the effects, first blue-lavender *(j)* and intensive white *(k and l)* to match the effects of the neighboring teeth (see maxillary lateral incisors in Fig 4-27m). *(m to o)* Once the effects are polymerized, the surface is coated with adhesive resin and completed for final shape with a skin of enamellike composite resin.

4-28o

4-28p

4-28q

4-28r

4-28s

FIG 4-28 *(cont) (p to s)* Following adhesive delivery (see step-by-step protocol in Fig 4-29), the restorations display appropriate integration (faithful to the wax-up/mock-up, symmetric gingival contours), incisal effects, and color. Note the dramatic result compared to the preoperative clinical view (overlay in *s*). A small direct composite restoration was placed on the mandibular left central incisor. (Case treated in collaboration with Dr Truman Nguyen.)

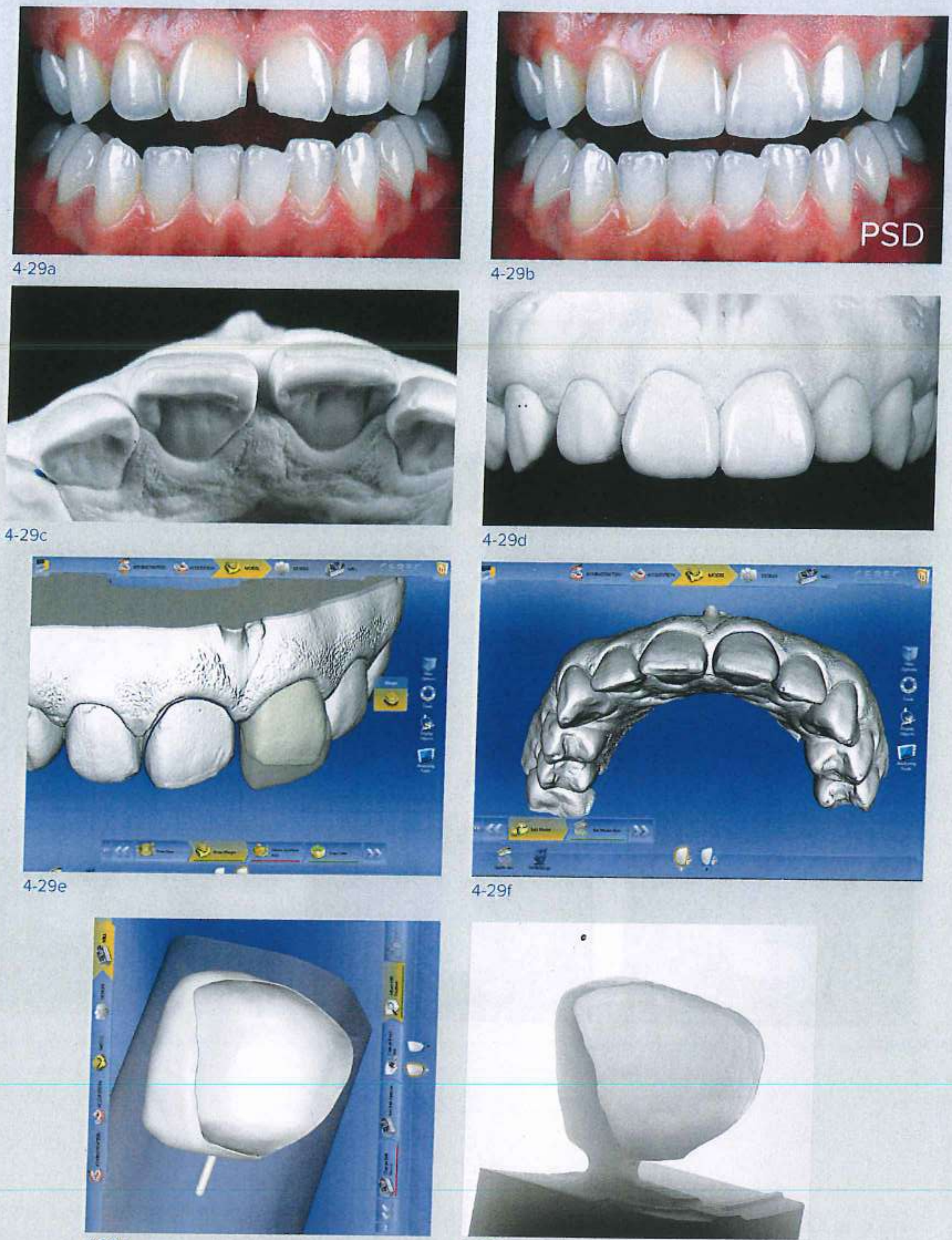
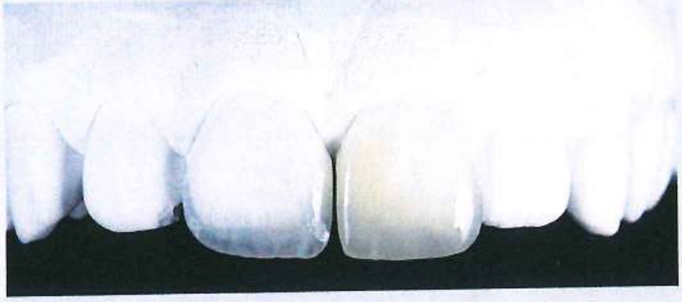


FIG 4-29 No-prep Biocopy workflow. *(a)* Case of biocorrosion lesions on maxillary central incisors ideal for no-prep approach. *(b)* A quick numeric simulation was obtained with Photoshop Smile Design (Liquify tool; see technique in chapter 5, Fig 5-2). *(c)* Small irregularities (chipped incisal enamel) were filled with wax before scanning the baseline model to form the first dataset. *(d)* The second dataset was obtained from the additive wax-up. *(e and f)* The Biocopy mode was used to obtain the design by tracing the margins nearest to the gingiva. *(g and h)* Note the faithful milling by comparing the "mill preview" to the final product, despite the extremely thin margins.



4-29i

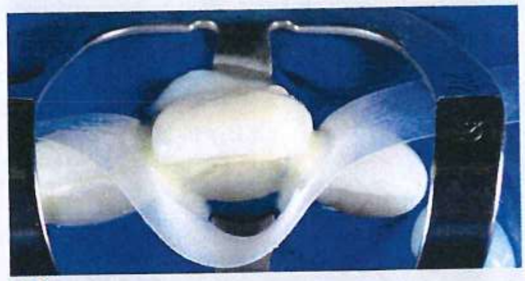
4-29j

4-29k

4-29l

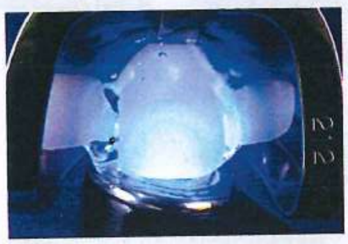
4-29m

4-29n



4-29o

4-29p



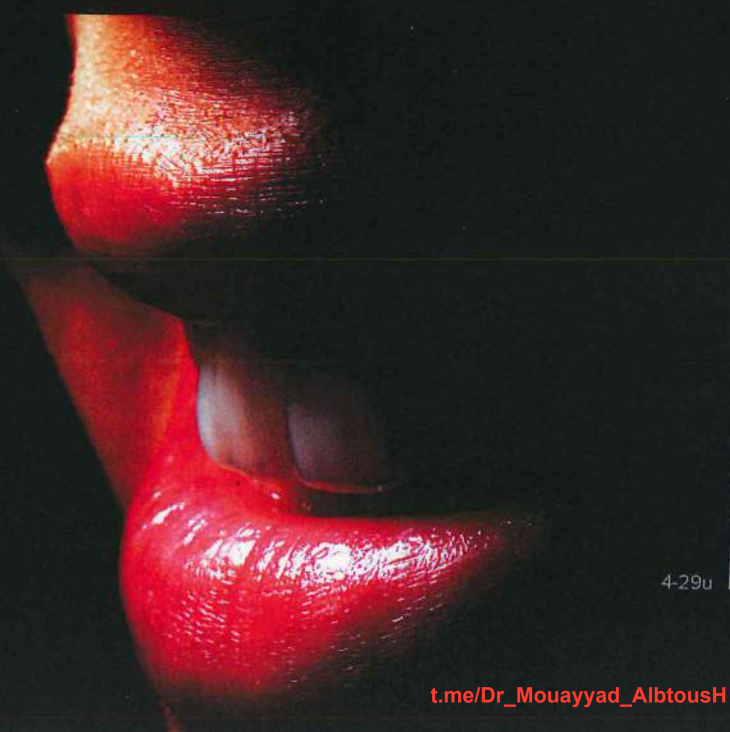
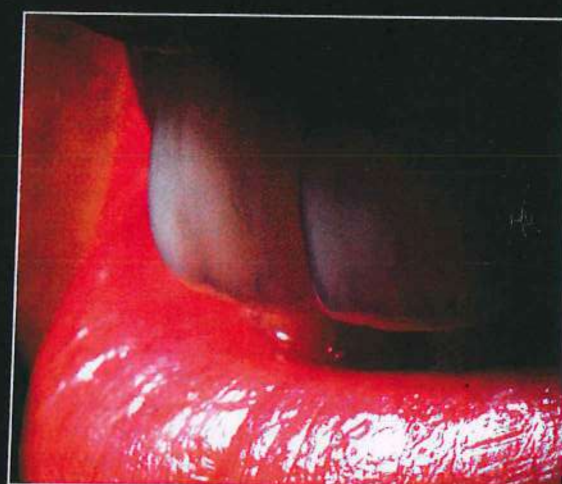
4-29q

4-29r

FIG 4-29 *(cont)* The composite resin veneers (from LT blocks shade B1) were seated on the baseline stone cast for customization as explained in the previous case (see Figs 4-28a to 4-28n). *(i)* Left central incisor with complete enamel skin and right central incisor before application of the enamel skin. Following air abrasion of the restoration and the tooth and etching of enamel *(j to l)*, the silane was applied and heat-dried *(m and n*, in this case with a hair dryer for 2 minutes). Delivery was performed with adhesive resin and preheated microhybrid restorative composite *(o)*, followed by polymerization (three times for 20 seconds per surface) and additional polymerization through glycerin gel and hand-instrument finishing *(p to r)*. *(s to u)* Postoperative views after 1 month showing natural effects matching those on the lateral incisors. Note that the use of LT (low-translucency) blocks is essential to avoid seeing the transition between the freestanding incisal edge and the tooth-supported part of the restoration. (Case treated in collaboration with Dr Andy Truong; parts *a, d, e, g to i,* and *s to u* reproduced with permission from Magne.[3])

4-29s

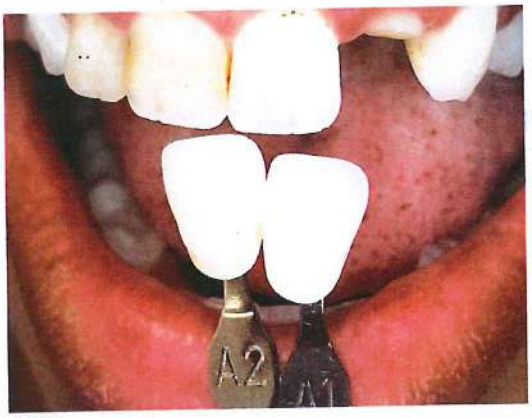
4-29t

4-29u

Incisor endocrowns

Endocrowns were described for posterior teeth (see section 4.6), and there are many reasons to anticipate that the same advantages apply to anterior teeth (Fig 4-30). ***Composite resin endocrowns especially mimic the resilience of the tooth, reducing stress at interfaces and even at the alveolar bone.***[187,188] Even though flexural strength of polymer-based CAD/CAM material is inferior to that of lithium disilicate, the endocrown performance proved identical. For those ferruleless teeth, endocrowns can even exceed the strength of any type of post-and-core buildup (see chapter 6, Fig 6-17).[189] Using IDS and engaging 4 mm into the root canal seems to partially compensate for the absence of a ferrule.[189]



4-30a

4-30b

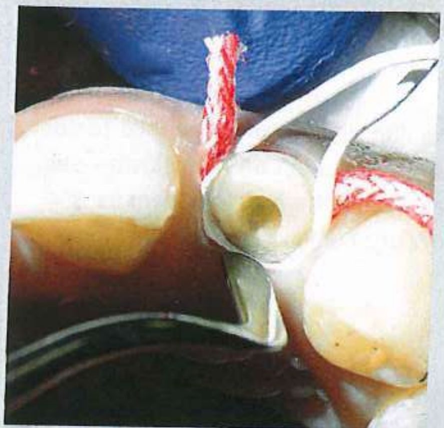
4-30c

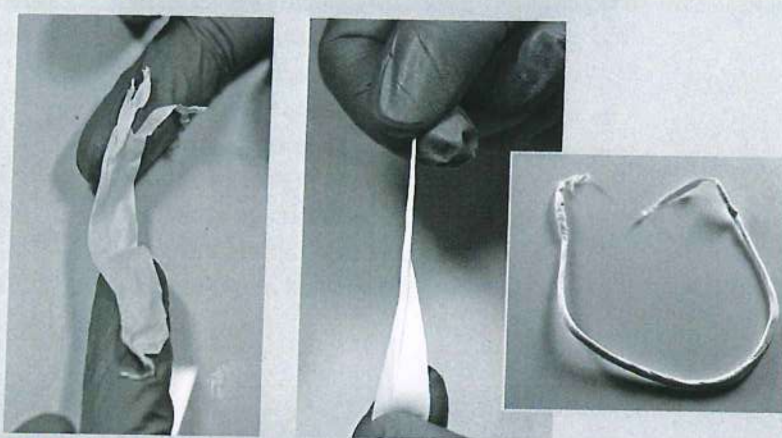
4-30d

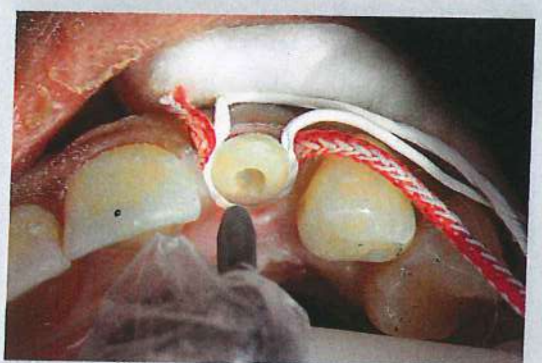
FIG 4-30 Emergency endocrown for single-tooth trauma. *(a)* Cross-polarized shade selection photograph of a young female patient presenting with an endodontically treated traumatized maxillary left lateral incisor. Endodontic treatment had been performed previously followed by the application of a bonded composite resin base to seal and partially restore the endodontic access. Tooth preparation only included a mini-chamfer at the labial cervical aspect, rounding off all internal sharp edges, leaving a small fossa facing the endodontic access *(b and d)*, and applying IDS to the exposed dentin. Note the slight remaining ferrule for the restoration *(c and e)*, which was then subjected to incisoproximal cutback *(f)* and customization according to the established protocol. *(g)* Due to the deep lingual margin, isolation was obtained with retraction cords. *(h)* Note that the superficial cord was obtained by twisting a piece of Teflon tape. *(k and l)* The integration of the restoration and tissue response was a success despite the numerous challenges. (Case treated in collaboration with Dr Mehrdad Razaghy.)


4-30e


4-30f


4-30g


4-30h


4-30i


4-30j


4-30k


4-30l

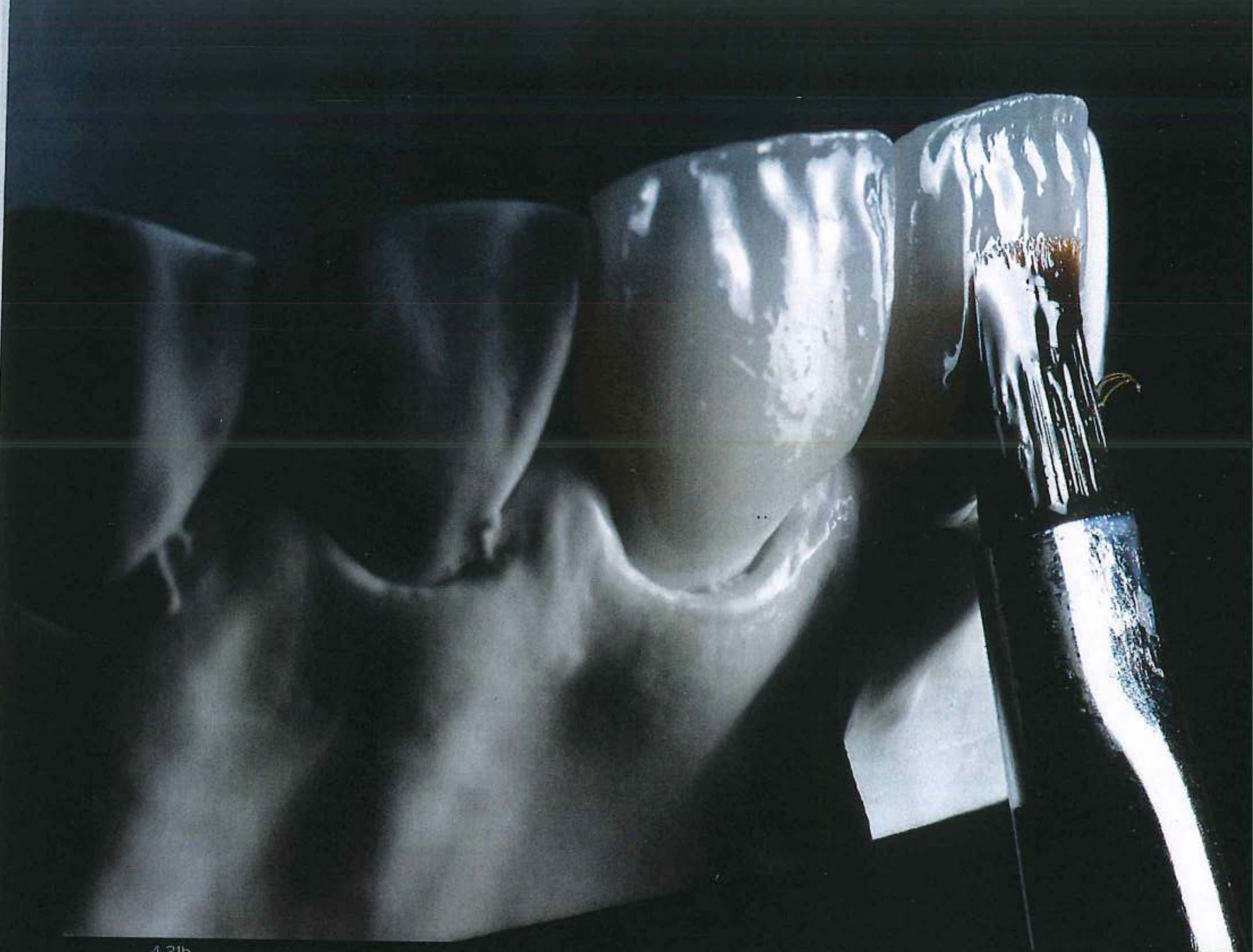
Technology meets handcrafting—3D to 4D and 5D

As is the case in other fields, some objects or parts can be produced by machines while others are made by hand. New technologies always challenge us because they are like a double-edged sword: tools that facilitate our daily life but also make us dependent. A major risk in those technologic advances is outsmarting the knowledge to the machine. A classic example is the knowledge of morphology. The CAD/CAM revolution has demonstrated the ability of machines to produce extremely accurate restorations based on natural morphologic databases. They are facilitating our work to design a new smile. But are they capable of esthetic integration as discussed in chapter 2 (see section 2.3)? Can they replace the experience, sensitivity, and intuition of the operator? Can they take into account the personality and character of the patient? ***For the time being, it seems wise to combine technology with reason, to use this sophisticated equipment to generate a foundation, which can still be subjected to handcrafting and receive the "human touch."*** The tridimensional aspect of the dental restoration work (volumes) can be mastered by machines (Fig 4-31), which will also soon be able to master the fourth dimension (histoanatomy, layers, and depth).[190–192] Technology, however, will always remain a tool.

The fifth dimension of esthetic restorations—intuition and sensitivity—still belongs to the precious senses and skills of a human being, the craftsman.

4-31a

FIG 4-31 The machine-human connection. Machines are tools to help us be more efficient and productive in generating the basic parts *(a)*, but the crafting of a skilled and experienced operator is still necessary for the final integration and natural beauty of the work *(b and c)*.



4-31b

4-31c

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