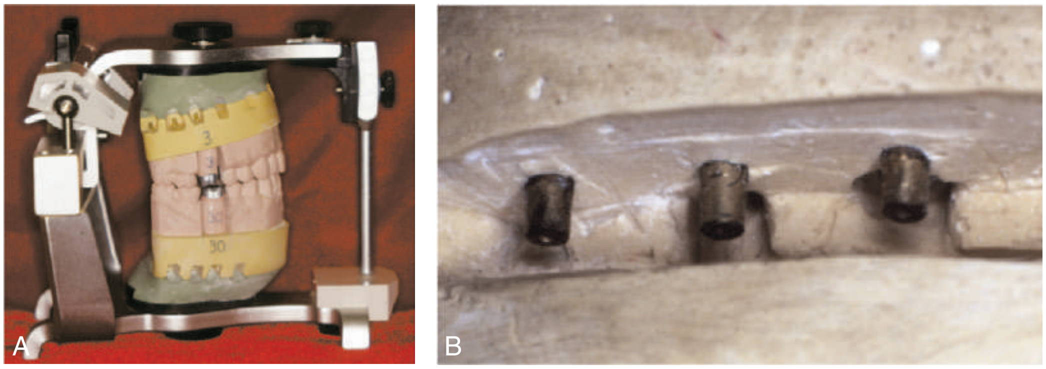

Fig. 17.26 (A) Definitive cast attached to an articulator. (B) To facilitate removal, the mounting should allow access to the end of each dowel. This is achieved by adding wax or weather stripping to the tips of the pins.

diagnostic casts can still provide much of the necessary information even when mounted slightly inaccurately, definitive casts must be mounted precisely if lengthy chairside adjustment of fabricated restorations is to be avoided.

Diagnostic casts are most useful when mounted with a centric relation (CR) record (see Chapter 2). This allows the practitioner to visualize the full range of mandibular movement for occlusal diagnosis, and on an appropriate articulator, it is possible to replicate any CR–maximum intercuspation (MI) difference that was diagnosed clinically. This enables the dentist to make appropriate decisions whether occlusal intervention is indicated before fabrication of definitive restorations (see Chapter 6).

Because of its material thickness, the CR record is made at an increased vertical dimension (see Chapter 2). Closing the articulator on removal of the record induces error if an average axis facebow is used.[32] There is a slight error even if a kinematic facebow is used.[33] Although such errors are probably not clinically significant with diagnostic casts, they are significant when definitive casts are involved because the degree of inaccuracy is transferred to restorations fabricated and adjusted on the casts. This subsequently translates into the necessity for additional chair time at the evaluation and clinical delivery appointment. Whenever possible, definitive casts should be mounted with a record made at the occlusal vertical dimension (OVD) at which the restoration will be fabricated. If possible, the MI of unprepared teeth should be used.[34] This eliminates any arcing movement of the casts once the record is removed without resulting inaccuracy in the static occluded position. If this is not possible, a kinematic facebow recording is recommended because it relates the maxillary cast in its correct position in relation to the hinge axis. Subsequent articulation of the mandibular cast with a CR record at an increased vertical dimension enables closing the articulator without introduction of error. Weinberg[35] analyzed problems associated with mounting casts with a CR record when an arbitrary facebow was used. He calculated that a 3-mm-thick record can create an occlusal discrepancy in the first molar region of 0.2 mm when the arbitrary axis differs from the true hinge axis by 5 mm (a common error).

In addition, an elastomeric (rather than an irreversible hydrocolloid) impression should be made for the opposing cast. The elastomer's improved precision results in a more accurate opposing cast, which reduces the need to adjust the restoration at evaluation.

Conformative Occlusion

On many occasions, a cast restoration is made to conform to the patient's existing occlusion, even if CR and MI positions are discrepant. Typically, if no significant signs of clinical disease are detected, fabricating simple prostheses in a stable MI position is acceptable. The objective is to maintain rather than reorganize a healthy dentition.

When a patient has symptom-free occlusion and requires relatively few restorations (i.e., when only a small part of the dentition needs to be restored), the MI position is the most desirable treatment. Therefore, in many patients who need only one or two single crowns (or a small FPD), the best restorations conform to their existing occlusion.

Articulating a definitive cast for a restoration that is to be waxed to conform to existing occlusion poses certain problems. If the cast is mounted with a CR record (as described for diagnostic casts in Chapter 2), the MI position is not reproduced accurately enough for precise waxing because it is in a translated mandibular position. This position cannot be reached with absolute precision on a semiadjustable articulator. In addition, during closing of the instrument, the stone cast can be easily abraded.

The most practical solution is to articulate the definitive cast in MI through the use of a small interocclusal record (e.g., with polyvinyl siloxane) interposed between the tooth preparation and the opposing arch in the closed position (Fig. 17.27). At evaluation, after the restoration has been fabricated, only minimal inaccuracies should exist in the occluded MI position. The patient's CR closure is examined next, to ascertain that the restoration conforms to the dynamic occlusion, specifically the slide from CR to MI. No premature contacts should occur on the new restoration. In CR closure, new occlusal interferences may have been introduced on the newly fabricated restoration, and the discrepancy between CR and MI may be effectively increased, which can lead to new problems (Fig. 17.28). It is therefore necessary to adjust the restoration to allow the original closing movement of the patient and to provide a smooth

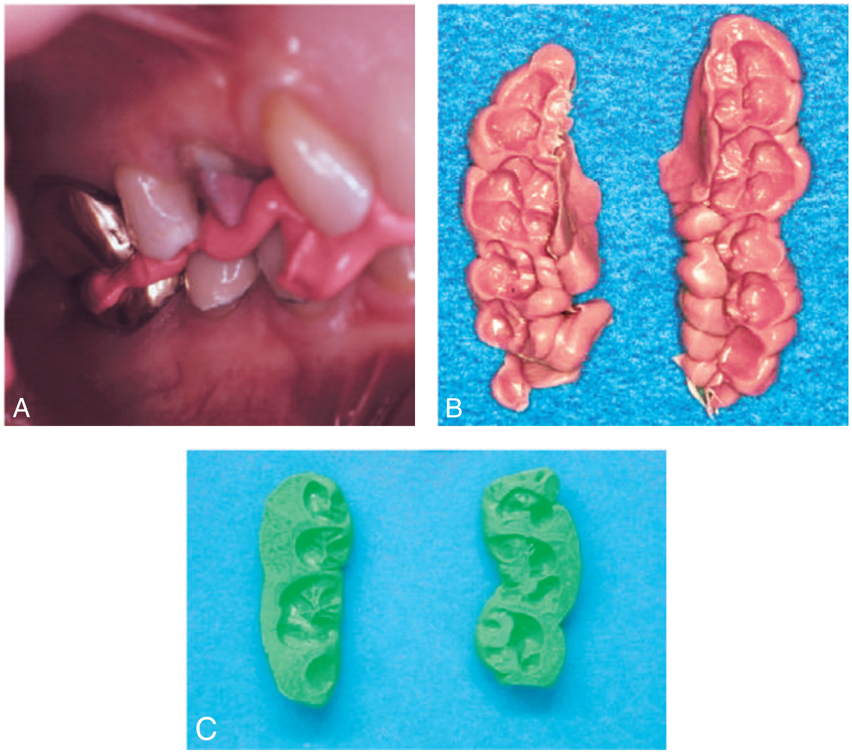

Fig. 17.27 (A) Interocclusal record made with polyvinyl siloxane polymer, conforming to the patient's existing occlusion. (B) Interocclusal records before trimming. (C) Trimmed interocclusal records.

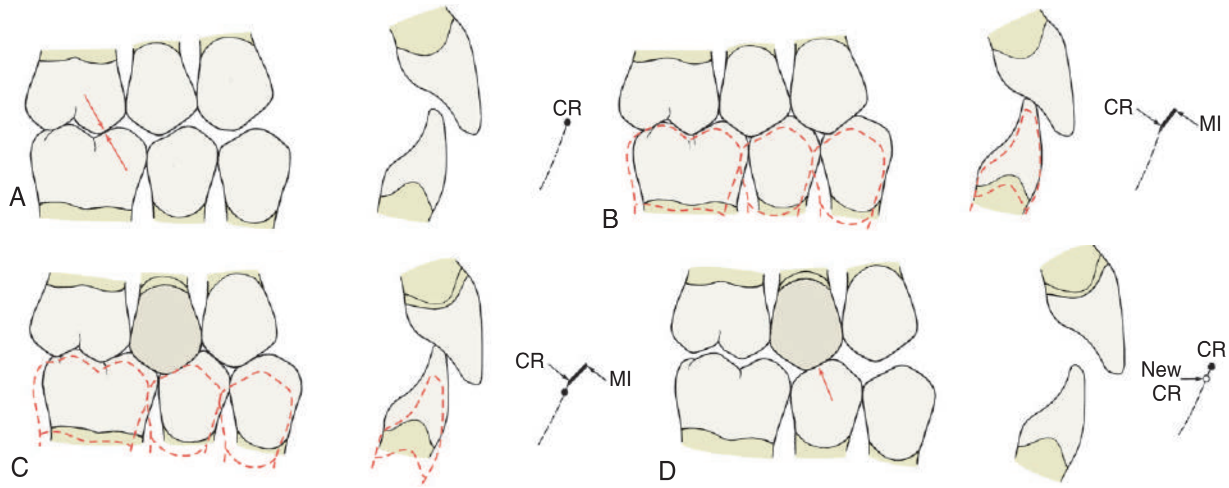

Fig. 17.28 In providing a restoration that conforms to an existing occlusion, it is important to assess both centric relation (CR) and maximum intercuspation (MI) carefully. (A) Before treatment, the CR contact is on the first molar *(arrows)*. (B) Preoperative MI. (C) The new restoration conforms to MI satisfactorily, but a new CR interference (D, *arrow*) has been created.

transition from the CO position to the MI position. After subsequent evaluation of excursive compatibility with the existing occlusion, the restoration is ready for cementation.

Reorganized Occlusion

The decision to reorganize a patient's occlusion (i.e., by making CO coincide with MI before the fabrication of the restoration begins) is made at the treatment planning stage (see Chapter 3). Treatment steps may then include occlusal adjustment of the existing dentition by selective reshaping (see Chapter 6) and reorganization of the anterior (incisal) guidance before tooth preparation for definitive cast restorations.

The following question should be asked during treatment planning: Has any discernible pathologic process arisen from malocclusion? In the presence of wear facets, widened periodontal ligament spaces, tooth mobility, elevated muscle tone, and muscle tenderness, the potential benefits of occlusal adjustment should be weighed. Two other questions must also be asked:

Will reorganization of the occlusion benefit the patient? Will it enhance the overall prognosis of the dentition? If the answers are yes, occlusal adjustment can be performed (see Chapter 6), first diagnostically on articulated casts, and then clinically, after which definitive tooth preparation for fixed prosthodontics should be initiated.

The definitive casts can then be related at the OVD with one of several techniques. Autopolymerizing resin may be used to record the relationship (Fig. 17.29). Alternative materials include impression plaster, zinc oxide–eugenol impression paste on a suitable carrier (e.g., autopolymerizing acrylic resin or gauze), and some of the stiffer elastomers (polyether or polyvinyl siloxane).

These records are optimal if they include only the cusp tips (see Fig. 17.27). If more detail of the grooves is inadvertently captured, it should be carefully trimmed away. Otherwise, the cast will not seat properly, and subsequently fabricated restorations will be in supraocclusion.

Verification of Mounting

It is essential to check the accuracy of the articulation before the laboratory phase of treatment. This is critical when prosthodontic treatment is complex (see Fig. 17.29). For less complex fixed prosthodontics, the dentist can check simply by comparing the occlusal contacts in the patient's mouth with those made by the casts. (Mylar shim stock or articulating film is suitable.) Occlusal wax (see Chapter 6) is also useful. For more extensive procedures, a second occlusal record is needed that can be compared with the first in a split-cast mounting technique (Fig. 17.30) or a system such as the Denar Vericheck (Denar Corp) (see Fig. 2.31).

TECHNIQUE FOR CLOSED-MOUTH IMPRESSIONS

The closed-mouth impression technique, also called the *dual-arch* or *triple-tray technique*, is popular for making impressions for single units and limited restorations made to conform to the existing occlusion (see Chapter 14).[36,37] Correct execution of the laboratory steps is extremely important. The procedure is different, depending on the articulator used. This description is for the V2 Quadrant Articulator (Monotrac Articulation, Fig. 17.31).

Step-by-Step Procedure

1. Trim the double-sided impression flat and parallel to the occlusal plane (see Fig. 17.31A).
2. Pour the prepared tooth side of the impression and the articulator base with die stone (see Fig. 17.31B).
3. Invert the impression, and align it onto the articulator base (see Fig. 17.31C).
4. Pour the opposing side of the impression and articulator base.
5. Engage the hinge, and close the articulator (see Fig. 17.31D).
6. Once the die stone has fully set, remove the base wall formers (see Fig. 17.31E).
7. Eject the die side of the cast by grasping the cast and tapping the base (see Fig. 17.31F and G).
8. Section and trim the cast (see Fig. 17.31H and I). The individual dies can be accurately returned to the articulator.

Digital Applications in Fixed Prosthodontics

Development of digital dentistry has rapidly increased since the successful introduction of digital techniques for collecting and processing information obtained from the oral cavity for designing and manufacturing dental restorations. Intraoral scanners and desktop scanners have played a significant role in these advancements. Using scanners, a 3D image is obtained in standard tessellation language (STL) file format, which is defined as a digital file used in stereolithographic display and printing; the 3D image surface is interpreted by a series of triangles (Fig. 17.32).[38] The collection of these triangles results in a model/digital cast that represent the scanned object, i.e., the oral cavity, tooth preparation, impression, or cast (Fig. 17.33). Once the STL file is obtained, the computer-aided design (CAD) and computer-aided manufacturing (CAM) process begins through one of the numerous software programs that are available in the market (Fig. 17.34).

Scanning accuracy. For diagnostic purposes intraoral scanning and desktop scanning are an acceptable alternative to the conventional analog workflow (Figs. 17.35 and 17.36).[39] Intraoral scanners are also comparable in terms of accuracy and reproducibility to analog workflow for complete coverage restorations.[40] However, intraoral scanners currently do not provide the same level of accuracy as conventional analog workflow for complete-arch fixed restorations.[41] In regard to implant impression, conventional impressions with impression copings are still considered the standard. However, intraoral scanning with a scan body attached to the implant can be an acceptable alternative for single implant crowns and short span FPDs.[42] However, 3D-printed casts for more complex implant-supported prostheses have been reported to have inferior accuracy compared with conventional stone casts.[43]

Step-by-step procedure to create digital definitive cast and die. When utilizing digital workflows (Fig. 17.37) for fabrication of casts and dies, multiple options exist that can be used which may vary among manufacturers. A general step-by-step digital workflow is provided:

1. Obtain an STL file through intraoral or cast scan
2. Import the STL file to a design software program
3. Follow manufacturer instructions for the digital workflow; these might include:
   a. Creating the base of the cast
   b. Outlining the tooth preparation margin
   c. Determining path of insertion
   d. Exporting CAM files for the cast and die in STL format or continue with design of restoration thereby eliminating need for printing.
4. Use exported files to print casts with 3D printer in suitable resin material
5. Follow 3D printer manufacturer instructions for post printing processing

Fig. 17.29 Mounting definitive casts on the articulator. (A) When extensive fixed prosthodontic care is necessary, accuracy of the articulation is essential for successful treatment. (B) Recording centric relation (CR) at the occlusal vertical dimension minimizes the error inherent in a facebow transfer. Autopolymerizing acrylic resin was used as the recording medium. (C) Manipulation of the mandible into CR. (D and E) Definitive casts articulated with the CR record interposed. (F–J) Restorations waxed to anatomic contour, with anterior guidance.

Fig. 17.29 Cont'd (K–M) Metal-ceramic restorations on the definitive cast. (N–R) The completed restorations (see Chapter 31).

Fig. 17.30 (A) Magna-Split system. In this system, indexed magnetic plastic mounting plates (A) are used to facilitate split-cast mounting (B and C). (D–F) The system is used to attach the maxillary cast. The second record is confirmed if the indices align precisely. (Courtesy Panadent Corporation, Colton, California.)

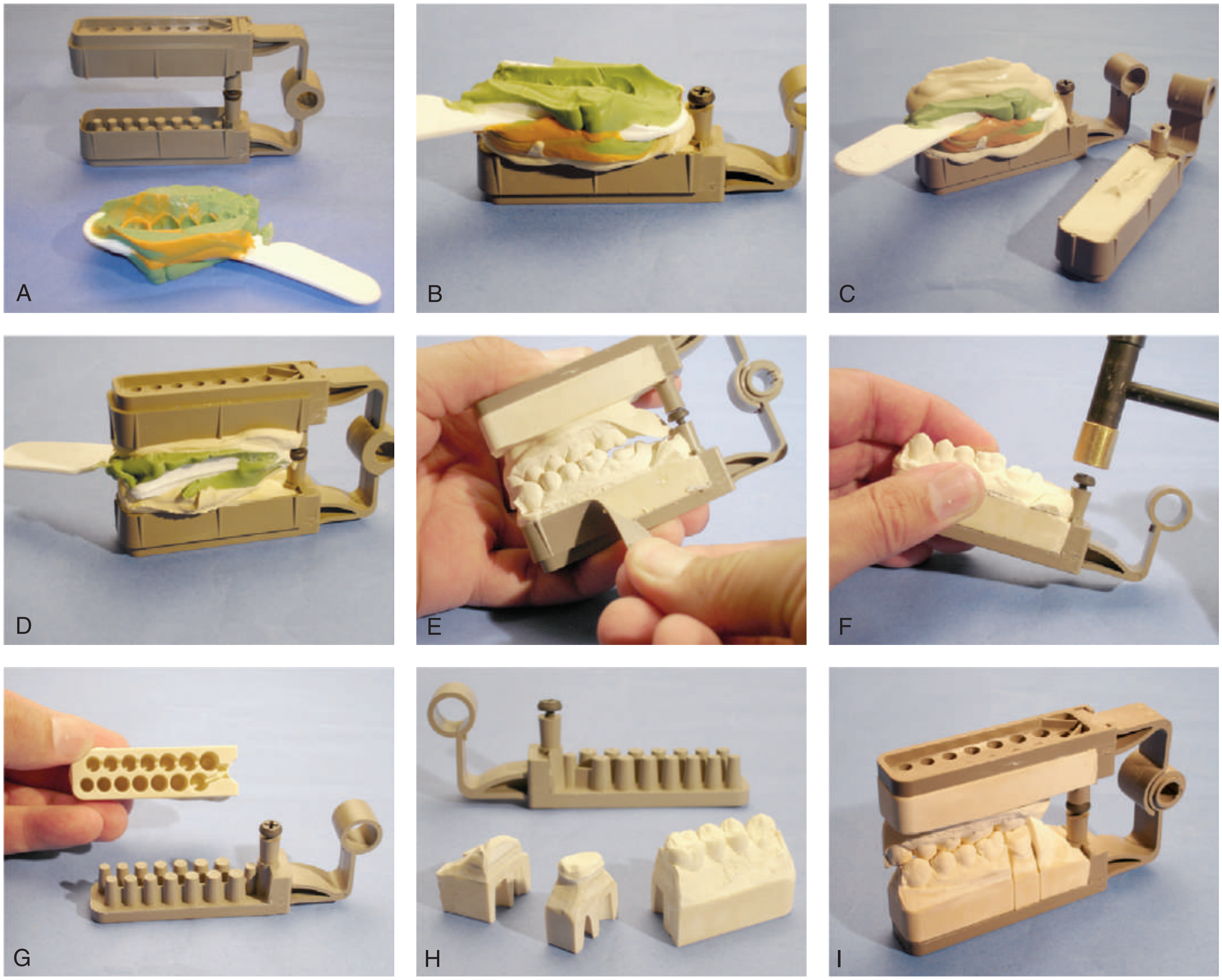

Fig. 17.31 The closed-mouth impression technique using the V2 Quadrant Articulator. (A) Trim the double-sided impression flat and parallel to the occlusal plane. (B) Pour the prepared tooth side of the impression and the articulator base with die stone. (C) Invert the impression, and align it onto the articulator base. (D) Pour the opposing side of the impression and articulator base. Engage the hinge, and close the articulator. (E) Once the die stone has fully set, remove the base wall formers. (F and G) Eject the die side of the cast by grasping the cast and tapping the base. (H and I) Section and trim the cast. The individual dies can be accurately returned to the articulator. (Courtesy Monotrac Articulation, Salt Lake City, Utah.)

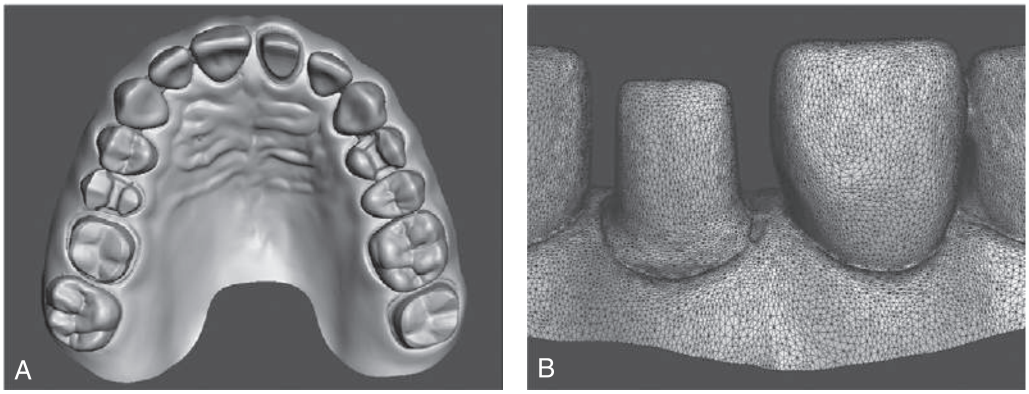

Fig. 17.32 Example of screenshots of standard tessellation language files. (A) Complete maxillary arch, occlusal view. (B) Close-up of preparation on central incisor .

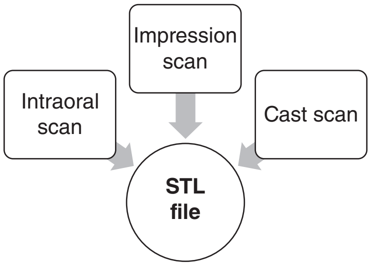

Fig. 17.33 Sources for obtaining standard tessellation language (STL) files.

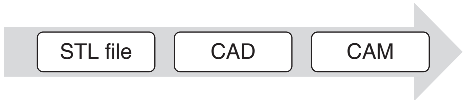

Fig. 17.34 Sequence of digital workflow. *CAD*, Computer-aided design; *CAM*, computer-aided manufacturing; *STL*, standard tessellation language.

Fig. 17.35 Examples of intraoral scanners. (A) 3Shape TRIOS 4, (B) Medit i700 Intraoral Scanner. (A, Courtesy of 3Shape A/S, Copenhagen, Denmark; B, Courtesy of Medit, Seoul, Republic of Korea.)

Fig. 17.36 Examples of desktop scanners. (A) E4 3Shape desktop scanner, (B) Medit T710 desktop scanner, (C) EinScan Dental three-dimensional (3D) Scanner AutoScan-DS-EX Pro. (A, Courtesy of 3Shape A/S, Copenhagen, Denmark; B, Courtesy of Medit, Seoul, Republic of Korea; C, Courtesy of SHINING 3D Technology Inc. San Francisco, CA.)

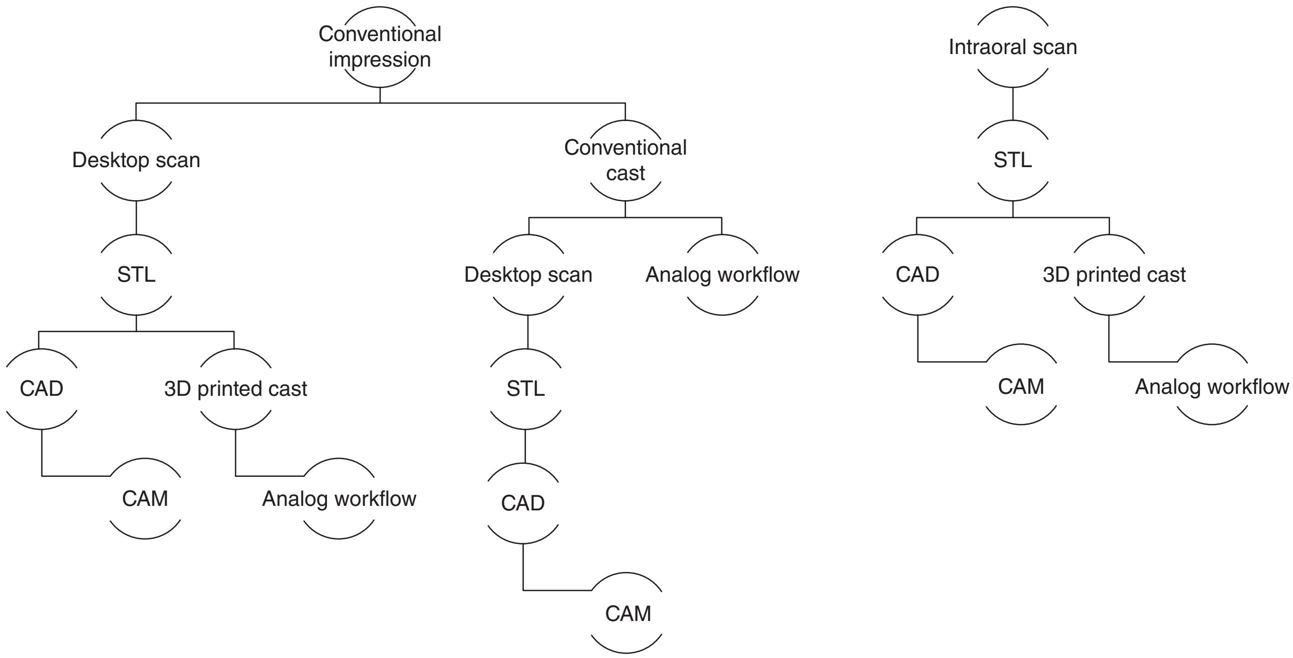

Fig. 17.37 Different pathways for digital and conventional workflows. *CAD*, Computer-aided design; *CAM*, computer-aided manufacturing; *STL*, standard tessellation language.

Digital manufacturing options. Upon completion of CAD steps and generation of CAM STL files there are two pathways for production of the definitive dental product: additive and subtractive manufacturing. In additive manufacturing, material is stacked layer by layer to develop the final 3D object, whereas in subtractive manufacturing, material is removed by power-driven machine tools until the final object shape is achieved (Table 17.3).

Additive manufacturing

Casts. Advantages of 3D-printed casts in resin material include (1) comparable or even improved accuracy, (2) reduced material weight, (3) increased density, (4) resistance to wear and damage during the restoration fabrication phase, and (5) archivable and retrievable digital data. Disadvantages include (1) learning curve associated with new CAD software programs, (2) high initial expense to procure CAD software printer, (3) impact on production time from new and different workflow needs, (4) lack of availability of printable materials for specific needs, and (5) post-processing procedures can take time and be technique sensitive (Fig. 17.38).[44]

Wax patterns. Internal fit and marginal adaptation of 3D-printed wax patterns for complete crowns have shown better results when fabricated with a recommended virtual die spacer thickness of 30 μm when compared with conventional and milled wax patterns.[45] 3D-printed wax patterns for lithium disilicate inlays showed comparable fit and marginal adaptation to conventionally fabricated wax patterns;[46] however, manual readaptation of the 3D-printed wax pattern is recommended for acceptable accuracy.[47]

Metallic structures. Selective laser melting (SLM) and selective laser sintering (SLS) are the two methods for printing metallic structures. Depending on the material, density levels can be controlled and up to 100% can be achieved with properties comparable to those from conventional casting methods.[48] When compared with the conventional lost-wax casting, advantages include reduced fabrication time and elimination of inter-operator variations.[49] In terms of corrosion resistance, 3D-printed metallic alloys exhibit similar behavior to that of conventional castable alloys.[50] Marginal adaptation of 3D-printed metallic copings is superior to that of its cast counterparts.[49,51] Also, when compared with milled implant frameworks, 3D-printed frameworks reveal less marginal discrepancy.[52]

Interim restorations. 3D-printed interim restorations offer mechanical properties that are comparable to conventional interim materials and are suitable for clinical

TABLE 17.3 Comparison Between Additive and Subtractive Manufacturing

Additive manufacturing	Subtractive manufacturing
Layers of material being added to create a 3D object	Layers of material being removed to create a 3D object
Surface finish cannot be controlled, usually leaves a rough surface	Surface finish can be controlled for a smoother finish
Finer details and small undercuts could be manufactured	Finer details and small undercuts difficult to manufacture
Generally slower process	Generally faster process
Minimal material waste	Significant material waste
Object weight can be controlled	Object weight cannot be controlled
Less operational cost	More operational cost
Less expensive	More expensive

3D, Three-dimensional.

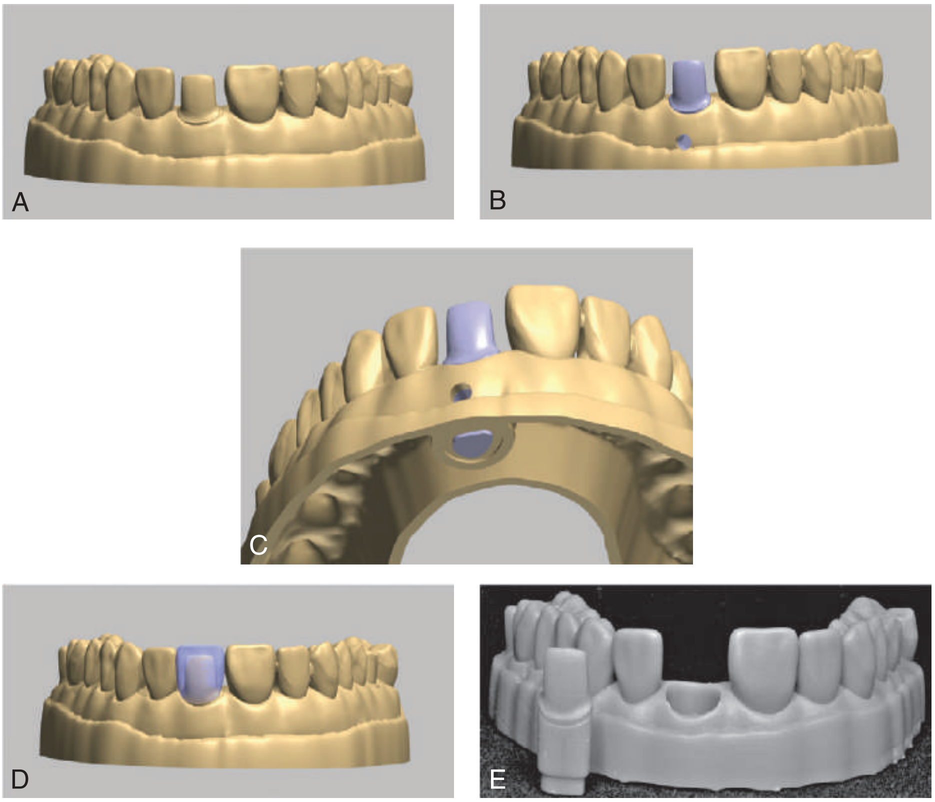

Fig. 17.38 Three-dimensional printed cast and die with crown design. (A) Printed cast resulting from intraoral scan in Fig. 17.32 (B) After manipulation, the die of the preparation of the central incisor is now separated, and the complete contour restoration is designed (C). (D) Printed solid cast and die. (E) The removable die can be pushed out of the complete arch cast from below.

application.[53] Based on an evaluation of printed polylactic acid (PLA) interim crowns, the marginal gap width was reported to be within clinically acceptable limits of 120 µm.[54] Furthermore, when compared with milled interim polymethyl methacrylate (PMMA) crowns, 3D-printed crowns demonstrate superior marginal and internal adaptation.[55] 3D-printed methacrylate oligomer interim crowns revealed better fit and marginal adaptation than conventionally polymerized interim materials.[56]

Subtractive manufacturing

Casts. Milled dental casts made using the subtractive manufacturing are less accurate than 3D-printed casts.[57] Also, milled casts with implant replicas have been shown to be less accurate compared with conventional or completely digital workflows.[58,59]

Wax patterns. For manufacturing crowns, milled castable wax patterns have been reported to be as accurate as conventionally carved wax patterns in terms of internal and marginal fit.[45] Milled wax patterns for heat pressed lithium disilicate inlays resulted in better fit and marginal adaptation than conventional and 3D-printed wax patterns.[46] Furthermore, milled castable wax pattern frameworks for implant-supported restorations were reported to be superior in fit compared with directly milled implant metal frameworks.[60]

Metal structures. Single metal copings produced through a milling process have shown superior marginal fit than copings made with a conventional casting process.[51] Also, milled FPDs and implant frameworks were reported to have higher precision of fit and superior marginal adaptation compared with those made with the conventional techniques.[61,62]

Ceramic structures. A variety of CAD-CAM ceramic materials are available; however, the selection should be based on the clinical situation and esthetic requirement. As a general guideline, there is an inverse relationship between flexural strength and esthetics when related to ceramic materials.[63] Also, physical properties of the restorative material and restoration design can affect the needed restorative clearance/space, which can range from 0.5 to 1.5 mm.[64,65]

Interim restorations. Milled interim PMMA materials are superior to conventional interim materials in terms of physical and mechanical properties and have been reported to have better color stability.[66] Also, milled interim crowns have superior marginal adaptation and fit when compared with conventional interim materials.[56,67–69]

Special consideration for tooth preparation. Basic tooth preparation principles have to be met with CAD-CAM crowns, however some modifications have been recommended to facilitate data acquisition through the scanning process, data processing in the designing software program, and manufacturing with both additive and subtractive production methods. For instance, milling machines currently have limitations with bur size, and therefore the preparation design requires modifications to enable the machine to produce an accurate restoration. In general, tooth preparations must not have any sharp angles. The recommended finish line for tooth preparations is a rounded shoulder or enhanced chamfer,[65,70,71] and recommended finish line width is at least 1 mm (Fig. 17.39).

Fig. 17.39 (A and B) Finish line width of 1 mm is needed for computer-aided manufactured restorations.

SUMMARY

Accurate definitive casts and dies are essential for the success of fixed prostheses. Various materials and techniques provide an extremely precise reproduction of the prepared teeth. Type IV stone is recommended in most instances, although careful handling is necessary to avoid chipping or abrading margins. Epoxy resin and electroplated metal (silver or copper) are durable alternatives. The die of the prepared tooth can be made removable by the use of dowels or the more convenient Pindex system. Alternatively, a solid definitive cast and separate die can be used. Whatever system is chosen, it must articulate precisely with an accurately made opposing cast. Digital technology offers a variety of solutions for prosthodontic reconstruction with a high degree of accuracy and ease of reproducibility. This can be of great advantage to the dental practitioner; however, knowledge and understanding of applicable limitations, advantages, and disadvantages for all techniques is essential to enable informed choices.

STUDY QUESTIONS

1. Discuss the material considerations for gypsum, resin, and digital die systems. List advantages, disadvantages, and typical indications for each category.
2. Contrast the advantages, disadvantages, and limitations of the following definitive cast-and-die systems:
   a. Solid cast with individual die
   b. Single brass dowel pin
   c. Pindex
   d. Di-Lok
   e. DVA
3. Discuss the Pindex system in a step-by-step manner. Identify critical steps and precautions.
4. For articulating definitive casts, which interocclusal record system results in the most accurate mounting? Why?
5. Describe how optical capture systems differ.
6. Describe current applications of virtual casts.
7. What are the advantages of 3D-printed casts?
8. What is the recommended workflow for full mouth rehabilitation cases and why?

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18

Restoration Design

Lee Culp, Contributing Author

The design of a restoration is a key factor in providing outstanding fixed prosthodontics. The design can be accomplished with the traditional lost wax process or increasingly via digital means. Independent of the process used, the fundamental principles for obtaining a biologically, mechanically, and esthetically successful prostheses remain the same. This chapter will detail both the digital and the traditional processes.

DIGITAL DESIGN

The Evolution of Digital Design

The goal when replacing any part of the natural dentition is to restore a patient to normal form, comfort, function, esthetics, and health. Accomplishing perfection in the duplication of natural teeth is the ultimate achievement in contemporary esthetic dentistry. Understanding the complex relationship between tooth form and function and how these relate and combine to create the esthetics of natural dentition is the basis of study for achieving predictable success in oral reconstruction. Over time, restorative trends and techniques have evolved. Some material developments have transformed esthetic dentistry, while other concepts have been phased out and largely forgotten.

As patients become more educated about the opportunities of contemporary dentistry, their motivation and desire for natural, esthetic restorative dentistry has increased at a dramatic rate. Dentists are now able to more predictably fulfill such demands, but not all dental laboratories and currently used restorative techniques offer predictable efficiency and quality. Digital dentistry can be used to expand the predictable aspect of restorative dentistry when replacing part or all of the natural dentition.

Digital dentistry has progressively increased, and its boundaries appear to be limitless. However, like any new technology in dentistry, it can only be successful if combined with a thorough understanding of the principles underlying comprehensive dentistry. While new technologies and digital workflows (Fig. 18.1) make procedures more efficient, less labor-intensive, and more consistent, they are no substitute for such thorough understanding, education, practical experience, and judgment.

The most exciting aspect of digital design is not merely its many potential current applications but the reality that many hypothetical applications are bringing these technologies together with the fundamentals and principles in contemporary fixed prosthodontics that evolved over many decades.

Computer-aided design and computer-aided manufacturing (CAD-CAM) is based on technology adopted from the aerospace, automotive, and even the watchmaking industries. It has been accepted because of the advantages of increased speed, accuracy, and efficiency. Contemporary CAD-CAM systems are being used to design and manufacture polymethyl methacrylate, metal, lithium disilicate, zirconia, and ceramic complete contour crowns, inlays, and veneers that may be stronger, fit better, and are often more esthetic than restorations fabricated with traditional methods (Fig. 18.2).

As dentistry continues to evolve into the digital world, the successful incorporation of computerization and future technologies will continue to provide more efficient methods of communication and fabrication while at the same time retaining the individual creativity and artistry of the skilled dentist and dental laboratory technician. The use of any new technology is enhanced by close cooperation between all members of the dentist and dental laboratory technician team. The evolution from hand waxing to digital waxing using the diagnostic waxing and interim restorations and their digital replicas to guide the creation of CAD-CAM restorations is presented here. Using these new technologies, the transition from hand to digital design, coupled with the addition of the latest developments in intraoral scanning, newly engineered materials, and additive and subtractive (printing and milling) technologies offers tremendous opportunities to enhance the close cooperation and working relationship between the dentist and dental laboratory team.

THE DIGITAL PROCESS

Digital Design and Fabrication

The introduction of CAD-CAM in dentistry began in the early 1980s.[1] The fundamental principle of this concept was to capture the image of a tooth preparation electronically and then use a software program to interpolate the information and create a digital replica of the tooth preparation. A virtual restoration design was then suggested, and after user-defined parameters were set, the restoration design would be milled from a ceramic block and seated, all in a single appointment.

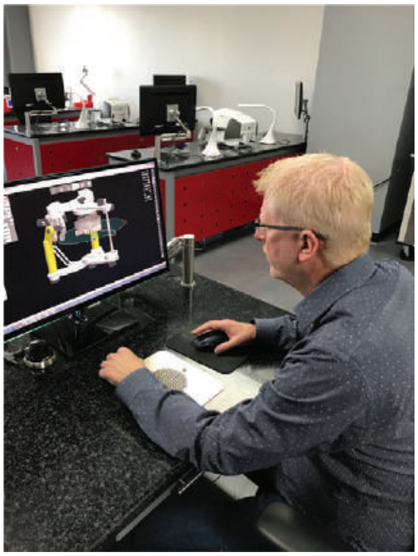
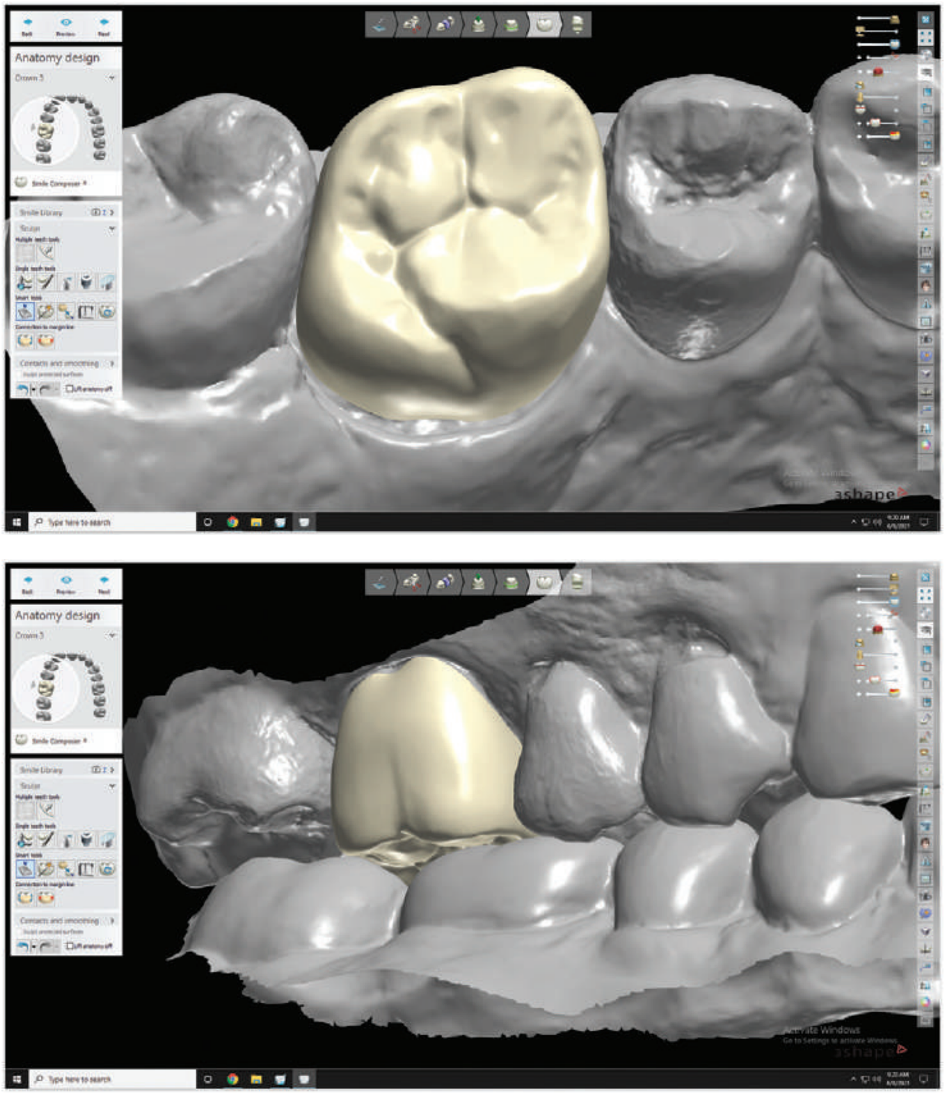


Fig. 18.1 Digital design dental laboratory technician at work on a restorative design.

Subsequent software and hardware upgrades have primarily focused on improvements on user-friendliness, accuracy, restoration complexity, and material milling options (Fig. 18.3A).

Fig. 18.2 Digital designed and milled complete-arch zirconia restoration.



A

B

Fig. 18.3 Digital design of a single posterior restoration. (A) Occlusal view. (B) Buccal view showing optimal occlusion.

The introduction of CAD-CAM dentistry, subsequent software upgrades, and the development of anatomic libraries evolved into technologies that accurately present a virtual model and may take into consideration the occlusal effect of an opposing (antagonistic) tooth. These systems essentially took complex occlusal schemes and parameters and condensed the information and display into an intuitive format that allowed anyone with basic knowledge of dental anatomy and occlusion to make dental restorations on a consistently functional basis (Fig. 18.3B).

For the dental laboratory, this technology effectively automated some of the more mechanical and labor-intensive procedures (waxing, investing, wax elimination, casting, and/or pressing) involved in the conventional fabrication of a dental restoration.

As with any conventional laboratory-prescribed restorative process, the initial steps are the same: the clinician prepares the teeth in accordance with prerequisite preparation guidelines, makes a conventional impression or an intraoral scan, and sends all relevant information to the dental laboratory technician (Fig. 18.4).

A file is created within the software program for each individual treatment. The operator inputs the patient's name, work authorization number, dentist's name, the date, the tooth numbers(s), and type of restoration to be provided (such as complete crown, veneer, inlay, onlay, or framework). Additional preferences can be set either globally for all restorations from an individual clinician or specifically based upon the individual work authorization. Options include proximal contact tightness preferred, occlusal contact strength, and the virtual die space, which defines the internal fit of the definitive restoration to the die and preparation. Once all this information has been entered, the software program can be used to search amongst the tooth database libraries to acquire the preferred tooth form (Fig. 18.5). A three-dimensional virtual cast is then presented on screen, which can be manipulated to be viewed from any perspective.

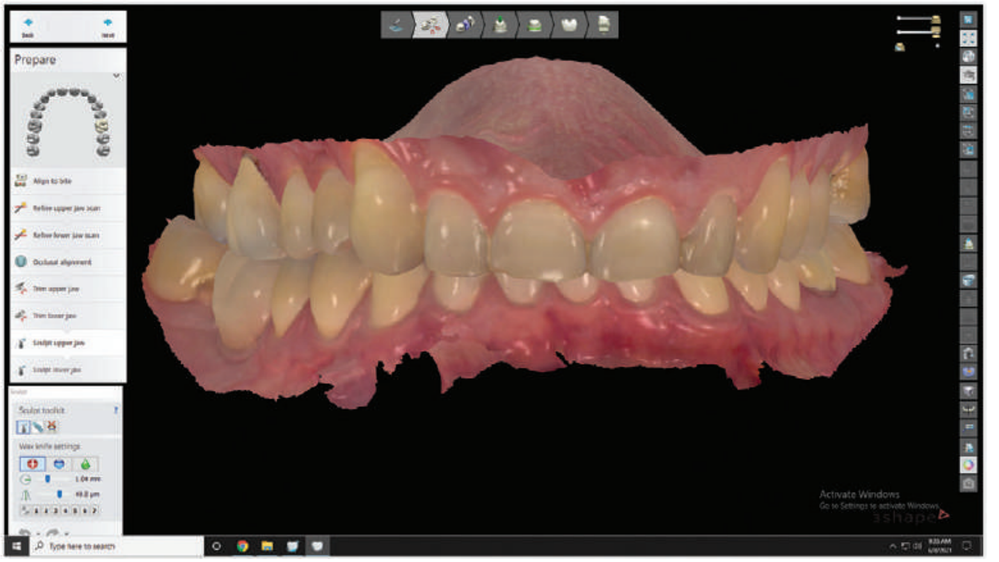


Fig. 18.4 Intraoral diagnostic scan before design and tooth preparation.

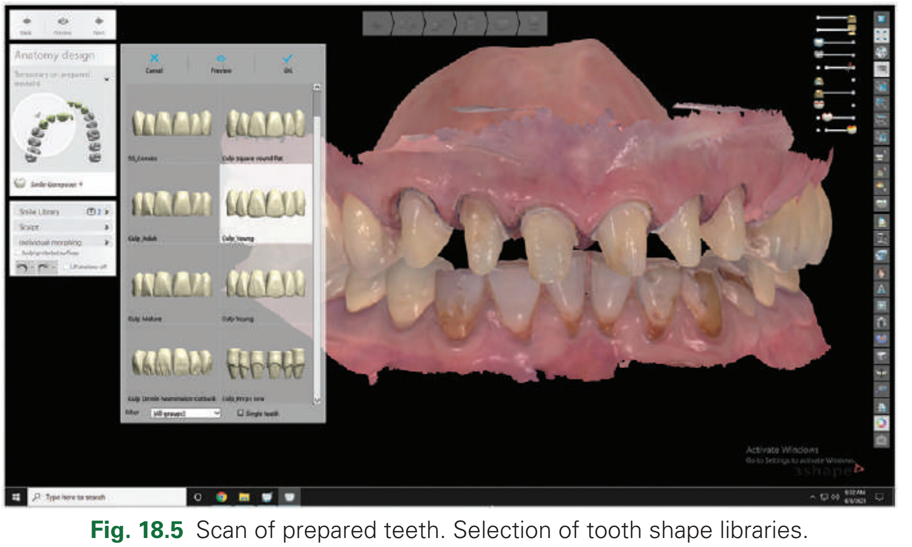


Fig. 18.5 Scan of prepared teeth. Selection of tooth shape libraries.

Digitally Designing Restorations

In recent years, dental CAD-CAM systems have transformed the process of exchanging information and records between clinicians and the dental laboratory. For example, optical scans made by using intraoral scanners (IOSs) help dentists and dental laboratory technicians analyze tooth morphology, contours, and position, as well as design the proposed restorations (Fig. 18.6). Because most dental CAD software programs feature a database of crown sizes and occlusal schemes, the ideally contoured option can be selected, positioned, and scaled to properly fit within the available space.

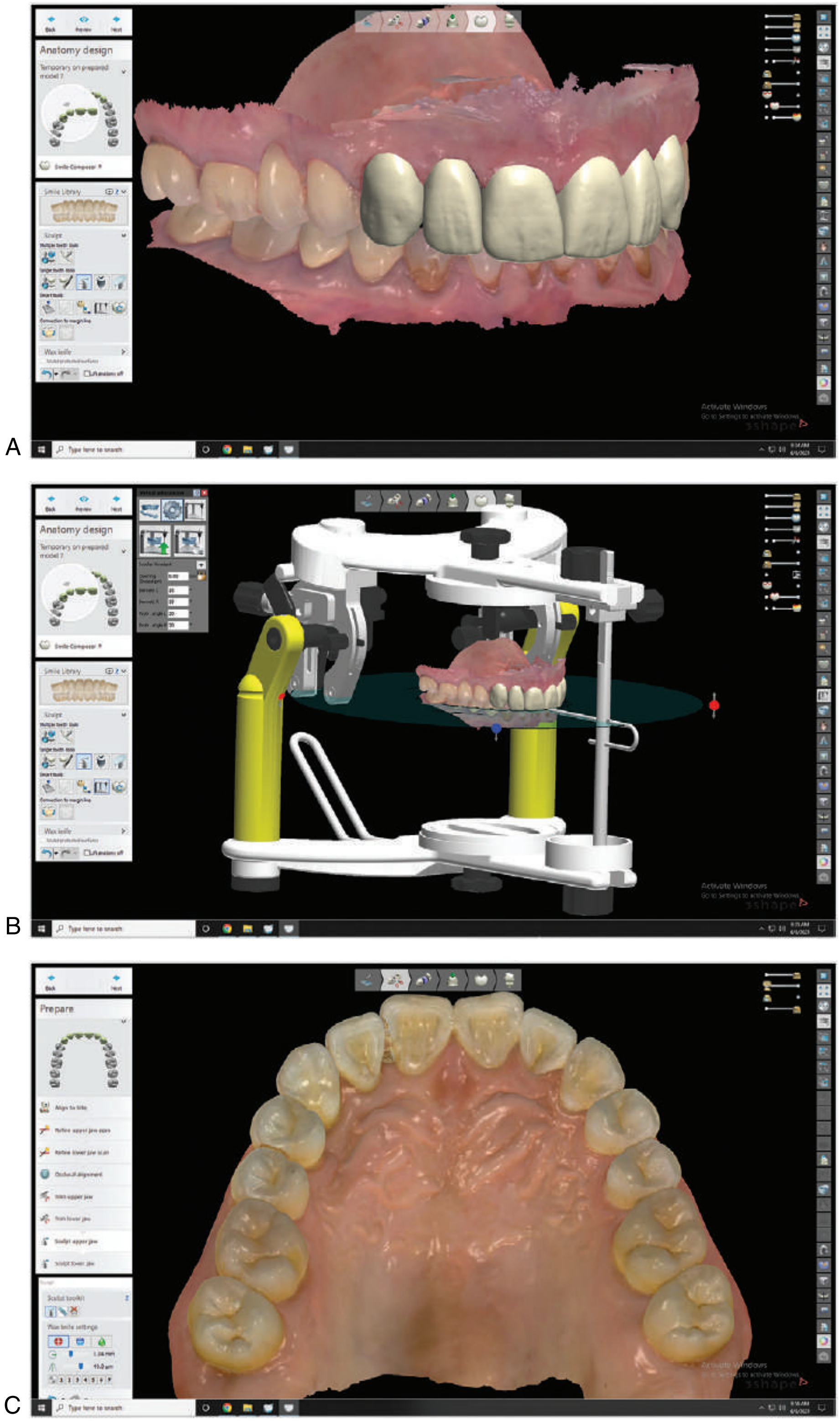


Fig. 18.6 Anterior tooth design. (A) Contours developed from tooth library. (B) Virtual articulator used to optimize design. (C) Intraoral scan of complete restorations showing natural tooth anatomy.

Despite automating the restoration design process, CAD capabilities encourage and facilitate the ability of dentists and dental laboratory technicians to exercise their creativity and judgment regarding digital manipulation of the selected occlusal anatomy, as well as other anatomical and morphological characteristics. For example, although many aspects of the CAD process are automated, it is still incumbent on the dentist or dental laboratory technician to match line angles, establish optimal emergence profiles, determine incisal edge position, and match the surface texture of adjacent teeth. Virtual tools (e.g., carvers, waxers) enable immediately visible modifications to restoration contours so occlusal preferences can be realized (Fig. 18.7).

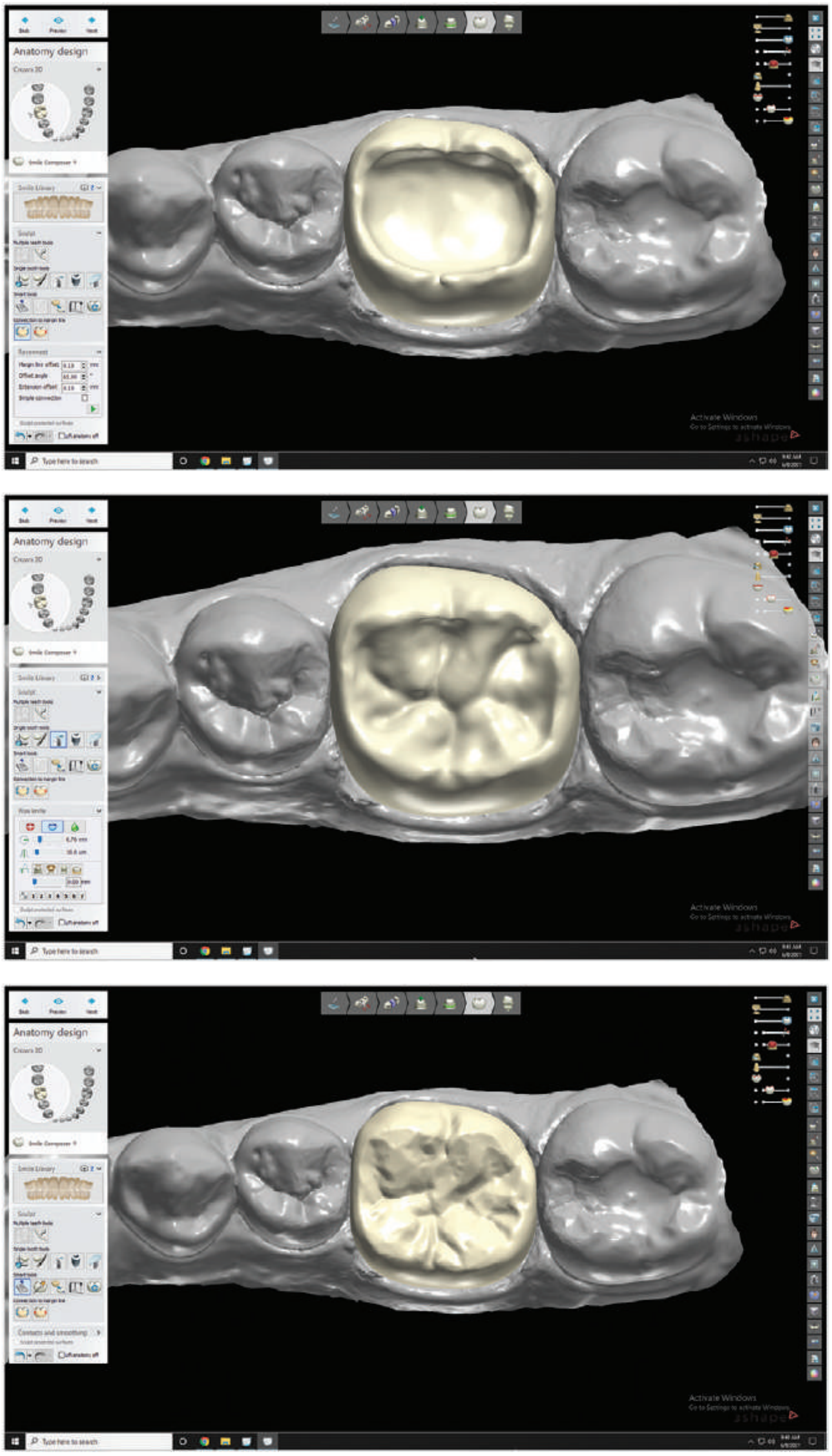


Fig. 18.7 Digital waxing a first mandibular molar. (A) Library tooth design selected with open occlusal design. (B) Digital design of occlusal anatomy. (C) Definitive digital occlusal anatomy waxing.

Thus, with today's digital CAD software programs, the analog laboratory process of hand waxing has evolved into digital waxing, and CAD processes are also enabling virtual articulation via digital occlusal registration with the opposing arch; a digital buccal scan can be made to facilitate evaluation of the interocclusal relationship. In fact, among the ways that occlusal contact can be designed in CAD-CAM restorations is to use a scanned occlusal record made from the buccal aspect using an IOS. While the patient is closed in maximum intercuspation, an IOS captures a static image of the occlusal relationship, which is then used in the CAD software program to refine the occlusal form and contact.

As a result, this process has simplified the development of occlusion—and to some degree articulation—for the dental laboratory technician.

Step 1. File Creation. A file is created within the software for each individual treatment.

The patient's name, number, dentist's name, the date and the tooth numbers(s), and type of restoration desired (complete crown, veneer, inlay, onlay, or framework) are entered (Fig. 18.8). Additional preferences are set for contact tightness preferred, occlusal contact intensity, and the virtual die (cement) spacer. Then the search among the tooth database libraries is initiated to acquire the optimal tooth form (Fig. 18.9).

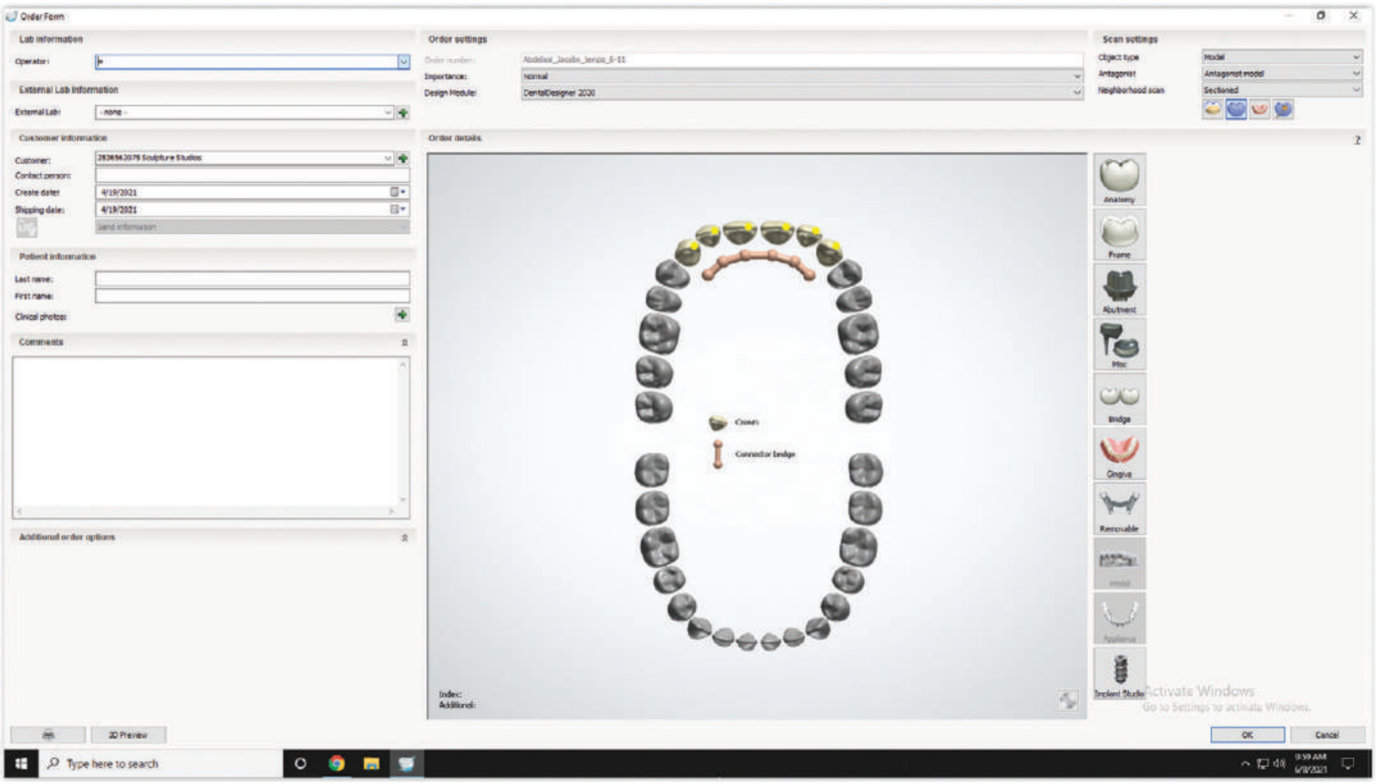


Fig. 18.8 Creating a digital work authorization.

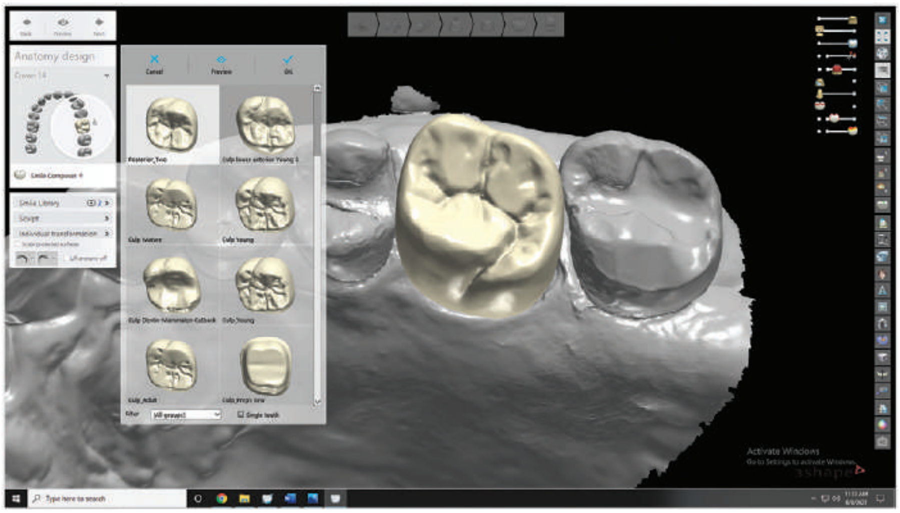


Fig. 18.9 Selection of tooth shape library from design software program.

Step 2. Scanning. Using an intraoral or desktop optical scanning device will determine how and when one will enter the digital design. With an intraoral scan, the files are directly transferred into the design program without the fabrication of stone casts. When traditional impressions are used, a laboratory desktop optical scanner can create digital files. When the scans are performed in the laboratory, the definitive stone cast with the die(s) trimmed is fabricated and scanned, a scan made of the opposing cast, and then a scan of both casts together that captures the occlusal relationship. Also, scans are made of each individual die and then related back to the virtual definitive cast (Fig. 18.10).

The computer now has all the information needed to work with the definitive cast, the preparation, and the occlusal parameters (from the image of the opposing arch).

Step 3. Virtual Model. The 3D virtual model is then displayed on screen and can be viewed from any angle (Fig. 18.11).

Step 4. Design. The first step in design of the restoration is to section the cast virtually and separate the dies. (At this stage, the virtual spacer parameters are applied depending on type of restoration to be fabricated.)

When designing dental restorations, the dentist must consider a number of tooth characteristics. For example, tooth shapes vary, with maxillary central incisors presenting either curved or straight edges, maxillary canines may demonstrate asymmetries, maxillary premolars may appear straight on their mesial aspect but slightly curved towards the distal. Therefore, designing restorations is predicated not only on knowledge of anatomic form but on careful identification of all

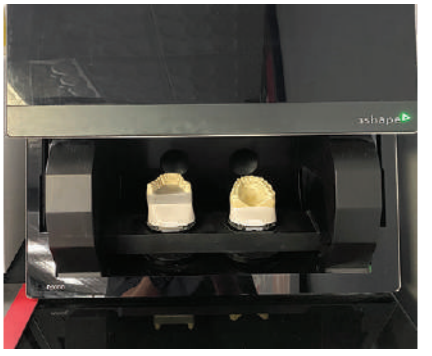


Fig. 18.10 Scanning stone casts with desktop scanner.

A

B

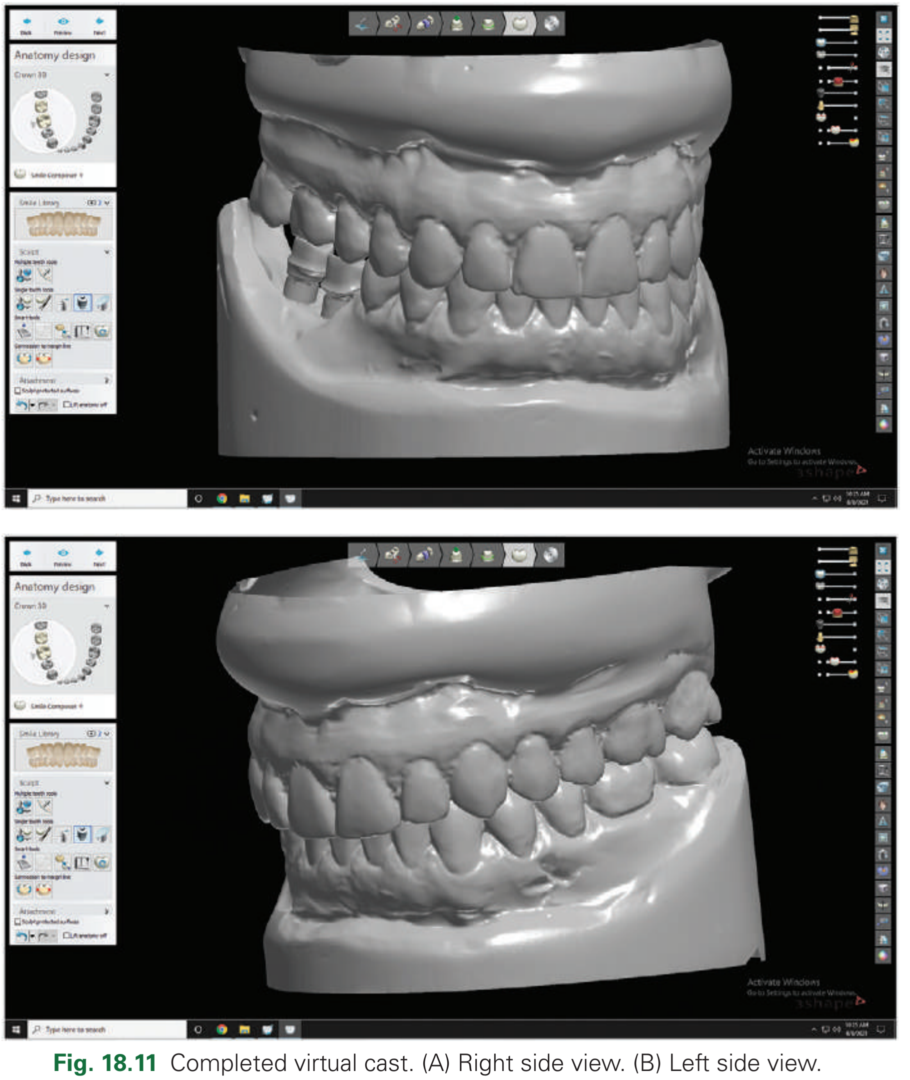


Fig. 18.11 Completed virtual cast. (A) Right side view. (B) Left side view.

aspects of variability of adjacent tooth form and an in-depth understanding of optimal contact and embrasure position and angulation.

Cloning Existing Teeth and/or Restorations

One often-used approach in digital design is to use an exact clone of an existing tooth or restoration, particularly applicable when the adjacent or contralateral tooth or restoration shade, size, form, and position provide ideal templates for the definitive restoration. Additionally, the preoperative impression, such as would be used to make the interim restoration (see Chapter 15), or a preoperative scan should be sent to the dental laboratory for scanning and the replication of axial contours. Suitable for optimizing the contours of crowns or veneers, this technique allows the CAD software program to copy an existing tooth or restoration, then use that information to design the new restoration. As a result, cloning represents a straightforward and predictable technique for designing single restorations.

To design restorations by cloning, a scan is made of the tooth to be treated, along with adjacent and/or contralateral teeth, and saved. The tooth is then prepared, and a scan of the preparation is made and saved. The scans are then evaluated on-screen. In particular, the preparation margins are clearly identified by marking them on the 3D image. Other aspects of the preparation significant to the restorations (e.g., path of insertion) can also be indicated. Then, a line can be drawn around the entire tooth to be cloned (i.e., including line angles, incisal edges, facial, and occlusal surfaces), and the CAD software program will subsequently render a restoration proposal that is an exact clone of the contours and shape of that tooth. If any surface texture or adjustments to the proposed restoration form are required, they can be completed by using CAD design tools. These tools can also be used to modify and verify proximal contacts on the virtual 3D model (Figs. 18.12 and 18.13).

Computer-aided Design Tooth Libraries

When existing natural teeth and/or restorations are not appropriate templates or clones for designing a specific restoration, digital CAD tooth shape libraries are the preferred method for digital design. These libraries have been created from scans of many natural teeth or denture teeth. These tooth libraries do not necessarily offer an efficient or predictable process since such stock scans of teeth may not optimally fit the specific needs for the restoration. Clearly, scans of denture teeth that were shaped for a specific denture tooth arrangement or digital copy of natural teeth will not always transfer optimally to a given situation and will often require further modifications to achieve esthetic and/or functional needs.

Optimal restoration form and contour need to be a balance of ideal function, in harmony with the principles of natural anatomic morphology. Artistry needs to be balanced, with predictability, efficiency, and the ability to design restorations at an efficient pace (Fig. 18.14). Digital tooth libraries also permit communication of the exact tooth form between the dentist, patient, and dental laboratory technician fabricating the definitive restoration. Advanced software programs that combine two-dimensional images with three-dimensional digital files allow the design team to create the exact preferred tooth shape in the patient's virtual mouth, allowing a very accurate preview of the definitive restorative outcome (Fig. 18.15).

Contemporary digital tooth libraries typically consist of engineered tooth forms that are a combination of denture tooth designs and natural anatomic morphology. Based on 30 years' experience of carving wax, forming dental ceramics, and designing denture teeth and digital tooth forms, the author has focused on the similarities of teeth rather than the differences. These observations were then used to create idealized tooth forms that would fit easily into a variety of restorative situations. For anterior tooth shape and arrangement, the teeth were classified into nine distinct tooth shapes. Each tooth has three planes and three shapes on its labial surfaces: convex, flat, and concave, with different tooth shapes: round on the mesial, round on the distal, square on the mesial, square on the distal, and square on the mesial and distal (Fig. 18.16).

The software program will place the restoration in the most appropriate position (based on all input), but operator experience and knowledge of form and function are needed to manually position and recontour the restoration to achieve optimal form. With a few mouse clicks, crown position and orientation can be altered as desired. Customization and artistic creativity are also possible through an array of virtual carving and waxing tools. These can be used to manipulate occlusal anatomy, contours, and occlusal preferences mimicking analog laboratory methods and armamentarium. Each step is immediately displayed on screen so the operator can see the effect of any changes (Fig. 18.17).

Digital 3D Smile Design

Smile design parameters have been well documented in other books and journal articles.[2–5] The following six-step approach to anterior digital design provides the technician and dentist a repeatable, predictable method to design, troubleshoot, and resolve any esthetic issues encountered during the final shape design, and to produce a more natural appearance for anterior restorations, regardless of the shade or material selected.

Maxillary Incisal Edge Position

Facially generated tooth positions are dependent on the vertical position and the length of the anterior teeth. Errors in incisal edge position will create catastrophic esthetic failures for a comprehensive reconstruction. A maxillary incisal edge that is incorrectly positioned too incisal will make a patient look young or toothy. When positioned incorrectly in an apical direction, one could age a patient 10 years or more (Chapters 2 and 23).

Midline

The most critical aspect in creating balance in anterior tooth form is the proper creation of the midline between the two maxillary central incisors; all other aspects of tooth form depend on the correct development and angulation of the midline. For optimal anterior esthetics, the midline does not necessarily mean the center of the face; instead, it is more important to have the midline follow the long axis of the face and that it is perpendicular to the facial horizon (Fig. 18.18).

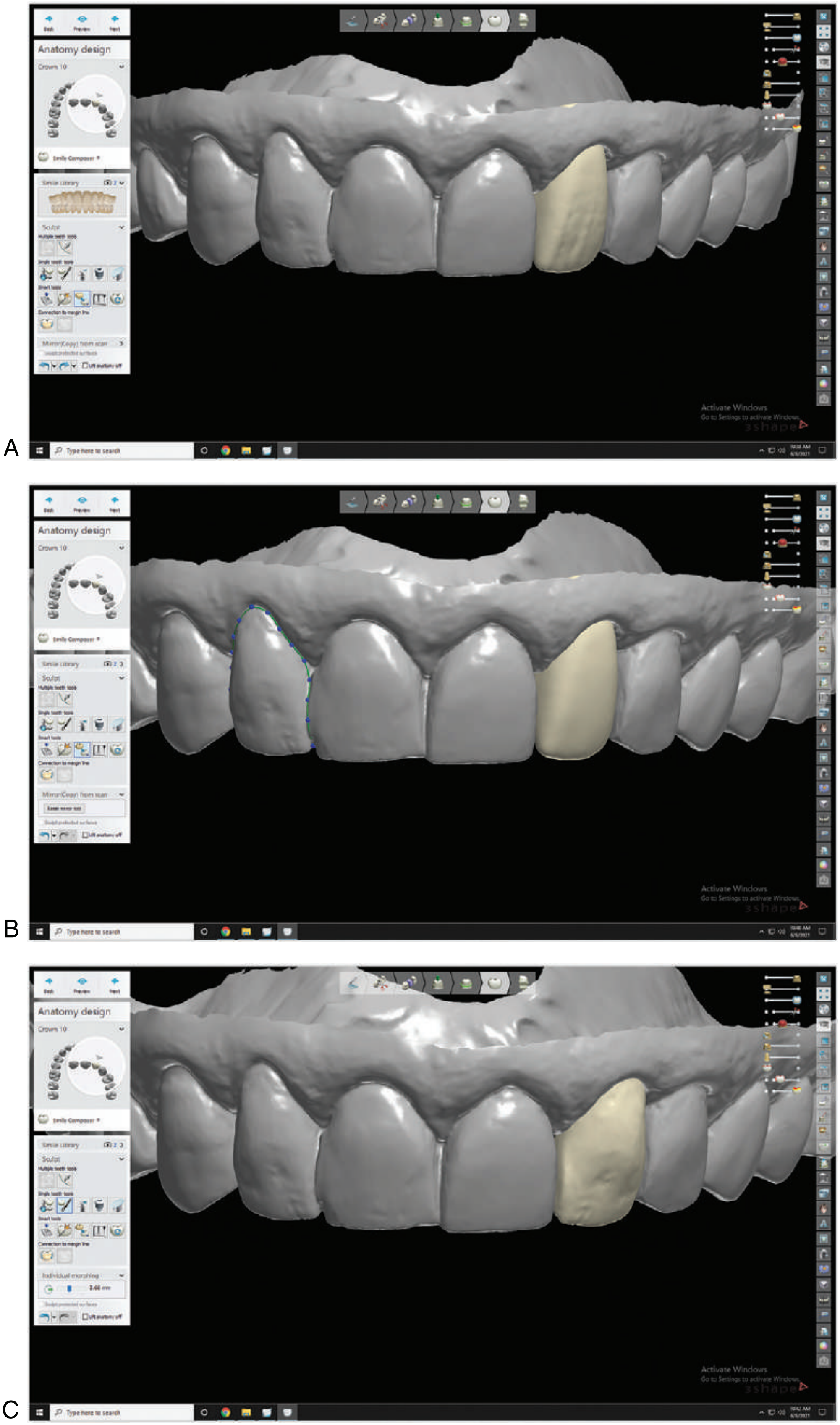


Fig. 18.12 Cloning contralateral anterior tooth. (A) Maxillary right lateral incisor will be cloned for the restoration of left lateral incisor. (B) Marking the outline of the right lateral incisor to be cloned. (C) Definitive design of cloned lateral incisor tooth, replicating mirror image of contralateral tooth.

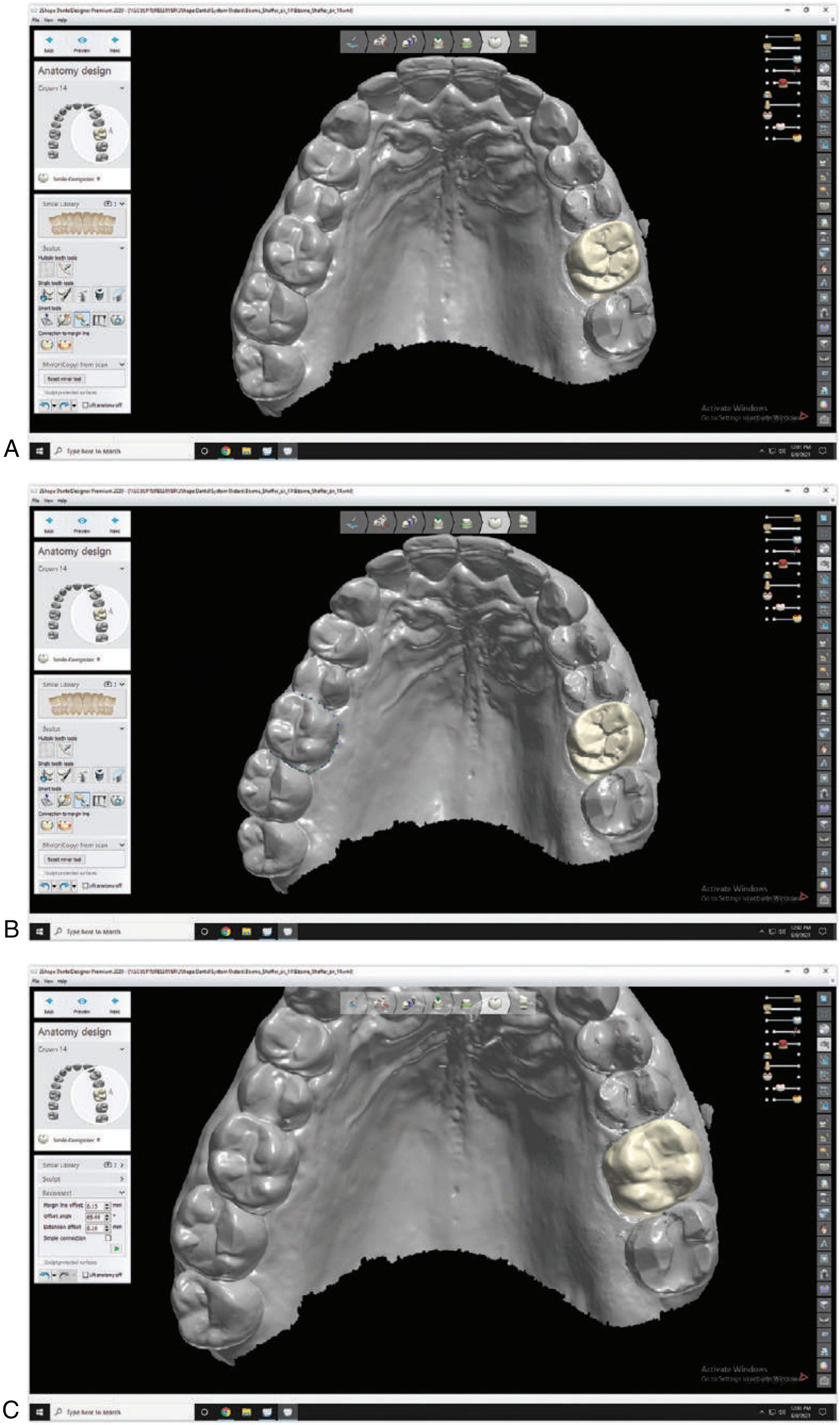


Fig. 18.13 Cloning contralateral posterior tooth. (A) Maxillary right first molar will be cloned for the restoration of left first molar. (B) Marking the outline of the right first molar to be cloned. (C) Definitive design of cloned maxillary molar, replicating mirror image of contralateral tooth.

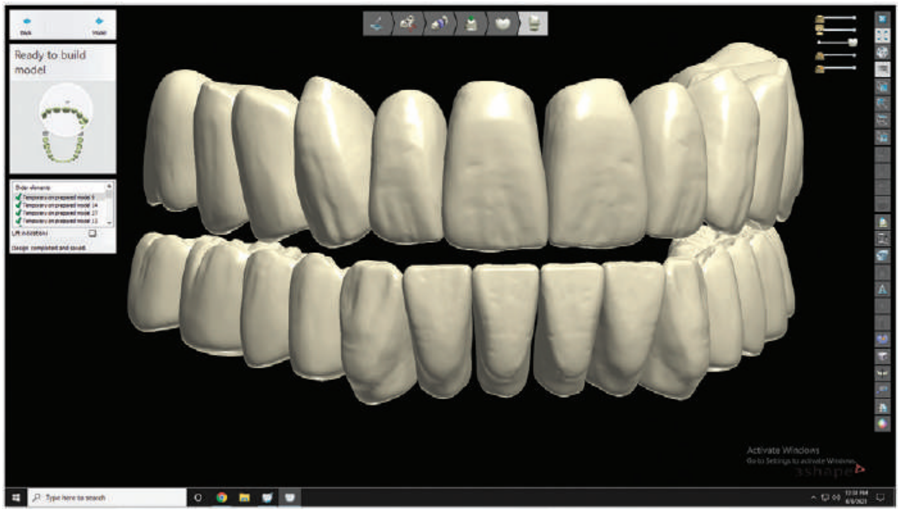


Fig. 18.14 Complete arch digital scan.

Profile—For Tooth Form

Profile is defined by the outside perimeter of the clinical crown or restoration. It is the physical, measurable distance between tissue and the desired incisal edge and the mesial and distal proximal contacts. Changes possible in the cervical half of the crown are limited because of the emergence profile that must be maintained based on tissue and bone height, root shape, root rotation, and definitive preparation margins. However, in the incisal half of the tooth, dental laboratory technicians have complete control in the development of incisal edge shape (round-square, round-round, or square-square). The three shapes, when combined with the basic facial contours of convex, flat, and concave, can be combined to create numerous shape possibilities and subtle esthetics. Tooth profile and incisal edge shape also define incisal edge embrasure form (Fig. 18.19).

Proximal Contacts and Facial Embrasure Form

Proximal contact placement helps to define facial embrasure form. Often, the contact area is placed far too facially, becoming too wide from a facial-lingual aspect, which reduces the size of the facial embrasure, causing the tooth to be perceived as being too wide. In a natural tooth, the interproximal contact rarely extends beyond the interproximal midpoint of the tooth. The proximal contacts should be placed more toward the lingual to increase the facial embrasure size, accurately replicating the natural dentition. Opening the facial embrasures between anterior teeth moves the facial height of contour slightly toward the center of the tooth. These mesial and distal heights of contour define the true facial surface of the anterior teeth. As the line angles are moved toward the center of the tooth and away from the proximal contacts, the light reflection area is reduced, and the restoration appears narrower (see also Chapter 20). Whereas profile defines the actual tooth shape and measurable size of the tooth, the proximal contact placement defines the visual perception of tooth shape. The majority of the design time (up to 80%) should be spent on ensuring compliance to these first three steps, which define the overall shape, and ultimately the acceptance of the definitive restoration by the patient (Fig. 18.20).

Primary Facial Contours

Once the location of the facial planes has been determined through the development of proximal contacts and embrasures, the primary developmental contours are placed. On a typical maxillary central incisor, there are two depression contours that follow the long axis of the tooth, one mesial and one distal. In primary plane development, the maxillary lateral incisor usually has only one dominant depression, extending from the mesial incisal edge to the mid-cervical. The distal contour is typically more convex as it contacts the canine. One of the more common mistakes in the creation of anterior tooth form is making the maxillary laterals look like miniature versions of the maxillary centrals. The maxillary lateral incisor has its own distinct shape and facial contours (Fig. 18.21).

Secondary Facial Contours

Secondary facial contours are placed primarily to subtly break up and soften the mesial and distal line angles. For the maxillary central incisors, the mesial secondary contour radiates across the junction between the middle-gingival third of the tooth. The distal secondary contour initiates from the cervical margin interproximally and passes across the distal line angle at the middle-gingival third. The secondary contour on the distal of the maxillary lateral incisor is located in the same position as on the central incisor but can be more accentuated (see Fig. 18.21).

Tertiary Facial Contours

Often described as surface texture or microcontours, these subtle contours are placed strategically across the facial surface of the tooth to create a nuance of light reflecting areas that improve the replication of the natural dentition. There are four common textures found on natural teeth, and all can be incorporated into the definitive contours of esthetic anterior restorations as necessary:

1. Broad horizontal striations;
2. Narrow horizontal striations;
3. Dimples;
4. Fine vertical striations.

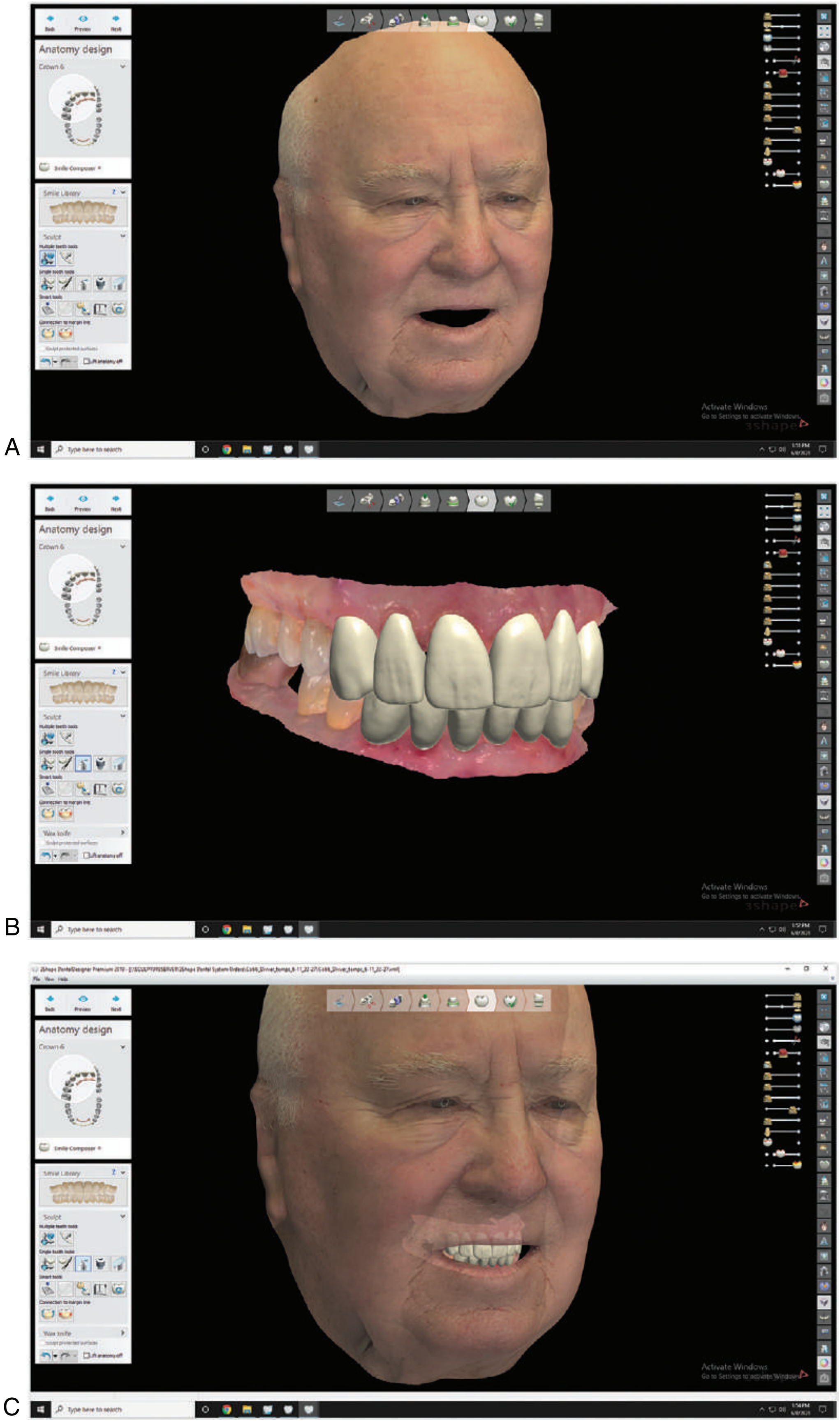


Fig. 18.15 Combining two-dimensional images with three-dimensional digital files to create a virtual mouth. (A) Digital face scan. (B) Digital tooth form design. (C) Digital face scan registered with digital tooth design.

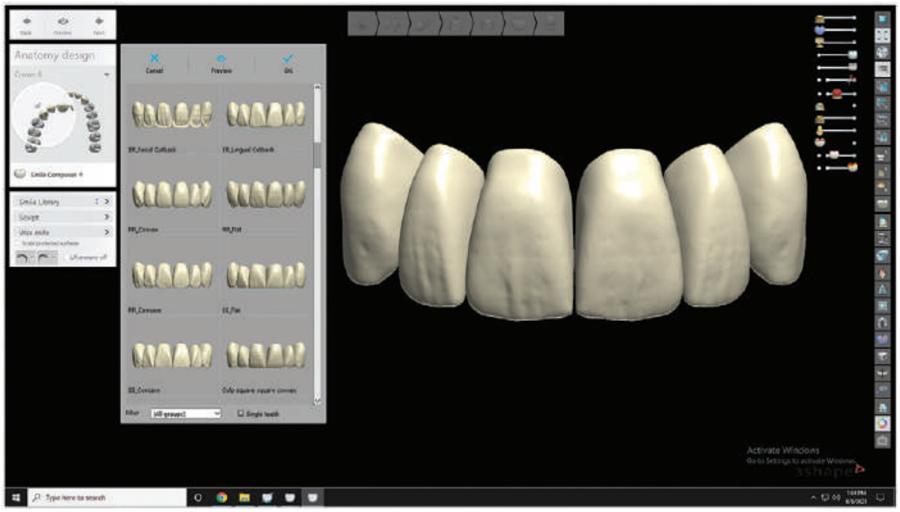


Fig. 18.16 Wide variety of tooth shapes offered in the tooth library to help ensure patient expectations are met.

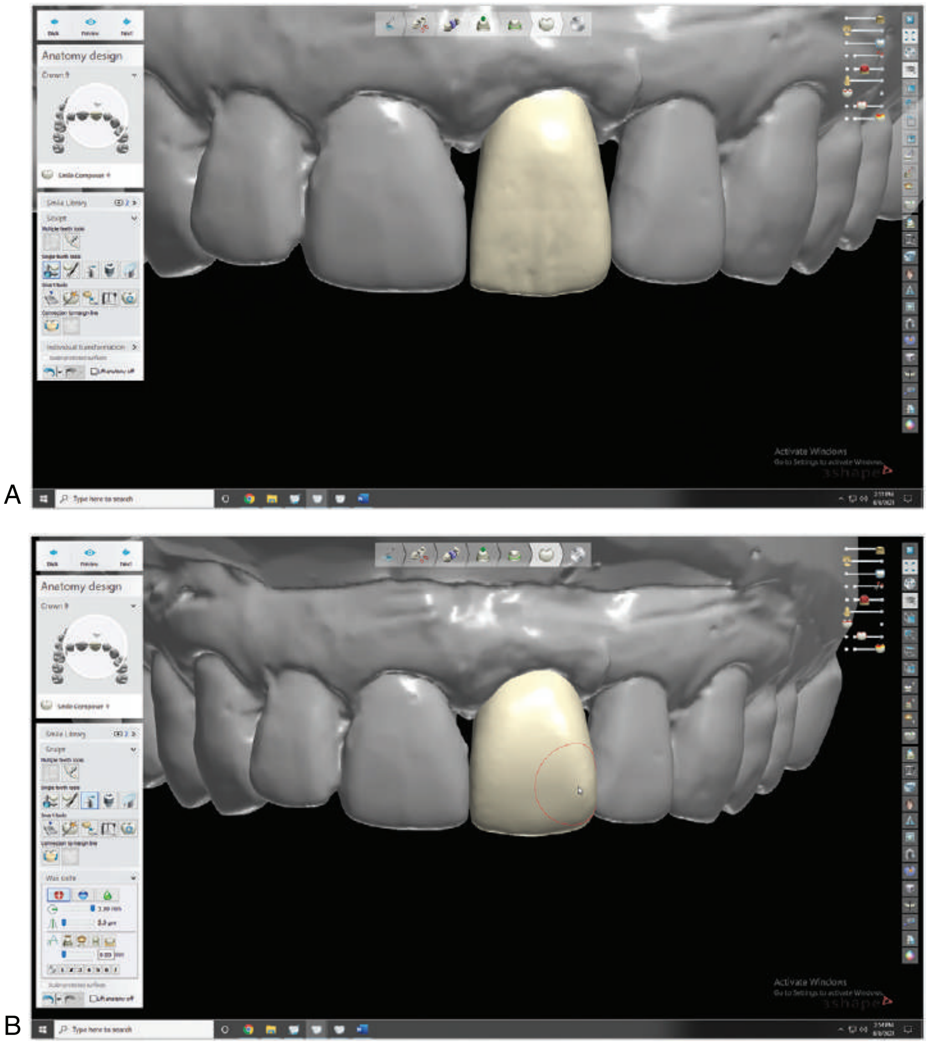


Fig. 18.17 Customizing with virtual carving and waxing tools. (A) Original tooth form from library. (B) Modified tooth shape using multiple design tools.

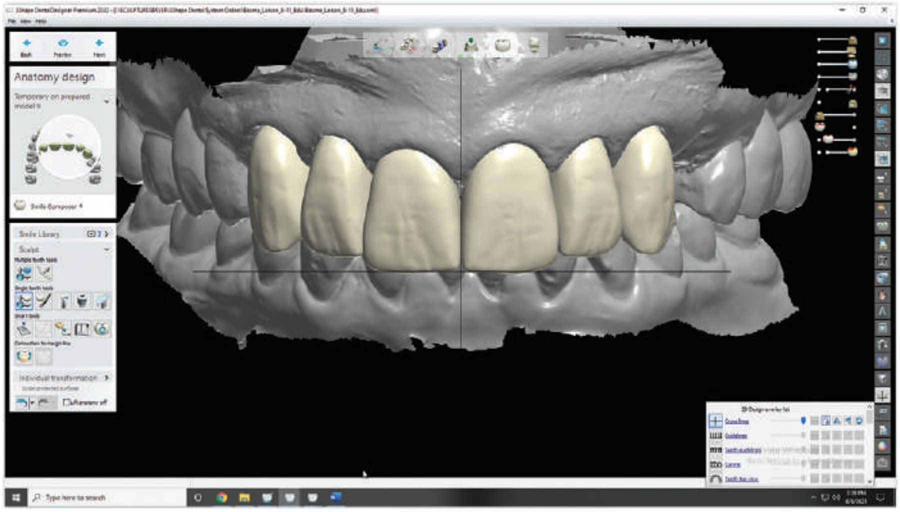


Fig. 18.18 Aligning image with midline crosshairs facilitates predictable anterior tooth arrangement.

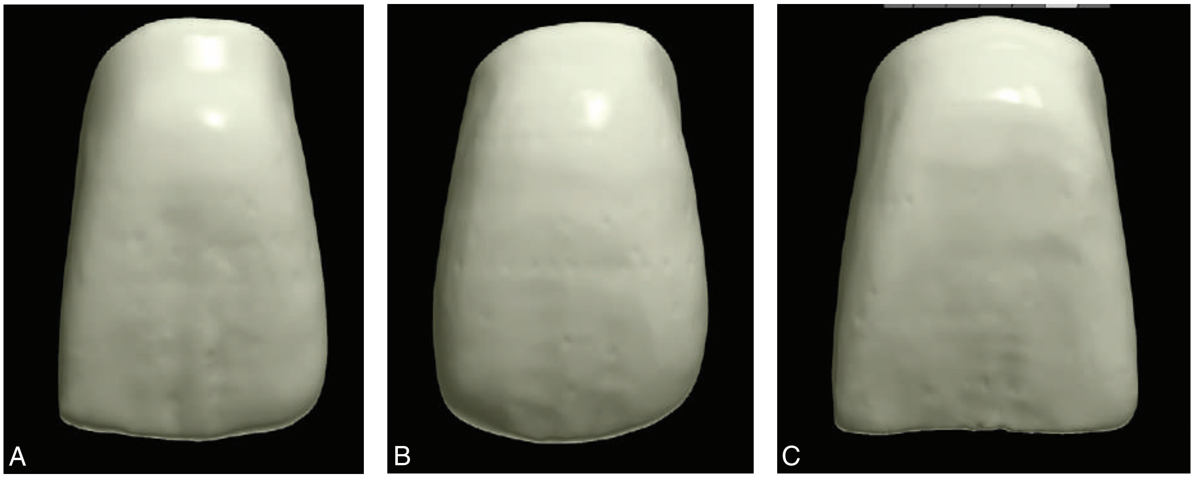


Fig. 18.19 Complete facial profile or outline of anterior tooth, showing three different profile shapes. (A) Round-square. (B) Round-round. (C) Square-square.

The severity of these irregularities depends on the age and state of the patient's existing dentition. As a general rule, a younger or especially newly erupted permanent tooth exhibits a high degree of surface roughness, whereas an older, more mature tooth, through years of function and the polishing actions of normal function, exhibits softer or even nonexistent surface effects (see Fig. 18.21).

Step 6. Occlusal Adjustment. The computer has placed the restoration in the most appropriate position (based on all input), but it is now that the operator's experience and knowledge of form and function are needed to manually position and contour the restoration to the functionally preferred shape.

The position and rotation of the crown can be altered as desired, and the software program's *Cusp Settling* application will automatically readjust each individual cusp tip, triangular ridge, the restoration's contours, contacts, and marginal ridges based on the preferences and information from the opposing arch according to the newly selected position and rotation. The virtual restoration responds and adapts all parameters immediately as they relate to the new position (Fig. 18.22).

Step 7. Occlusion Confirmation. An automated function of most software programs is that they are designed to propose fossa-point contacts on the appropriate triangular ridges. Using the virtual auto-adjustment tool, this can be easily modified to provide a different design, such as occlusal-fossa contacts with broad flat holding areas for the opposing cusp tips. The position and intensity of each contact point are graphically demonstrated, and color mapped immediately on the screen, and can be adjusted pending operator and clinical preference (Fig. 18.23).

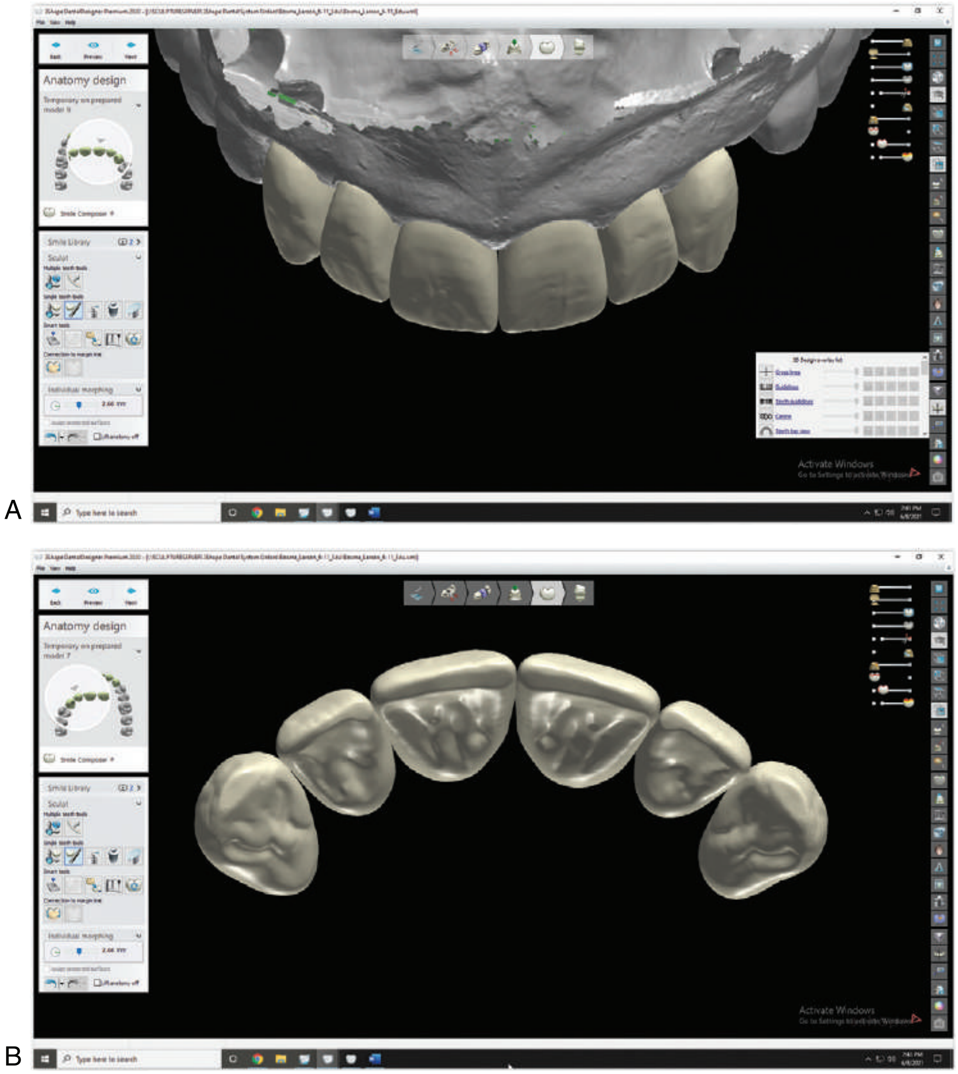


Fig. 18.20 Optimal proximal contacts. (A) Facial view. (B) Incisal view.

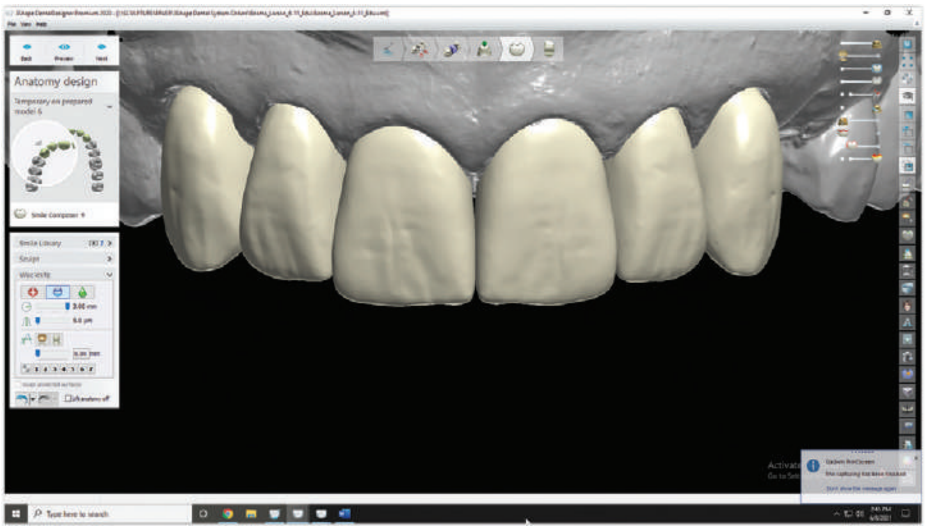


Fig. 18.21 Facial contours. Note that primary, secondary, and tertiary anatomy has been developed.

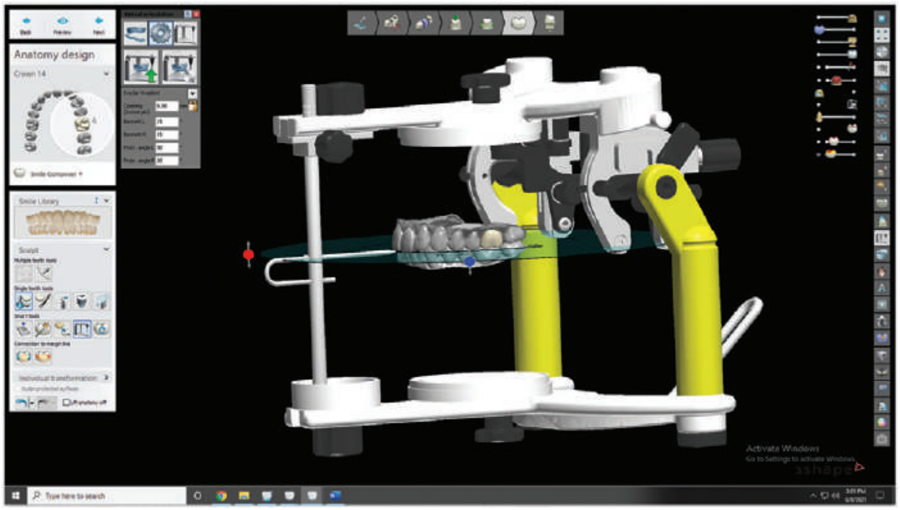


Fig. 18.22 Virtual articulated casts assist in optimizing occlusal design.

A

B

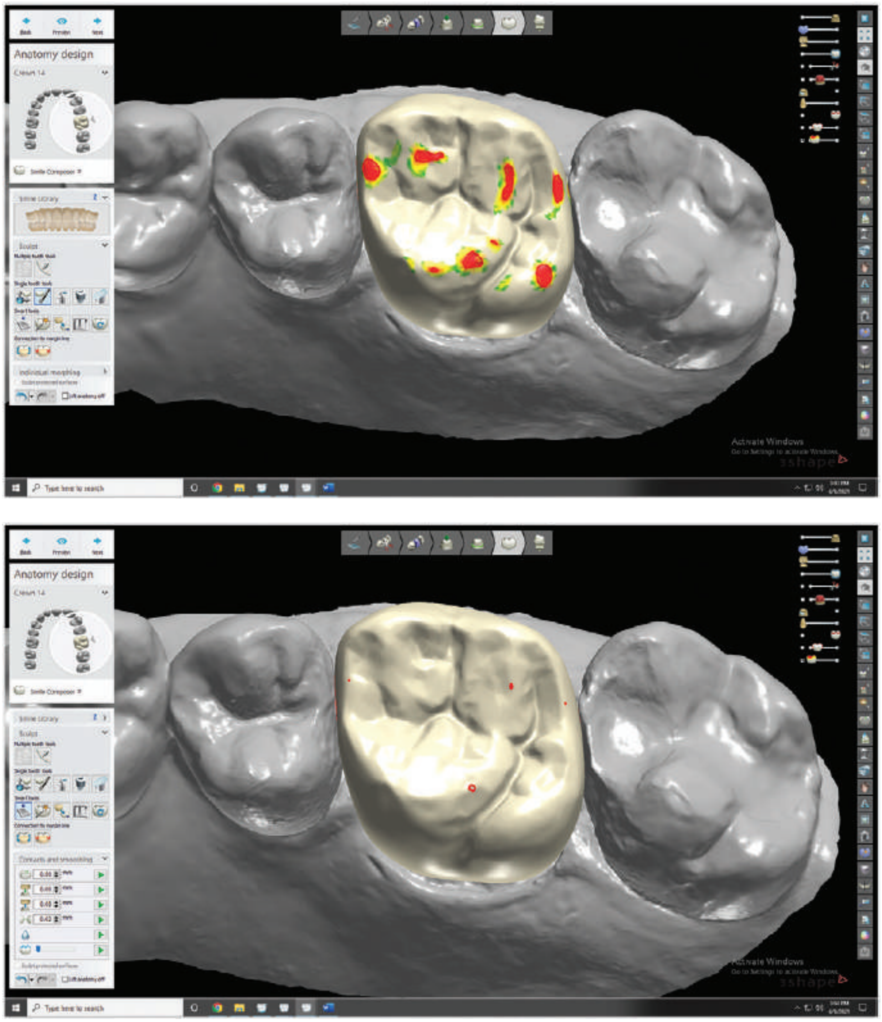


Fig. 18.23 Digital auto-adjustment of posterior restoration. (A) Before auto-adjustment. (B) After auto-adjustment.

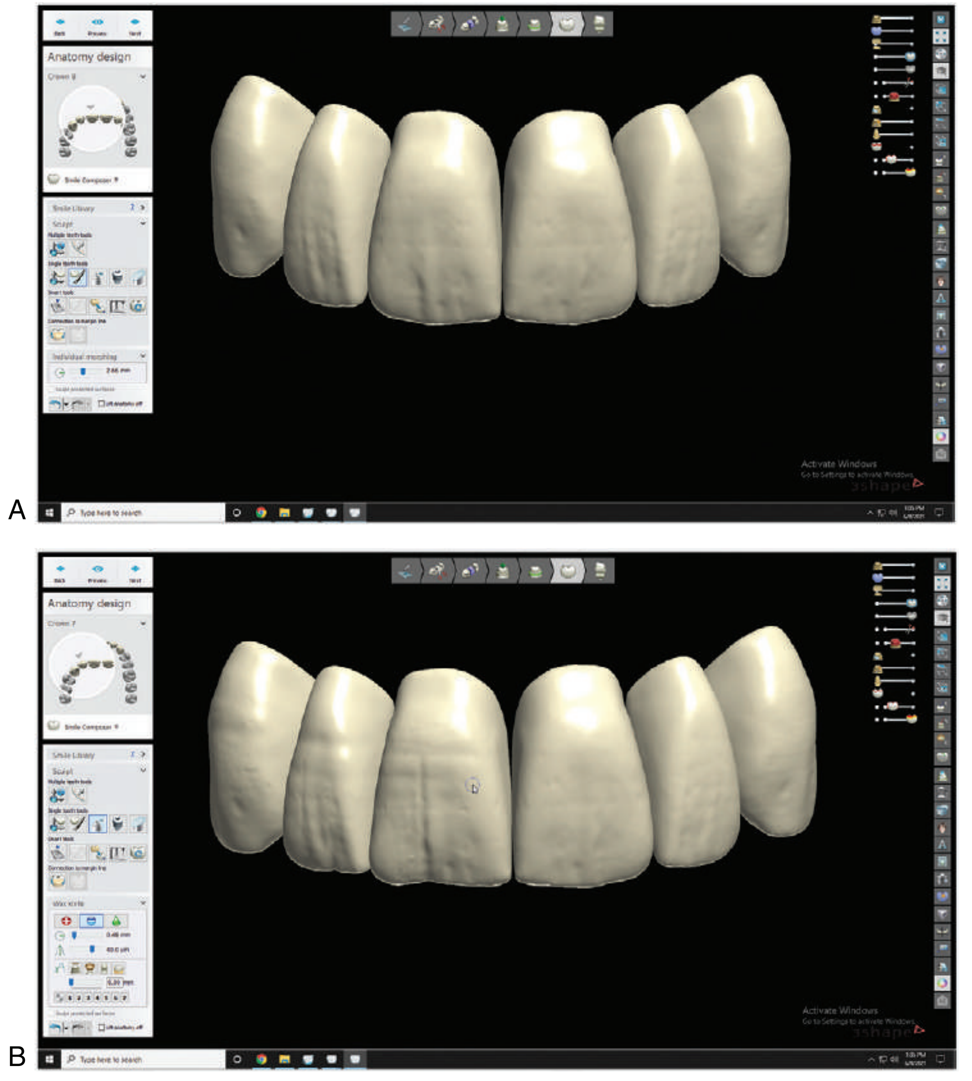


Fig. 18.24 Custom shape characterization of anterior tooth shape. (A) Before custom shape characterization. (B) After custom shape characterization.

Step 8. Anatomical Customization. Custom aspects and artistic creativity are possible through an array of virtual carving and waxing tools. These can be used to manipulate occlusal anatomy, contours, and occlusal preferences mimicking the traditional laboratory methods and armamentarium. Each step is immediately updated on the screen so the operator can see the effect of any changes (Fig. 18.24).

Step 9. Milling or Printing. Once the definitive virtual restoration has been designed, it is processed. If milling is used, a block of material of the selected shade, ceramic or composite resin, is placed in the chamber of the milling unit. The typical milling time for single ceramic crowns is approximately 15 minutes to generate a replica of the digital design (Fig. 18.25). Alternatively, especially for diagnostic purposes, the designed prosthesis can be 3D-printed in tooth-colored resin for clinical evaluation of the designed restorations with the patient (Fig. 18.26). In addition, 3D printing of definitive ceramic restorations has recently been developed.[6]

Step 10. Finishing and Polishing. The milled restoration can then be characterized conventionally using staining and glazing techniques appropriate for the ceramic selected (Fig. 18.27 and Chapter 29).

Contemporary digital dental technology can contribute to a substantial reduction of many of the tedious and time-consuming analog tasks associated with designing restorations, establishing ideal occlusal relationships, and performing occlusal adjustments and articulation. On-going improvements to dental CAD offerings will continue to streamline the digital restoration design, as well as the virtual dynamic articulation of proposed treatments.

The philosophy, technique, and procedures that have been outlined are fundamental principles of restorative dentistry. New technologies in dentistry will only be successful if they are combined with a thorough understanding of basic comprehensive dentistry. While new technology and computerization can make procedures more efficient, less labor-intensive, and more consistent, it will not replace the need for education, practical experience, and clinical and technical judgment (Fig. 18.28).

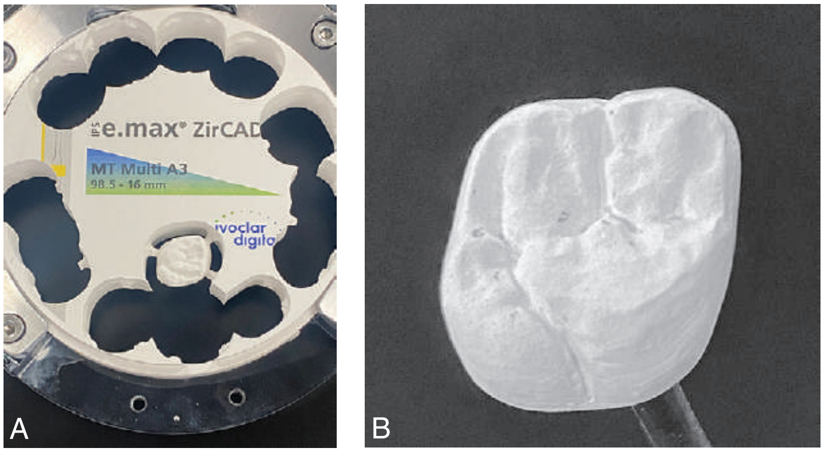


Fig. 18.25 Milling anatomical contour zirconia restoration. (A) Zirconia disk with restoration milled. (B) Anatomical contour restoration, in presintering state.

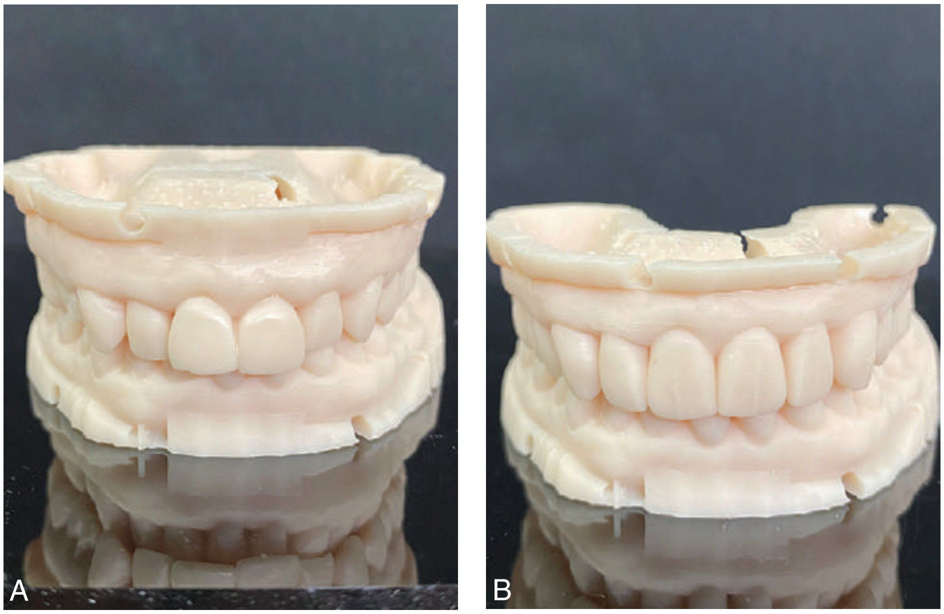


Fig. 18.26 3D Printed diagnostic design for evaluation. (A) Before diagnostic design. (B) After diagnostic design.

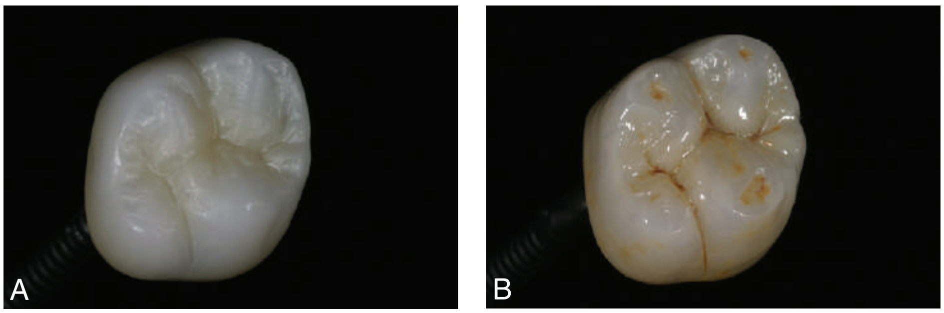


Fig. 18.27 Anatomic contour restoration. (A) After sintering. (B) After characterization.

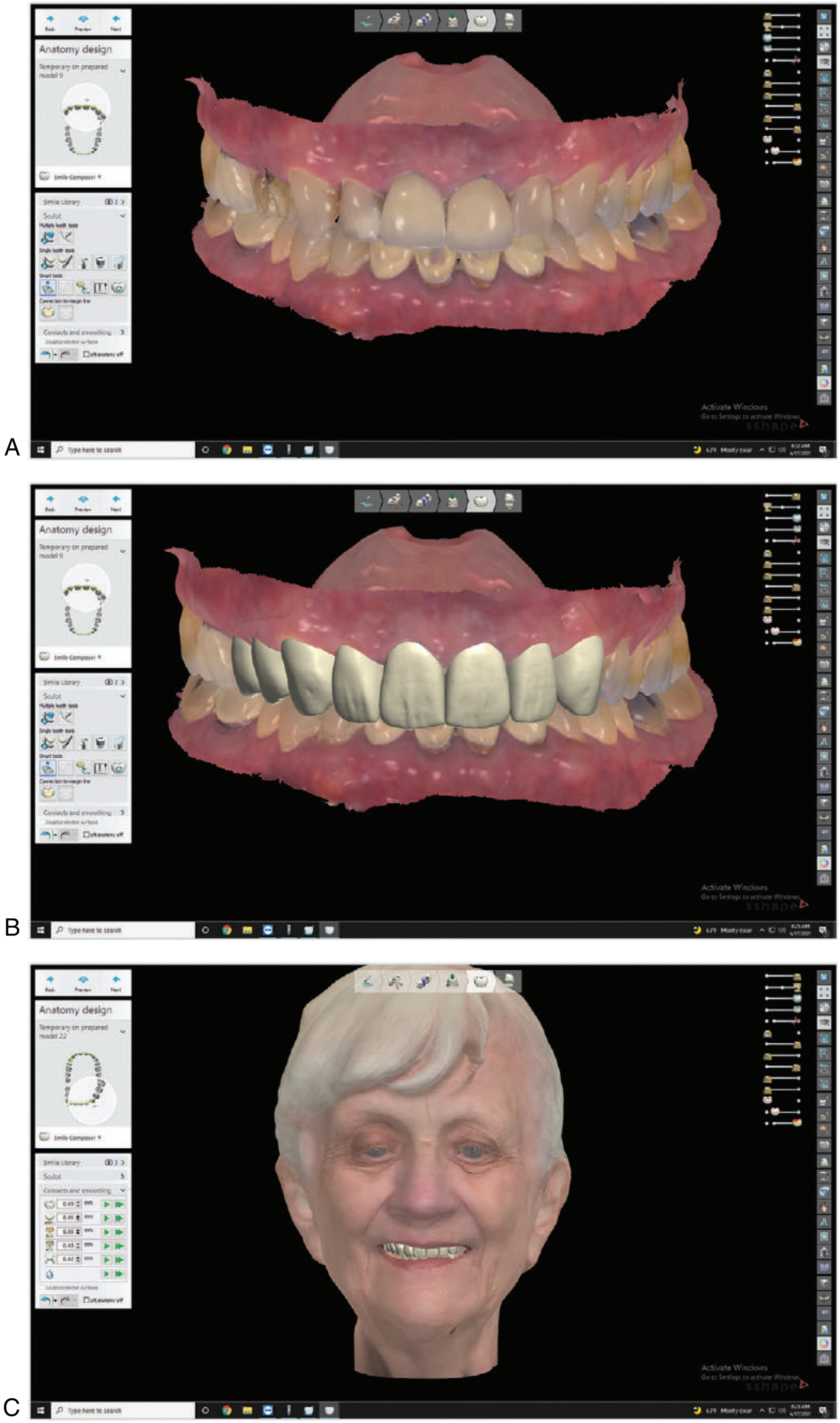


Fig. 18.28 Virtual restoration design. (A) Pretreatment scanned image. (B) Diagnostic virtual restorations. (C) Restorations evaluated in virtual patient.

TRADITIONAL RESTORATION DESIGN WITH WAX PATTERNS

Metal or pressed-ceramic fixed prostheses have traditionally been made from wax patterns, and considerable time and effort must be devoted to producing a very accurate wax pattern. From this pattern, the finished restoration is duplicated through the use of the lost-wax process as part of the indirect procedure.

The technique consists of obtaining an accurate impression of the prepared tooth (Fig. 18.29A) and making a cast from the impression (see Fig. 18.29B) on which a wax pattern resembling the shape of the definitive restoration is shaped (see Fig. 18.29C). A mold is then made around the wax pattern with a refractory investment material (see Fig. 18.29D). When the investment has set, the wax is vaporized in an electric furnace. The hollow mold is then filled with molten casting alloy, or pressed ceramic, reproducing every detail of the wax pattern (see Fig. 18.29E). The casting is retrieved, excess material is removed, and after finishing, the cast restoration is ready for clinical evaluation (see Fig. 18.29F).

If an optical capture is used (see Chapter 14), a virtual cast can be generated on which the crown can be designed (Fig. 18.30). The wax pattern can then be milled from a solid block of specially formulated wax, or it can be printed (Fig. 18.31).[7] The margins of the resulting patterns are then readapted manually to ensure optimal adaptation, invested, and cast as described previously.

As the solidifying metal (casting) cools to room temperature, it shrinks. Dimensional accuracy of the casting is achieved by balancing this shrinkage against the precisely controlled expansion of the mold (see Chapter 22). Wax is used to make the patterns because it can be conveniently manipulated and precisely shaped. With heating, it can be completely eliminated from the mold after investing.

The lost-wax technique is widely used in industrial and jewelry manufacturing. The first bronze castings reportedly were made in the third millennium BCE with beeswax and clay refractory materials. Ancient lost-wax castings such as Chinese bronzes, Egyptian deities, and Greek statues have withstood the centuries, yielding information about ancient societies and cultures. The lost-wax method may have been used in Sumer as early as the Second Early Dynastic Period (2700–2500 BCE) for figurines and even larger body parts.[8]

In the dental laboratory, *successful results depend on careful handling of the wax*. Technicians must understand that every defect or void in the wax will appear in the casting. Most defects can be corrected easily in wax but not in a metal casting. Compensating for an error in waxing technique is typically impossible once the metal casting has been formed. Careful

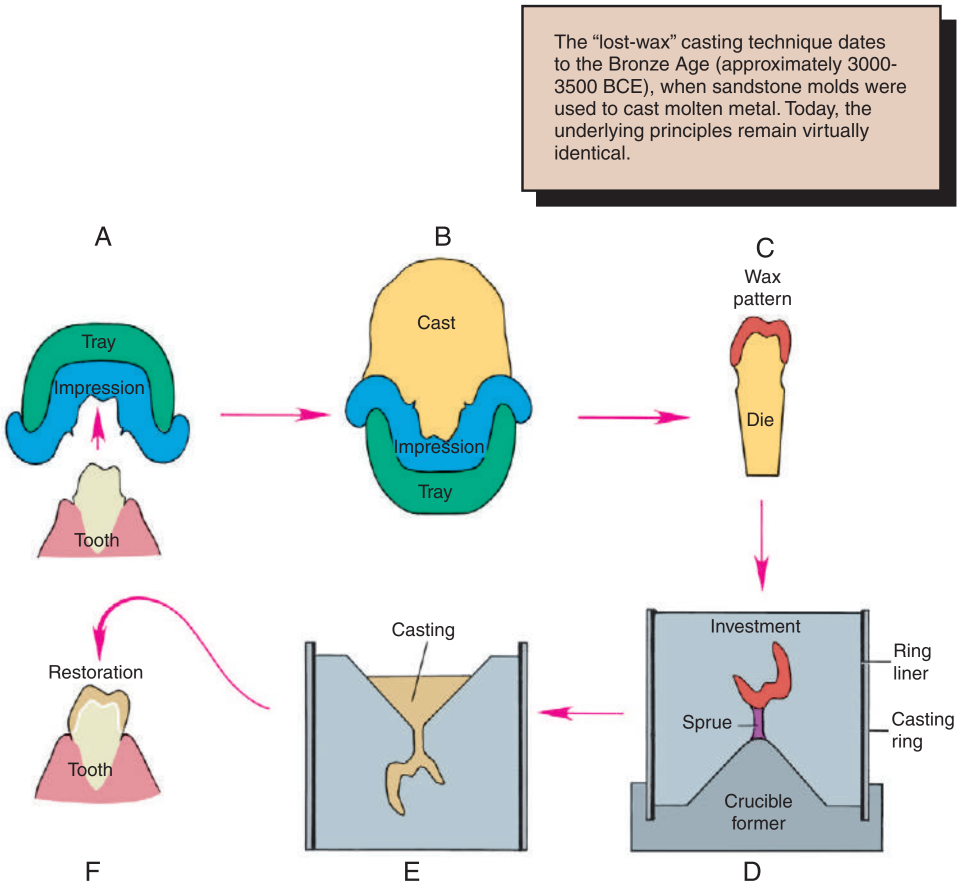


Fig. 18.29 Most dental castings are made indirectly by the lost-wax process. (A) Impression. (B) Cast. (C) Wax pattern on die. (D) The pattern is attached with sprue to a rubber crucible former and invested. (E) Casting. (F) Luted restoration.

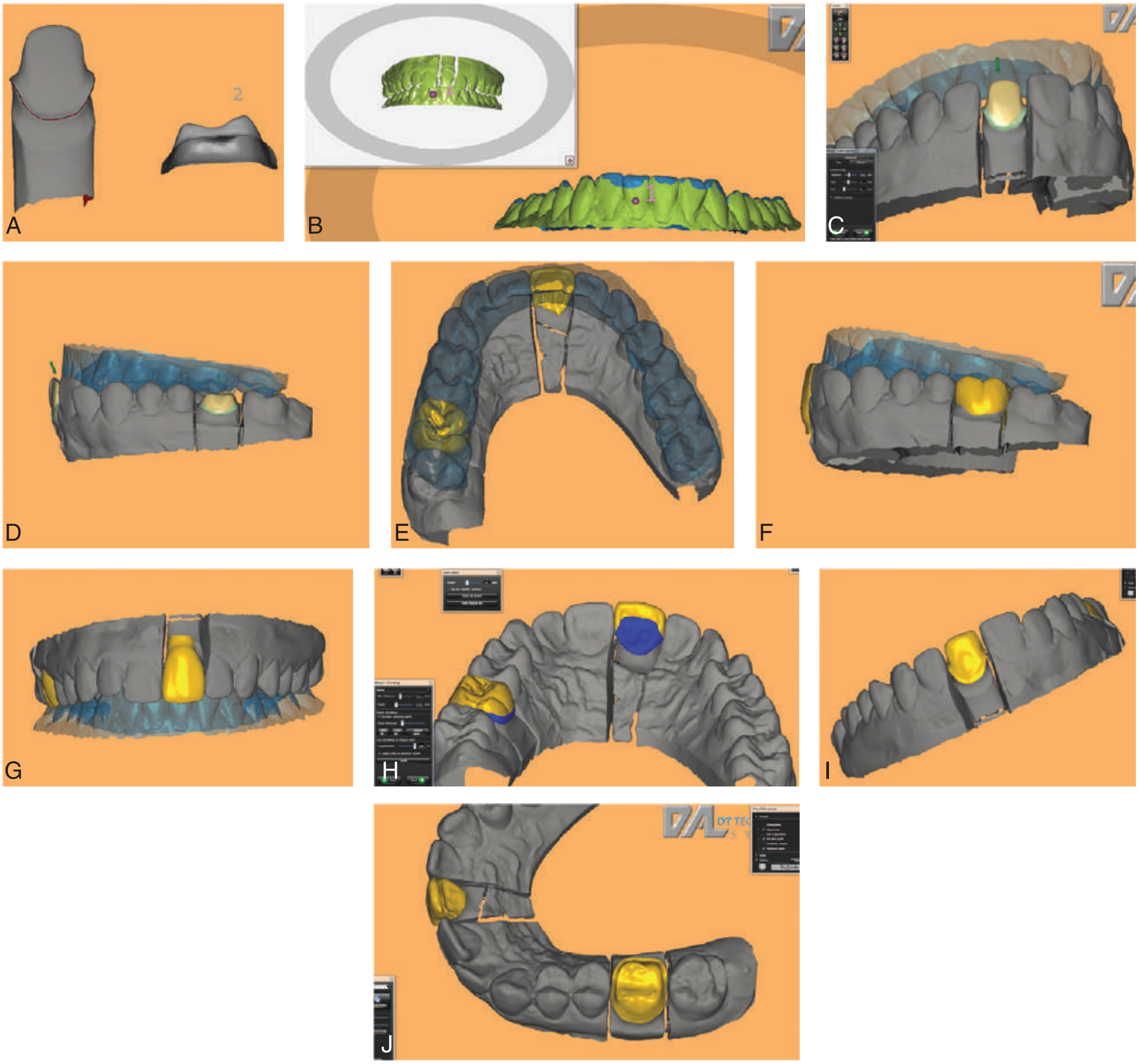


Fig. 18.30 Virtual renderings of substructures. (A) The margin has been delineated on the virtual die *(red line)*. (B) The optical scan of the occluded position (index) used to properly relate the definitive virtual cast to the opposing cast. (C and D) Insertion of the opposing cast in relation to the molar and incisor preparations. (E–G) Anatomic contour renderings are then morphed, after which the area that is to be veneered is delineated (H). (I and J) Virtual renderings of the completed substructure designs. (Courtesy Mr. William Schwenk, CDT, Dental Arts Laboratories, Inc., Peoria, Illinois.)

evaluation of the pattern, preferably under low-power (up to 10 times) magnification, is crucial to obtain a good casting.

This chapter approaches the waxing procedure in a logical sequence. As with most aspects of fixed prosthodontics, a restoration is successful only if each step is carefully followed and evaluated before the dentist moves on to the next.

PREREQUISITES

The definitive die and cast may require small modifications before waxing is started. Depending on the procedure, the dentist can increase the size of the die slightly by applying a thin layer of painted-on spacer, which helps slightly enlarge the internal diameter of the restoration.

Correction of Defects

Even a very small undercut on the die of a tooth preparation makes wax pattern removal very difficult. Small dimples in the die (resulting from caries removal or loss of a previous restoration) may be undercut in relation to the path of placement of the planned restoration. Such areas are normally blocked out intraorally with glass ionomer or restored with amalgam or another suitable foundation material as part of the mouth preparation phase (see Chapter 6). On occasion, however, blocking them out on the working die may be more practical and convenient, as long as the defect does not extend to within 1 mm of the cavity margin. Zinc phosphate cement is a suitable material (see Chapter 30), but other commercial products (e.g., resin) are available for this purpose (Fig. 18.32).

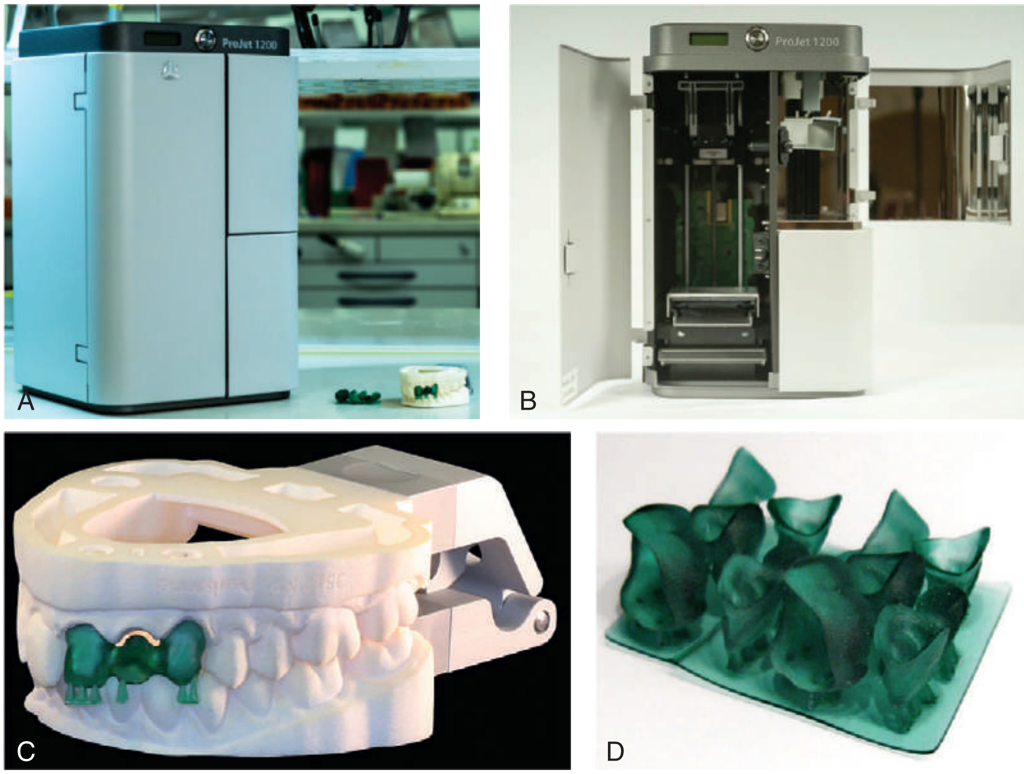


Fig. 18.31 Printing wax patterns. (A and B) ProJet 1200 3D printer. (C) Printed pattern for a three-unit metal-ceramic fixed dental prosthesis seated on its corresponding solid cast. (D) Printed patterns for crowns. Note the supporting struts to maintain positional stability during the printing process. (Courtesy Whip Mix Corporation, Louisville, Kentucky.)

Fig. 18.32 Blocking out undercuts on a die. (A) Photopolymerizing resin being applied (A) and light-polymerized (B). Alternatively, autopolymerizing resin (C) can be used. (D) Autopolymerizing resin being applied. (E) Monomer spray results in almost instantaneous polymerization.

Provision of Adequate Space for the Luting Agent

Since the 1920s,[9] practitioners have recognized that a space should exist between the internal surface of the casting and the prepared surface of the tooth everywhere except immediately adjacent to the margin. The space provides room for the luting agent (a material that on hardening fills the space and binds the tooth and crown together) and allows complete seating of the restoration during cementation (see Chapters 7 and 30). At the preparation margin, there should be a band of close adaptation (about 1 mm wide) to prevent disintegration and dissolution of the luting agent. The ideal dimension[10–12] for the luting agent space has been suggested at 20 to 40 µm for each wall, which implies that a complete crown should have an internal diameter between 40 and 80 µm larger than the diameter of the prepared tooth. Through the use of available techniques in an appropriately standardized manner, such a degree of casting adaptation can be obtained routinely, independent of the geometry of the finish line.[13,14]

If the luting agent space is too narrow, the restoration will not seat properly during cementation because of hydraulic pressure that develops when the viscous mass of luting agent cannot escape through the narrow gap between crown and preparation as the restoration is seated. Conversely, if the luting agent space is too wide, the casting is loose on the tooth, resistance form (see Chapter 7) is reduced, and the position of the crown is difficult to maintain accurately during evaluation and occlusal adjustment (see Chapter 28). In addition, the risk that the crown will loosen during function increases considerably, and its longevity is adversely affected. The precise amount of space for the luting agent that is obtained depends on the materials and techniques used in the indirect process, particularly the choice of impression material (see Chapter 14), die material (see Chapter 17), investment (see Chapter 22), and casting alloy (see Chapters 19 and 24 and Fig. 18.29). Furthermore, the minimal film thickness of the specific luting agent selected must be considered. These factors directly affect the size of the cement space.

Increasing the Space for the Luting Agent

A number of factors increase the space for the luting agent for a complete crown:

- Increased thermal and polymerization shrinkage of the impression material (see Chapter 14)
- Use of a solid cast with individual stone dies (see Chapter 17)
- Use of an internal (initial) layer of soft wax in the wax pattern
- Use of die spacers
- Increased expansion of the investment mold (see Chapter 22)
- Removal of metal from the fitting surface by grinding, airborne-particle abrasion, etching with aqua regia, or electrochemical milling

All other conditions remaining equal, each of these factors individually results in an increased distance between the internal surface of the casting and the surface of the prepared tooth. Although the dentist has little control over the polymerization shrinkage of impression materials, die system selection has a direct influence on the size of the wax pattern. With some impression materials, using a multiple-pour system for fabrication of a solid, definitive cast and a separate die yields a die that is slightly larger than the prepared tooth. The pattern is, in effect, stretched during manipulation, which results in a proportionally larger internal casting diameter. An internal layer of soft wax is subject to slightly more compression by the setting refractory investment material, which leads to a looser fit. Spacers enlarge the die by coating the occlusal surface and vertical axial walls with a thin layer of rapidly drying paint. To increase the expansion of the investment mold, the mold can be heated to a slightly higher temperature during the wax elimination phase, and metal can be removed from the internal surface of a cast crown through airborne-particle abrasion, etching, or milling procedures.

Reduction of the Space for the Luting Agent

A number of factors reduce the cement space:

- Reduced thermal and polymerization shrinkage of the impression material (see Chapter 14)
- Use of resin or electroplated dies
- Use of alloys with a higher melting temperature range
- Reduced expansion of the investment

Resin and electroplated dies are slightly smaller than stone dies and therefore result in a smaller casting. As alloys cool over a larger temperature range, the additional shrinkage that takes place also results in a smaller casting. There are multiple ways in which to reduce investment expansion; technique selection, burnout temperature, and water-to-powder ratio are the most convenient (see Chapter 22). If the investment is mixed with an adjusted water-to-powder ratio, which results in less setting expansion, the size of the resulting casting is again reduced. When problems routinely surface with castings that are either too loose or too tight, any of the previously mentioned variables may be altered, which leads to more predictable results.

Problems with fitting castings become apparent at two stages of the indirect procedure: when the casting is evaluated on the die and when it is cemented. Recognizing problems at each stage and correcting them before proceeding is crucial. Difficulty with seating the casting on the die is generally caused by *wax distortion*, the presence of *flash* (excess wax that was not removed before the investing and casting procedure) extending cervical to the preparation margin, *improper investment expansion* (underexpansion; Fig. 18.33), or a *casting nodule*. Modification

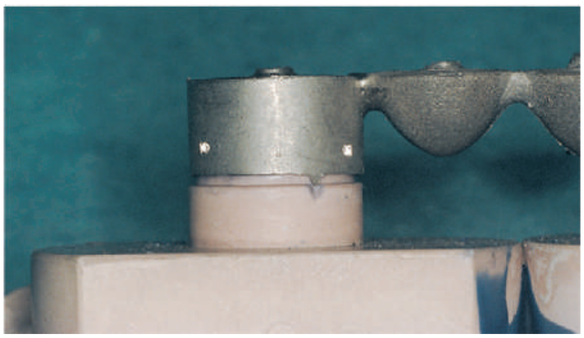


Fig. 18.33 This experimental near-cylindrical casting failed to seat because of inadequate expansion of the investment, not because of inadequate die spacing.

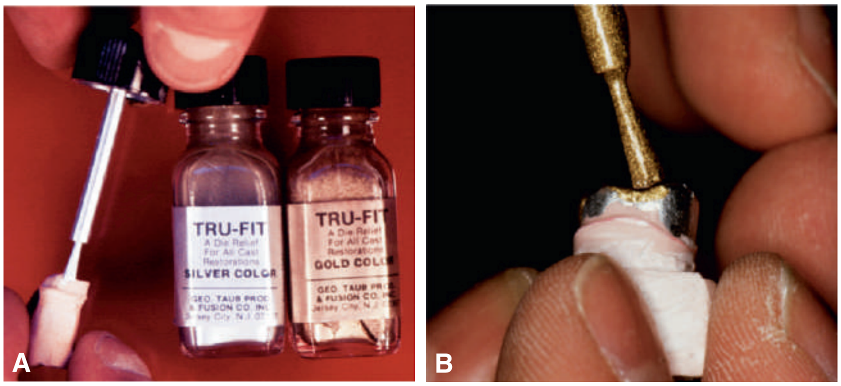


Fig. 18.34 Applying die spacer. (A) The material is available in contrasting colors to facilitate applying the required number of coats. (B) Care must be taken to keep the material at least 1 mm from the margin.

of the investing and casting protocol solves these problems (see Chapter 22). Consistent problems with castings that do not seat completely when evaluated on the prepared tooth may be corrected by a change in just one variable in the protocol. Although many technicians advocate the routine use of die spacer, this is just one of many options to influence the size of the resulting cement space.

Die Spacer

This material (Fig. 18.34) (similar to model airplane paint[15]) is applied to the die to increase the cement space between axial walls of the prepared tooth and the restoration. It is formulated to maintain constant thickness when painted on the die. However, it should not coat the entire preparation. For adequate marginal adaptation, a band of about 1 mm immediately adjacent to the preparation margin must be left unpainted.[16] Thinner is provided to replace the solvent, which tends to evaporate. Use of thickened die spacer can result in an excessive thickness of spacer.

Marking the Margins

The technician's awareness of the precise location of the preparation margin is crucial. By marking it with the side of a colored pencil tip, the technician can pinpoint this location (Fig. 18.35). The color should contrast with that of the wax that will be used (e.g., a red pencil can be used for green wax). An ordinary lead pencil is not recommended because it can abrade the die, its darker color can interfere with efforts to verify that the wax has been properly adapted at the margin, and traces of the graphite (an antiflux) can prevent complete casting of the margins. The marked margins can be coated with low-viscosity cyanoacrylate resin and immediately blown dry. If performed properly, this procedure adds no more than 1 µm to the die.[17] Although removing the excess with acetone is sometimes possible, care must be taken not to create a thick layer of cyanoacrylate, which can result in an unacceptable fit of the definitive cast restoration. For this reason, higher viscosity resins must be avoided.

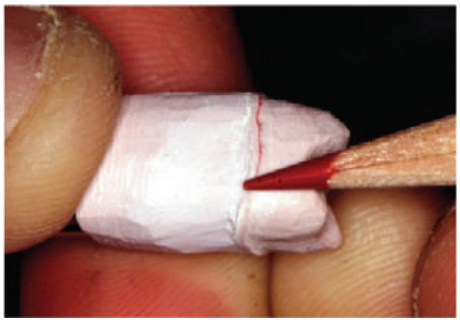


Fig. 18.35 Marking the preparation margin. Note that the side of the colored pencil tip is used to keep line width to a minimum.

MATERIALS SCIENCE

M.H. Reisbick

Inlay casting wax (the name given all wax used in forming the pattern for cast restorations) is actually composed of several waxes. Paraffin is usually the main constituent (40% to 60%). The remaining balance consists of dammar resin (to reduce flaking) plus carnauba, ceresin, candelilla wax (to raise the melting temperature), or beeswax. Sometimes a synthetic wax is substituted for the natural material. Dyes are added to provide color contrasts. Exact formulations are trade secrets, but Coleman[18] published the formula for an experimental compound.

The American National Standards Institute (ANSI) and the American Dental Association (ADA)[19] categorized waxes into two types:

1. Type I: a medium-hardness wax (generally used with the direct technique for making patterns in the oral cavity)
2. Type II: a softer wax (generally used for the indirect fabrication of castings)

Waxes used with direct techniques must not flow appreciably at mouth temperature. Those used with indirect techniques must resist flow at room temperature to maintain their newly shaped forms.

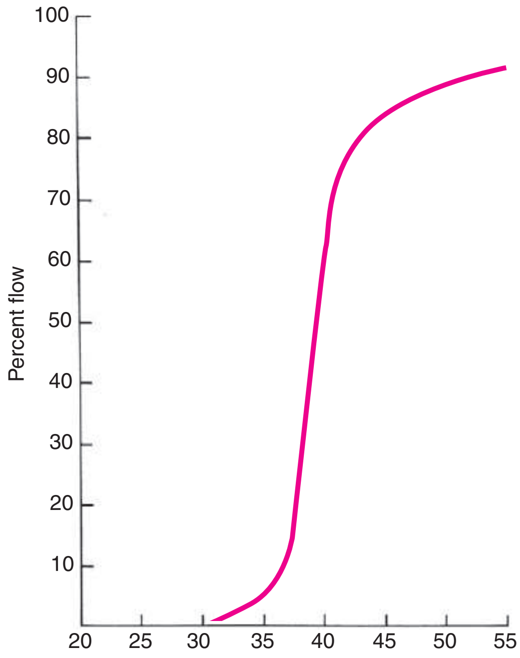


Fig. 18.36 Wax flow curve.

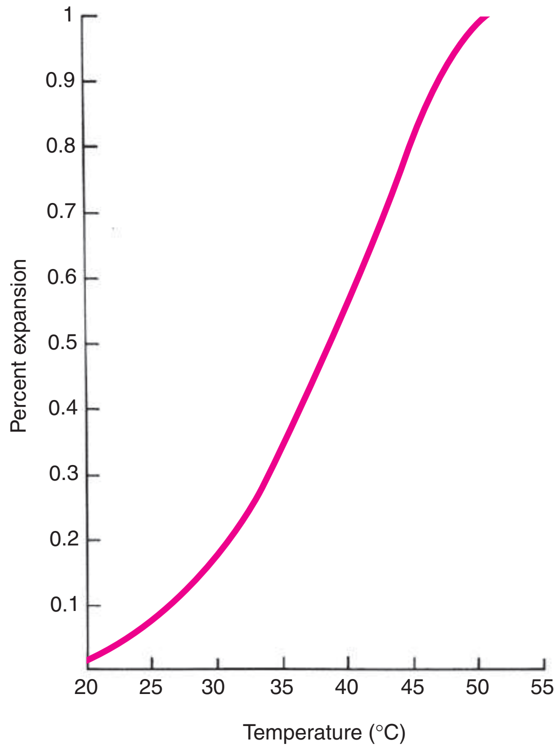


Fig. 18.37 Wax expansion curve.

Specifications of the ANSI and ADA govern use of the important properties of residue, flow, and expansion. Because the mold must burn out cleanly to allow the escape of gases and the complete entry of molten alloy, there can be no residual ash. However, the specifications allow a 0.1% residue, which apparently is negligible. Flow requirements, as previously stated, are necessary to control the stability of the wax once it has reached the temperature (37°C [99°F] for type I waxes, 25°C [77°F] for type II waxes) at which it is carved, burnished, and polished. In addition, the wax must flow well at typical forming temperatures. Curves of temperature plotted against percentage flow (Fig. 18.36) are furnished by reputable manufacturers and should be consulted when a casting wax is chosen. All waxes expand and contract when heated and cooled, respectively. Manufacturers' curves of percentage expansion and contraction at various working temperatures (Fig. 18.37) are helpful when methods to use in the investing and casting process are considered. For example, a wax that solidifies at a higher temperature shrinks more and therefore necessitates more compensation to control fit than does a wax that solidifies at a lower temperature (a reason for not interchanging type I and type II waxes within an established technique). These properties can be adversely affected by repeated heating of the wax, which drives off the more volatile components.[20] When waxes are selected for optimal casting accuracy, the use of waxes with different properties for the margin and occlusal portions may be necessary.[21] If a casting is to be accurate, the wax pattern must not become significantly distorted. One reason for distortion is that wax has "memory," which means that it exhibits some elasticity unless it is thoroughly liquefied. To overcome this problem, the initial layer of wax is applied in melted increments or drops. An alternative method is to make the initial coping by dipping the die into thoroughly melted wax.

However, a serious problem arises when the added wax incorporates strain within the pattern as each increment solidifies. This strain tends to be released with time and subsequently distorts the wax pattern. The rate of wax change is temperature dependent, which means that it increases at higher ambient temperatures. Because wax has a relatively high coefficient of thermal expansion and changes dimension subject to air temperature changes, and because the pattern tends to release its incorporated strain, the margins must be remelted, readapted, and resmoothed immediately before investing. The internal fit of the remelted portion is then closer to the prepared surface of the tooth than is the rest of the casting and therefore may help create the necessary space for the luting agent.

TECHNIQUE

A step-by-step approach to development of optimal form in wax is recommended. The dentist evaluates each step before proceeding to the next, which minimizes extra work. The finished wax patterns should be an accurately shaped anatomic replica of the original teeth that meets all functional dynamic requirements. Information needed to shape the restoration correctly is derived from the contours of the unprepared tooth surface, adjacent tooth surfaces, the opposing occlusal surfaces, and reproduction of mandibular movement in the dental laboratory. The dentist's thorough knowledge of tooth anatomy and the ability to copy three-dimensional structures accurately are needed as well.

When making a drawing or painting, artists constantly refer to the real-life scene they are trying to reproduce. Similarly, when waxing a restoration, the technician should refer to a suitable model (e.g., diagnostic casts, unworn extracted teeth, a contralateral tooth) or casts of unworn natural teeth. It is unwise to copy reproductions of natural teeth (i.e., plastic teeth or casts of restored mouths), no matter how skillfully they have been made. This would be like an artist trying to render a scene from another artist's painting rather than from real life.

Evaluating a three-dimensional shape correctly is difficult. The finished wax pattern for a tooth may be too bulbous or too flat. Although it appears "wrong," pinpointing and correcting the exact problem are skills achieved only after in-depth study of what constitutes "normal" anatomic form and with the ability to interpret that shape. To evaluate occlusal form, breaking down the complex surfaces into individual components is helpful. When evaluating axial contours, the practitioner should assess a series of two-dimensional outlines by rotating the wax pattern. These outlines can easily be compared with an appropriate model, and any aberrations can be corrected. It is helpful to recognize that the human eye excels at interpreting even very small differences in height and width of objects (two dimensions) but is not as adept at interpreting similarly subtle differences in depth. Therefore, the practitioner must systematically look at cross sections through the pattern and evaluate its silhouette (Fig. 18.38). Rotation of the pattern and repeating this process from all angles of observation speed up this intricate process. Photographing one's work with a digital camera gives the operator immediate two-dimensional feedback to assess the progress of anatomical forms.

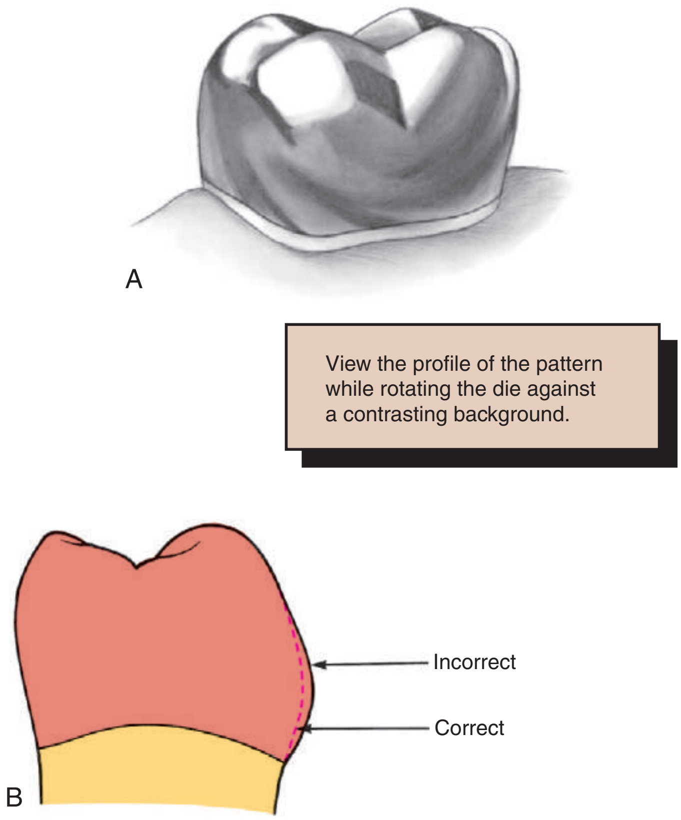


Fig. 18.38 (A) Incorrect midfacial contour is difficult to determine from a direct view of a three-dimensional object. (B) It is more easily seen *(dashed red line)* by sequential evaluation of the profile of the pattern as it is rotated.

Armamentarium

The following equipment is needed (Fig. 18.39):

- Bunsen burner
- Inlay wax
- Waxing instruments
- Cotton cleaning cloth
- Sharp colored pencil (in color that contrasts with wax)
- Separating liquid
- Occlusal indicator powder: zinc stearate or powdered wax (note: Zinc stearate may present a health hazard if inhaled; powdered wax is a safer alternative)
- Soft toothbrush
- Double-sided brushes (soft/rigid)
- Cotton balls
- Fine nylon hose

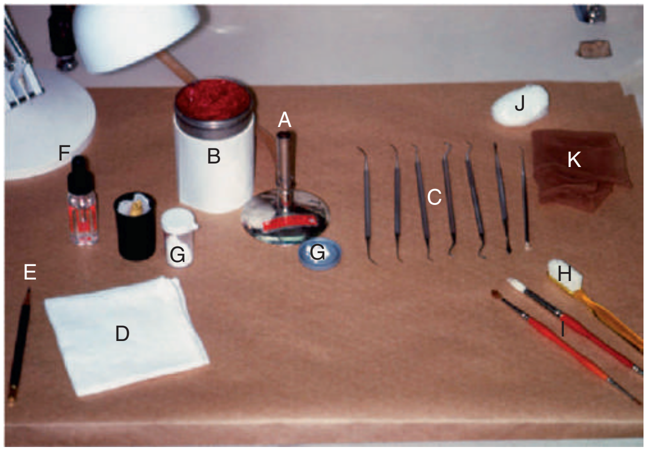


Fig. 18.39 Waxing armamentarium: Bunsen burner (A); inlay wax (B); waxing instruments (C); cotton cleaning cloth (D); sharp colored pencil (E); separating liquid (F); occlusal indicator powder (G); soft toothbrush (H); double-sided brushes (I); cotton balls (J); and fine nylon hose (K).

Waxing Instruments

Waxing instruments can be categorized by the intent of their design: wax addition, carving, or burnishing. Of the popular PKT instruments (Fig. 18.40) (designed by Dr. Peter K. Thomas specifically for the additive waxing technique), Nos. 1 and 2 are wax addition instruments, No. 3 is a burnisher for refining occlusal anatomy, and Nos. 4 and 5 are wax carvers.

Wax is added by heating the shank of the instrument in the Bunsen flame, touching it to the wax, and quickly reheating its shank in the flame. Wax flows away from the hottest part of the

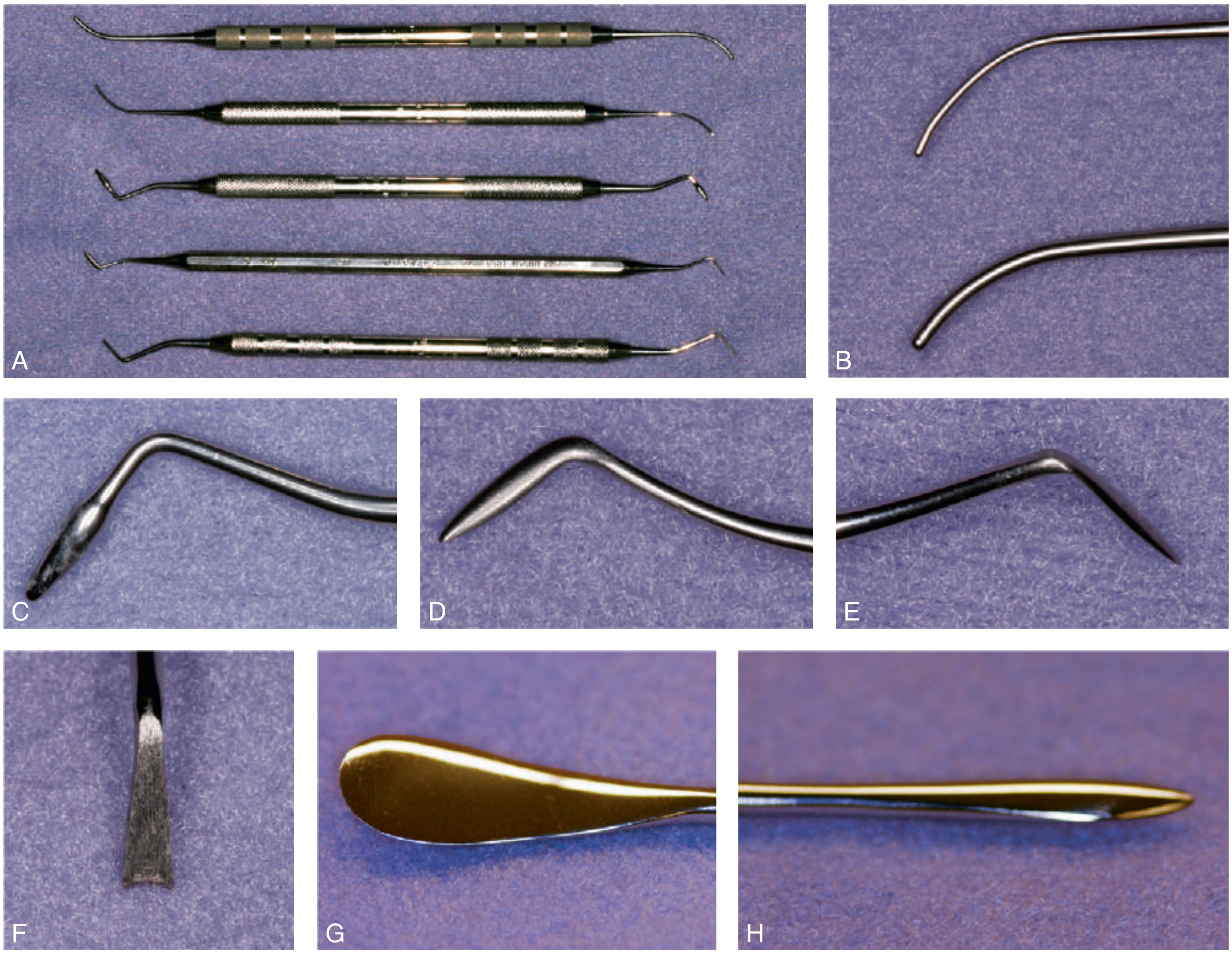


Fig. 18.40 Waxing instruments. (A) Top to bottom: PKT Nos. 1 to 5 instruments. (B) Top to bottom: PKT Nos. 1 and 2 wax addition instruments. (C) PKT No. 3 burnisher. (D and E) PKT No. 4 wax carver. (F) PKT No. 5 wax carver instrument. (G and H) PKT No. 7 waxing spatula.

instrument so that if the shank is heated, a bead of wax flows off the tip (Fig. 18.41). However, if the tip is heated, the wax flows up the shank of the instrument (to the considerable annoyance of inexperienced operators). The PKT No. 1 instrument is used for large increments; the smaller No. 2 is used for lesser additions. A No. 7 or 7 A waxing spatula (see Fig. 18.40G and H) is useful for adding large amounts of wax, particularly in forming the initial coping (the thimble-like layer of wax that covers all prepared surfaces). Some technicians prefer electric waxing instruments (Fig. 18.42) because they enable precise control of the wax temperature, which is important for proper manipulation. Another advantage is that they minimize carbon buildup, which easily results from overheating a waxing instrument in a Bunsen flame. However, because the instrument remains hot, it is not possible to draw solidifying wax in the required direction.

Wax carvers should be kept sharp and should never be heated. In addition to the PKT instruments, the Nos. ½ and 3 Hollenback and the No. 2 Ward carvers (Fig. 18.43) are popular.

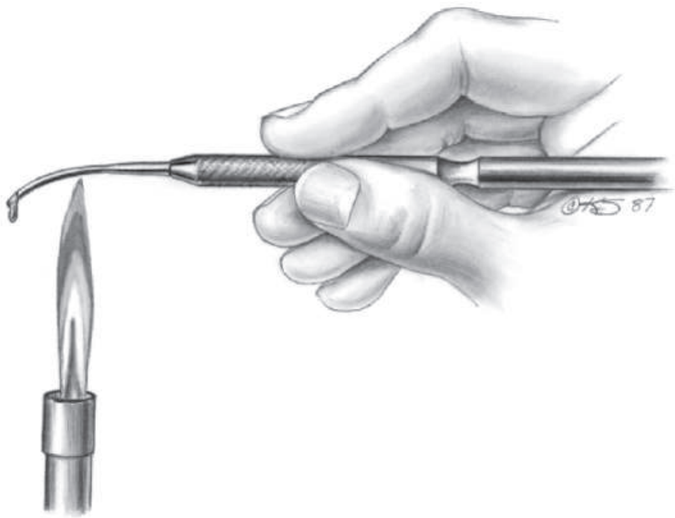


Fig. 18.41 The practitioner must always heat the shank of the instrument so that wax flows off its tip.

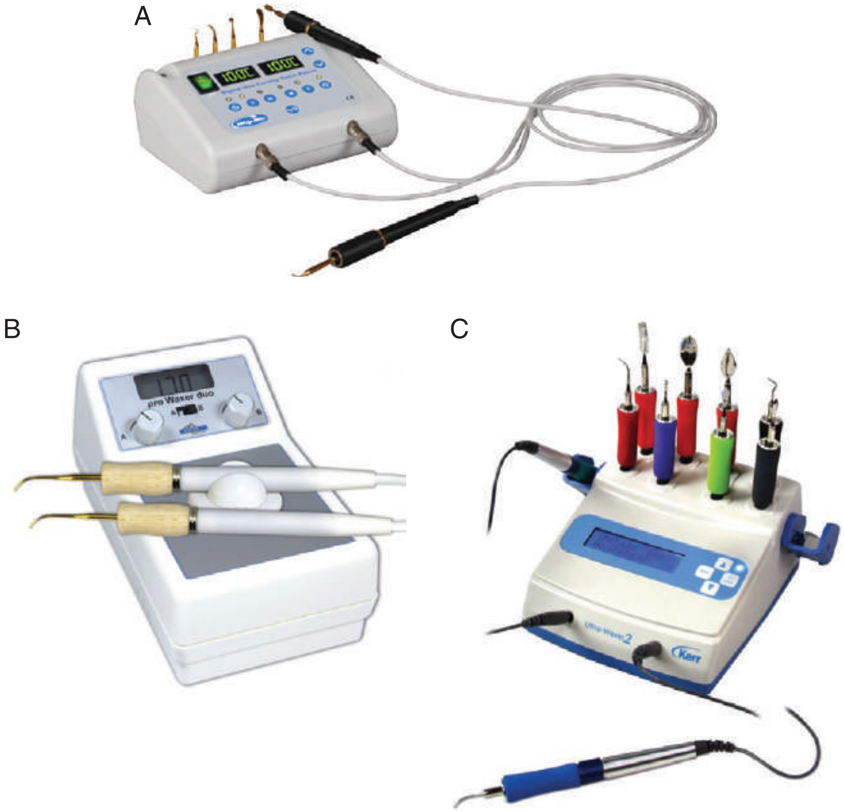


Fig. 18.42 Electric waxing instruments. (A) (Dual Digital Wax Carving Touch Pencils. (B) Pro Waxer Duo. (C) Ultra-Waxer 2. (A, Courtesy Whip Mix Corporation, Louisville, Kentucky. B, Courtesy Keystone Industries, Gibbstown, New Jersey. C, Courtesy Kerr Corporation, Orange, California.)

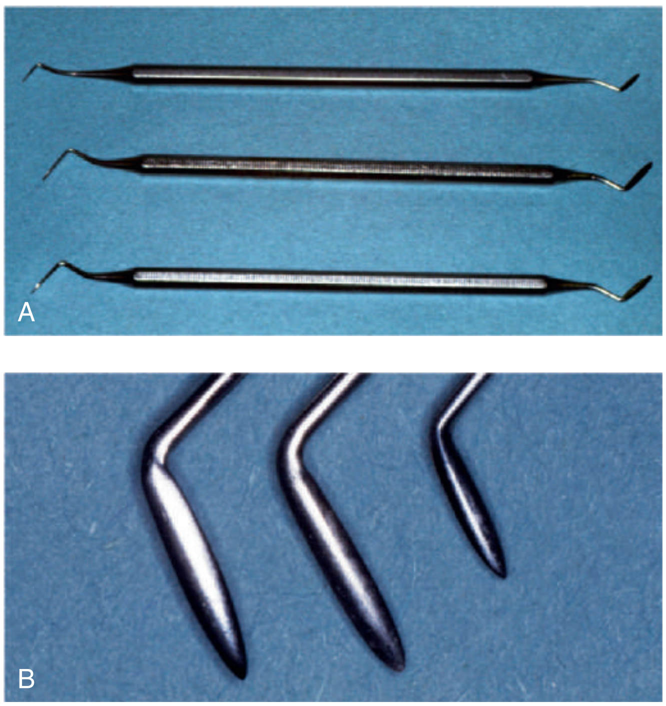


Fig. 18.43 Wax carvers. (A) Top to bottom, No. 2 Ward and Nos ½ and 3 Hollenback. (B) Left to right, closer view of the tips of these three instruments.

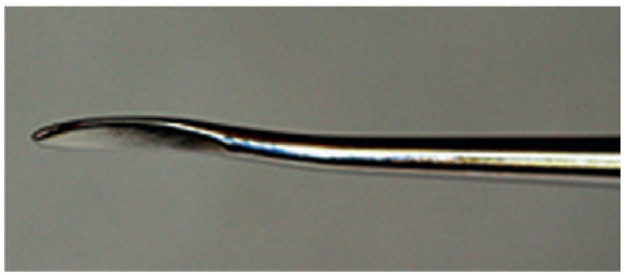


Fig. 18.44 PFI Land trimmer (wax burnisher), available from Hu-Friedy, Chicago.

When wax is carved, light pressure should be used to obtain the desired smooth surface.

Burnishing is an alternative to carving for obtaining a smooth wax pattern of the desired contour. Burnishing entails slightly warming a blunt instrument and rubbing the wax. The instrument should not be so hot that it melts the wax surface. The PKT No. 3 instrument is useful for burnishing the occlusal surfaces. The PKT Nos. 1 and 2 instruments can be used for burnishing, as well as for wax addition. Another popular burnisher, the PFI Land trimmer (Fig. 18.44; available on special order from Hu-Friedy Mfg. Co., Chicago), is based on the DPT6 Darby Perry trimmer.

For excess wax removal, burnishing is less effective than carving, but it is probably easier to control. It leaves a smoother surface, which can be particularly important when excess wax is trimmed near the margin. Careless (excessive) carving in this area can lead to abrasion of the die, which results in a ledge at the margin of the finished casting.

Waxing Posterior Teeth

The following sequence is recommended for waxing posterior teeth:

1. Internal surface
2. Wax pattern removal and evaluation
3. Proximal surfaces
4. Axial surfaces
5. Occlusal surfaces
6. Margin finishing

Internal Surface

Forming a closely adapted internal surface is the first step in waxing. The wax *must* reproduce all retention features of the restoration.

Step-by-step procedure

1. Apply die lubricant generously with a clean brush (Fig. 18.45A). Allow the lubricant to dry, and paint on a second coat (repeat periodically as needed). Waxing should not begin until the lubricant has been allowed to soak in completely. (On dies that have been coated with cyanoacrylate resin, lubricant must be reapplied more frequently.)
2. If pinholes have been prepared, fit in plastic pins that match the bur used to prepare the hole. Seat the pins in the die, and use a heated PTK No. 7 instrument to flatten their tops to provide retention in the wax (see Fig. 18.45B).
3. Flow wax onto the die from a well-heated, large waxing instrument (Fig. 18.46A), making sure that any previous application is partially remelted. A large instrument holds sufficient heat to partially remelt previous wax increments and to prevent folds or lines from developing in the fitting surface. Waxing is easier if the instruments are kept clean and only the shank is heated.
4. When applying the initial layer, be sure that the wax is fully molten. If it is not, wax solidity may cause distortion. Very hot wax flows rapidly over the die. Use cooler instruments

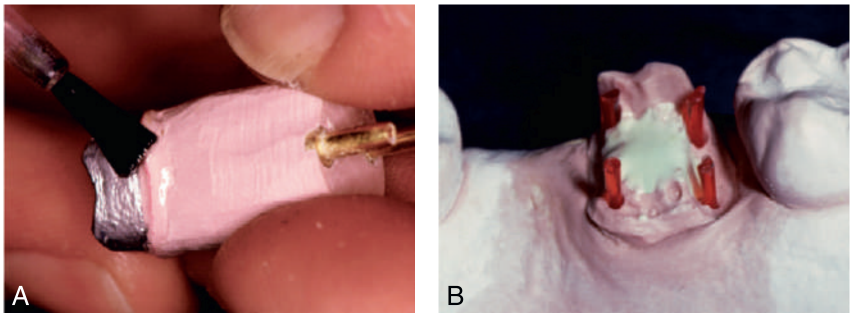


Fig. 18.45 Starting the waxing procedure. (A) Lubricating the die. (B) Adapting plastic pins.

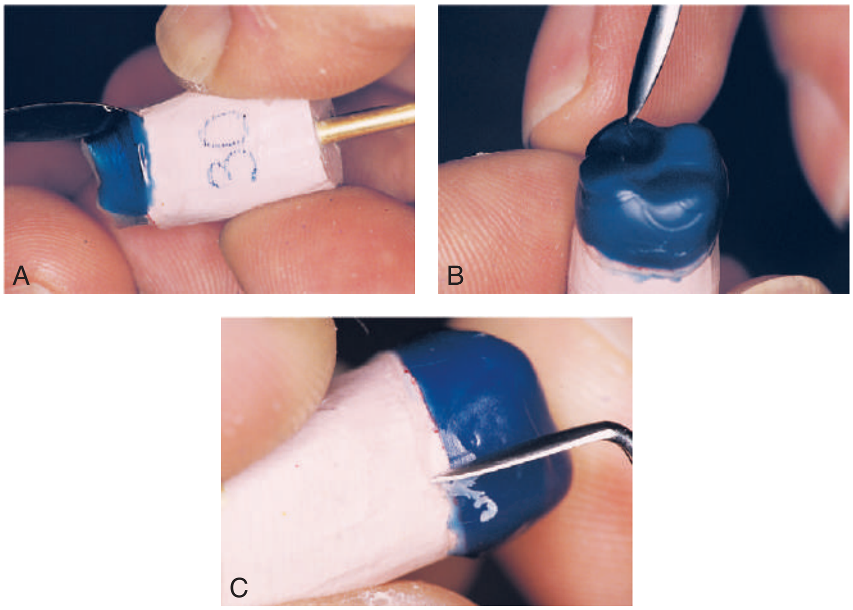


Fig. 18.46 Forming the initial copings. (A) A large instrument is used to keep the wax sufficiently hot. Previous applications should be remelted as additional wax is added. (B) Wax is added to build up adequate bulk for rigidity. (C) The wax is trimmed very carefully to the margin.

Fig. 18.47 Wax dipping pot. (Courtesy Whip Mix Corporation, Louisville, Kentucky.)

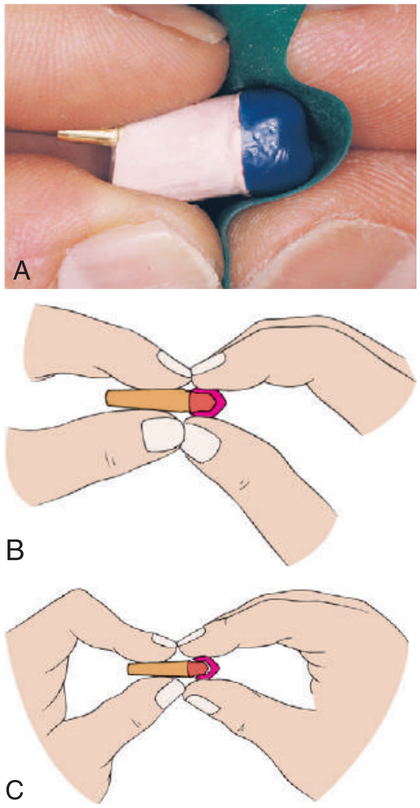


Fig. 18.48 Wax pattern removal. (A) A sheet of washed rubber dam increases friction and aids removal. (B) The fingers of the left hand hold the die. The right hand holds the pattern. (C) To pull the die from the pattern, the fingers of the left hand squeeze the die.

for subsequent waxing of external anatomic details, which allows small additions to be placed accurately. Dipping the lubricated die in a pot of melted wax is another method for making well-adapted internal surfaces (Fig. 18.47). This method works well for complete-coverage restorations.

5. Add sufficient wax with a large instrument to allow the coping to be handled without deformation or breakage (see Fig. 18.46B). A large instrument keeps the wax hot more effectively than does a small instrument.
6. Give the proximal areas extra bulk for strength and to help grip the coping and prevent its distortion on removal from the die. The wax should cool between applications. At this point, no attempt should be made to contour the axial walls.
7. Trim the wax back to the margin (see Fig. 18.46C) so that the coping can be removed and evaluated. Excess bulk can be removed safely with a carving instrument. When only a thin excess layer remains, trimming is performed most safely with a burnisher. Careless use of a sharp carver at this stage may scratch the fragile margin of the die or chip it. Therefore, a slightly warmed blunt instrument should be used, and the margins rubbed with a burnishing action. A carver can be used, but meticulous technique and great care are required.

Wax Pattern Removal

The wax should be allowed to cool thoroughly before the coping is removed from the die (Figs. 18.47 and 18.48). To remove the coping, the thumb and forefinger of one hand maintain a constant light grip on the pattern while pressure is applied against them with the thumb and forefinger of the other hand, which also holds the die (see Fig. 18.48B). A small square of washed rubber dam increases friction between the fingers and the pattern. If the pattern fails to move, excess wax may be present beyond the margin, locking the pattern in place.

Evaluation. The objective of the first waxing step is a perfectly adapted reproduction of the prepared tooth surfaces. Identifying defects may take some practice. The examiner rotates the pattern under a bright light and looks for shadows formed by folds or creases (Fig. 18.49). A binocular microscope or a high-quality magnifying loupe is helpful not only for this step but also throughout the laboratory phase. Ten-power magnification is practical and helpful. Using higher power interferes with maintaining orientation.

Proximal Surfaces

The proximal surfaces of natural teeth are not convex (Fig. 18.50). They tend to be flat or slightly concave from the contact area to the cementoenamel junction, and any restoration must reproduce this feature. Overcontouring often makes maintaining periodontal health difficult, particularly if drifting of teeth has increased root proximity.[22] Excessively concave or undercontoured proximal surfaces also make flossing ineffective and must be avoided.[23]

Contact areas. The size and location of the contact areas should be established before the remaining proximal surfaces are waxed. Reference is made to contacts between the contralateral teeth and knowledge of anatomic form.

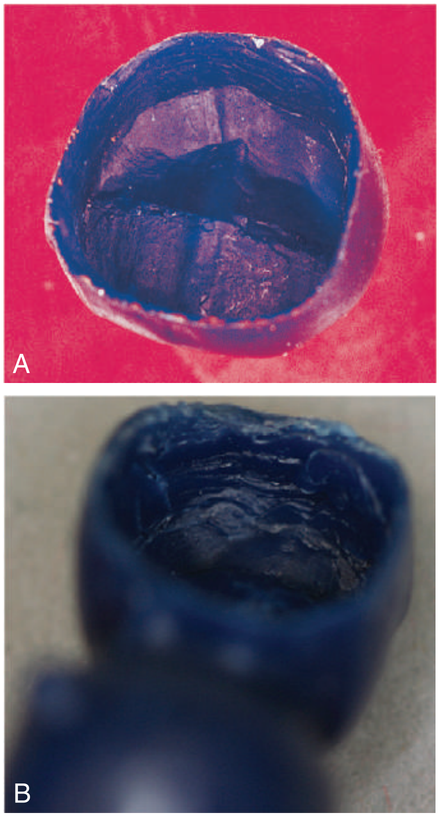


Fig. 18.49 Evaluation. (A) Well-adapted pattern. (B) Poor adaptation. Folds and creases indicate that the wax was not hot enough when applied.

Fig. 18.50 Proximal surfaces gingival to the contact area are normally flat or concave. Note the triangular shape of the posterior embrasures.

Abnormally large proximal contact areas make plaque control more difficult, which can lead to periodontal disease. Very small (point) contacts may be unstable and cause drifting. Deficient contacts can also lead to food impaction; although this is not a direct cause of chronic periodontal disease, it can be very uncomfortable and painful for the patient.

Most posterior contact areas (Fig. 18.51) are located in the occlusal third of the crown. However, the maxillary first and second molars make contact in the middle third.[24] The contact areas between mandibular teeth and maxillary molars are generally central. Between maxillary premolars and molars, the contact areas are usually toward the buccal surface (which makes the lingual embrasure larger than the buccal). Under no circumstances should a proximal contact area in the restoration be concave. If overlooked during waxing or rendering, concavities must be recontoured in the finished restoration.

Step-by-step procedure

1. Replace the wax coping on the lubricated definitive cast or removable die. When a removable die system is used, care must be taken to ensure that the locating pin or pins and stone surfaces are absolutely free of excess wax or other debris that could prevent complete seating of the die (Fig. 18.52). To ensure that proximal contacts are not deficient, relieve the adjacent proximal surface slightly by scraping (Fig. 18.53A).
2. Adjust the coping as necessary to be completely clear of the opposing occlusal surfaces. The structure will be developed with the wax additive technique later.
3. Add wax to the contact areas until they are the correct size, properly located, and consistent with anatomic form (see Fig. 18.53B).
4. When this has been accomplished, shape the proximal surfaces gingival to the contacts to the correct contour. A properly trimmed die is of great assistance in accomplishing this. The unprepared tooth structure that was reproduced in the "cuff" of the impression now serves as an effective guide to orienting the waxing instruments properly.

Evaluation. The location of the contact area is checked once again. Where multiple restorations are being made, the proximal embrasure is shaped symmetrically to provide adequate room for the free gingival tissues of adjacent teeth (Fig. 18.54). The proximal surfaces should be flat or slightly concave and should be shaped to eliminate any directional change between the root surface and the finished restoration. The cervical contour of the restoration should be continuous, with the contour of the unprepared tooth structure immediately cervical to the preparation margin.

Axial Surfaces

The buccal and lingual surfaces should be shaped to follow the contours of the adjacent teeth. The location of the height of contour (or, alternatively, the survey line for retainers for removable dental prostheses) is particularly important. It is generally located in the gingival third of most teeth, although on mandibular molars, it is usually in the middle third of the lingual surface.

Restorations are often made too bulky. Natural teeth are rarely more than 1 mm wider at their height of contour than at the cementoenamel junction. This width should not be exaggerated when a tooth is re-created in wax. The tooth surface gingival to its height of contour immediately adjacent to the gingival soft tissues sometimes called the *emergence profile*,[25] is usually flat or concave. Creation of a convexity in this area or a shelf or ledge[26] makes bacterial plaque removal more difficult and has been shown to cause inflammatory and hyperplastic

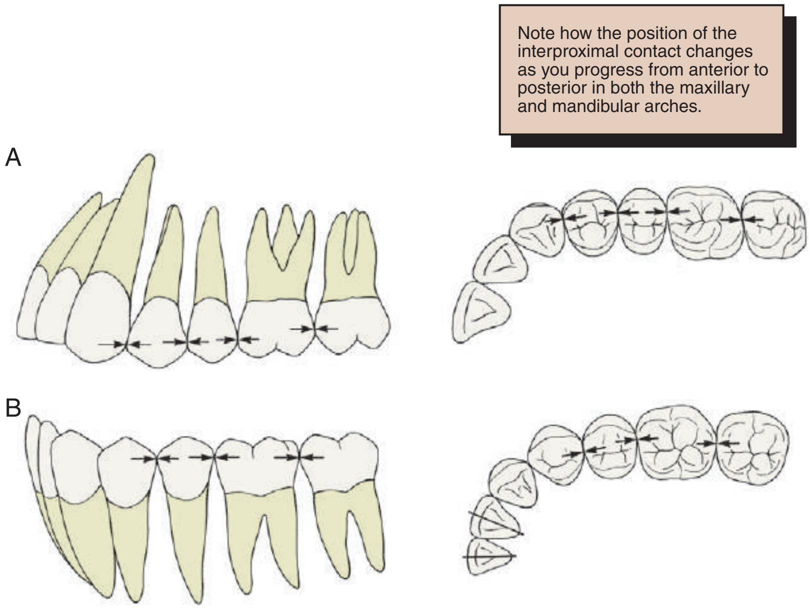


Fig. 18.51 Location of the proximal contact areas. (A) On maxillary teeth: progressively more occlusal and buccal the more anterior the tooth. (B) On mandibular posterior teeth: central.

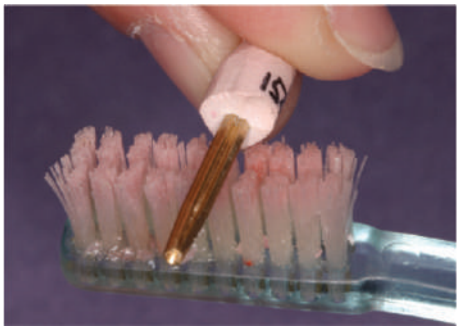


Fig. 18.52 Wax chips that accumulate on the dowel pin or in the sleeve prevent a die from seating. Periodic cleaning with a brush is recommended.

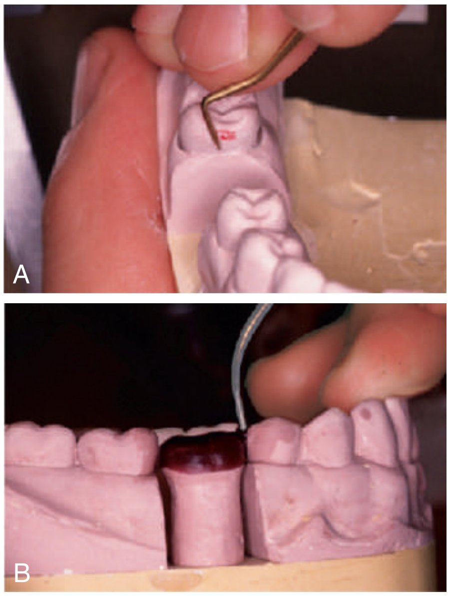


Fig. 18.53 (A) To ensure that proximal contacts are not deficient, a slight amount of stone is scraped from the adjacent tooth before waxing. (B) Wax is added to the contact area to establish a correctly located proximal contact.

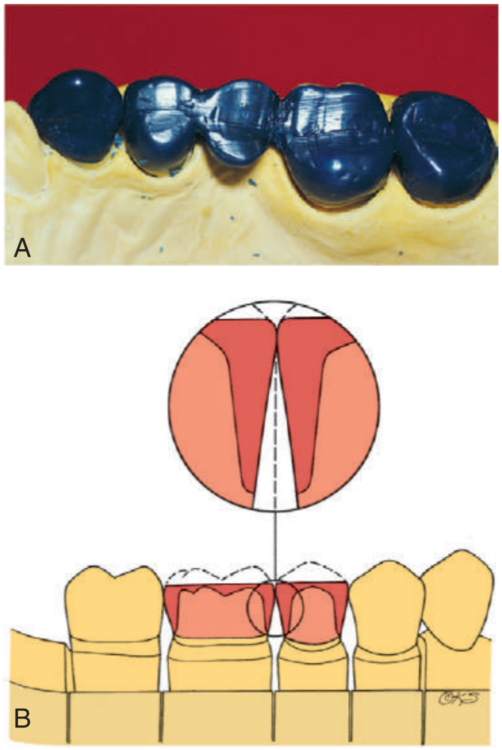


Fig. 18.54 (A) From the occlusal view, proper buccal and lingual embrasure form have been established. (B) The contact areas should be shaped so that the gingival embrasures are symmetric.

changes in the marginal gingiva in individuals with poor oral hygiene. Before dental plaque was identified as the direct etiologic agent in periodontal disease,[27] an excessive axial contour was considered necessary to keep food from entering the gingival sulci.[28] However, no evidence supports this concept. Indeed, artificially reduced axial contours (as when a prepared tooth is left unprotected for an extended period)[29] are associated with healthy gingival tissue. Overcontoured axial surfaces result if axial reduction during tooth preparation has been insufficient. Special care is needed where bone loss has occurred as a result of periodontal disease, particularly when this has caused exposure of the root near the furcation. The axial contour should then be modified to improve access for plaque removal (Fig. 18.55).

Step-by-step procedure

Axial contours

1. Establish the location, position, and overall outline of the contour, using the adjacent and contralateral teeth as a guide.
2. Wax the axial surfaces gingivally to form a smooth, flat profile. There should be no change of direction from unprepared tooth structure to the axial restoration contour.
3. Shape the middle third of the axial surface, using the adjacent tooth as a guide (Fig. 18.56A).
4. Add wax to join the axial and proximal surfaces, and smooth them, paying particular attention to the location and shape of the mesial and distal transitional line angles. A Boley gauge may prove helpful (see Fig. 18.56B). The line angles should correspond to those on the contralateral teeth if those are intact.

Evaluation. The examiner should evaluate the shape of the tooth at its greatest convexity by looking at the wax pattern and comparing its shape with that of the contralateral tooth. Each part of the outline should be carefully scrutinized. An outline that is too square or too round is modified. The buccal and lingual contours and the embrasures should all be assessed. Initially, assessing individual components rather than the entire contour or outline is helpful. The practitioner should try to relate the shape under evaluation to a "neutral" reference point, such as the midsagittal plane in viewing from the occlusal surface. In the learning phases, it is valuable to evaluate one's work through digital photographs to assess the work in 2D. With more experience, the practitioner will find it easier to review multiple forms simultaneously.

Each contact area has four embrasures: gingival, buccal, lingual, and occlusal. All but the occlusal will have been completed by this stage. The embrasures are normally symmetric about a line drawn through the contact area (Fig. 18.57).

Occlusal Surfaces

The cusps and ridges of the occlusal surfaces should be shaped to allow even contact with the opposing teeth while the teeth are stabilized and forces are directed along their long axes (see Chapter 4). Nonfunctional cusps (buccal cusps of the maxillary teeth, lingual cusps of the mandibular teeth) should overlap vertically and horizontally, preventing accidental biting of the cheek or tongue and keeping food on the occlusal surface. The esthetic cusps (buccal cusps of the maxillary teeth) should follow the occlusal plane that is esthetically positioned in a smile (see Fig. 18.28C).

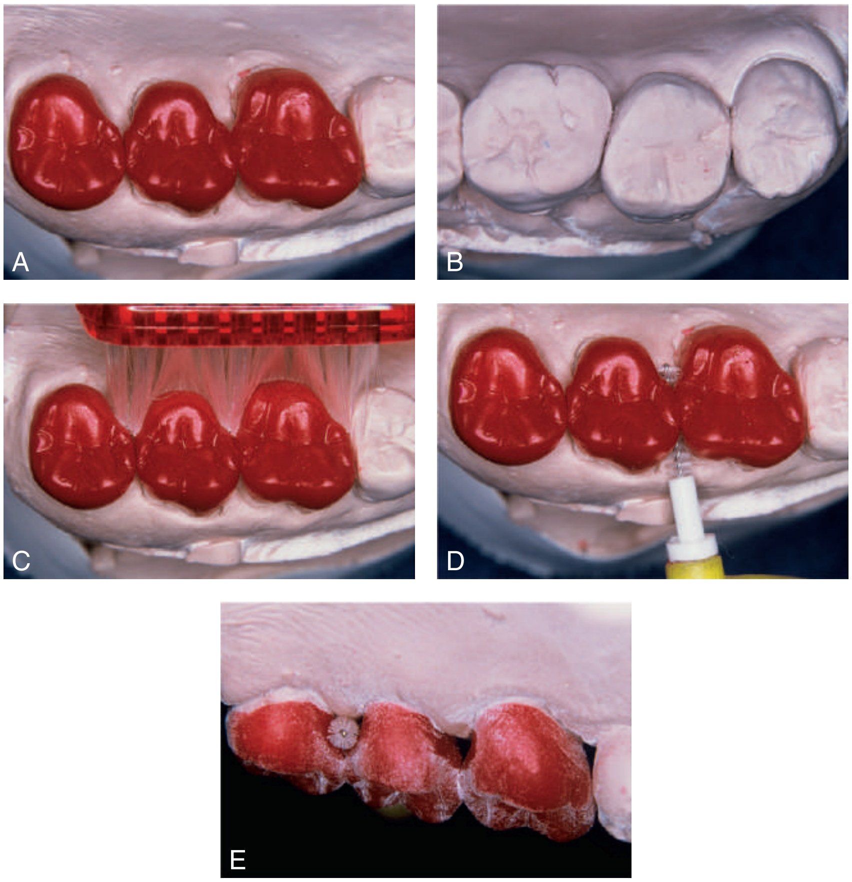


Fig. 18.55 As the cervical margin is placed near root furcations, the axial contour is modified to improve access for plaque control in patients with extensive bone loss. (A) Modified wax patterns for a periodontally compromised patient. Note the change in the outline form of the occlusal tables. (B) The contralateral teeth have normal axial contour. (C–E) Modified contour allows better access for oral hygiene.

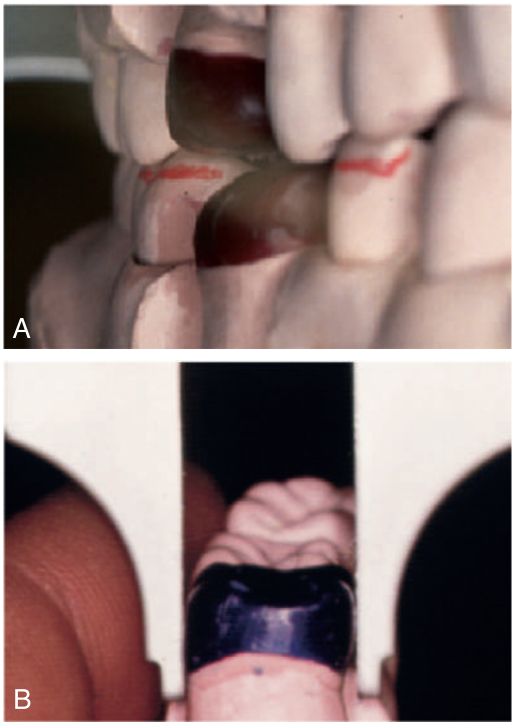


Fig. 18.56 (A) Waxing axial contours. (B) Evaluating the buccolingual dimension with a Boley gauge. This instrument is also helpful in assessing axial shape and height of contour.

> Establishing the correct embrasure form is essential. Only when proper anatomic form is obtained can the patient maintain plaque control.

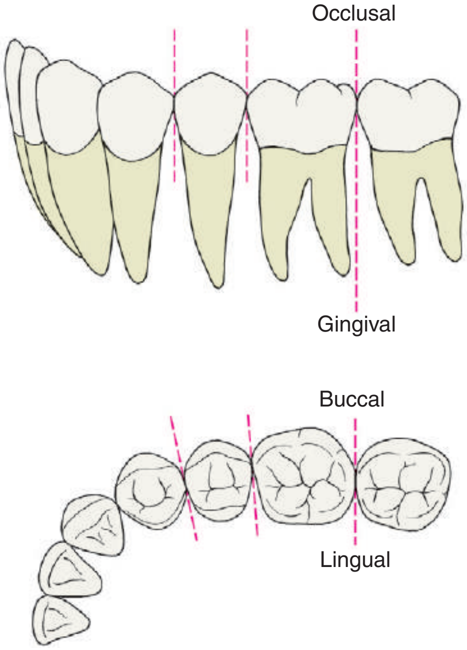


Fig. 18.57 Symmetry of embrasures.

Point contacts between opposing teeth are preferable to broad, flat occlusal contacts because wear of the restorations is minimized, and mastication of tough or fibrous foods is improved. The occlusal surfaces of natural teeth consist of a series of convexities with developmental grooves where the convex ridges meet. The opposing cusps should travel through pathways paralleling these grooves without tooth contact in excursive jaw movements. The occlusal surfaces can be precisely developed with a wax addition technique similar to the one devised by Payne[30] that is used in many schools to teach occlusal structure and function (Figs. 18.58 and 18.59).[31–33]

Occlusal scheme. Two occlusal schemes are generally recognized and should be understood when the restorations are planned: cusp–marginal ridge and cusp-fossa (see Chapter 4). In the cusp–marginal ridge scheme, the buccal cusps of the mandibular premolars and the mesiobuccal cusps of the mandibular molars contact the embrasures between the maxillary teeth (i.e., they each contact two teeth). In the cusp-fossa scheme, these mandibular functional cusps contact farther distally into the fossa of the maxillary tooth and contact only one tooth (Tables 18.1 and 18.2). The lingual functional cusps of the maxillary teeth contact the fossae of the mandibular teeth in both schemes.

Most adults with an Angle class I occlusion and unworn teeth have a cusp–marginal ridge scheme. In natural dentitions, the cusp-fossa arrangement is found only when a slight Angle class II malocclusion is present. However, for the following reasons, the cusp-fossa arrangement has been recommended over the cusp–marginal ridge when occlusal reconstruction is undertaken:

- Food impaction is prevented.
- Centric relation closure forces are nearer the long axes of the teeth.
- Improved stability results from the tripod contacts for each functional cusp.

When the mesiodistal relationships of opposing teeth favor it, the cusp-fossa scheme is optimal. If these relationships are not present, the choice is between (1) distorting coronal axial form to accommodate the preferred occlusal scheme and (2) altering the occlusal structure to accommodate normal axial form. Significant deviation from normal axial form by overcontouring invariably results in adverse soft tissue responses. Altering axial form by undercontouring rarely causes such problems. Depending on the specific spatial relationship between the antagonists, the cusp–marginal ridge scheme may be a better choice in such situations. However, the decision is not always a clear one. Tooth size and position variations among patients produce a continuum between the optimal cusp–marginal ridge and cusp-fossa schemes. Common sense dictates using the scheme that produces the best overall functional and esthetic result. In many cases, this can be determined only by trial and error. The placement of cones before any other occlusal waxing is often the most expedient way to accomplish this.

Cusp height and location

1. Determine the position and height of the cusps with wax cones (Fig. 18.60). This is done so that necessary modifications can be made rapidly. Add wax cones for each cusp, and mark the central fossae of opposing teeth to help position the cusps correctly.

Fig. 18.58 Occlusal waxing with the sequential wax addition technique. (A) To develop accurate occlusal contacts, wax is added in small increments, and the articulator is closed while the added wax is still soft. (B) Powder is used to verify the location and size of the contact. (C) Cones are used to determine the location of the lingual cusp tips. (D and E) The various features of the occlusal surface are developed sequentially in wax. (F and G) Secondary occlusal features can be refined by reflowing the wax and burnishing the fissures. (H–K) Completed waxing with occlusal contacts marked. (For the cusp–marginal ridge scheme, numbers refer to cusp position in Table 18.1.)

2. Position the centric or functional cusps (mandibular buccal and maxillary lingual) so that they occlude along the buccolingual center of the opposing tooth. The actual cusp tips do not contact the opposing tooth. Greater stability and reduced wear are possible with small points of contact distributed around the cusp tips.
3. Use the mesiodistal location of the cones to determine the type of occlusal scheme to be attempted: cusp–marginal ridge or cusp-fossa (Fig. 18.61; see also Fig. 18.58H–K, and Tables 18.1 and 18.2).

Evaluation. The cones should be positioned so that they follow the anteroposterior curve (sometimes referred to as the *curve of Spee;* Fig. 18.62). This is the anatomic curve established by the occlusal alignment of the teeth, as projected onto the median plane, beginning with the cusp tip of the mandibular canine and following the buccal cusp tips of the premolar and molar teeth, continuing through the anterior border of the mandibular ramus, ending with the most anterior portion of the mandibular condyle. The mandibular cusps should become taller farther distally, and the maxillary cusps should become shorter. The cusps should also follow a mediolateral curve (sometimes referred to as the *curve of Wilson*). In the mandibular arch, this is the curve (viewed in the frontal plane) that is concave above and contacts the buccal and lingual cusp tips of the mandibular molars; in the maxillary arch, it is the curve (viewed in the frontal plane) that is convex below and contacts the buccal and lingual cusp tips of the maxillary molars. When viewed

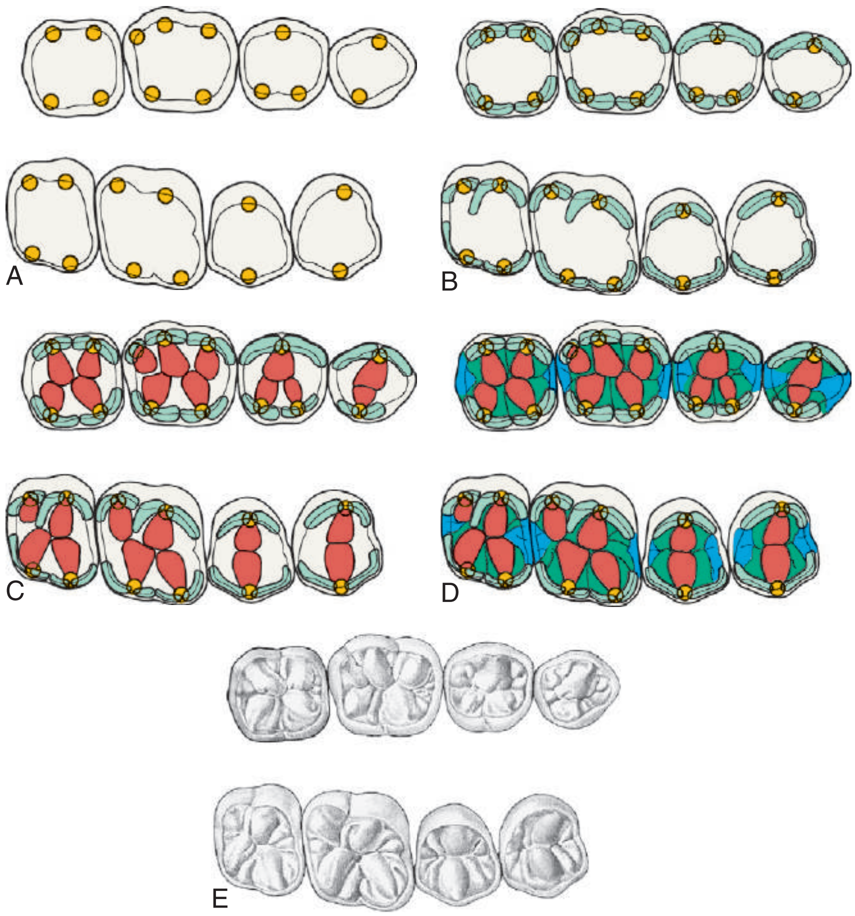


Fig. 18.59 Sequence of occlusal wax addition. (A) Step 1: placement of cones. (B) Step 2: superimposition of cuspal ridges. (C) Step 3: placement of cones, cuspal ridges, and triangular ridges. (D) Step 4: placement of cones, cuspal ridges, triangular ridges, and secondary and marginal ridges. (E) Step 5: finished occlusal waxing.

TABLE 18.1 Features of Cusp–Marginal Ridge Scheme: Functional Cusp Articulation

Tooth	Cusp Position	Functional Cusp	Opposing Fossa	Opposing Marginal Ridge[a]
Maxilla				
First premolar	1	L	D	—
Second premolar	2	L	D	—
First molar	3	ML	C	—
	4	DL	—	D and M (second molar)
Second molar	5	ML	C	—
	6	DL	—	D
Mandible				
First premolar	1	B	—	M
Second premolar	2	B	—	D and M (first premolar)
First molar	3	MB	—	D and M (second premolar)
	4	DB	C	—
Second molar	5	MB	—	D and M (first molar)
	6	DB	C	—

[a]Same tooth unless otherwise specified.
B, Buccal; *C*, central; *D*, distal; *DB*, distobuccal; *DL*, distolingual; *M*, mesial; *MB*, mesiobuccal; *ML*, mesiolingual.
See Fig. 18.61A.

TABLE 18.2 Cusp-Fossa Scheme: Functional Cusp Articulation

Tooth	Cusp Position	Centric Cusp	Opposing Marginal Ridge[a]
Maxilla			
First premolar	1	L	D
Second premolar	2	L	D
First molar	3	ML	C
	4	DL	D
Second molar	5	ML	C
	6	DL	D
Mandible			
First premolar	1	B	M
Second premolar	2	B	M
First molar	3	MB	M
	4	DB	C
	5	D	D
Second molar	6	MB	M
	7	DB	C

[a]Same tooth unless otherwise specified.
B, Buccal; *C*, central; *D*, distal; *DB*, distobuccal; *DL*, distolingual; *M*, mesial; *MB*, mesiobuccal; *ML*, mesiolingual.
See Fig. 18.61B.
Courtesy Dr. A.G. Gegauff.

from the front, the nonfunctional cusps are slightly shorter than the centric cusps. All eccentric movements should be reproduced on the articulator; if unwanted contact results in protrusive, working, and nonworking excursions, they should be eliminated by either reduction or repositioning of the cones. Proper cone height and position are key to the development of proper occlusal form.

Completion of axial contours

4. Complete the axial contours (marginal ridges and cuspal ridges; Fig. 18.63). Be especially careful not to alter the location or height of the cusps as previously determined with the cones.
5. After each addition of wax, check for occlusal contact by closing the articulator. Do not increase the occlusal vertical dimension.

Evaluation. At this stage, the buccal, mesial, lingual, and distal surfaces have been completed (see Fig. 18.63). When viewed from these perspectives, the wax pattern should appear identical to an intact tooth. When viewed from the buccal perspective, each cusp should have a distinct profile, with the cusp tip highest and a gentle slope down to the marginal ridges. Adjacent marginal ridges should be of the same height. Occlusal contacts in excursive movements must also be evaluated. If there is unwanted contact, grooves can be created in the cuspal ridges to allow the passage of opposing cusps.

Triangular ridges

6. Give each cusp a triangular ridge (Fig. 18.64 and Fig. 18.58A) that runs toward the center of the occlusal surface. The apex (or point) of the triangle should be at the cusp tip, and the base should be in the center of the occlusal surface.

Fig. 18.60 (A) Adding wax cones to determine cusp height and location. (B) The cusp's height is determined by the anteroposterior curve (curve of Spee). (C) Marking the central fossae of opposing teeth helps position the functional cusps correctly. (D) All cones are positioned and tested for interferences in all excursions. (E–G) The wax additive technique is especially useful when multiple restorations are provided simultaneously.

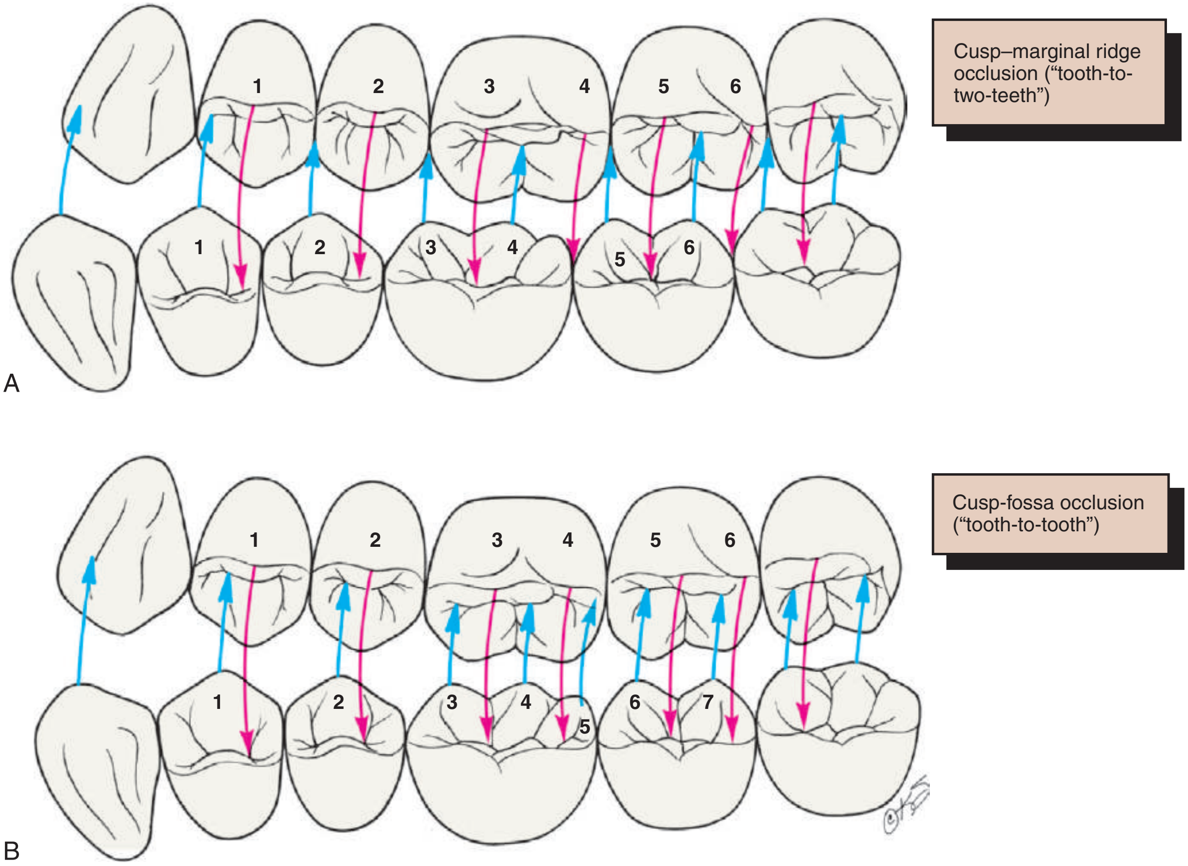


Fig. 18.61 (A) Cusp–marginal ridge occlusion ("tooth-to-two-teeth"). (B) Cusp-fossa occlusion ("tooth-to-tooth"). The numbers refer to those in Tables 18.1 and 18.2.

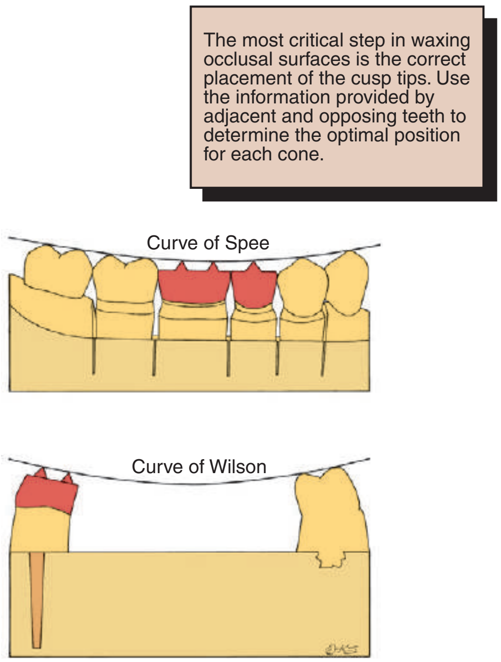


Fig. 18.62 Cones should follow the anteroposterior curve (curve of Spee) and the mediolateral curve (curve of Wilson).

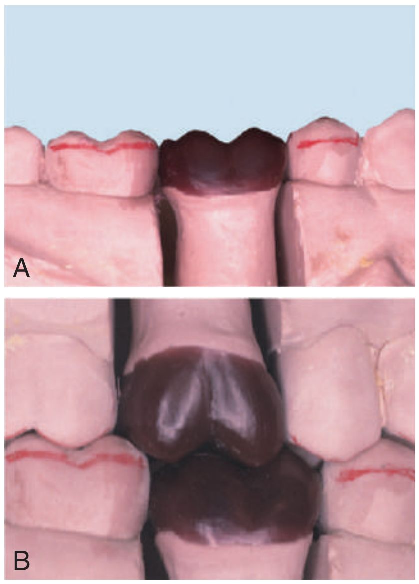


Fig. 18.63 Completed axial contours. (A) The maxillary buccal cusp ridges. (B) At this stage, the buccal surface is complete and should be evaluated for correct contour.

Fig. 18.64 Waxing maxillary triangular ridges.

Fig. 18.65 Evaluating occlusal contacts.

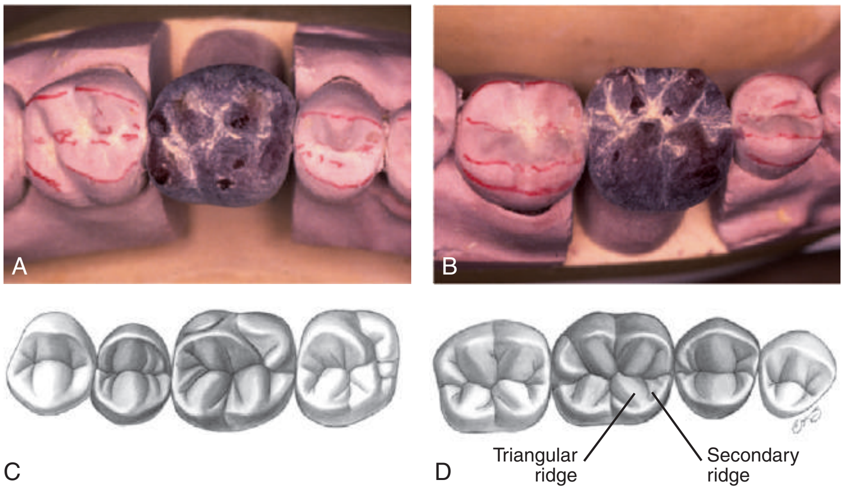


Fig. 18.66 Adding secondary ridges. (A and C) Maxillary first molar. (B and D) Mandibular first molar.

7. Make the bases of the buccal and lingual triangular ridges convex mesiodistally and buccolingually.
8. As each ridge is added, close the articulator. Where the occlusal surface meets an opposing tooth, note the small depression and adjust this to form a convex surface so that pinpoint contact exists.

Evaluation. The triangular ridges are dusted with zinc stearate or powdered wax (Fig. 18.65 and Fig. 18.48B). The cusps should still have their correct sharp contour and should not be rounded by improper polishing.

Secondary ridges

9. Make two secondary or supplemental ridges adjacent to each triangular ridge (Fig. 18.66 and Fig. 18.58F). All cusps should have a single triangular ridge and two secondary ridges. The degree of specific delineation between the triangular and secondary ridges varies, depending on the prominence of the cusp within the occlusal surface of the tooth that is being waxed.
10. Make the secondary ridges convex with grooves where they meet the convexities of the triangular ridges. The most mesial and most distal secondary ridges are often contiguous with the marginal ridges.

Evaluation. If the ridges have been carefully formed, only a small amount of finishing is needed at this stage (Figs. 18.67 and 18.68). Any pits can be filled with wax and the grooves carefully smoothed (see Fig. 18.58G). Initially, obtaining smooth transitions between the occlusal components may be difficult. Smoothing from the grooves onto the individual occlusal features, rather than back and forth, prevents unnecessary accumulations of wax residue in the grooves.

The occlusal surfaces are redusted with zinc stearate or powdered wax, and the occlusal contacts are checked. If a contact has inadvertently been polished away, it can be quickly re-formed by the addition of a drop of wax, closing of the articulator to verify that contact was restored, and subsequent reflowing and reshaping of the occlusal feature to reestablish a convex contour.

Margin Finishing

To optimize the adaptation of the wax pattern (and the pressed or cast restoration) to the die, the margins must be reflowed and refinished immediately before the wax pattern is invested. The two principal objectives are (1) minimizing dissolution of the luting agent and (2) facilitating plaque control.

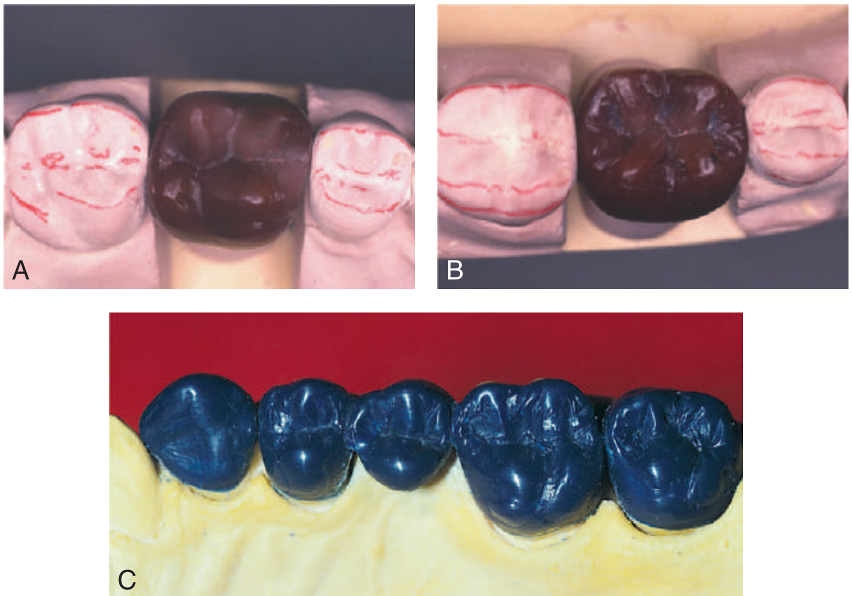


Fig. 18.67 Evaluating the completed wax patterns (A) Maxillary first molar. (B) Mandibular first molar. (C) Maxillary quadrant.

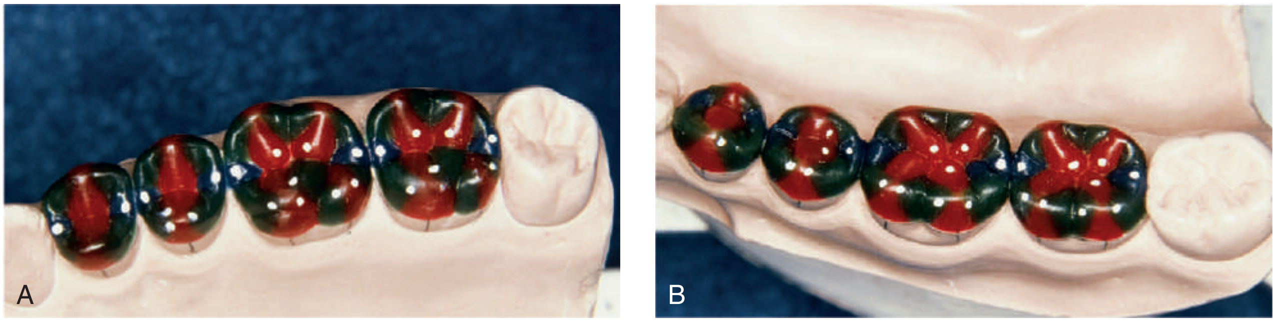


Fig. 18.68 Completed cusp–marginal ridge waxing. (A and B) The occlusal contacts have been marked.

If a zone of superior adaptation (i.e., minimum marginal gap width) between the casting and the prepared tooth surface is created, cement dissolution is reduced,[34] and the exposure of the rough cement surface is minimized. To obtain this superior adaptation, the pattern should be reflowed over a band approximately 1 mm wide, measured from the margin onto the prepared surface (Fig. 18.69).

Plaque control is facilitated when the transition from cast restoration to tooth is smooth, without any sudden directional change. In addition, the axial surface of the restoration must be highly polished (see Chapter 28). Because the use of any metal polishing compound or abrasive material results in removal of restoration material, metal finishing procedures should be kept to a minimum near the margin. The best way to prepare for this step is to ensure superior smoothness of the wax pattern when the reflowing process is complete. This should be verified under magnification with loupes or a binocular microscope.

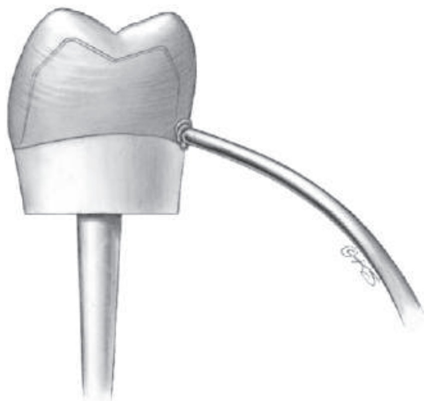


Fig. 18.69 Reflowing the margins. The objective is to create a well-adapted, 1-mm zone to prevent cement dissolution.

Step-by-step procedure

1. Relubricate the die and reseat the wax pattern (Fig. 18.70A). Because of the time and attention devoted to developing occlusal and axial form, the margins of the pattern are not properly adapted at this stage. Use a large, well-heated waxing instrument to melt completely through the wax.
2. Push the heated instrument through the pattern and completely remelt the marginal 1 to 2 mm (see Fig. 18.69).

3. Draw the instrument along the margin until resistance is felt because the instrument has begun to cool and no longer easily melts the wax.
4. Reheat the instrument and repeat the procedure, always overlapping with the previously melted area to remelt it and to preclude internal folds, voids, and defects. When the entire margin has been reflowed circumferentially, a depression is seen around the margin as a result of the readaptation.
5. Fill the depression with additional wax (see Fig. 18.70B).
6. Trim excess wax from beyond the margin (see Fig. 18.70C).
7. Rectify any pits or defects in the axial surfaces, and smooth the wax pattern. Wax chips can be removed from the occlusal surface with a cotton pellet; however, the surface should not be rubbed. Otherwise, the occlusal contacts that were so carefully generated will be destroyed.

The wax pattern is removed from the die without distortion and may be replaced for final evaluation before investing. However, if the pattern is not repositioned in exactly the same direction as that in which it was removed, reburnishing of the margins may be necessary.

Evaluation. Being thorough at this stage will contribute to the success of the restoration. Because of the wax pattern's color and glossy surface, small defects can be difficult to identify. If they are not noticed, a later remake may be necessary.

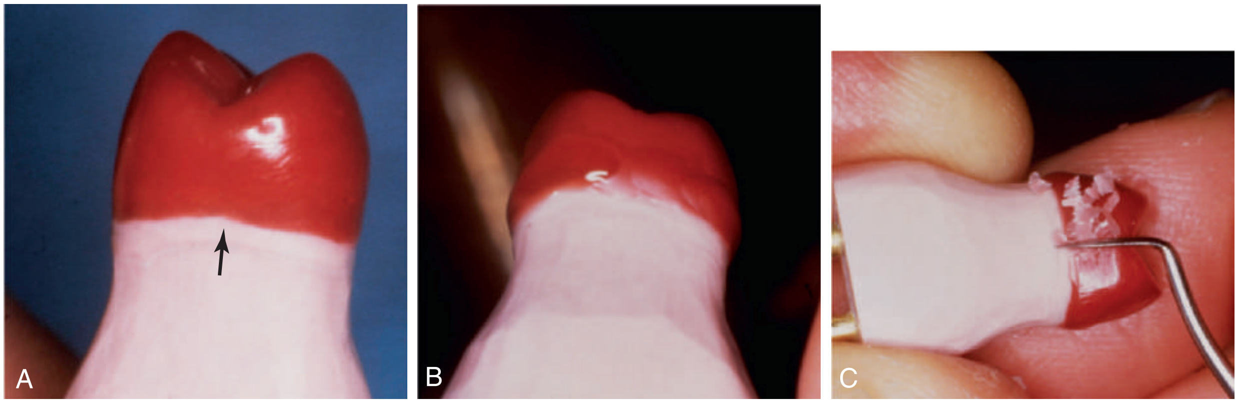


Fig. 18.70 Reflowing margins. (A) After waxing, a marginal discrepancy is normally apparent *(arrow)*. This must be corrected before investment. (B) A large, well-heated instrument is used to melt completely through the wax. Then the practitioner continues around the preparation margin and adds wax to fill the depression. (C) When the pattern has cooled, the marginal excess is carefully trimmed or burnished.

Overwaxing must be avoided. Very little finishing of a cast metal margin is possible without damaging the die. Any flash of wax that extends beyond the finish line *must* be trimmed at this stage; otherwise, it will cause distortion as the pattern is removed, or it will prevent the cast metal restoration from completely seating. A gap between the wax and the die, resulting in an open margin, can be difficult to detect. The die should be oriented so that the observer's line of sight is precisely along the wax-die interface. If the wax is not well adapted, a black shadow line will be visible. This is hard to see in wax but easier to see (but too late) in metal. A binocular microscope or loupe is very helpful for detecting this line (Fig. 18.71). To ensure that new debris has not accumulated during the finishing procedures, a final evaluation of the occlusal and axial surfaces is performed. The pattern is now ready for investing (see Chapter 22).

Waxing Inlays and Onlays

The sequence of steps for fabricating a wax pattern for an inlay or onlay is similar to that for a complete crown, although the unprepared tooth can often serve as a guide to axial and occlusal contour (Fig. 18.72). Sometimes manipulation of a small inlay can be difficult. One approach is to embed a loop of floss into the pattern for easier removal.

Waxing Anterior Teeth

The approach to waxing anterior teeth is slightly different from the approach to waxing posterior teeth. Anatomic contour waxing is recommended for metal-ceramic restorations because there is better control over the thickness of porcelain and the smoothness of the metal-ceramic junction. When several anterior teeth are to be restored, a guide to the lingual and labial contours is essential (Fig. 18.73). The contour of the palatal and incisal surfaces significantly influences the articulation. They are most effectively re-created with the use of a custom anterior guide table (see Chapter 2). This can be made from diagnostic casts (if their initial form was satisfactory) or from a diagnostic waxing or cast made from an impression of interim restorations. The latter can be used when the interim restorations result in clinically satisfactory function and appearance. The shape of the anterior teeth affects the patient's speech, lip support, and appearance. Those characteristics

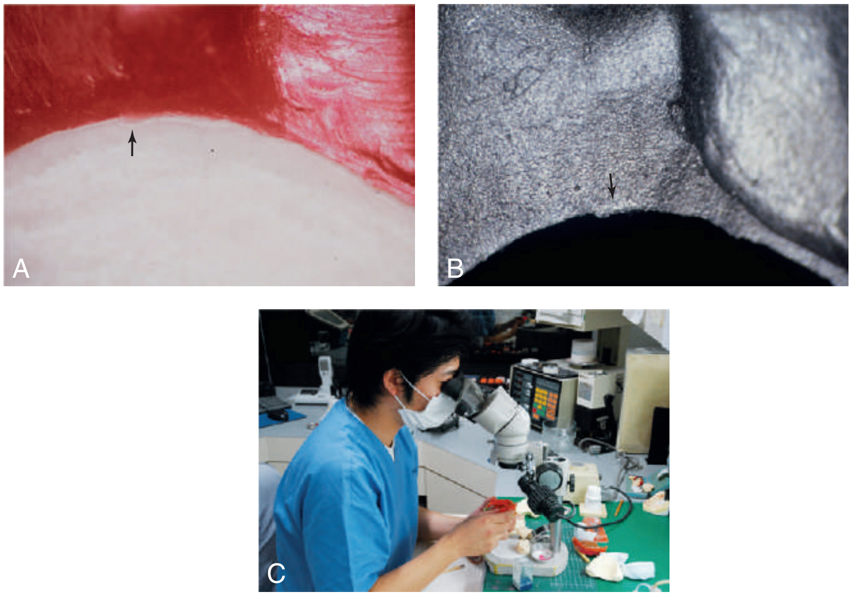


Fig. 18.71 Evaluation. Defects must be identified and corrected before investment. (A) Marginal excess or flash *(arrow)* is difficult to see in wax but must be carefully removed. (B) A small defect *(arrow)* is easier to see in the metal but harder to correct. (C) Magnification is the most practical way to finish margins properly.

should be determined carefully and with as many diagnostic aids as necessary.

Lingual and Incisal Surfaces

The position of the incisal edges is determined by the overall arch form of the anterior teeth and the functional occlusal requirements (Fig. 18.74). As with waxing of posterior occlusal surfaces, cones can be used to initially delineate the approximate position of the incisal edge. Additional wax can then be applied as necessary.

Opposing incisors should contact evenly during protrusive movements but not during lateral excursions. To achieve this result, a concavity is made in the lingual surface of maxillary incisors. The ability to make this concavity smooth is very important. As a result, the patient acquires a smooth protrusive movement, and potential neuromuscular disturbances are avoided. In maximum intercuspation, anterior teeth ideally should be just out of contact. Mylar shim stock should just “drag” between the patterns. The lingual surfaces of mandibular incisors and canines are noncontacting surfaces. Nevertheless, they should be shaped for easy plaque control. They should not be overcontoured.

Labial Surfaces

The shape of the labial surfaces, particularly the locations of the mesiolabial and distolabial line angles, determines the appearance of anterior teeth (Fig. 18.75). If the labial surface is too bulbous, plaque control may be difficult, and there may be lingual tilting of the tooth caused by the force exerted by the upper lip. When individual anterior teeth are waxed, careful study of the embrasure form of adjacent teeth can be particularly helpful.

Wax Cutback

If a ceramic veneer is to be used, once the definitive contour of the wax pattern has been completed, the pattern is cut back over an even thickness—usually approximately 1 mm—to provide room for the porcelain fused onto the cast metal substructure (Fig. 18.76). The design and technique are discussed in Chapter 19.

Waxing Connectors

The connectors that join the separate components of a fixed dental prosthesis are created in wax just before the margins are finalized (Fig. 18.77). Whether the connectors are cast or soldered, they must be shaped in wax so that their size, position, and configuration are controlled precisely. Connector size is important primarily from a mechanical perspective. To ensure optimal strength, the connector should be as large as possible. However, from a biologic perspective, connectors should not impinge on the gingival tissues and should be at least 1 mm above the crest of the interproximal soft tissue. Embrasure form gingival to the connectors must enable optimal plaque control. The cervical aspect of the connector must be shaped to a smooth, archlike configuration. In esthetic areas (i.e., anterior fixed dental prostheses), connectors should be hidden behind the esthetic ceramic veneer. Therefore, connectors are often placed slightly lingually when connectors are waxed for anterior prostheses (Fig. 18.78). Connector form and design are discussed in detail in Chapter 27.

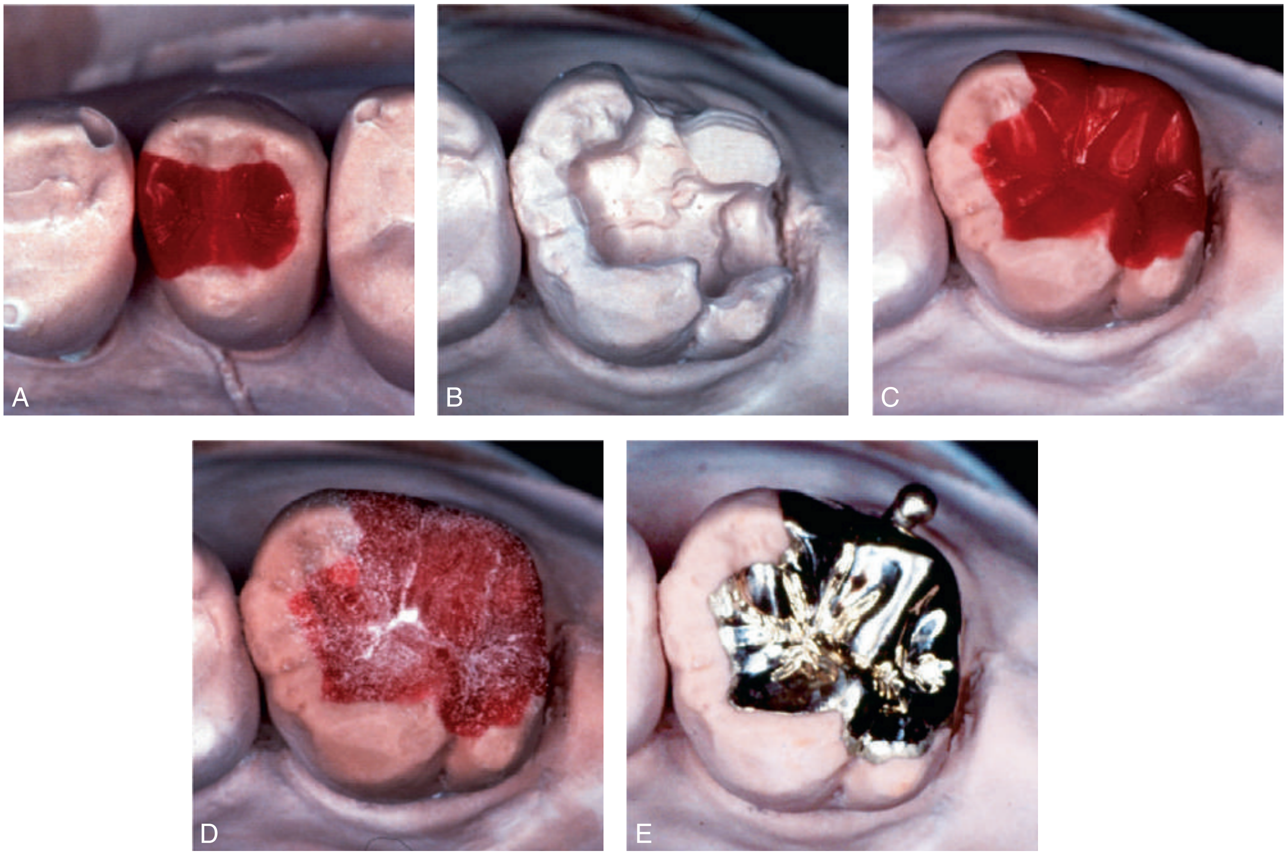


Fig. 18.72 Waxing inlay and onlay restorations. (A) Mesio-occlusal inlay wax pattern. (B–E) Disto-occlusal–distobuccal onlay wax pattern and casting.

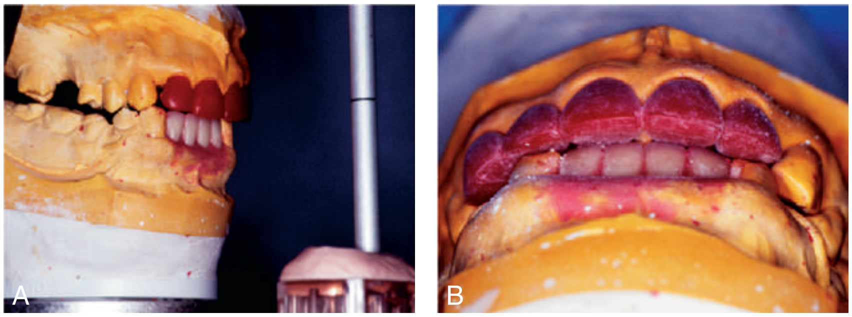


Fig. 18.73 (A and B) Optimum contours for anterior restorations are developed with the aid of a custom anterior guide table (see Fig. 19.4).

Fig. 18.74 When the lingual surface of an anterior tooth is waxed, the contralateral tooth should be used as a guide.

Printed Wax Patterns

Additive fabrication of wax patterns is a rapidly developing field in dental technology.[35] With the advances in three-dimensional printing, dental applications include the printing of patterns from a CAD (see Fig. 18.31). Laboratory three-dimensional printers have become a part of conversion to digital workflow in many dental laboratories. They expel microdroplets of proprietary wax blends or resins, developing a pattern from a CAD in a layer-by-layer manner. In some systems, heated wax that solidifies on cooling

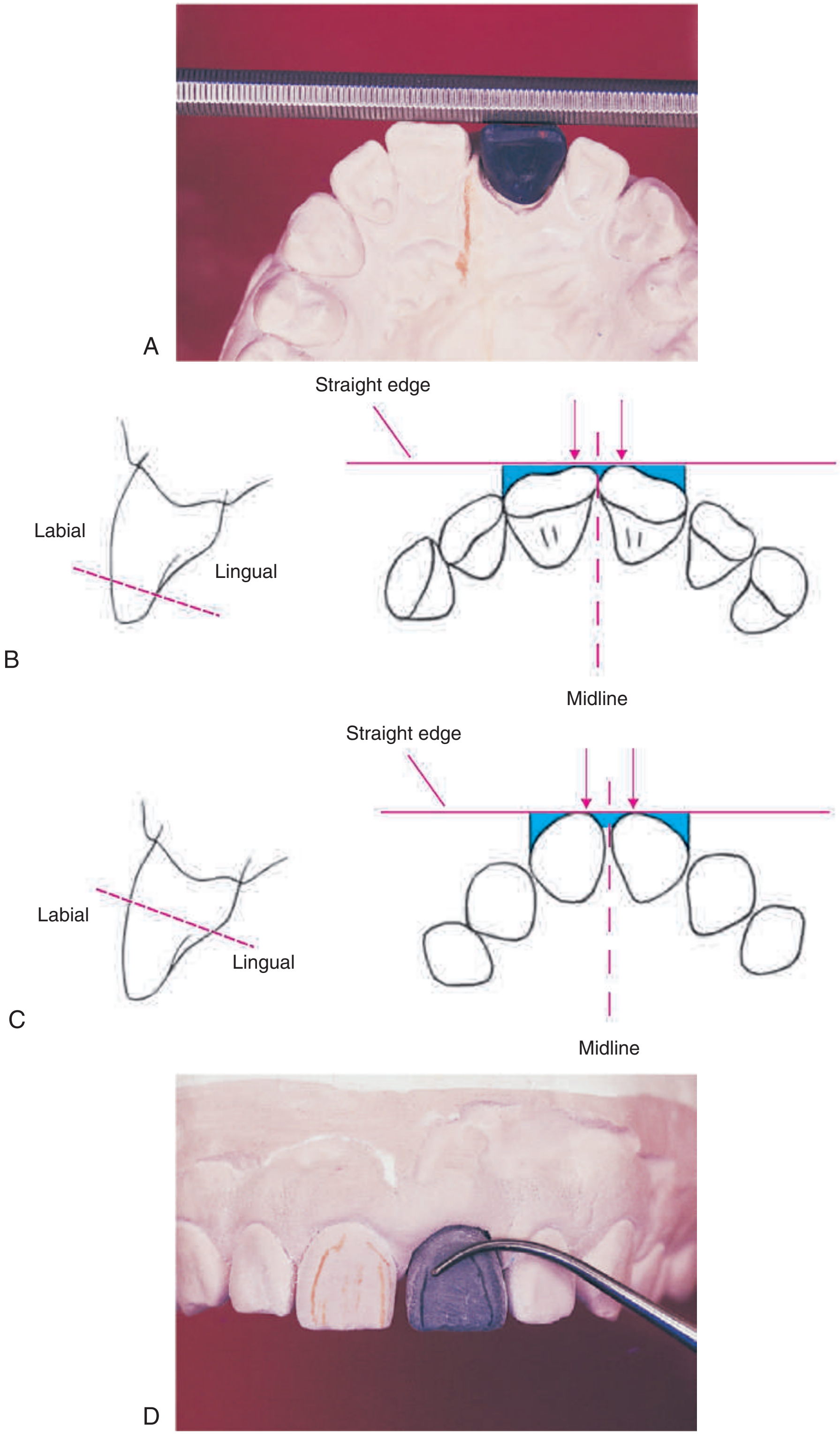


Fig. 18.75 Waxing the labial surfaces of maxillary incisors. Typically, the two central incisors should possess mirror symmetry around the midline. (A) As the waxing progresses, symmetry can be judged by placing a straight edge near the incisal edge and exactly perpendicular to the palatal midline. (B) The straight edge should contact each central incisor at precisely the same distance from the midline *(arrows)*. The wax can be easily adjusted if proper contact does not occur. Then the spaces between the straight edge and the wax pattern *(blue areas)* are evaluated. The left and right teeth should be mirror images both mesially and distally. (C) The straight edge is repositioned farther apically, and the analysis is repeated. Note how the form of the embrasures varies at the different locations. (D) Dusting the wax pattern and marking the mesial and distal line angles. These should correspond to the line angles marked on the contralateral tooth.

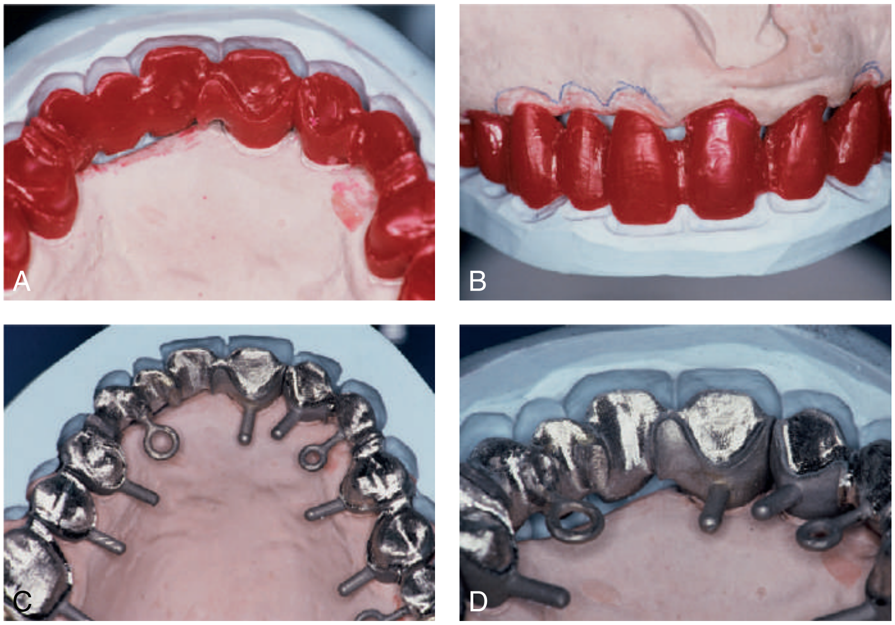


Fig. 18.76 (A–D) Wax patterns cut back to provide room for the porcelain (see Chapter 19).

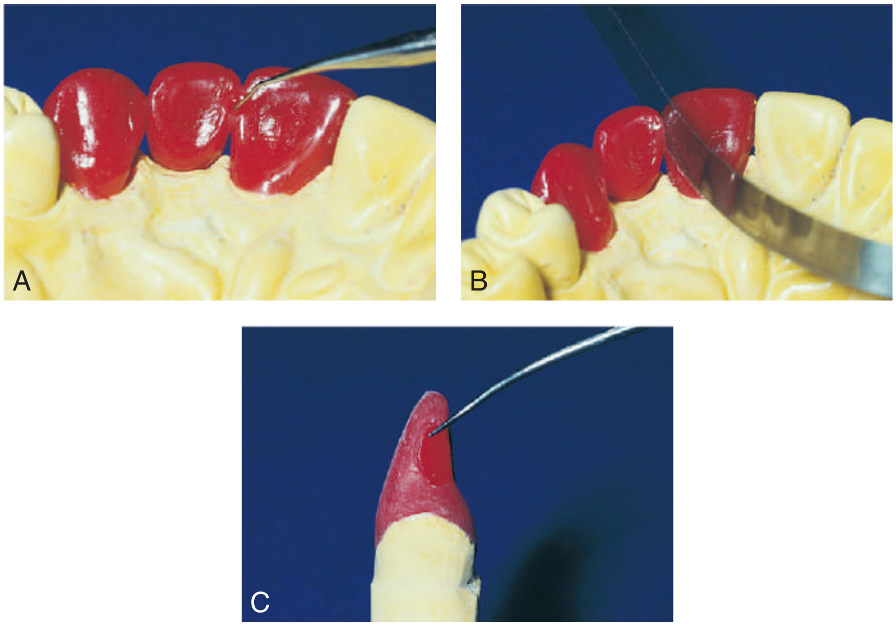


Fig. 18.77 Waxing connectors. (A) The clinician can control the shape, size, and location of connectors by forming them in wax. (B) A ribbon saw is then used to section them. (C) The correct cross-sectional configuration of an anterior connector.

is used, much like conventional waxes. The materials that require polymerization can be activated by either ultraviolet or visible light, which can be provided by a light source such as a xenon lamp or a light-emitting diode (LED). Some manufacturers claim resolutions in the range from 13 to 50 μm.[36] The margins of the resulting patterns can be manually readapted before investing for subsequent conventional casting of metal prostheses (see Chapter 22) or pressing of ceramic crowns. Stabilization of the pattern requires printing supporting struts or matrices as the patterns are gradually built up. On completion of the printing procedure, the supporting sacrificial material is dissolved in a water or oil bath and rinsed away, after which the pattern can be invested (Fig. 18.79).

Milling Wax Patterns

The same technology that is used to mill ceramic crowns (see Chapter 25) has been applied to the fabrication of wax patterns.[37] Sophisticated milling machines can mill multiple patterns from a single specially formulated wax puck. The CADs are positioned in a virtual puck before the milling procedure,

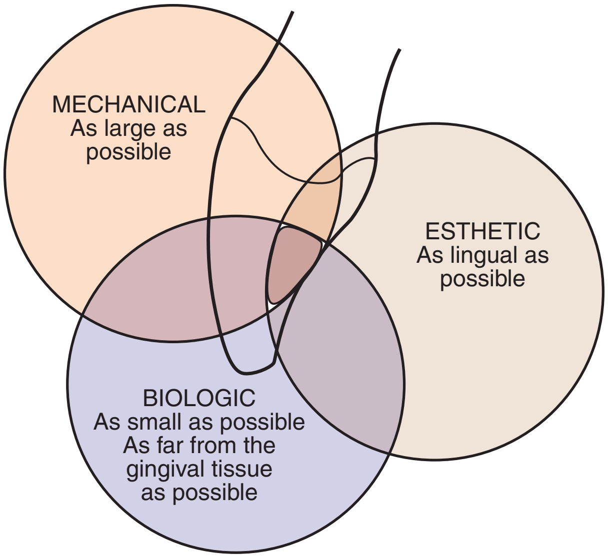


Fig. 18.78 Considerations for anterior connector placement. Mechanically, the connector should be as large as possible for strength. From a biologic perspective, the connector is most effectively placed in the incisal half of the proximal wall. For esthetics, the connector should be placed in the lingual (palatal) half of the proximal wall.

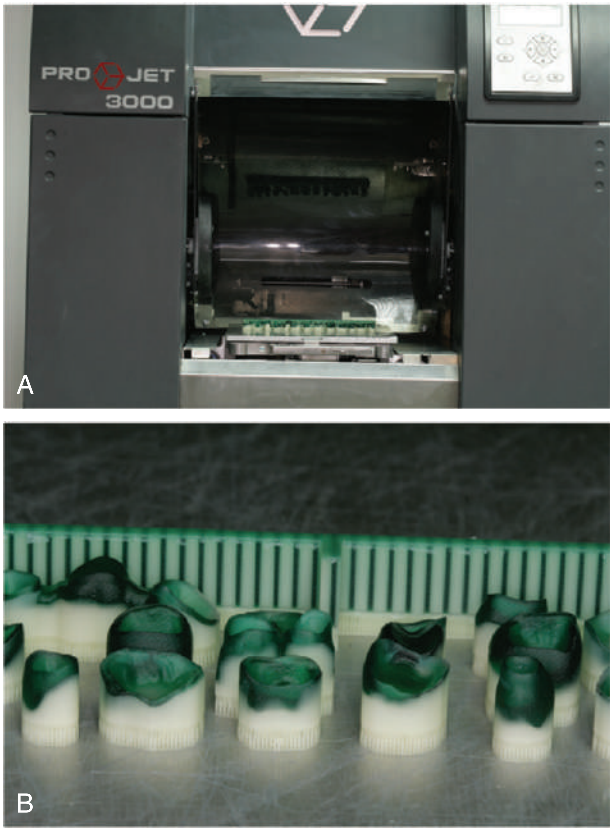


Fig. 18.79 Printing wax patterns. (A) Wax pattern printer. (B) Close-up of printed patterns. Note the supporting material *(white)* that is necessary for pattern stabilization during the additive printing process. The supporting material will be eliminated before investing. (Courtesy Dental Arts Laboratory, Peoria, Illinois.)

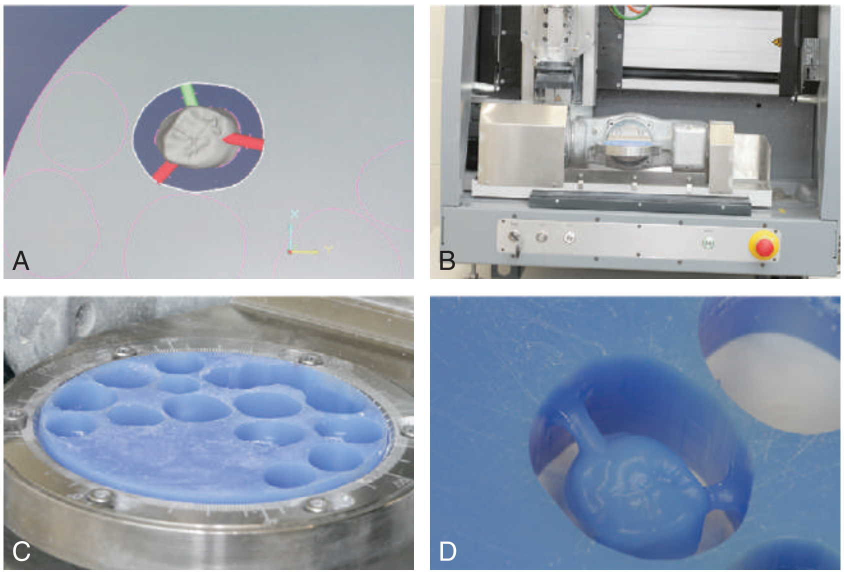


Fig. 18.80 Milling wax patterns. (A) Computer-aided design (CAD) of a wax pattern for a complete cast crown. (B) Specially formulated wax disk positioned in milling machine. (C) Wax disk and close-up view (D) of milled wax pattern for complete cast crown. (Courtesy Dental Arts Laboratory, Peoria, Illinois.)

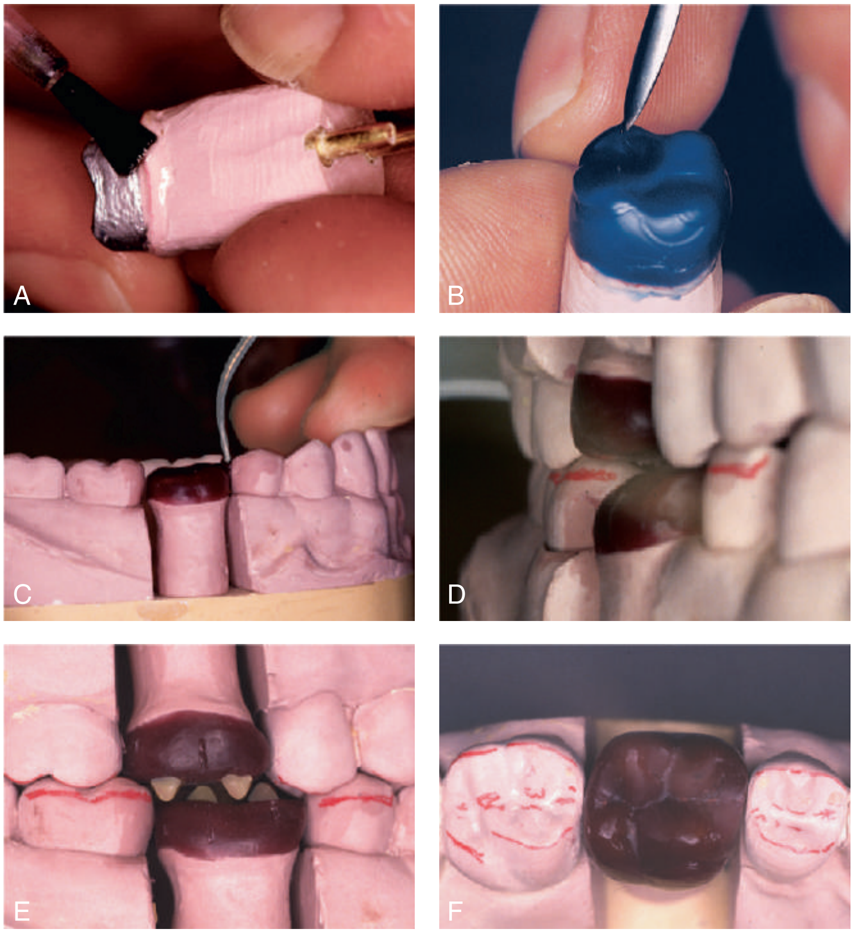


Fig. 18.81 Technique review. (A) The die is modified as necessary and lubricated. (B) An initial coping is waxed; this forms the internal surface. (C) The proximal surfaces are developed with correctly located contact areas. (D) The axial surfaces are waxed. (E) The occlusal surfaces are developed with a wax addition technique. (F) The margins are reflowed, and the wax pattern is finished.

and the software is designed to attempt and nest the patterns in such a manner that the optimal number of patterns is derived from a single puck (Fig. 18.80).

REVIEW OF TECHNIQUE

Fig. 18.81 summarizes the steps for waxing to anatomic form.

- The die is modified as necessary and lubricated (see Fig. 18.81A).
- An initial coping is waxed; this forms the internal surface (see Fig. 18.81B).
- The proximal surfaces are developed, with correctly located contact areas (see Fig. 18.81C).
- The axial surfaces are waxed. Overcontouring near the gingival margin must be avoided (see Fig. 18.81D).
- The occlusal surfaces are developed with a wax addition technique, which makes it easier to determine the best location of cusps and occlusal contacts (see Fig. 18.81E).
- The margins are reflowed, and the wax pattern is finished (see Fig. 18.81F).

SUMMARY

Whether the definitive restoration is designed through a digital or traditional waxing workflow, the principles of form and function remain the same. In this chapter, different principles were addressed under the digital and traditional workflow; however, one must understand that a thorough understanding of both needs to be grasped to fully master either workflow. In a CAD/CAM restoration design, many restorative parameters (for example, cement space) are predetermined in program settings. Without an understanding of predetermined settings within a program, the wrong settings may negatively affect the restoration design and future function.

If the waxing procedure is followed in a sequential order, inexperienced but conscientious operators should have no problem achieving excellent results. With more experience, they can combine and modify some of these steps; however, waxing up teeth "from memory" is not advised. Even the most experienced technician should copy the shape of natural teeth rather than redesign them.

STUDY QUESTIONS

1. Discuss and explain the various techniques used to reduce or increase the resulting luting agent space. What is considered a desirable cement space?
2. What are the available techniques for producing a digital waxing?
3. What are the primary components of inlay casting waxes? What is wax "memory," and how does it affect the various technical procedures?
4. What are the recommended procedure and sequences for designing a ceramic crown on a maxillary incisor?
5. What is the recommended procedure and sequence for waxing a complete cast crown on a mandibular first molar?
6. What is the best way to evaluate wax pattern adaptation and contour?
7. How does the digital restoration design enhance the ability of the evaluator?
8. Discuss how the location of posterior proximal contacts changes as a function of tooth position in the arch.
9. What are the fundamental differences between the cusp–marginal ridge and cusp-fossa occlusal schemes? What are the primary reasons for selecting one scheme over the other? Does one have advantages over the other? If so, what are they?
10. Define the curve of Wilson and the curve of Spee. What is their importance with regard to occlusal form?
11. Why is it necessary to create connectors as a separate step in the fabrication of a fixed dental prosthesis?

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19

Framework Design and Metal Selection for Metal-Ceramic Restorations

Esthetics is an essential part of restorative practice: All patients want a pleasing smile. Particular scrutiny must be given to color, shape, surface texture, and proportion. Because anterior and maxillary posterior teeth are the most visible, they require the greatest attention to esthetic detail.

Tooth-colored restorative materials have evolved from the soluble silicate cements of the past to the composite resin materials and resin-modified glass ionomer cements of today. Currently, metal-ceramic prostheses are widely accepted and, despite some esthetic limitations, remain commonly used and reliable extracoronal restorations. They combine the superior fit of a casting with the outstanding esthetics of dental porcelain. Because the ceramic veneer is chemically bonded to the metal substructure (with the possible exception of the press-on technique [see Chapter 24]), such restorations are not subject to the discoloration problems associated with acrylic resin veneer crowns and, provided that appropriate clinical and laboratory protocols are followed, longevity can be excellent.[1,2] In addition, the material properties of dental porcelain are better able than resin to withstand wear under functional loading.

The concept of combining a brittle material with an elastic material to achieve more desirable physical properties has many engineering applications. Dental porcelains (which are, chemically speaking, glasses) resist compressive loading but tend to succumb to tensile stress. Therefore, the metal substructure must be designed so that any tensile stresses in the porcelain are minimized.

To avoid fracture, the thickness of a ceramic veneer must not exceed 2 mm; however, 1 mm is the minimum thickness needed for an esthetically pleasing restoration.

Restorations with porcelain occlusal surfaces must be planned carefully. Although they are esthetically very acceptable, these restorations have disadvantages, especially wear of the opposing enamel.[3] Ideally, an esthetic restoration should wear at approximately the same rate as the enamel it replaces (approximately 10 μm per year[4]). In addition, the restoration should not increase the wear rate of an opposing enamel surface. Dental porcelain is more abrasive of enamel than of other restorative materials (e.g., gold or amalgam[5–9]) and has been implicated in severe occlusal wear, particularly when the porcelain is not glazed or highly polished (Fig. 19.1).[10] This should be considered whenever a metal-ceramic restoration is being designed,[11] and the practitioner should realize that although abrasiveness may be correlated with the composition of the ceramic material, the selection of a lower fusing ceramic (sometimes labeled by the manufacturer as *low-wear*) does not necessarily mean less wear of opposing enamel.[12] Less wear has been cited as the most important need for improvement of posterior tooth-colored crowns.[13] In addition, porcelain occlusal coverage results in restorations with lower strength,[14] and anatomically correct occlusal form with sharp cusps can be difficult to obtain in dental porcelain.

Some dental laboratory technicians may attempt to fabricate a framework by dipping the die into molten wax, obtaining an even metal framework thickness. After the excess wax is trimmed away, a gingival collar is added, and the pattern is sprued, invested, and cast. When it is completed, the ceramic veneer is then applied. This technique almost always results in an uneven porcelain thickness, with increased potential for porcelain fracture as a result of lack of proper support (Fig. 19.2). If porcelain thickness is not well controlled, appearance suffers as well because the shade of the definitive crown depends on porcelain thickness.[15] For predictable success, the framework must be carefully designed and shaped.

PREREQUISITES

Framework design for a fixed partial denture (FPD) should be considered during the treatment planning stage (see Chapter 3) and should be evaluated at the diagnostic tooth preparation and waxing stages, particularly for more complex treatments. Proper framework configuration for a metal-ceramic crown or FPD can be achieved routinely only through waxing of the restoration to final anatomic contour, followed by cutting back of a consistent amount for the veneer. This allows for even thickness of porcelain, proper porcelain-metal interfaces, good connector design, and optimally placed occlusal contacts.

Waxing to Anatomic Contour

The main objective is to shape a substructure that supports a relatively even thickness of porcelain. Simultaneously, if the retainer is to serve as part of an FPD, it must allow for proper connector configuration and location. Furthermore, the restoration must conform to the normal anatomic configuration of the tooth that is being replaced. At the porcelain-metal interface, the ceramic material should be at least 0.5 mm thick. The framework should be shaped to allow for a distinct margin so that the porcelain is not overextended (Fig. 19.3). There should be no abrupt contour change between the metal and the adjacent porcelain, and the definitive restoration must exhibit an optimal emergence profile (see Chapter 18).

The most effective way to consistently meet these criteria is to develop the definitive contours of the proposed restoration in wax (Fig. 19.4). Once this is completed, the area to

Fig. 19.1 (A–D) Destructive enamel wear associated with metal-ceramic restorations. (Courtesy Dr. M.T. Padilla.)

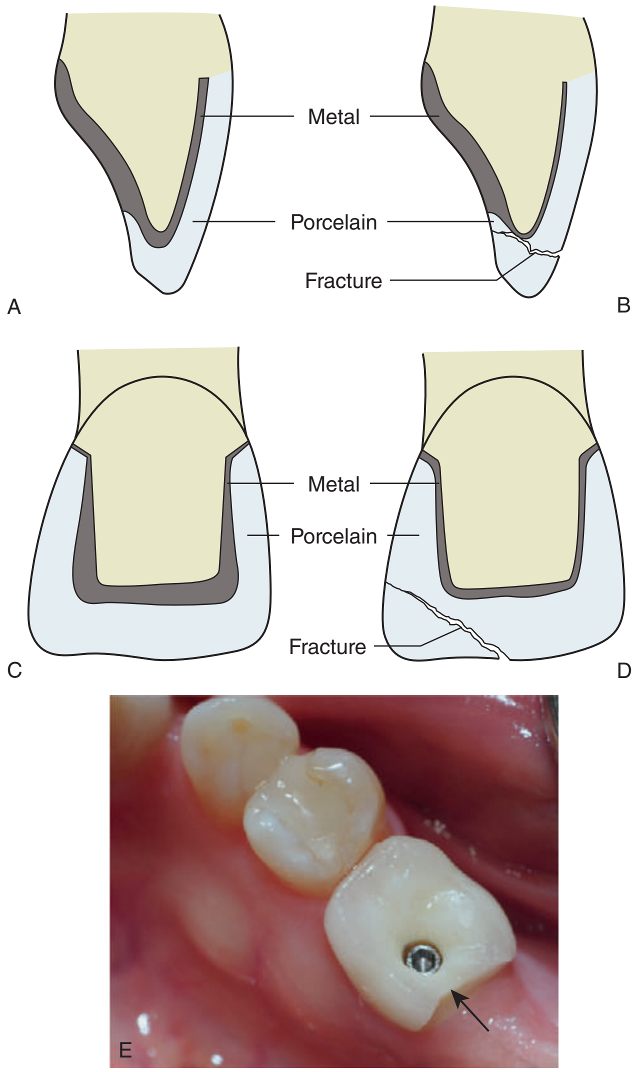
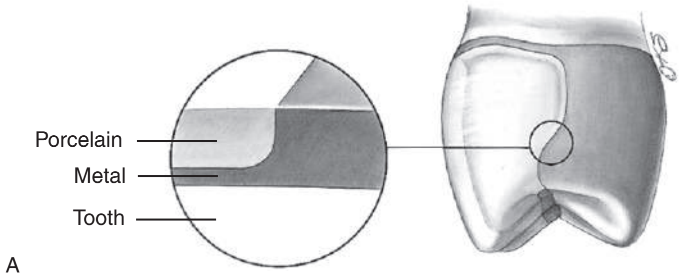


Fig. 19.2 Cross sections through a metal-ceramic restoration. (A and C) Ideal porcelain thickness is ensured by waxing to the complete anatomic contour and cutting back. (B and D) Incorrect framework design has insufficient support for the incisal porcelain. This can lead to fracture. (E) On this implant-supported crown with a zirconium substructure, the feldspathic veneer failed (*arrow*) because support was insufficient.



There should not be any sharp angles or pits on the surface that is to be veneered.

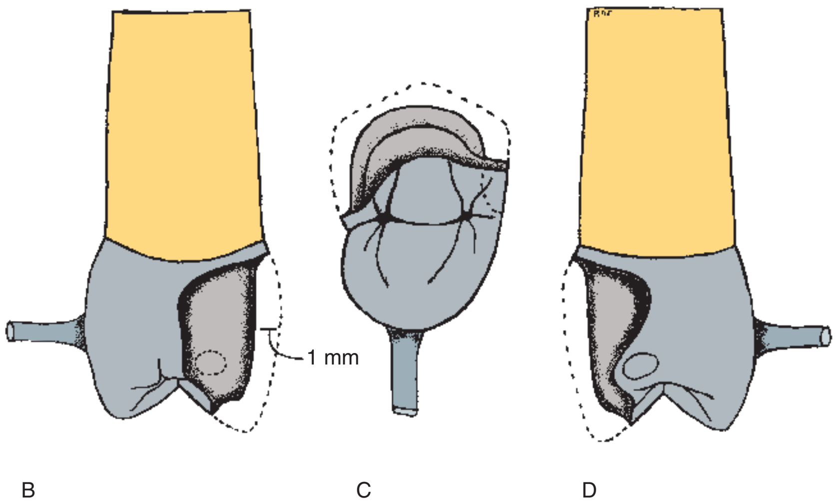


Fig. 19.3 (A) The metal substructure should have a distinct margin for finishing the veneer. The location of the ceramic-metal interface varies, depending on the material chosen to contact adjacent and opposing teeth. (B) Cutback for proximal contact in porcelain. (C) Occlusal contact in metal. (D) Proximal contact in metal. (B to D, Courtesy Dr. R. Froemling.)

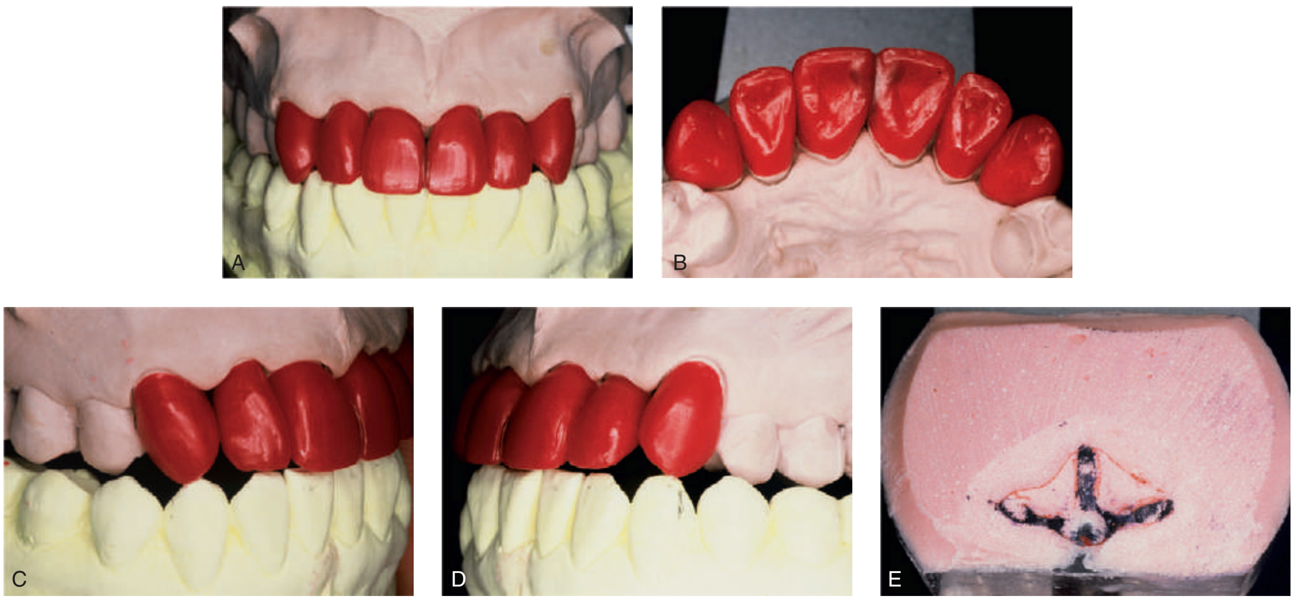


Fig. 19.4 (A and B) Anterior metal-ceramic restorations after waxing. (C) Right lateral excursion. (D) Left lateral excursion. (E) The anterior guidance is determined with a custom table fabricated from the diagnostic waxing procedure (see Chapter 2).

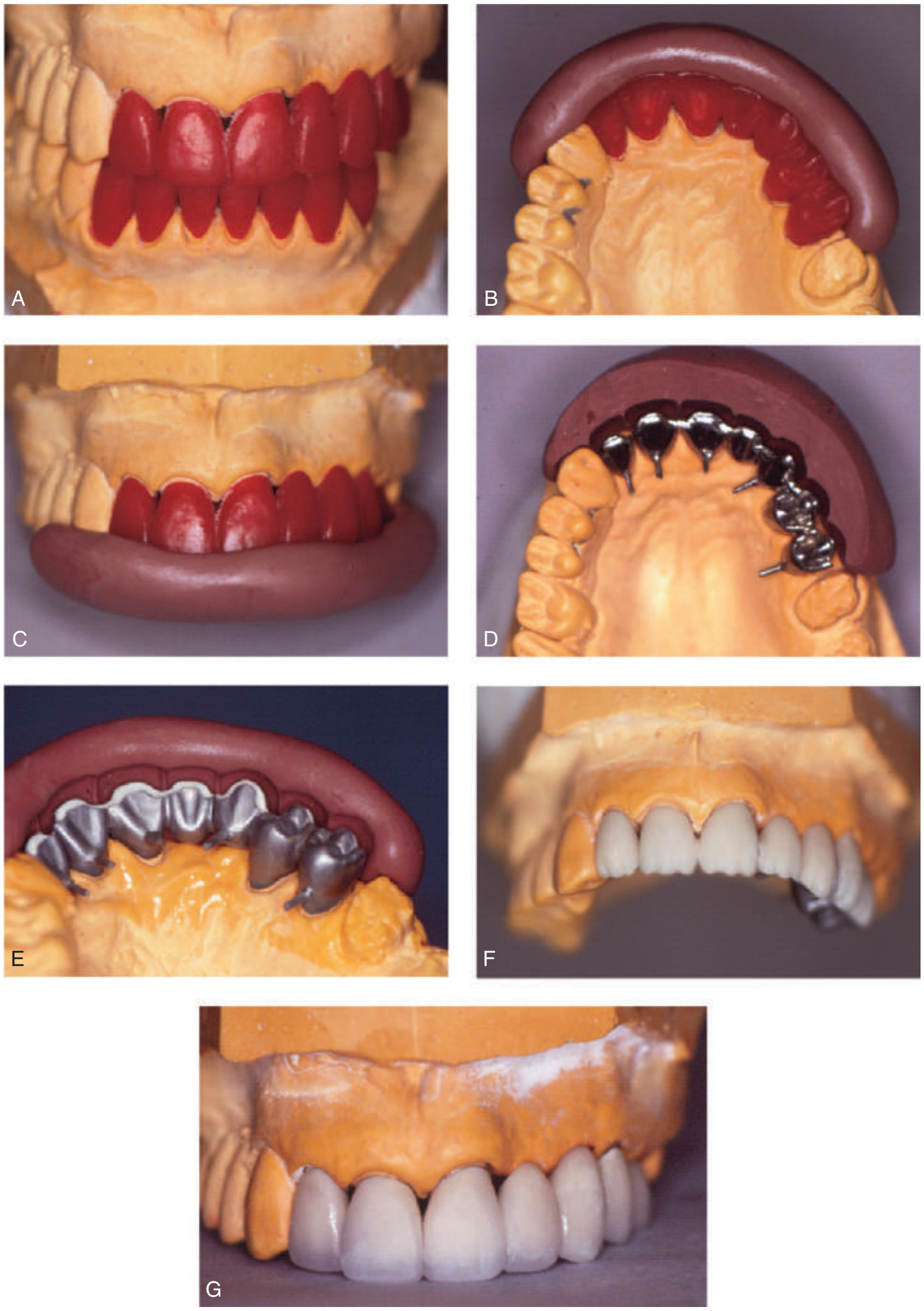


Fig. 19.5 Predictable esthetic result ensured by waxing to anatomic contour. (A) Anatomic contour wax patterns. (B and C) Incisal and labial indices were used to verify even cutback. (D) Cast substructures. (E) The labial index is reused during porcelain application. (F) The porcelain application. (G) After contouring, the restorations are ready for clinical evaluation. (Courtesy Dr. M. Chen.)

be veneered can be demarcated and an even thickness of wax removed. If this technique is not followed, one or more of the objectives is almost certainly missed, and the contours of the framework are not in harmony with the optimal ceramic configuration (Fig. 19.5).

Occlusal Analysis

The centric stops of any metal-ceramic restoration can be located on either porcelain or metal. However, they must be at least 1.5 mm away from the junction[16] to prevent porcelain fracture from deformation of the metal (Fig. 19.6). Care is needed to minimize sliding contacts across the porcelain-metal interface. When this is not possible, the framework must be modified so that the porcelain is well supported in the area of functional contact.

Existing restorations in the opposing arch can influence framework design. Because sliding contact of a porcelain restoration with a cast crown abrades the gold, the framework design must be modified as necessary. A complete cast crown in the mandibular arch presents little difficulty. It can be opposed by a maxillary restoration with a metal occlusal surface and only a facial ceramic veneer (Fig. 19.7). An

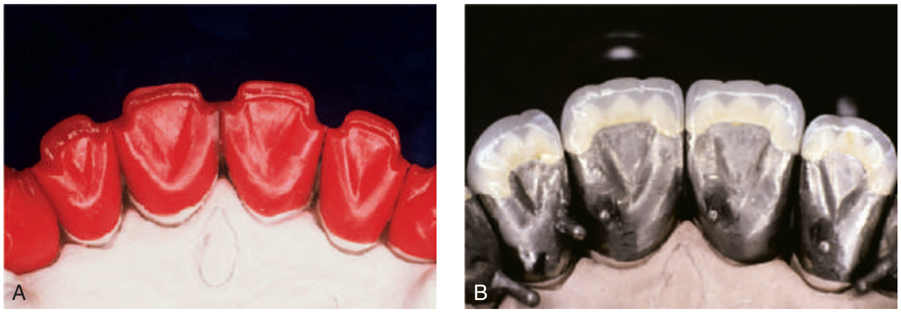


Fig. 19.6 (A) The metal-ceramic junction must be carefully placed to avoid areas of high stress near occlusal contacts. (B) Waxing to the anatomic contour ensures a smooth transition from porcelain to metal.

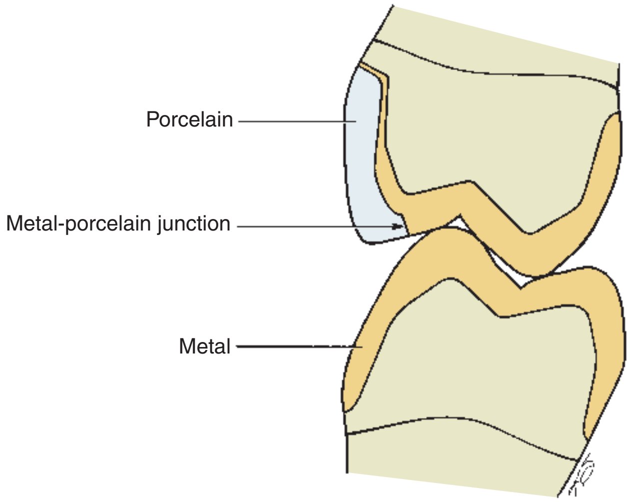


Fig. 19.7 The metal-ceramic restoration should be designed so that porcelain does not oppose an existing gold restoration. This presents few problems in the maxillary arch because the less visible lingual cusps are in contact.

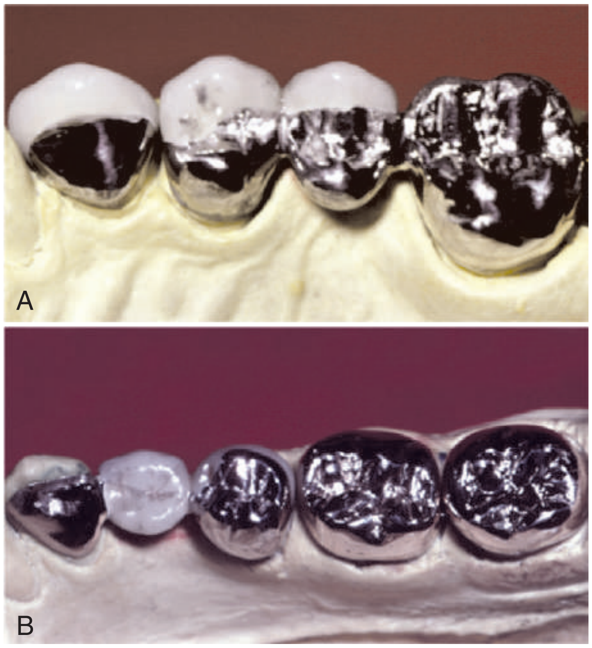


Fig. 19.9 (A and B) Opposing restorations must be carefully planned so that contacting surfaces are of the same material (i.e., metal opposing metal, porcelain opposing porcelain).

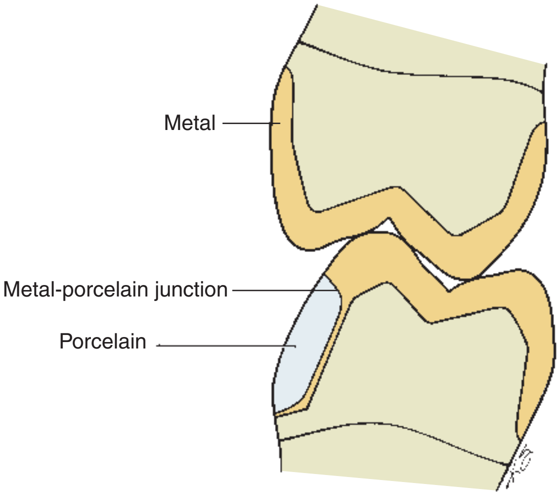


Fig. 19.8 In the mandibular arch, the functional cusps are visible, and only a buccal window of porcelain can be made without its contacting an opposing metal crown. Under these circumstances, it must be decided whether the patient should accept an esthetic or functional compromise.

existing metal crown on a maxillary molar, however, restricts the design of a mandibular metal-ceramic restoration if metal-to-porcelain contact is to be avoided (Fig. 19.8). In this situation, the facial veneer can no longer be extended to include the buccal cusp tips and associated centric stops without contacting the opposing restoration. A complete cast crown is usually more conservative because most patients do not show the facial surfaces of their mandibular posterior teeth. In other situations, particularly on mandibular first premolars, a facial veneer is esthetically essential, and the design of opposing restorations should allow for it (Fig. 19.9).

CUTTING BACK

The criteria for waxing to anatomic contour are discussed in Chapter 18. This section deals with cutting back the veneering area.

Armamentarium

- Bunsen burner
- Inlay wax
- Cloth
- Sharp pencil
- Die-wax separating liquid
- Powdered wax
- Waxing instruments
- Nylon hose and silk cloth
- Cutback instrument
- Scalpel
- Discoid carver
- Wax saw
- Waxing brushes

Step-by-Step Procedure

Designing the Cutback

Esthetic and functional needs govern the design of the veneering surface. The ceramic veneer should extend far enough interproximally, particularly in the cervical half of the restoration, to avoid metal display. Wherever possible, the functional occlusal surfaces should be designed in metal because an accurate occlusion is then easier to achieve (Fig. 19.10). However, esthetic demands may necessitate extension of the porcelain veneer (e.g., on the mesial incline of a mandibular buccal cusp). The extent to which a restoration can be veneered is determined largely by the location of the centric stops.

1. Do not place any proximal contacts on the junction between metal and porcelain: Plaque accumulation there may result

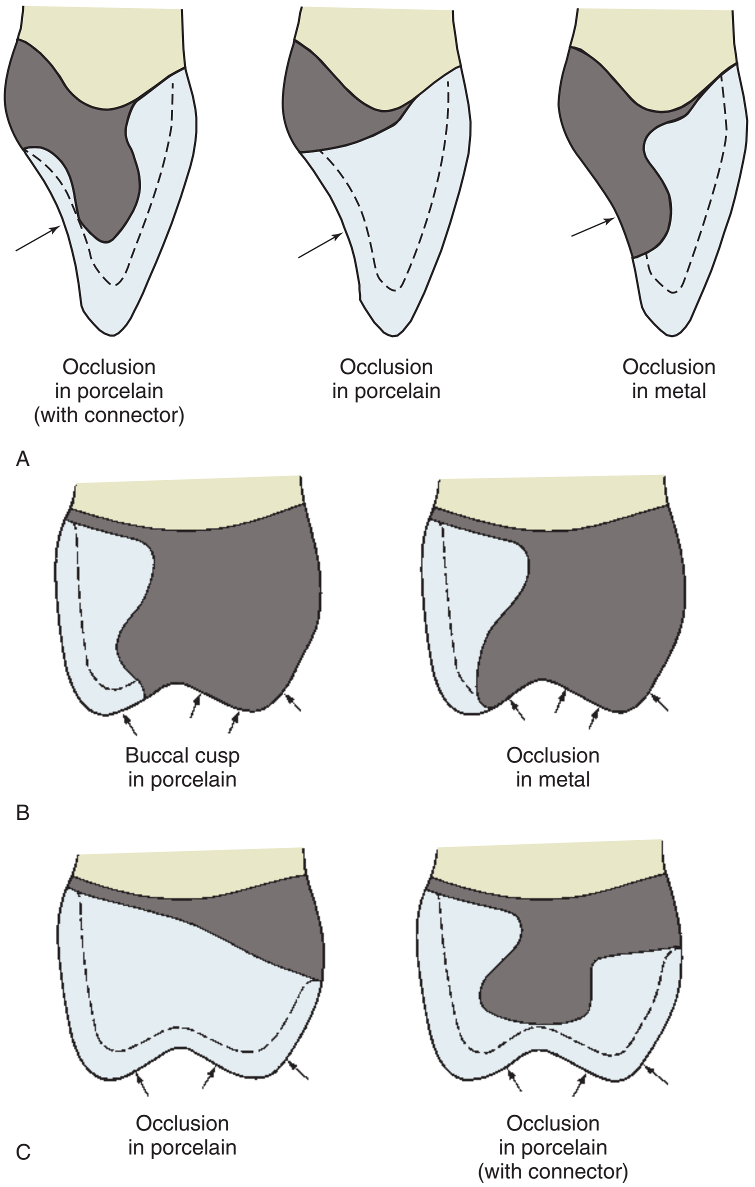


Fig. 19.10 Framework designs for a maxillary incisor (A) and a maxillary posterior tooth (B). The cutback should be designed so the occlusal contacts *(arrows)* are 1.5 mm away from the porcelain-metal junction. (C) Framework designs for porcelain occlusal surfaces.

in caries of the adjacent tooth. Normally, for good appearance and because it is more easily cleaned, proximal contacts are designed to be in porcelain. On some posterior teeth, however, where the interproximal area cannot be easily seen, a more conservative preparation may be possible, with the contacts entirely in metal (see Fig. 19.3D).

2. Once the extent of the cutback area has been determined, use a sharp instrument (e.g., an explorer or scalpel) to mark a line delineating the porcelain-metal interface.
3. Dust the pattern with powdered wax, and close the articulator to determine the location of the centric contacts.
4. Inspect the design to verify that the proposed junction is far enough away from the contacts (1.5 mm) to prevent distortion of the metal and porcelain fracture.

Troughing the Pattern

Just as guiding grooves are used to mark the amount of substance to be removed in tooth preparation, depth cuts *(troughing)* can be used to standardize the amount of wax to be removed from the veneering area.

5. Modify an old or damaged hand instrument with a separating disk to serve as a cutback instrument (Fig. 19.11).[a] The cutting edge should resemble the tip of a straight chisel. There should be a flat stop exactly 1 mm from the cutting edge.
6. Make depth cuts around the periphery of the cutback area that are perpendicular to the surface of the wax pattern. Depending on the size of the cutback area, one or more vertical and horizontal cuts can also be made.
7. Remove the islands in between with a scalpel or another carving instrument (Fig. 19.12A–E).

[a]A suitable instrument is available from Hu-Friedy Manufacturing Co., Inc, Chicago, Illinois.

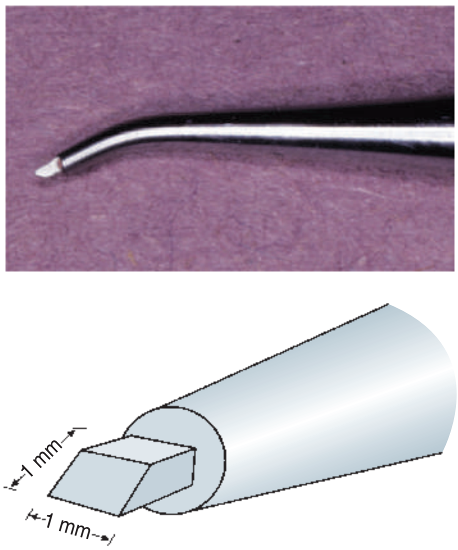


Fig. 19.11 A cutback instrument can be readily made from a damaged hand instrument.

Finishing

8. Once the bulk reduction has been completed, smooth the veneering surface of the wax. This ensures a rounded design and minimizes the time spent on metal finishing. Sharp angles on the veneering surface concentrate stresses, which may lead to fracture of the restoration.[17] Smoothing is much easier in wax than in metal, although this is not always appreciated by the less experienced.
9. Finish the porcelain-metal interface to a 90-degree butt joint (see Fig. 19.12F–J). Reflowing the margin is essentially the same as for conventional wax patterns (see Chapter 18).
10. Reestablish the collar (obliterated during reflowing) immediately before investing. Make it slightly thicker (approximately 0.5 mm) to ensure an undistorted complete casting (Fig. 19.13). When waxing for the porcelain labial margin technique (see Chapter 24), some technicians prefer to wax a collar and cut back the metal; others wax to the collarless shape, but care should then be exercised to avoid distorting the fragile pattern.

Connector Design

11. Establish the connectors in wax as described in Chapters 18 and 27. Properly shaped and positioned connectors are very important. If soldering is planned before or after ceramic application, separate the patterns with a fine saw.
12. If only a facial veneer is involved, make the connectors identical to those for a conventional restoration. If the incisal or occlusal aspect is involved in the porcelain veneer, do not displace the connector cervically (a common error) because access for oral hygiene will be impeded (Fig. 19.14).

Pontics

13. Because glazed vacuum-fired porcelain is easy to keep clean, include the tissue-contacting surfaces of pontics in the veneering surface (Fig. 19.15).
14. To improve handling and stability of the wax pattern, be sure to cut back this area last (see Chapter 20).

Evaluation

Immediately before the investing stage, the following criteria should have been met:

1. The pattern should conform to normal anatomic form. Centric stops should be located at least 1.5 mm from the porcelain-metal junction.
2. The angle between the veneering surface and the metal framework should be 90 degrees.
3. The internal surface of the veneering area should be smooth and rounded.
4. The collar height should be approximately 0.5 mm in wax with connectors of adequate size, but it should not impinge on the soft tissue in the interproximal areas.
5. The pattern should be smooth so that metal-finishing procedures are minimized.

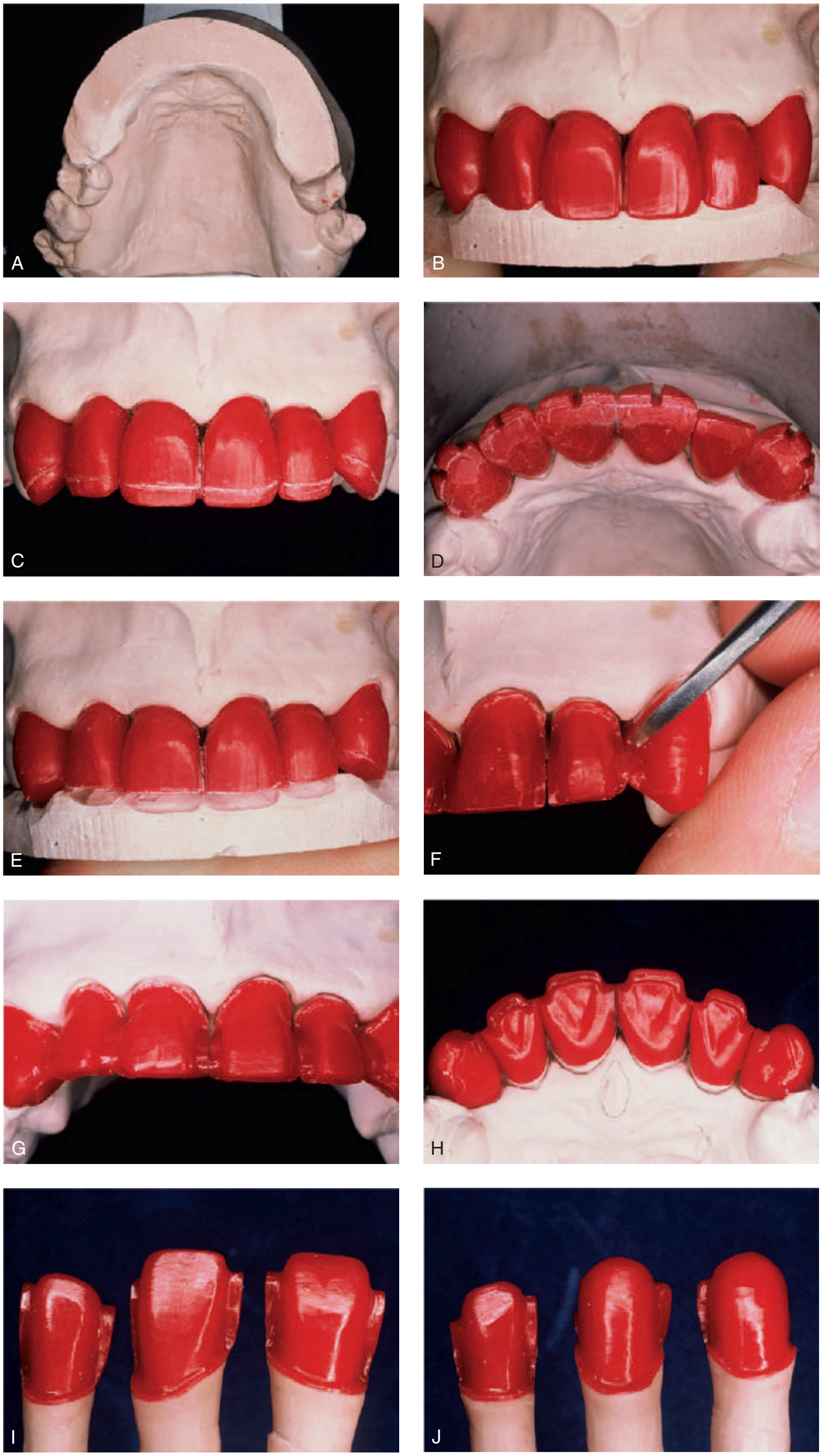


Fig. 19.12 Cutback procedure. (A and B) For extensive restorations, a matrix or index can be made to assist with the evaluation of the cutback and subsequent porcelain application. (C) It is important to follow the incisal contour carefully. (D) Guiding troughs are prepared in the area to be veneered. (E) Wax is removed from between the troughs. (F) The porcelain-metal interface is carved to a distinct butt joint. (G) Note the correctly shaped proximal contour. These units will have soldered connectors. (H) The finished cutback. (I and J) Patterns before reflowing of the margins.

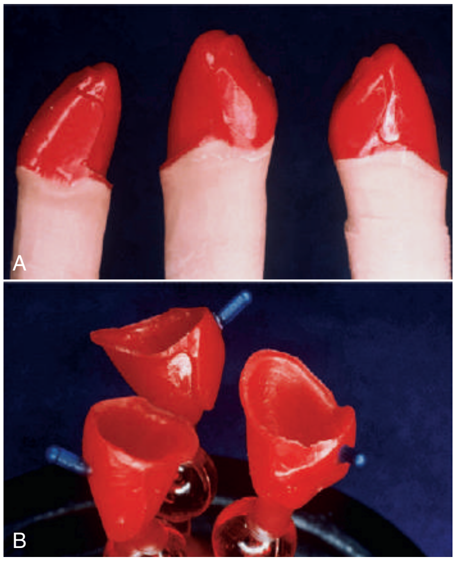


Fig. 19.13 (A) Margins reflowed. This ensures optimum adaptation of the wax pattern in the critical margin area. (B) Patterns before investing.

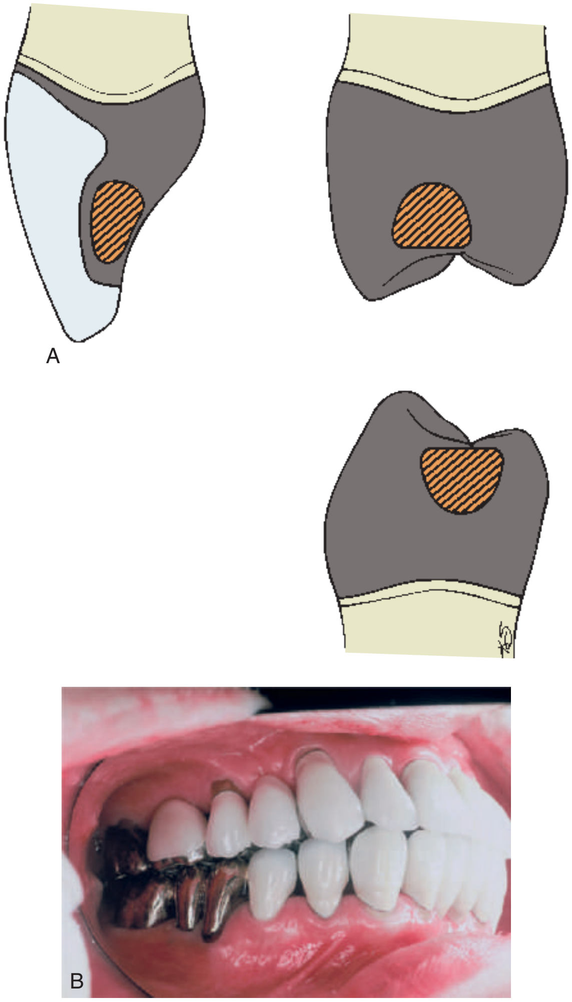


Fig. 19.14 (A and B) Connectors should be in locations where they do not impede oral hygiene measures.

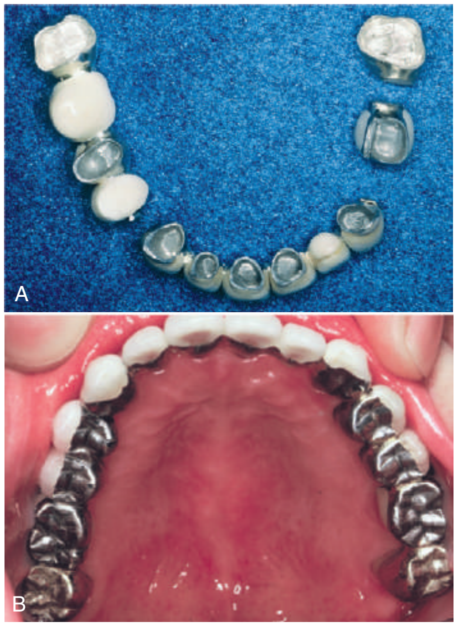


Fig. 19.15 (A and B) The tissue contact on the pontics of this extensive fixed prosthesis was established in porcelain.

PRINTED FRAMEWORK PATTERNS

Many dental laboratories now generate plastic patterns for metal ceramic restorations with a three-dimensional printing process (see Chapter 18).[18] The process is somewhat similar to that used for making household objects with a three-dimensional printer. The dental laboratory technician uses a special computer software program to generate a file of the framework design, and a pattern is fabricated by a stereolithographic process (see Chapter 17 for definitive casts and die systems). An advantage of this technology is that space for the porcelain and its proper support can be accurately designed into the framework. Dental students have been found to prefer the computer-aided design and computer-assisted manufacturing (CAD-CAM) process.[19] The process is illustrated in Fig. 19.16.

METAL SELECTION

William A. Brantley • Leon W. Laub • Carl J. Drago

Clinicians and dental laboratories face a potentially bewildering set of choices in selecting alloys for metal-ceramic restorations. Both noble metal and base metal casting alloys are available, and there are different alloy types for each of these two major groups. Each alloy type has advantages and disadvantages, including significant cost differences. Successful clinical practice depends on the selection of a compatible metal-porcelain combination that provides predictable results, depending on the particular patient's needs. Improper selection can cause catastrophic failure (Fig. 19.17). For a better understanding of the different properties provided on the packaging of casting alloys, the meanings and clinical relevance of these properties are discussed next.

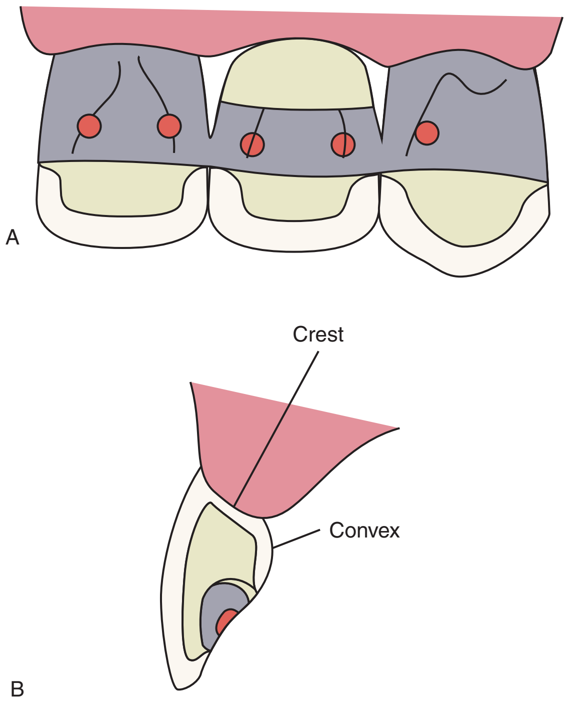


Fig. 19.16 Cutback design for a lateral incisor pontic with modified ridge-lap design (see Chapter 20). (A) Lingual view of cutback. The design provides uniform porcelain thickness, adequate distance between occlusal stops *(red circles)* and the metal-ceramic interface, and accessible cervical embrasures that allow for finishing and cleaning. (B) Faciolingual view through the pontic. Note the porcelain tissue contact, the relationship of the metal-ceramic junction to the connector *(gray area)*, and the location of the occlusal contacts *(red area)*.

Fig. 19.17 Failure caused by improper material selection.

Dental Connotations of Mechanical and Physical Properties for Ceramic Alloys

Mechanical properties of major clinical relevance are modulus of elasticity (elastic modulus), yield strength (or proportional limit), hardness, and creep or distortion at elevated temperatures. Ultimate tensile strength (UTS), ductility, and toughness should also be reviewed, although these properties have less relevance for metal-ceramic restorations. Except for hardness (and elevated temperature creep or distortion), all these mechanical properties are determined by the loading of a cast specimen of the alloy to the point of failure in a tension test at room temperature. The physical property of thermal contraction is crucial in the choice of an alloy that is compatible with the porcelain selected. From a practical standpoint, the density is important in both the economics of alloy selection and the dental laboratory procedure with the casting machine.

Modulus of Elasticity

Fig. 19.18 illustrates schematically the tensile stress-strain plot for a ductile casting alloy that undergoes substantial permanent deformation before fracture. This plot consists of two portions: (1) a linear or elastic region that ends at the proportional limit, where the stress is proportional to strain, and (2) a subsequent curved region corresponding to plastic or permanent deformation (which terminates when the test specimen fractures). The modulus of elasticity (also called *Young modulus*) is the slope of the stress-strain plot in the elastic region. The elastic modulus has the same value for tensile and compressive strains, which occur during bending of a prosthesis, in which regions on opposite sides of the neutral axis (center line for a symmetric cross section) undergo deformation in opposite directions. An alloy with a higher modulus of elasticity has greater stiffness or rigidity for elastic deformation. For the fabrication of a long-span FPD, an alloy with a relatively high elastic modulus to reduce the amount of bending deflection under loading is preferred because excessive flexure can cause fracture of the brittle porcelain (Fig. 19.19). The modulus of elasticity is represented as units of stress/strain and is reported for dental alloys in gigapascals ($1\,\text{GPa} = 10^9\,\text{Pa} = 145{,}000$ pounds per square inch [psi]). The unit of $1\,\text{Pa} = 1\,\text{N/m}^2$ is much too small to be useful for the elastic modulus of materials.

Proportional Limit and Yield Strength

In standard testing practice, investigators determine the proportional limit of an alloy by placing a straight edge on the stress-strain plot (or performing this operation with computer software) and noting the value at which the plot first deviates from a straight line. The proportional limit is often considered synonymous with the *elastic limit*, which corresponds to the value of stress at which permanent deformation occurs. However, the value of the elastic limit is highly dependent on the sensitivity of the strain-measuring apparatus. Moreover, precise location of the proportional limit on the stress-strain plot is somewhat problematic. Consequently, the *yield strength* (sometimes called *offset yield strength*) corresponds to the amount of stress for a very small designated amount of permanent deformation, such as 0.1% or 0.2% (permanent strains of 0.001 or 0.002, respectively). In the current standard for dental alloys used in prosthodontics (ISO 22674),[20] the term *proof stress* is used instead of *yield strength*. Table 19.1 presents information from the standard about the two alloy classifications appropriate for this chapter. The unit for yield strength is megapascal: $1\,\text{MPa} = 10^6\,\text{Pa} = 145\,\text{psi}$. As shown in Fig. 19.18, the investigator calculates the yield strength by constructing a line parallel to the initial straight-line portion of the stress-strain plot, starting with the specified value of offset on the horizontal strain axis and then noting the point of intersection with the curved portion of the plot. It follows that the

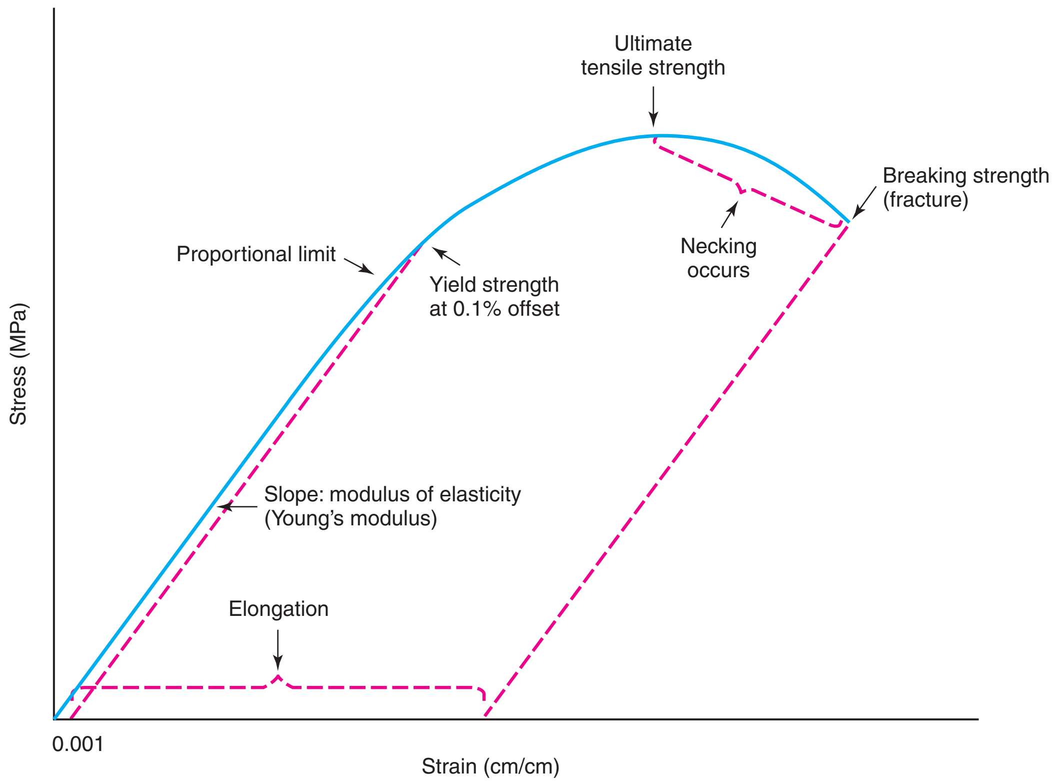


Fig. 19.18 Stress-strain curve.

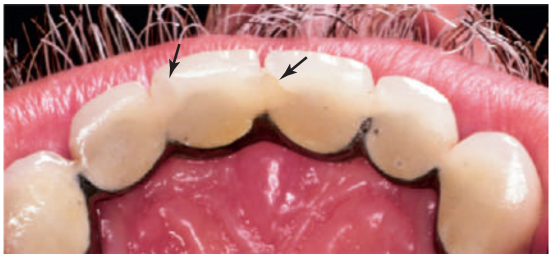


Fig. 19.19 Fracture *(arrows)* resulted from flexing of the substructure of this long-span partial fixed partial denture.

TABLE 19.1 Relevant Portion of Alloy Classifications from Standard ISO 22674:2006

Alloy Type	Minimum 0.2% Yield Strength (MPa)	Minimum Elongation (%)	Examples of Uses
3	270	5	Multiple-unit fixed partial dentures
4	360	2	Thin veneered crowns Long-span fixed partial dentures Small cross-section fixed prostheses Implant superstructures

Note: The alloy classification is generally provided by the manufacturer. There are six classifications. Types 0 and 1 are applicable to low stress-bearing single-tooth fixed restorations. Type 2 is applicable to single-tooth fixed restorations (inlays or crowns). Type 5 is applicable to partial removable partial dentures other parts with thin cross sections, and clasps. The minimum Young modulus requirement is 150 GPa for type 5 alloys, but not for types 0 to 4.
From International Organization for Standardization. *Dentistry—Metallic Materials for Fixed and Removable Restorations and Appliances [Standard ISO 22674:2006]*. Geneva: International Organization for Standardization; 2006.

0.2% yield strength can be substantially higher than the 0.1% yield strength for a given alloy, depending on the rate of work hardening (slope of the curved portion of the stress-strain plot). ISO 22674 stipulates that the value of the 0.2% yield strength is provided for a dental alloy by the manufacturer.[20] The yield strength is often called the *useful strength* of a dental alloy because stresses caused by masticatory forces should not exceed the yield strength, which would result in permanent deformation of the alloy. Although a sufficiently high yield strength is essential for a ceramic alloy, values that are too high create difficulties when the casting is adjusted in the dental laboratory or dental office.

Hardness

The Vickers hardness number (VHN) is generally measured for dental alloys by means of a symmetric diamond pyramidal indenter. The VHN is the quotient of the indenting load and the surface area of the permanent indentation, for which the square of the mean diagonal length is multiplied by a constant related to the indenter geometry.[21] The Knoop hardness number (KHN), obtained with a diamond indenter that has long and short axes, is sometimes reported for dental alloys.

For the KHN, only the length of the long diagonal side of an indentation is measured, and the indenting load is divided by the unrecovered projected area of the indentation because the elastic recovery after removal of the indenting load is along the shorter diagonal.[21] Harder alloys, which have smaller indentations, have higher VHN and KHN values. Conversion scales available for the two different hardness tests should be used with caution because such conversions are alloy dependent. Both the VHN and KHN are measures of the microhardness, in contrast to the older Brinell and Rockwell tests, in which much larger indenters are used to measure the macrohardness. When the Vickers hardness of an alloy is measured, an understanding of the microstructure is crucial. Use of a large indenting load of 1 kgf (49 N) for dental alloys provides information about the overall hardness of the alloy microstructure, whereas light indenting loads (e.g., 0.5 N) can be used to obtain information about the hardness of individual grains, constituents, or phases. The hardness is an important practical property, inasmuch as very high values of hardness cause difficulty in the dental laboratory when the casting is ready to be finished. Alloys with VHN or KHN values exceeding that of enamel (approximately 350) cause abrasive wear of opposing teeth, although hardness values are not included in ISO 22674.[20]

Elevated-Temperature Creep and Distortion

During the porcelain firing cycles, castings undergo dimensional changes as a result of elevated temperature. These changes have many causes, such as bulk creep of the alloy from several metallurgical mechanisms, distortion of the alloy as a result of the relief of residual stresses from the casting process, and alloy oxidation. The latter may be higher for high-palladium and other alloys that undergo internal (bulk and grain boundary) oxidation with the formation of oxide precipitate particles, in addition to the formation of an external oxide layer. Measuring the dimensional changes that occur in alloys during the porcelain bonding sequence is tedious, but concern has been expressed about the clinical fit for castings prepared from certain alloys. Nevertheless, in most situations, an experienced dental laboratory technician should be able to vary techniques and obtain successful results.

Ultimate Tensile Strength

The UTS (also called *tensile strength* or simply *strength*) is the maximum point on the stress-strain curve (see Fig. 19.18) and represents the greatest value of stress that can be developed in the alloy without fracture. The unit of measure for UTS is the megapascal. Two types of stress-strain curves are observed for tensile testing of casting alloys. Alloys of high ductility undergo substantial necking in the central portion of the test specimen between the UTS and the breaking strength. The load required to impose increasing true stress over the instantaneous cross-section area actually decreases with increasing permanent strain (see Fig. 19.18). Other alloys of more limited ductility undergo much less necking, and the stress continues to increase after the yield strength until fracture occurs at the UTS. The UTS has minimal practical importance for a ceramic alloy because the corresponding permanent strain does not occur under clinical conditions for a restoration. Nevertheless, this property is easy to measure, inasmuch as a strain-gauge extensometer does not need to be attached to the specimen, and manufacturers often quote the UTS.

Percentage Elongation

For metals, ductility—the capability of undergoing permanent tensile deformation—is measured in two ways when the test specimen is loaded to fracture: as percentage elongation or as reduction in area. For dental alloy castings, ductility is measured as the percentage of permanent elongation of the starting gauge length, after the two portions of the fractured specimen are placed back together. This measurement is made because castings typically fracture on inclined planes whose locations are determined by porosity, and a well-defined area for the fracture surface is not available for measurement of the reduction in area. It is difficult to obtain precise registration of the two fractured portions and to define the location of the original gauge length; therefore, it is difficult to determine the percentage elongation to better than the nearest 1%, although values to the nearest 0.1% have been quoted. In principle, the percentage elongation (often termed *elongation*) can be calculated during the stress-strain test if a breakaway extensometer is attached to the specimen. However, such extensometers are rarely available in dental materials laboratories. Fig. 19.18 exaggerates the more important elastic range of the stress-strain curve, inasmuch as for current casting alloys used for porcelain veneering, the values of percentage elongation generally exceed 10% (Table 19.2). The stress-strain plots for some alloys listed in Table 19.2 are instructive because they show readily that the region of permanent deformation is much more extensive on the strain axis than in the region of elastic deformation. An excellent example of a published stress-strain plot for an alloy with high percentage elongation is provided in the classic article by Asgar and colleagues.[22] When considering the ease of adjustment for cast restorations, the practitioner must remember that both yield strength and percentage elongation are involved.[23] Alloys with high yield strength cannot be burnished by hand, even if they have high values of percentage elongation.

Toughness

Toughness, the total area under the stress-strain curve, was historically considered an important property of casting alloys. However, with the focus on stresses that do not exceed the yield strength, this property no longer receives as much attention. Toughness represents the total energy per unit volume necessary to fracture the alloy and is represented as units of stress × strain, or megapascals. For an alloy that does not harden greatly and has substantial ductility, toughness is approximately equal to UTS × elongation. Determining toughness from stress-strain plots is laborious, and manufacturers do not report this property.

TABLE 19.2 **Alloys for Porcelain Veneering**

	HIGH-NOBLE ALLOYS											
	Gold-Platinum-Palladium (Au-Pt-Pd)				Gold-Palladium-Silver (Au-Pd-Ag)				Gold-Palladium (Au-Pd)			
Characteristic	Jelenko o (Jelenko/ Argen)	Image 2 (Dentsply)	y (Ivoclar AG)	Argedent y86 (Argen)	Cameo (Jelenko/ Argen)	Veritas (Dentsply)	W-2 (Ivoclar AG)	Argedent 52 (Argen)	Olympia (Jelenko/ Argen)	Eclipse (Dentsply)	W-3 (Ivoclar AG)	Argedent 65SF (Argen)
Composition (weight %)	Au: 87.4 Pt: 4.5 Pd: 5.9 Ag: 1 Sn, In, Ir, Fe: <1	Au: 84.5 Pt: 6.9 Pd: 5.0 Ag: 1.0 Other: In, Fe, Zn, Re	Au: 84.0 Pt: 7.1 Pd: 5.7 Ag: 1.5 Sn, In, Re, Fe, Li: <1	Au: 86 Pt: 10 Pd: 1.9 In: 2 Ir: <1	Au: 52.5 Pd: 26.9 Ag: 16 In: 2.5 Sn: 2 Ru: <1	Au: 40.0 Pd: 45.0 Ag: 4.9 Other: Sn, Zn, In, Re	Au: 44.8 Pd: 40.5 Ag: 5.9 In: 3.3 Sn: 2.2 Ga: 1.8 Ru, Re, Al, Si, B, Ni, Li: <1	Au: 52.5 Pd: 26.9 Ag: 16 In: 2.5 Sn: 2 Ru: <1	Au: 51.5 Pd: 38.4 In: 8.5 Ga: 1.5 Ru: <1	Au: 52.0 Pd: 37.5 Other: Zn, Sn, In, Re	Au: 48.7 Pd: 39.6 In: 10.6 Sn, Ga, Ru, Re, B, Li: <1	Au: 65 Pd: 26 In: 8.7 Ga, Ru: <1
Yield strength (MPa)	401 (S) 448 (H)	671 (AF)	435 (AF)	405 (S) 469 (H)	540 (S) 586 (H)	425 (AF)	540 (AF)	540 (S) 586 (H)	550 (S)	575 (AF)	495 (AF)	550 (S)
Elastic modulus (GPa)	97	—	81	76	118	—	113	118	124	—	128	121
Tensile strength (MPa)	438 (S) 490 (H)	—	—	475 (S) 530 (H)	642 (S) 690 (H)	—	—	642 (S) 690 (H)	790 (S)	—	—	690 (S)
Elongation (%)	9 (S) 5 (H)	7 (AF)	10 (AF)	12 (S) 9 (H)	12 (S) 10 (H)	40 (AF)	20 (AF)	12 (S) 10 (H)	30 (S)	23 (AF)	17 (AF)	15 (S)
Vickers hardness number (VHN)	150 (AF) 185 (H)	230 (AF)	170 (AF)	160 (AF) 195 (H)	200 (AF) 225 (H)	232 (AF)	205 (AF)	200 (AF) 225 (H)	250 (AF)	254 (AF)	225 (AF)	250 (AF)
Density (g/cm^3)	18.5	18.0	17.4	18.4	14.2	13.0	13.4	14.2	14.4	13.8	13.8	15.2

Continued

TABLE 19.2 **Alloys for Porcelain Veneering—cont'd**

	NOBLE ALLOYS								
	Palladium-Silver (Pd-Ag)					**Palladium-Copper-Gallium (Pd-Cu-Ga)**			
Characteristic	**Jelstar (Jelenko/ Argen)**	**Applause (Dentsply)**	**W-1 (Ivoclar AG)**	**Argelite 55 (Argen)**	**Argistar Yellow If (Argen)**	**Liberty (Jelenko/ Argen)**	**Option (Dentsply)**	**Spartan Plus (Ivoclar AG)**	**Argelite 76SF + (Argen)**
Composition (weight %)	Pd: 59.9 Ag; 28 Sn: 6 In: 6 Ru: <1	Pd: 54.9 Ag: 35.0 Other: Sn, Zn, Ir	Pd: 53.3 Ag: 37.7 Sn: 8.5 In, Ru, Li: <1	Pd: 55 Ag: 34 In: 6 Sn: 3 Zn: 1 Ga, Ru: <1	Pd: 40 Ag: 24.8 In: 32 Au: 2 Zn: 1 Ir: < 1	Pd: 75.9 Cu: 10 Ga: 5.5 Sn: 6 Au: 2 Ru: <1	Pd: 78.9 Cu: 10.0 Au: 2.0 Other: Ga,[a] Ir, B	Pd: 78.8 Cu: 10.0 Ga: 9.0 Au: 2.0 Li, Ge, Ir: <1	Pd: 75.7 Cu: 7.5 Ga: 6.3 In: 8 Au: 1.8 B, Ru, Sn: <1
Yield strength (MPa)	462 (S)	590 (AF)	450 (AF)	400 (S) 724 (H)	271 (S)	689 (S)	900 (AF)	795 (AF)	1005 (S) 1103 (H)
Elastic modulus (GPa)	137	—	114	125	64	138	—	97	130
Tensile strength (MPa)	648 (S)	—	—	641 (S) 966 (H)	—	999 (S)	—	—	1,201 (S) 1,310 (H)
Elongation (%)	20 (S)	11 (AF)	11 (AF)	38 (S) 10 (H)	5 (S)	20 (S)	23 (AF)	20 (AF)	19 (S) 16 (H)
Vickers hardness number (VHN)	190 (AF)	240 (AF)	240 (AF)	170(AF) 330 (H)	180 (AF)	345 (AF)	425 (AF)	310 AF)	290 (AF) 315 (H)
Density (g/cm^3)	11.4	10.8	11.1	11.1	10.6	10.7	10.6	10.7	11.2

TABLE 19.2 Alloys for Porcelain Veneering—cont'd

	NOBLE ALLOYS			PREDOMINANTLY BASE ALLOYS					
	Palladium-Gallium (Pd-Ga)			Nickel-Chromium (Ni-Cr)			Cobalt-Chromium (Co-Cr)		
Characteristic	**Legacy (Jelenko)**	**Protocol (Ivoclar AG)**	**Argelite 80 + 5 (Argen)**	**Argeloy N.P. (Argen)**	**Argeloy N.P. (Be-Free) (Argen)**	**4 all (Ivoclar AG)**	**Genesis II (Jelenko)**	**Argeloy N.P. Special (Argen)**	**D.Sign 30 (Ivoclar AG)**
Composition (weight %)	Pd: 85.1 Ga: 10 In: 1.2 Ag: 1.2 Au: 2 Ru: <1	Pd: 75.2 Ga: 6.0 In: 6.0 Au: 6.0 Ag: 6.5 Ru, Li: <1	Pd: 79.9 Ga: 6.3 In: 6.5 Au: 4.8 Ag: 1.8 Ru, Zn: <1	Ni: 76 Cr: 14 Mo: 6 Al: 2 Be: 1.8 C, Si, Fe: <1	Ni: 54 Cr: 22 Mo: 9 Fe: 4 Nb: 4 Ta: 4 C, Si, Al: <1	Ni: 61.4 Cr: 25.7 Mo: 11.0 Si: 1.5 Mn, Al, C: <1	Co: 52.6 Cr: 27.5 W: 12 Ru: 2.5 Ga: 2.5 Fe: 1.0 Cu: 1.0 Si, Nb, Ta: <1	Co: 59.5 Cr: 31.5 Mo: 5 Si: 2 B, Fe, Mn: <1	Co: 60.2 Cr: 30.1 Ga: 3.9 Nb: 3.2 Mo, Si, B, Fe, Al, Li: <1
Yield strength (MPa)	634 (S)	500 (AF)	585 (S)	552(S)	360 (S)	375 (AF)	517 (S)	710 (S)	520 (AF)
Elastic modulus (GPa)	117	103	120	192	160	200	172	280	234
Tensile strength (MPa)	793 (S)	—	815 (S)	1,138 (H)	580 (S)	—	765 (H)	765 (S)	—
Elongation (%)	18 (S)	34 (AF)	33 (S)	12 (S)	6 (S)	12 (AF)	15 (S)	5 (S)	6 (AF)
Vickers hardness number (VHN)	265 (AF)	235 (AF)	260 (AF)	240 (AF)	240 (AF)	235 (AF)	325 (AF)	430 (AF)	385 (AF)
Density (g/cm^3)	11.4	11.0	11.5	7.8	8.6	8.4	8.8	8.8	7.8

[a]The amount of gallium in Option is not provided on the Dentsply Prosthetics website, but Carr and Brantley[29] described it as approximately 9%.
Notes: Composition information was obtained from manufacturers' websites. Information about mechanical properties was also obtained from these websites, and they correspond to the condition after porcelain firing *(AF)*, the hardened condition *(H)* after furnace heat treatment, or the soft condition *(S)* after quenching, depending on the manufacturer. Yield strength values correspond to 0.2% offset.[20] *Dash* indicates that no value of the mechanical property was provided by the manufacturer.
Information about Jelenko alloys can be accessed at http://www.jelenko.com. In February 2006, Jelenko was acquired by Argen Corporation (http://www.argen.com).
Dentsply Prosthetics (http://prosthetics.dentsply.com/fixed) markets the former Ney alloys.
Ivoclar AG (www.ivoclarvivadent.us.com) markets the former Williams/Ivoclar alloys.
Al, Aluminum; *B*, boron; *Be*, beryllium; *C*, carbon; *Fe*, iron; *Ge*, germanium; *H*, hard; *In*, indium; *Ir*, iridium; *Li*, lithium; *Mn*, manganese; *Mo*, molybdenum; *Nb*, niobium; *Re*, rhenium; *Ru*, ruthenium; *Si*, silicon; *Sn*, tin; *Ta*, tantalum; *W*, tungsten; *Zn*, zinc.

Thermal Expansion/Contraction

The linear coefficient of thermal expansion is a crucial property for an alloy for porcelain veneering. These coefficients should be closely matched to within approximately 0.5×10^{-6}/°C below the glass transition temperature of the porcelain (which can range from approximately 500° to 700°C, depending on the cooling rate and specific product[24–26]), at which the ceramic can no longer undergo viscous flow to relieve thermal incompatibility stresses. The thermal contraction coefficient (α), generally assumed to be the same as that for thermal expansion, should be slightly higher for the metal so that the ceramic is in a state of beneficial residual *compressive stress* at room temperature. Values of α typically range from 13.5 to 14.5×10^{-6}/°C for metals and 13.0 to 14.0×10^{-6}/°C for porcelains, and there is some dependence of α on the heating/cooling rate of the porcelain.[27]

Density

Density is the ratio of mass to volume; specific gravity is the ratio of the density of a substance to the density of water. Densities for the important types of noble and base metal casting alloys are provided in Table 19.2. The alloys with high gold content have much higher densities than those with low gold content, palladium-based alloys, and base metal casting alloys. This is because gold has a much higher density (19.3 g/cm^3) than palladium (12.0 g/cm^3), nickel (8.9 g/cm^3), and cobalt (8.8 g/cm^3). These differences in density have two consequences. First, for cast restorations of the same size and configuration, less mass of metal is required for the lower density alloy; the difference in the metal cost for a restoration can be substantial when both the unit metal cost and the density difference are considered. Second, additional winding of the spring on the centrifugal casting machine is necessary to achieve the needed casting pressure for the lower density alloys.

Available Alloy Systems

The nomenclature for dental casting alloys can create confusion. Classifying noble and base metal casting alloys according to the mechanism for corrosion resistance is the preferred method of categorization. The gold-based and palladium-based noble metal casting alloys achieve corrosion resistance because of the inherent nobility of the gold and palladium atoms, which do not form stable oxides at room temperature. In contrast, the conventional base metal casting alloys—in which nickel and cobalt are the principal elements and chromium is present to provide corrosion resistance—oxidize rapidly to form a chromium oxide surface layer that blocks the diffusion of oxygen and prevents corrosion of the underlying metal (passivation). Titanium and titanium alloys also oxidize rapidly, and the thin surface layer of titanium oxide provides corrosion resistance.

Historically, terms such as *precious, semiprecious*, and *nonprecious* have been used to describe dental casting alloys. Precious or semiprecious alloys usually contain a greater quantity of silver, along with more palladium and less gold. Silver, which is not a noble metal in the oral environment, assumes some noble metal character in the presence of palladium. The terms *precious, semiprecious*, and *nonprecious*, which refer to unit metal cost, are now less preferable than the terms *noble* and *base* metals, which refer to the electrochemical character of the alloys.

The major noble metals in dental alloys are gold, platinum, and palladium. (The other noble metals are iridium, ruthenium, rhodium, and osmium.) The total percentage of gold, platinum, and palladium in a dental alloy is referred to as the *noble metal content*. Iridium (much less than 1% by weight) and ruthenium (up to approximately 1%) are used as grain-refining elements in gold-based and palladium-based casting alloys, respectively. The original metal-ceramic alloy compositions (e.g., Jelenko O, described in Table 19.2) had approximately 98% noble metal content by weight. Rapid increases in the price of gold during the 1970s stimulated the development of alloys with lower gold content (from approximately 85% to 50% by weight) and base metal alloys for fixed prosthodontics.[28] During the 1980s, the high-palladium alloys were developed as economic alternatives to the gold-based alloys,[29] but there has been substantial volatility in the price of palladium in recent decades.[b]

After a report by its Council on Scientific Affairs,[30] the American Dental Association (ADA) revised the classification system for alloys for fixed prosthodontics;[31] the revised system is presented in Table 19.3 and now includes a fourth group, which comprises titanium and titanium alloys. The classifications are based solely on gold, noble metal, or titanium content, and other, often crucial, alloying elements are ignored; therefore, general statements cannot be made about mechanical properties, clinical performance, and biocompatibility, even within each of the four groups in Table 19.3. Hundreds of dental alloys are commercially available, and appropriate testing is necessary to characterize the properties, safety, and efficacy of each. However, when major groups are further subdivided into alloy types, some accurate generalizations are possible. They are discussed in the following sections.

High-Noble Alloys

The high-noble alloys are gold based and contain a minimum of 60% by weight of noble elements; at least 40% is gold. There are three systems in this class: gold-platinum-palladium (Au-Pt-Pd), gold-palladium-silver (Au-Pd-Ag), and gold-palladium (Au-Pd), in the historical order of their development.

[b]In February 2022, the price of palladium was approximately $2300 per troy ounce, in comparison with a price of approximately $1850 per troy ounce for gold. In January 2006, the price of palladium was approximately $275 per troy ounce, in comparison with a price of approximately $555 per troy ounce for gold. In January 1997, the price of palladium was $120 an ounce, which increased to approximately $1000 per ounce by January 2001 and then began to decline thereafter, but price fluctuations have persisted. The corresponding rapid increases in palladium dental alloy prices have caused problems for alloy selection by dentists and the dental laboratory industry. The large increase in the price of gold, with fluctuations, since 2005 has renewed interest in alternative, less expensive alloys and new dental laboratory technologies for fixed prosthodontics.

TABLE 19.3 Revised American Dental Association Classification of Alloys for Fixed Prosthodontics

Classification	Requirement[a]
High-noble alloys	Noble metal content ≥60% (gold + platinum group metal) and gold ≥40%
Titanium and titanium alloys	Titanium ≥85%
Noble alloys	Noble metal content ≥25% (gold + platinum group metal)
Predominantly base alloys	Noble metal content <25% (gold + platinum group metal)

[a]The platinum group metals are platinum, palladium, rhodium, iridium, osmium, and ruthenium.

Table 19.2 lists some mechanical properties and the density for representative alloys of each system.

Gold-platinum-palladium. As previously noted, these were the first casting alloys formulated to bond with dental porcelain. Because of concern about adverse effects on the color of dental porcelain, copper (which was traditionally used for strengthening the high-noble casting alloys for all-metal restorations) could not be incorporated in the ceramic alloy compositions. Instead, these alloys were strengthened by precipitates of an iron-platinum (Fe-Pt) intermetallic compound.[32] Porcelain adherence was achieved by the incorporation of tin and indium in the alloys, in addition to the contribution from iron. During the initial alloy oxidation step for the porcelain firing cycles, tin and indium (as well as some iron) diffused to the alloy surface and became oxidized. Subsequent chemical bonding was achieved between this oxide layer and the dental porcelain (see Chapter 24). Although these alloys have excellent corrosion resistance, they are susceptible to some dimensional changes during the porcelain firing cycles and are not recommended for multiple-unit FPDs.

Gold-palladium-silver. These were the first lower gold content alternative alloys to be widely used in the 1970s. Platinum was eliminated from the alloy compositions, and the gold content was reduced to approximately 50%, with corresponding increases in the amounts of palladium and silver.[33,34] Some alloy strengthening was achieved by solid solution hardening from the dissimilar atomic sizes of the three major elements (gold, palladium, and silver), which form solid solutions with each other. Additional solid solution strengthening was hypothesized to be caused by tin or indium, which were again incorporated as oxidizable elements to provide porcelain bonding. Further alloy strengthening may be caused by precipitates formed by these elements. Although these alloys have excellent mechanical properties and porcelain adherence, green discoloration (resulting from diffusion of silver atoms into the porcelain) has been reported for some Au-Pd-Ag alloy–porcelain combinations.[35] Possible reasons for this effect may be the high sodium concentration of the porcelain or the relative sizes of the metal ions in the porcelain. The discolored region can be ground away, but this involves an additional processing step. In addition, silver vapor generated in the porcelain furnace during processing can contaminate the muffle, and periodic purging of the furnace with a carbon block is required. Green discoloration has apparently been eliminated in some porcelain compositions by the substitution of potassium ions for sodium ions; the larger potassium ions impede the diffusion of silver into the porcelain.

Gold-palladium. Gold-palladium alloys that are silver-free were developed during the late 1970s and have become very popular. Alloy strengthening is achieved with a combination of solid solution hardening and microstructural precipitates. The hardness (assumed to be related to strength) of these alloys is independent of heat-treatment temperature within the porcelain-firing range, unlike that of Au-Pd-Ag alloys.[34] The Au-Pd alloys have excellent mechanical properties, elevated-temperature creep behavior,[36] and porcelain adherence,[37] without the green discoloration associated with Au-Pd-Ag alloys.

Discussion. The data in Table 19.2 show that the Au-Pd and Au-Pd-Ag alloys, in comparison with the Au-Pt-Pd alloys, generally have higher values of yield strength and elastic modulus, along with lower density. Consequently, FPDs fabricated from alloys in the former two groups are more resistant to masticatory forces and undergo less bending deflection. They are also economically advantageous in that more restorations can be made per unit of alloy cost. Selection of the proper porcelain for Au-Pd-Ag alloys is essential if discoloration problems are to be avoided.

Noble Alloys

Noble alloys have a minimum of 25% by weight of noble metal, with no requirement for gold percentage, and are palladium based. There are three alloy systems in this class: palladium-silver (Pd-Ag), palladium-copper-gallium (Pd-Cu-Ga), and palladium-gallium (Pd-Ga), in the historical order of their development. Table 19.2 lists some mechanical properties and the density for representative alloys of each system.

Palladium-Silver. These alloys, developed in the 1970s, continued the trend by manufacturers of reducing the gold content (to between 0% and 2% by weight), with corresponding increases in the palladium and silver contents.[38] A small percentage of gold in these alloys and the high-palladium alloys has little effect on their properties but may facilitate third-party payments. As previously noted, in the presence of palladium, silver appears to assume noble metal character, which is beneficial for corrosion resistance. Because of their high silver content (approximately 30% to 35% by weight), these alloys have been called *semiprecious*, a term that should no longer be used. In comparison with the Au-Pd-Ag and Au-Pd alloys, the Pd-Ag alloys have similar values of yield strength and elastic modulus and much lower density values. Because of their high silver contents, porcelain greening and furnace contamination can result during fabrication of such FPDs, unless the porcelain is carefully selected. Nevertheless, these alloys are frequently chosen as a compromise between the more expensive high-noble alloys and the relatively inexpensive base metal alloys. Microstructural details have been reported for conventional Pd-Ag alloys, which can undergo age hardening and have excellent tolerance of casting porosity for fatigue behavior.[39–41] It should be noted that porcelain bonding to the Pd-Ag alloys may involve mechanical bonding at metallic surface nodules, rather than chemical bonding via an interfacial oxide layer, based upon the study[42] of high-temperature oxidation behavior of the Will-Ceram W-1 alloy (now W-1 from Ivoclar AG). While this hypothesis has not been verified by studies on other Pd-Ag alloys, these alloys have very similar compositions (see Table 19.2).

An exciting development is the introduction of a new palladium-silver-indium (Pd-Ag-In) alloy composition for low-fusing and high–thermal expansion porcelains by Argen that contains only 2% gold by weight but has an esthetically pleasing yellow shade. This alloy (Argistar Yellow LF) is included in Table 19.2, where it can be seen that it has lower values for yield strength, elongation, and elastic modulus than do the other listed conventional Pd-Ag alloys. The yellow appearance results from the proportions of indium and palladium in the alloy composition. Metallurgical characterization of a Pd-Ag alloy[43] that also contained large relative proportions of palladium and indium suggests that the Pd-In intermetallic compound has a pivotal role in the mechanical properties and appearance of this alloy.

Palladium-copper-gallium. The Pd-Cu-Ga alloys contain more than 70% by weight of palladium and were developed in the early 1980s as economical alternatives to the gold-based alloys.[29] The melting point of palladium (1555°C) is much higher than that of gold (1064°C); gallium has a melting point of 30°C. The addition of gallium to palladium yields high-palladium alloys that can be fused and cast with the same dental laboratory technology developed for the gold-based casting alloys. Multiorifice torches are necessary to fuse the high-palladium alloys, and the use of ceramic crucibles dedicated to individual alloys is recommended.[29] Carbon-containing investments should not be used because the incorporation of very small amounts of carbon in these alloys degrades the bond strength with porcelain.[44] The casting accuracy of Pd-Cu-Ga alloys appears comparable with that of the high-noble metal alloys.[45]

Measurements[46,47] of the mechanical properties of some Pd-Cu-Ga alloys have produced values of yield strength, elastic modulus, and percentage elongation that differ from values in Table 19.2. This suggests some technique sensitivity in the fabrication of cast specimens for the tension test. Although a near-surface eutectic structure was present in castings from one Pd-Cu-Ga alloy that simulated copings for maxillary incisors,[29] this constituent was absent in the 3-mm diameter cast specimens for the tension test.[47] Some Pd-Cu-Ga alloys have hardness values comparable with or exceeding that of tooth enamel, and castings from these alloys may be difficult to finish in the dental laboratory. In addition, chairside adjustments may be difficult for patients. However, substitution of indium for tin yields Pd-Cu-Ga alloys with much lower hardness (VHN = 270).[48] All these alloys achieve substantial hardening by solid-solution incorporation of other elements within the palladium crystal structure. The hardest Pd-Cu-Ga alloys (VHN > 300) contain a hard grain boundary phase whose composition is close to that of Pd_5Ga_2.[48]

Transmission electron microscope studies indicate that representative high-palladium alloys (both Pd-Cu-Ga and Pd-Ga alloys) have the same bulk ultrastructure at the submicron level, termed *tweed structure*.[49,50] Analyses of x-ray diffraction patterns have revealed that oxidized Pd-Cu-Ga alloys have complex internal oxidation regions that can exhibit up to five different oxide phases.[51] Oxides of copper, gallium, tin, indium, and even palladium that were formed under the conditions present in the porcelain furnace were subsequently detected in the oxidized alloys at room temperature. The results of creep experiments on the Pd-Cu-Ga alloys have been mixed.[36] The creep rates associated with relatively high thermal incompatibility stresses near the glass transition temperature of dental porcelain were high for two Pd-Cu-Ga alloys, whereas these alloys had excellent creep resistance at high temperatures and low stresses simulating the deflection of a long-span FPD as a result of gravity during processing.

Palladium-gallium. The copper-free Pd-Ga alloys were subsequently developed during the 1980s to provide compositions with hardness lower than those of the initial Pd-Cu-Ga formulations. The hard Pd_5Ga_2 phase is absent in these alloys, which are strengthened by solid solution hardening.[48] The alloys have a complex fine precipitate structure at the grain boundaries,[52] and their mechanical properties are generally more similar to those of Pd-Ag alloys than to the Pd-Cu-Ga alloys. A palladium-gallium-cobalt (Pd-Ga-Co) alloy[53] has a particularly dark oxide that is more difficult to mask with dental porcelain, and this alloy did not achieve widespread clinical acceptance.

Discussion. In one study, investigators compared the dimensional changes at various stages of the simulated porcelain firing cycles in copings for metal-ceramic single-unit restorations of selected high-palladium alloys.[54] They found that most of the selected high-palladium alloys had acceptable high-temperature distortion. Because the price of palladium has been volatile since the mid-1990s, dentists and dental laboratories have tended to select Au-Pd alloys, Pd-Ag alloys, and alloys with lower gold content, rather than alloys with high palladium content. Currently, the unit metal cost of palladium ($2365) is substantially higher than that of gold ($1880, both in late December 2020). Nonetheless, the high-palladium alloys still have an economic advantage over the highly popular gold-palladium alloys because of the much higher density of gold (18.3 g/cm^3) compared to palladium (12.0 g/cm^3). When the high-palladium alloys were introduced in the 1980s, the unit metal cost was between half and one-third that of the Au-Pd alloys.[29] However, caution is needed with the Pd-Ag alloys to prevent porcelain from acquiring green discoloration. Some biocompatibility concerns have been raised about the high-palladium alloys, particularly in Germany with the Pd-Cu-Ga alloys. Two review articles[55,56] suggested that minimal health hazards are associated with the palladium dental alloys, and this has been supported by studies of potentiodynamic polarization,[57–59] cell culture,[60] elemental release,[58,61] and animal implantation.[62] However, another review article cautioned about drawing conclusions for the biocompatibility of casting alloys from in vitro studies.[63]

Predominantly Base Metal Alloys

Table 19.3 defines these alloys (sometimes termed *nonprecious*) as having less than 25% by weight of noble metal with no requirement for gold. Of these alloys, most used for fixed prosthodontics are nickel-chromium (Ni-Cr) alloys, but some cobalt-chromium (Co-Cr) alloys have also been formulated for porcelain application. While permitted by the ADA classification, the commercially available predominantly base metal alloys do not contain noble metals.

Nickel-chromium. The complex metallurgy and manipulation of these alloys are described in a review article.[64] Yield strength and hardness can be greatly affected by small differences in weight percentages of secondary elemental components among the compositions of these alloys, which can alter the complex dendritic microstructures. Table 19.2 illustrates some of these variations. For example, values of yield strength for the three representative alloys listed vary from approximately 360 to 550 MPa, whereas the average VHN for these alloys is approximately 240. Consequently, the selection of a specific brand of Ni-Cr alloy depends on the strength needed for the particular clinical application. If burnishing or extended finishing of a crown is anticipated, a brand with a relatively low yield strength and low hardness should be used.

One benefit of these alloys is that their values of elastic modulus are much higher than those of the noble metal alloys. Therefore, long-span fixed prostheses fabricated from Ni-Cr alloys undergo much less flexure than do similar prostheses fabricated from noble metal alloys, and the brittle dental porcelain component is less likely to fracture. These base metal casting alloys are generally considered more technique sensitive and difficult to cast than the noble metal casting alloys. However, this assessment may reflect the lack of experience of some dental laboratories with the Ni-Cr alloys; excellent results for castability of these alloys have been published.[65] Therefore, the choice of dental laboratory is particularly important when these alloys are selected.

Beryllium. Many Ni-Cr alloy formulations contain up to 2% by weight of beryllium. The major reason for incorporating this element in the alloy is to lower the melting range and to decrease the viscosity of the molten alloy, thereby improving its castability. Beryllium also provides strengthening and affects the thickness of the oxide layer when the alloy is oxidized for porcelain firing. The thickness of the oxide layer is an important consideration for base metal casting alloys, which can form much thicker oxide layers than noble metal casting alloys. Fracture through the oxide layer may occur and cause failure of the base metal-ceramic restoration.

The use of beryllium has created some doubt about the safety of some Ni-Cr alloys. Of importance is that when the densities of nickel (8.9 g/cm^3) and chromium (7.2 g/cm^3) are compared with that of beryllium (1.8 g/cm^3), 2% by weight of beryllium in the alloy composition can be equivalent to nearly 10% beryllium on an atomic basis. Consequently, the atomic proportion of beryllium atoms in these alloy compositions can be relatively large.

Nickel. The US federal standard for exposure to metallic nickel and soluble nickel compounds (1 mg/m^3 for an 8-hour time-weighted average concentration) is much higher than the recommendation by the National Institute for Occupational Safety and Health for such exposure (15 μg/m^3 for a 10-hour time-weighted average workday). Occupational exposure of refinery workers to nickel has been associated with lung and nasal cancer. Acute effects of exposure to nickel include skin sensitization that can lead to chronic eczema. Therefore, as a health precaution, an operator should wear a mask and use efficient suction when grinding and finishing a dental nickel-based alloy.

It has been reported that 9% of the female population and 0.9% of the male population are sensitive to nickel.[66] This prompts a question: Are such individuals likely to manifest an adverse reaction to dental Ni-Cr alloys? In a 20-participant clinical study[67] to investigate this question, each of 10 control participants (who had no known sensitivity to nickel) showed a negative dermal response and a negative intraoral response to a dental Ni-Cr alloy. Of 10 participants with a known sensitivity, 8 showed a positive dermal response to the alloy. When the sensitive participants wore an intraoral appliance containing the Ni-Cr alloy, 30% manifested an allergic response within 48 hours.

According to the ADA labeling requirement for base metal alloys that contain nickel, such alloys should not be used in individuals with known nickel sensitivity. Another question now arises: Can patients who are not allergic to nickel become sensitive to it from FPDs made with nickel-containing alloys?

In one investigation,[68] researchers found that Ni-Cr alloys not containing beryllium were more resistant to in vitro corrosion than were beryllium-containing alloys. The four alloys studied showed lower corrosion rates in cell culture solutions after cold solution sterilization. Although the corrosion products released from the alloys did not alter the cellular structure and viability of human gingival fibroblasts, reductions in cellular proliferation were observed. The authors concluded that biocompatibility concerns still exist relating to the exposure of local and systemic tissues to elevated levels of corrosion products from the Ni-Cr alloys.

Cobalt-chromium. The potential health problems associated with beryllium- and nickel-containing alloys have led to the development of another alternative base metal alloy system: cobalt-chromium.[69,70] The representative Co-Cr alloys listed in Table 19.2 have higher hardness than do the Ni-Cr alloys listed, which suggests that finishing restorations made with the former alloys may be more difficult. The absence of other definitive comparisons in mechanical properties of these currently marketed Ni-Cr and Co-Cr alloys in Table 19.2 is the result of their complex metallurgic characteristics.

Titanium and titanium alloys. Titanium-based alloys have been studied since the late 1970s as potential dental casting alloys.[71] Advantages of titanium and titanium alloys include excellent biocompatibility and corrosion resistance, which results from the previously noted presence of a thin, adherent, passivating surface layer of titanium dioxide (TiO_2). The low density (4.5 g/cm^3) of titanium, in comparison with that of gold or palladium, also results in lighter restorations that are potentially less expensive. (However, the laboratory cost of fabricating cast restorations from titanium alloys may be high.) Pure titanium below approximately 882°C exists in the α phase, which has a hexagonal close-packed structure; at higher temperatures, the atomic arrangement transforms to the body-centered cubic β phase. Some alloying elements, such as aluminum, stabilize in the α phase at higher temperatures, whereas other alloying elements, such as vanadium, stabilize in the β phase at lower temperatures.[72]

For fixed prosthodontics, the focus has been on (1) commercially pure titanium (sometimes termed *unalloyed titanium*), which is α phase and contains an upper limit of 1% by weight of impurities for American Society for Testing and Materials (ASTM) grade 4 (strongest grade), and (2) the highly popular engineering alloy titanium–6% aluminum–4% vanadium (Ti-6Al-4V), containing 90% titanium by weight. The Ti-6Al-4V alloy, sometimes referred to as ASTM grade 5 titanium, has a duplex microstructure containing both α and β phases and is much stronger than commercially pure titanium.

There has been interest in the titanium–6% aluminum–7% niobium (Ti-6Al-7Nb) α-β alloy, which was advocated because of concern with the cytotoxicity of vanadium and the poor wear resistance of commercially pure titanium.[73–76] According to one report of laboratory investigations of SaOS-2 (sarcoma osteogenic) cells, titanium, tantalum, niobium, and zirconium in bulk form (not powders) exhibited excellent cytotoxicity.[77] The titanium–35% niobium–5% zirconium (Ti-35Nb-5Zr; α-β structure) and titanium–35% niobium–10% zirconium (Ti-35Nb-10Zr; β structure) casting alloys for dental implants have been investigated,[78] but further studies of corrosion resistance and alloy biocompatibility are needed. The β-Ti alloys have lower values of elastic modulus than do the α-Ti and α-β Ti alloys, which make them desirable for orthopedic implant alloys, in which stress shielding of bone is a concern.[79]

The dental casting of titanium and titanium alloys poses special problems because of the high melting point of titanium (1668°C) and its strong tendency to oxidize and react with other materials.[80] These problems were well known by earlier investigators.[80–90] Titanium dental casting machines that represent a substantial expense must provide either a vacuum environment or an argon atmosphere. Both vacuum/argon pressure and centrifugal casting machines have been developed, and both argon-arc melting and induction melting have been used to fuse titanium and titanium alloys. Patterns for casting are coated, and special investments must be used to provide the appropriate expansion. Reaction of titanium or titanium alloy with the investment (and perhaps with the residual atmosphere in the casting machine) results in a very hard near-surface region (termed α *case*) that can exceed 50 µm in thickness. Selecting a dental laboratory experienced in fabricating titanium and titanium alloy castings is essential, and such dental laboratories are not common in the United States.

Advances have occurred in investments,[91–94] casting methodology,[95–99] and understanding of the castability and casting accuracy[100–102] of titanium, along with increased knowledge about α case and the grindability[88,103–105] of castings. Currently, titanium castings of clinically acceptable accuracy can be produced, whereby the marginal fit of cast complete crowns is superior to that for titanium crowns milled by the CAD/CAM technique.[106]

New Technologies for Base Metal Alloys

Optomec (http://www.optomec.com) developed laser deposition technology, or laser-engineered net shaping (LENS), in which a high-power laser in an argon environment is used for melting elemental or alloy powders, which are directed onto a small area of a substrate through special nozzles to build up, layer by layer, a complex part in a raster pattern. One study revealed that idealized Ti-6Al-4V crowns prepared by laser deposition had poor marginal adaptation, but no near-surface α case, and a desirable fine-scale microstructure because of the rapid solidification conditions.[107,108] This technique enables functionally graded titanium alloy compositions to be created with controlled microstructures and mechanical properties for orthopedic applications.[109] However, further development of the LENS system is needed for clinical usage in prosthodontics, because dental restorations are much smaller than orthopedic implants.

In laser sintering/melting dental technology, developed by several companies (BEGO, Lincoln, RI; Phenix Systems, Riom, France; EOS, Krailling, Germany; and Biomain AB, Helsingborg, Sweden [now Kulzer GmbH]), a high-power laser is used to selectively fuse particles lying on a powder bed and build a complex part layer by layer, as the powder bed is moved back and forth with fresh alloy particles being exposed to the laser irradiation. Successful results for single crowns, three-unit FPDs, and an implant framework have been achieved with this process.[110–117] Biocompatible Co-Cr alloys have been used in most of these reported studies, but laser sintering has also been performed on a gold-platinum alloy[110] and titanium.[118] Studies have shown that the laser-sintered Co-Cr alloy has a fine-scale microstructure[117,119] because of the small starting particle size and rapid fusing. This should be advantageous for mechanical properties. Detailed metallurgical mechanisms involved in the selective laser sintering of the particles are complex and involve a binder used in the powder bed.[120] As a result of further developments in laser sintering, this technology may replace the dental casting technology that has served the profession well for the past century.

In addition to the foregoing areas of laser deposition and laser sintering, which are examples of additive manufacturing, the complementary approach of subtractive manufacturing also has promise for the future. Amann Girrbach introduced Ceramill Sintron partially sintered Co-Cr alloy blanks that can be readily dry-milled by means of a desktop machine and subsequently final sintered in a special furnace with an argon atmosphere.[121] Both the milling machine and the furnace can be obtained from the manufacturer, which claims that the process yields restorations and frameworks with homogeneous and distortion-free structures. In a review article, van Noort[122] discussed the use of additive and subtractive manufacturing

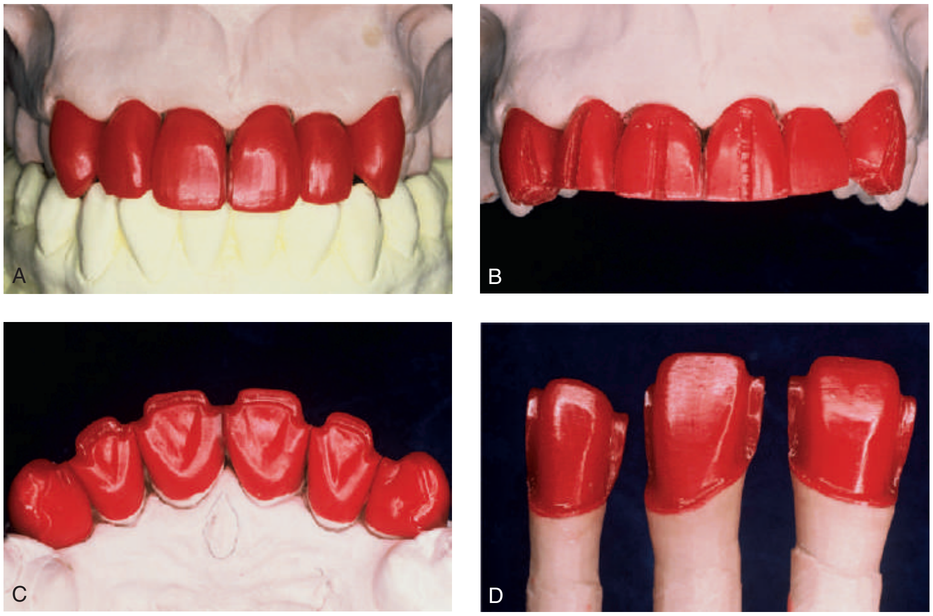


Fig. 19.20 Technique review. (A) The restorations are waxed to anatomic contour. (B) The patterns are troughed to obtain correct porcelain thickness in the completed restoration. (C) The cutback is completed. (D) The margins are finalized before investing.

with CAD-CAM, along with other promising digital technologies that have the potential to revolutionize dental laboratory practice. Kim and colleagues[123] reported that the fit of dental prostheses (single crowns) prepared from a Co-Cr alloy was superior for the laser sintering and the subtractive manufacturing techniques, compared to the traditional lost wax and casting process. A more recent systematic review that assessed CAM-CAM techniques and other fabrication techniques employed to achieve marginal adaptation concluded that the majority of Co-Cr restorations and infrastructures produced by laser sintering displayed better marginal accuracy than those fabricated by casting.[124]

■ ■ ■

REVIEW OF TECHNIQUE

Fig. 19.20 summarizes the steps involved in producing wax patterns for metal-ceramic restorations.

1. The restorations are waxed to anatomic contour (see Fig. 19.20A).
2. The patterns are troughed to obtain correct porcelain thickness in the completed restoration (see Fig. 19.20B).
3. The cutback is completed (see Fig. 19.20C).
4. The margins are finalized before investing (see Fig. 19.20D).

SUMMARY

Framework design for metal-ceramic restorations must be based on an understanding of fundamental material properties. Restorations should be waxed to anatomic contour and then cut back in the area that is to be veneered (Fig. 19.21). This creates an even porcelain thickness, which provides superior mechanical properties in the completed restoration while simultaneously standardizing shade reproduction.

STUDY QUESTIONS

1. Explain all reasons for full-contour waxing before cutting back a wax pattern for a metal-ceramic restoration.
2. Why should the framework of a metal-ceramic crown not be of consistent thickness on the veneering surface?
3. How does the practitioner determine the location of the metal-ceramic interface? Interproximally on a maxillary central incisor? Interproximally on a maxillary premolar? Occlusally on a mandibular premolar? Lingually on a maxillary canine?
4. Discuss the appearance of the stress-strain curve for a ductile dental alloy. What does it mean when the straight portion of the curve is steeper or more horizontal? What is the importance of a flatter curve versus a curve with a greater slope after the initial linear portion of the plot? What does it mean if the maximum point of the curve is higher or lower? What does the total surface area under the curve signify?
5. Explain the classification of alloy systems for metal-ceramic restorations. Select two categories and give two examples of alloys in each category. Contrast the physical properties of the alloys chosen and provide examples of recommended use.
6. Briefly discuss the health hazards that can be associated with the various alloys used in the metal-ceramic technique.
7. Describe the processes of laser sintering and laser deposition. Which process has become widely accepted for prosthodontic applications and currently yields marginal adaptation results comparable to those achieved by casting? What are the limitations of these two processes?

Fig. 19.21 Step-by-step fabrication of metal-ceramic restorations. (A and B) Definitive casts are articulated with an arbitrary facebow transfer and interocclusal records. (C–E) The restorations are waxed to full anatomic contour, and the desired occlusal arrangement is verified. (F and G) Elastomeric indexes fabricated from the anatomic contour waxing are used during the cutback phase to create a uniform space for the ceramic veneer. (H) The same index is used when the metal substructure is finished. (I–K) Bisque bake is completed. At this stage, all functional and esthetic aspects of the restorations are refined. (L–N) The completed restorations after glazing and metal finishing.

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20

Pontic Design

Pontics are the artificial teeth of a fixed partial denture (FPD) that replace missing natural teeth, restoring function and appearance (Fig. 20.1). They must enable continued oral health and comfort. The edentulous areas where a fixed prosthesis is to be provided may be overlooked during the treatment-planning phase. Unfortunately, any deficiency or potential problem that may arise during the fabrication of a pontic is often identified only after the teeth have been prepared or even when the definitive cast is ready to be sent to the dental laboratory technician. Proper preparation includes a careful analysis of the definitive dimensions of the edentulous areas: mesiodistal width, occlusocervical distance, buccolingual dimension, and location of the residual ridge. To design a pontic that meets hygienic requirements and prevents irritation of the residual ridge, particular attention must be given to the form and shape of the gingival surface. Merely replicating the form of the missing tooth or teeth is not enough. The pontic must be carefully designed and fabricated not only to facilitate plaque control of the tissue surface and around the adjacent abutment teeth, but also to adjust to the existing occlusal conditions. In addition to these biologic considerations, pontic design must incorporate mechanical principles for strength and longevity, as well as esthetic principles for satisfactory appearance of the replacement teeth (Fig. 20.2).

Because the pontic mechanically unifies the abutment teeth and covers a portion of the residual ridge, it assumes a dynamic role as a component of the prosthesis and cannot be considered a lifeless insert of gold, porcelain, acrylic resin, or zirconia.[1]

PRETREATMENT ASSESSMENT

Certain procedures enhance the success of an FPD. In the treatment-planning phase, diagnostic casts and waxing procedures may prove especially valuable for determining optimal pontic design (see Chapters 3 and 18).

Pontic Space

One function of an FPD is to prevent tilting or drifting of the adjacent teeth into the edentulous space. If such movement has already occurred, the space available for the pontic may be reduced and its fabrication may be complicated. In such circumstances, creating an acceptable appearance without orthodontic repositioning of the abutment teeth is often impossible, particularly if esthetic appearance is important. (Modification of abutments with complete-coverage retainers is sometimes feasible.) Careful diagnostic waxing procedures help determine the most appropriate treatment (see Chapters 2). Even with a lesser esthetic requirement, as for posterior teeth, overly small pontics are unacceptable because they trap food and are difficult to clean. When orthodontic repositioning is not possible, increasing the proximal contours of adjacent teeth may be better than making an FPD with undersized pontics (Fig. 20.3). If there is no functional or esthetic deficit, the space can be maintained without prosthodontic intervention.

Residual Ridge Contour

The edentulous ridge's contour and topography should be carefully evaluated during the treatment-planning phase. An ideally shaped ridge has a smooth, regular surface of attached gingiva, which facilitates maintenance of a plaque-free environment. Its height and width should allow placement of a pontic that appears to emerge from the ridge and mimics the appearance of neighboring teeth. Facially, it must be free of frenum attachment and be of adequate facial height to sustain the appearance of interdental papillae.

Loss of residual ridge contour may lead to unesthetic open gingival embrasures ("black triangles"; Fig. 20.4A), food impaction (see Fig. 20.4B), and percolation of saliva during speech. Siebert[2] classified residual ridge deformities into three categories (Table 20.1; Fig. 20.5):

- Class I defects: faciolingual loss of tissue width with normal ridge height
- Class II defects: loss of ridge height with normal ridge width
- Class III defects: a combination of loss in both dimensions

The incidence of residual ridge deformity after anterior tooth loss is high at 91%[3]. In the majority of these patients, the deformities are class III defects. Many patients with class II and class III defects are dissatisfied with the esthetics of their FPDs.[4] Preprosthetic surgery to augment such residual ridges should be carefully considered.

Surgical Modification

Although residual ridge width may be augmented with hard tissue grafts, this is usually not indicated unless the edentulous site is to receive an implant (see Chapter 13).

Class I Defects

Soft tissue procedures have been advocated for improving the width of a class I defect. However, because class I defects are infrequent and are not esthetically challenging, surgical

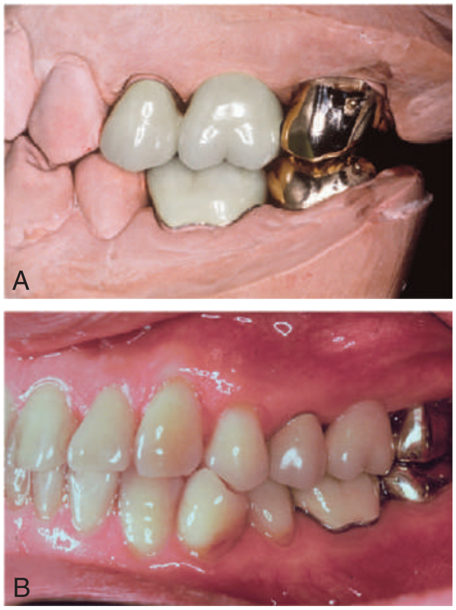


Fig. 20.1 (A and B) A metal-ceramic pontic in this three-unit fixed partial denture replaces the maxillary first molar.

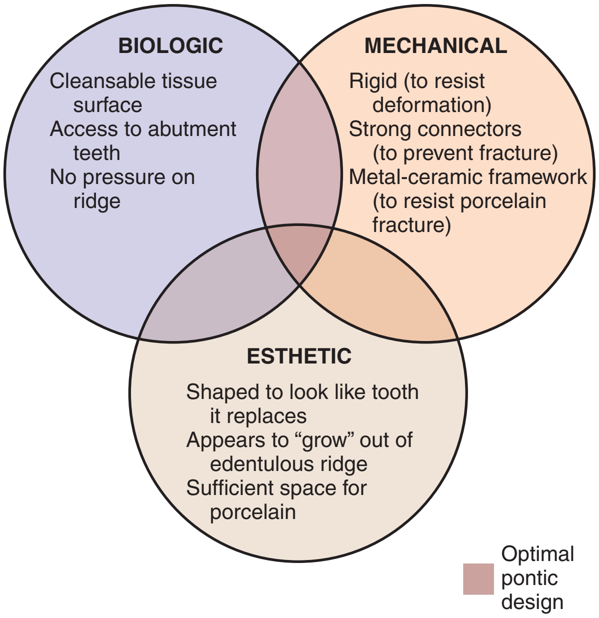


Fig. 20.2 Biologic, mechanical, and esthetic considerations for successful pontic design.

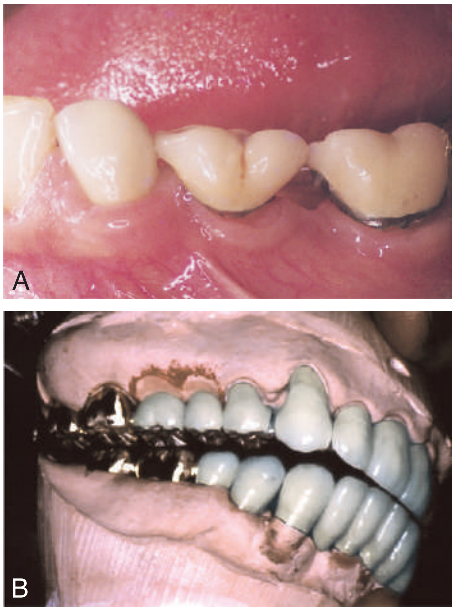


Fig. 20.3 Careful planning is always necessary in deciding how to restore an undersized pontic space when orthodontic treatment is not practical. (A) In this patient, individual crowns of increased proximal contours were preferred over a fixed partial denture with undersized pontics. Excellent plaque control has been demonstrated, and the design provided the optimum occlusal relationship. (B) Two small pontics were used to replace the missing maxillary teeth.

Fig. 20.4 Loss of residual ridge contour has led to unesthetic open gingival embrasures (A) and food entrapment *(arrow)* (B).

augmentation of ridge width is uncommon. By paying careful attention to interim pontic contour, the operator can identify patients who would benefit from surgery. In the roll[5] technique, soft tissue from the lingual side of the edentulous site is used. The epithelium is removed, and the tissue is thinned and rolled back upon itself, thereby thickening the facial aspect of the residual ridge (Fig. 20.6). Pouches may also be prepared in the facial aspect of the residual ridge[6] into which subepithelial[7,8] or submucosal[9] grafts harvested from the palate or tuberosity may be inserted (Fig. 20.7).

Class II and Class III Defects

Unfortunately, few soft tissue surgical techniques can increase the height of a residual ridge with predictability. The interpositional graft[2,10] is a variation of the pouch technique in which a wedge-shaped, connective tissue graft is inserted into a pouch

TABLE 20.1 Incidence of Maxillary Anterior Residual Ridge Defects

		INCIDENCE (%)	
Class	**Description**	**Abrams et al.[3]**	**Siebert[2]**
0	No defect	12	0
I	Horizontal loss	36	13
II	Vertical loss	0	40
III	Horizontal and vertical loss	52	47

Adapted from Edelhoff D, Spiekermann H, Yildirim M. A review of esthetic pontic design options. *Quintessence Int.* 2002;33:736.

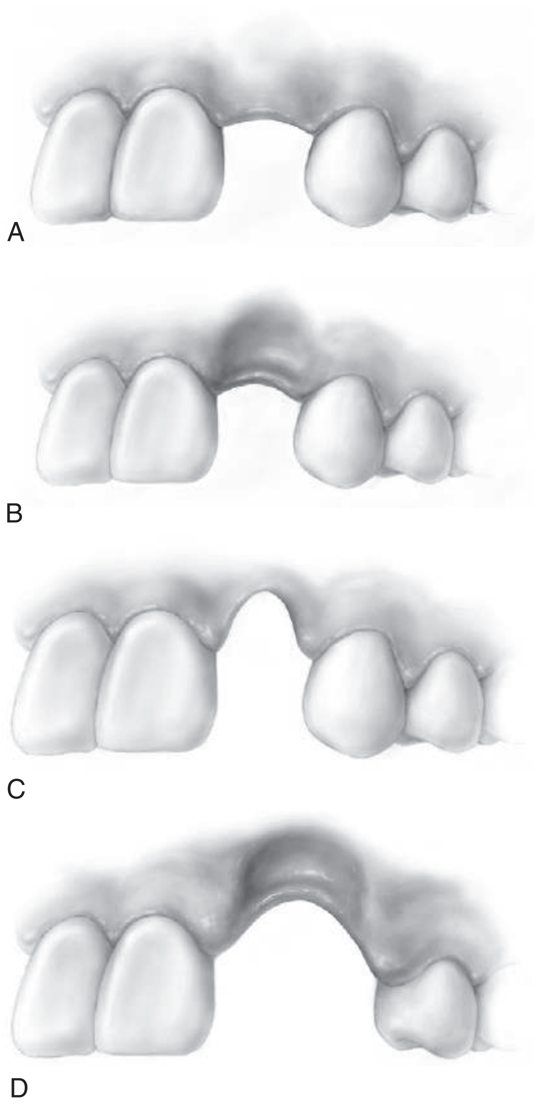


Fig. 20.5 Residual ridge deformities as classified by Siebert.[2] (A) Class 0, no defect. (B) Class I defect. (C) Class II defect. (D) Class III defect.

preparation on the facial aspect of the residual ridge. The epithelial portion of the wedge may be positioned coronally to the surrounding epithelium if an increase of ridge height is desired (Fig. 20.8). The onlay graft is designed to increase ridge height,[2,11] but also contributes to ridge width, which makes it useful for treating class III ridge defects (Fig. 20.9). It is a thick "free gingival graft," harvested from partial- or full-thickness palatal donor sites. Because the amount of height augmentation can be only as thick as the graft, the procedure may have to be repeated several times to reestablish normal residual ridge height. Although the onlay graft has greater potential for increasing ridge height than the interpositional graft, its survival is greatly dependent on revascularization, which requires meticulous preparation of the recipient site. Therefore, the onlay graft is more technique-sensitive than the interpositional graft. In fact, connective tissue grafts have been demonstrated to achieve approximately a 50% increase in ridge-volume 3.5 months after surgery than free gingival grafts in single-tooth residual ridge defects.[12]

Gingival Architecture Preservation

Resorption of the alveolar ridge, after tooth extraction, occurs primarily at the buccal plate, typically resulting in a horizontal defect. Bone loss averages 3 to 5 mm at 6 months after extraction; 50% of the width of the alveolar ridge is lost at 12 months.[13,14] Although the degree of residual ridge resorption after tooth extraction is unpredictable, resulting deformities are not inevitable. The alveolar process can be preserved through immediate restorative and periodontal intervention at the time of tooth removal. By conditioning the extraction site and providing a matrix for healing, the dentist can preserve the pre-extraction gingival architecture or "socket."

Preparing the abutment teeth before the extraction is the preferred technique. An interim FPD can be fabricated indirectly, ready for immediate insertion. Because socket preservation is dependent on underlying bone contour, the extraction of the tooth to be replaced should be atraumatic, with the aim of preserving the facial plate of bone. The scalloped architecture of interproximal bone forming the extraction site is essential for proper papilla form, as are facial bone levels in the prevention of alveolar collapse. If bone levels are compromised before or during extraction, the sockets can be grafted with an allograft material (hydroxyapatite, tricalcium phosphate, or freeze-dried bone).[13,15,16]

Immediately after preparation of the extraction site, a carefully shaped interim FPD is placed (Fig. 20.10A and B). The tissue side of the pontic should be an ovate form, and, according to Spear,[17] it should extend approximately 2.5 mm apical to the facial free gingival margin of the extraction socket (see Fig. 20.10C and D). Because the soft tissues of the socket begin to collapse immediately after the tooth extraction, the pontic causes tissue blanching as it supports the papillae and facial/palatal gingiva. The contour of the ovate tissue side of the pontic is critical and must conform to within 1 mm of the interproximal and facial bone contour to act as a template for healing. Oral hygiene in this area is difficult during the initial healing period, so the interim restoration should be highly polished to minimize plaque retention. After approximately 1 month of healing,

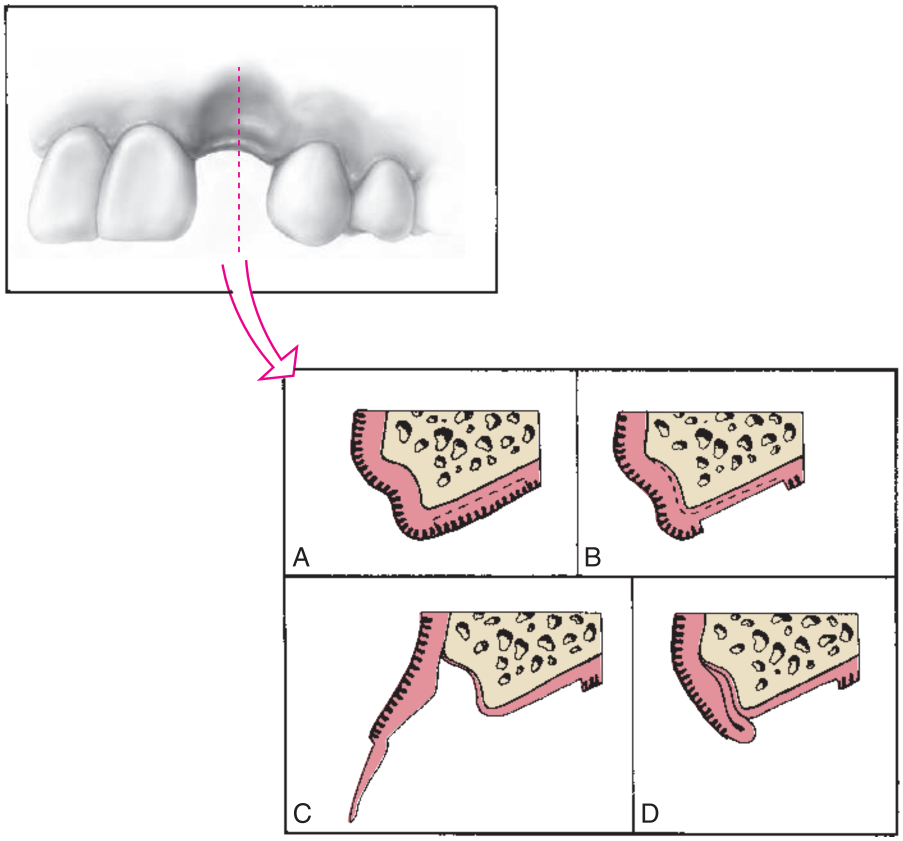


Fig. 20.6 Cross-section illustrations of the roll technique for soft tissue ridge augmentation. (A) Class I residual ridge defect before augmentation. (B) Epithelium is removed from palatal surface. (C) The flap is elevated, which creates a pouch on the vestibular surface. (D) The flap is rolled into the pouch, which enhances ridge width.

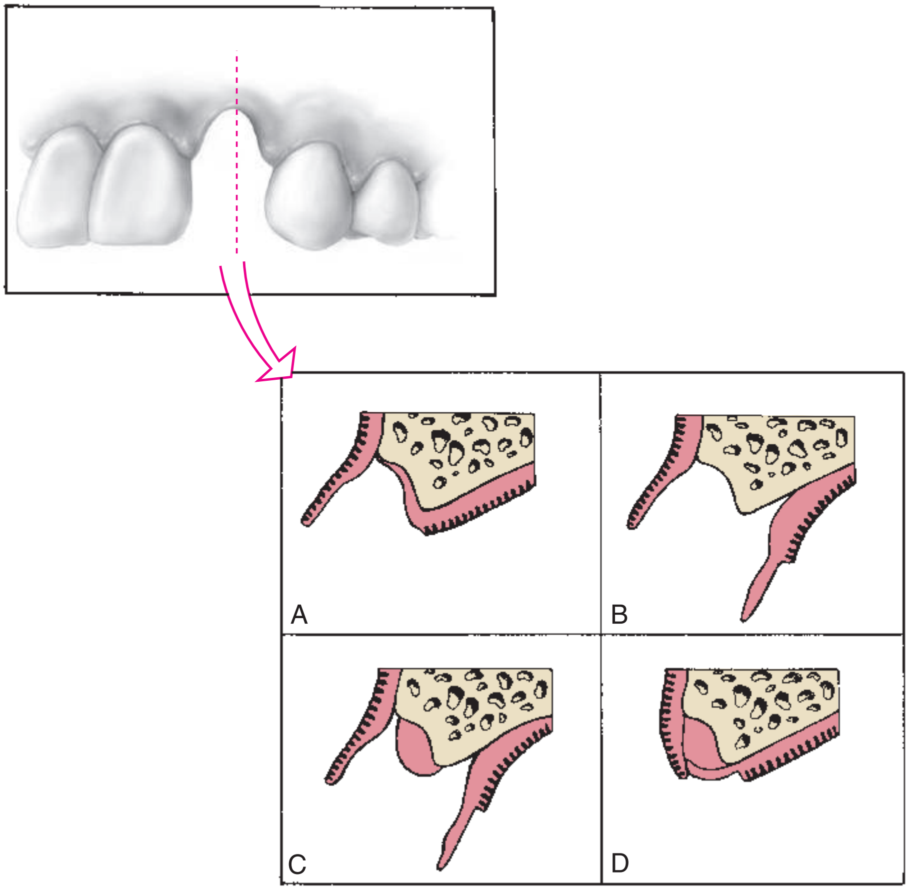


Fig. 20.7 Cross-section illustrations of the pouch technique for soft tissue ridge augmentation. (A) and (B) Split-thickness flap is reflected. (C) Graft material is placed in the pouch, which increases ridge width. (D) Flaps are sutured in place.

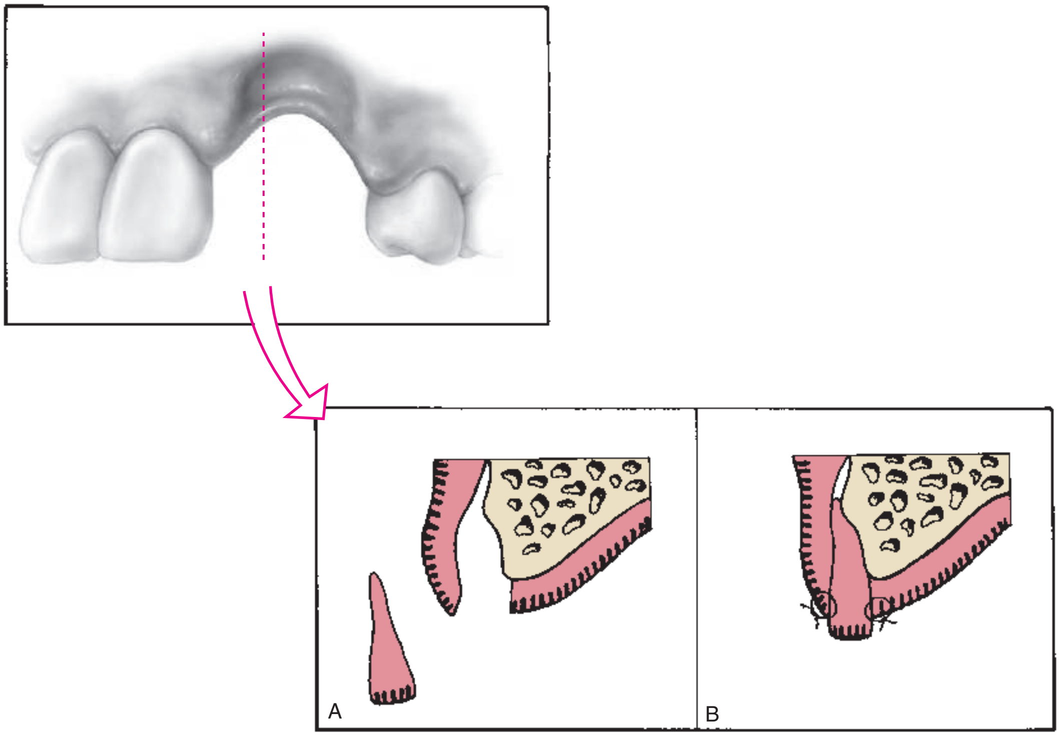


Fig. 20.8 Cross-section illustrations of an interpositional graft for augmentation of ridge width and height. (A) Tissue is reflected. (B) Graft is positioned and sutured in place.

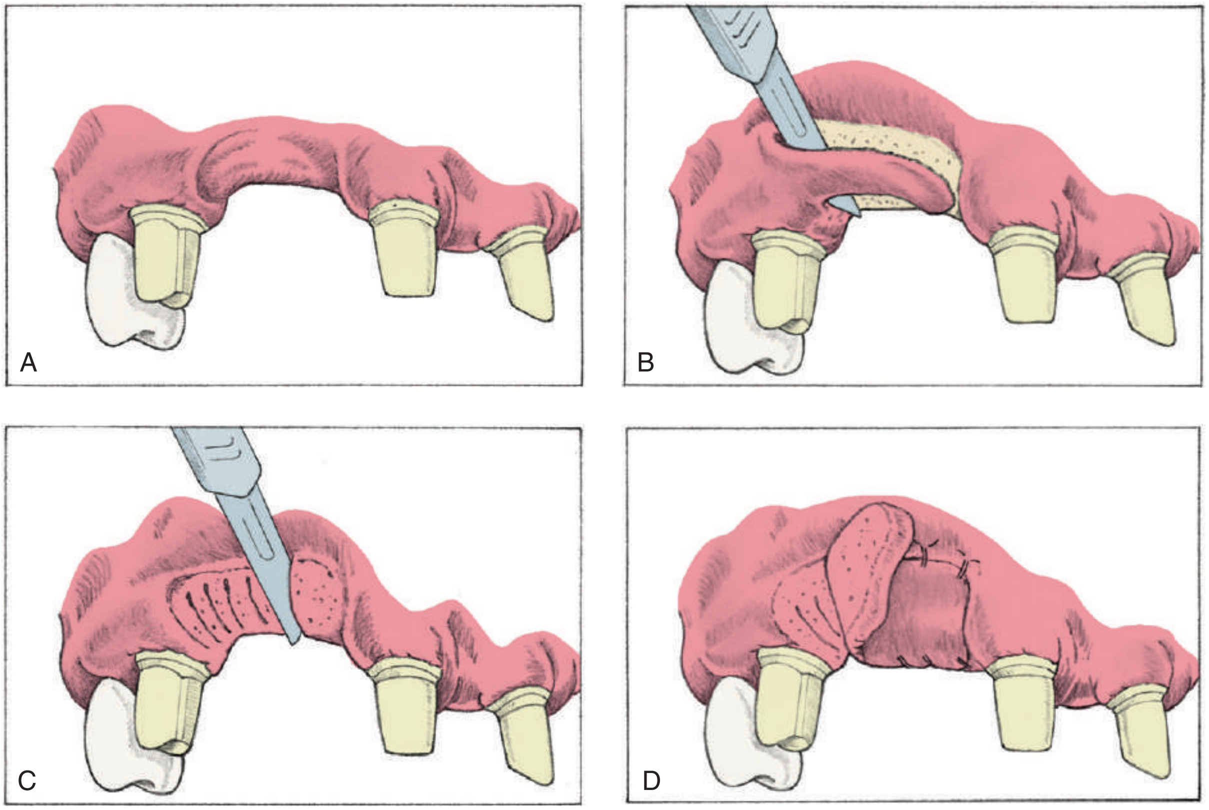


Fig. 20.9 An onlay graft for augmentation of ridge width and height. (A) Presurgical illustration of class III residual ridge defect with abutment teeth prepared. (B) Recipient bed is prepared by removal of epithelium. (C) Striation cuts are made in connective tissue to encourage revascularization. (D) Onlay graft is sutured in place.

Fig. 20.9, cont'd (E) An interim fixed partial denture with open embrasures is placed immediately to allow adaptation of tissue during healing. (F) Cast with class III residual ridge defect; the lateral incisor was unrestorable. (G) Donor site for graft. (H) Graft sutured in place. (I) Augmented ridge. (J and K) Definitive restoration with improved contours.

Fig. 20.10 Alveolar architecture preservation technique. (A) Atraumatic tooth extraction. (B) Cross-sectional view of the immediate interim fixed partial denture, demonstrating ovate pontic form. (C) Interim restoration. Note the 2.5-mm apical extension of the ovate pontic. (D) The seated interim restoration should cause slight blanching of interdental papilla. (E) Interim restoration 12 months after extraction. Note the preservation of interdental papilla. (Courtesy Dr. F.M. Spear and Montage Media, Mahwah, New Jersey.)

oral hygiene access is improved by recontouring the pontic to provide 1 to 1.5 mm of relief from the tissue. When the gingival levels are stable (approximately 6 to 12 months) the definitive restoration can be fabricated (see Fig. 20.10E).

Techniques involving orthodontic extrusions have also been employed to preserve ridge form before extraction. In these proactive methods, light forces are used to extrude the teeth destined to be extracted. As the teeth are extruded, apposition of bone occurs at the root apex, thereby filling the socket with bone as the tooth is slowly extracted orthodontically. First employed to avoid ridge augmentation and to increase vertical ridge height before immediate implant placement,[18] the orthodontic extrusion technique has been used successfully to maintain ridge contour before treatment with conventional FPDs (Fig. 20.11). In addition to the additional time and expense of orthodontic treatment, endodontic treatment is necessary beforehand because the teeth to be extracted must continuously be adjusted as they are extruded.

Although maintenance of the residual ridge after extraction is desirable, socket-preservation techniques are technically challenging, require frequent patient monitoring, and necessitate conscientious hygiene by the patient. Even when the procedure is performed meticulously, success is unpredictable because of the variability in patients' healing responses. Rarely can socket preservation completely preserve the alveolar ridge frame.[19] Additional surgical augmentation of the ridge may still be necessary for some patients.

As an alternative to socket preservation and ridge augmentation surgery, root submergence techniques have been recommended to preserve alveolar bone heights. Originally

Fig. 20.11 Orthodontic extrusion to preserve alveolar architecture. (A) Pretreatment (note discrepancy in gingival crest heights between the maxillary central incisors). (B) Orthodontic extrusion. (C) Preextrusion and postextrusion radiographs. *Red line* denotes reference point; *blue* and *yellow lines* denote change in gingival crest height. (D) Postextraction evaluation of interim restoration with ovate pontics. (E) Gingival architecture immediately before pression. (F) Definitive restoration.

documented in the 1970s, root submergence technique involves the resection of the tooth crown and the subsequent covering of the remaining root with a gingival flap. This technique has been successfully employed to preserve ridge height for patients with complete dentures.[20] The technique has been performed with vital and nonvital roots. Root submergence can also be used to preserve the alveolar ridge for anterior pontic sites between natural tooth abutments[21] and implant abutments (Fig. 20.12).[22]

PONTIC CLASSIFICATION

Pontic designs are classified into two general groups: those that contact the oral mucosa and those that do not (Box 20.1). Several subclassifications exist within these groups that are based on the shape of the gingival side of the pontic. Pontic selection depends primarily on esthetics and oral hygiene. In the anterior region, where esthetic appearance is a concern, the pontic should be well adapted to the tissue to make it appear as if it emerges from the gingiva. Conversely, in the posterior regions (mandibular premolar and molar areas), contours can be modified in the interest of designs that are less esthetic but amenable to oral hygiene. The advantages and disadvantages of the various pontic designs are summarized in Table 20.2.

Sanitary or Hygienic Pontic

As its name implies, the primary design feature of the sanitary pontic allows easy cleaning because its tissue surface remains clear of the residual ridge (Fig. 20.13A). This hygienic design enables easier plaque control by allowing gauze strips and other cleaning devices to be passed under the pontic and seesawed in a shoeshine manner. Disadvantages include entrapment of food particles, which may lead to tongue habits that annoy the patient. The hygienic pontic is the least tooth-like design and is therefore reserved for teeth seldom displayed during function (i.e., the mandibular molars).

A modified version of the sanitary pontic has been developed (see Fig. 20.13B and C).[23] Its gingival portion is shaped like an archway between the retainers. This geometry allows for an increase in connector size and a decrease in the stress concentrated in the pontic and connectors.[24] It is also less susceptible to tissue proliferation that can occur when a pontic is too close to the residual ridge (see Fig. 20.13D).

Fig. 20.12 Clinical (A) and (B) and radiographic (C) appearance of the teeth of a 55-year-old woman who presented with esthetic and masticatory disturbances. (D) Periapical radiograph of the anterior teeth after orthodontic therapy. The plan was for both central incisors and the left lateral incisor to be replaced with an implant-supported restoration. (E) Anterior view of the result. Esthetics and function were maintained. An interdisciplinary approach was needed. (F) Posttreatment panoramic radiograph. Positions of the teeth and implants were optimal. (G) The pontic site shows excellent shape because of the submerged root. (H) The definitive restoration looked natural. The submerged root of the right maxillary central incisor maintained the surrounding alveolar bone and soft tissues of the pontic in the most coronal position. A normal pontic is not typically able to reproduce these ideal tissue frames and papilla heights because the needed underlying bone support is lacking. (I) Posttreatment periapical radiograph obtained 27 months after root submergence. The submerged root maintained an ideal mesiodistal alveolar bone level. (From Salama M, Ishikawa T, Salama H, et al. Advantages of the root submergence technique for pontic site development in esthetic implant therapy. *Int J Periodontics Restorative Dent*. 2007;27:521.)

Box 20.1 Pontic Design Classification

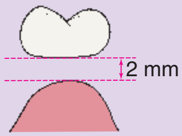
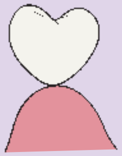
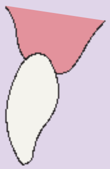
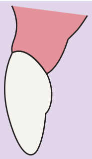
Mucosal Contact
Ridge-lap
Modified ridge-lap
Ovate
Conical

No Mucosal Contact
Sanitary (hygienic)
Modified sanitary (hygienic)

Saddle and Ridge-Lap Pontics

The saddle pontic has a concave fitting surface that overlaps the residual ridge buccolingually, simulating the contours and emergence profile of the missing tooth on both sides of the residual ridge. However, saddle or ridge-lap designs should be avoided because the concave gingival surface of the pontic is not accessible to cleaning with dental floss, which leads to plaque accumulation (Fig. 20.14). This design deficiency has been shown to result in tissue inflammation (Fig. 20.15).[1]

TABLE 20.2 Pontic Design

Pontic Design	Appearance	Recommended Location	Advantages	Disadvantages	Indications	Contraindications	Materials
Sanitary/hygienic		Posterior mandible	Good access for oral hygiene	Poor esthetics	Nonesthetic zones Impaired oral hygiene	Where esthetics is important Minimal vertical dimension	All metal
Saddle/ridge-lap		Not recommended	Esthetic	Not amenable to oral hygiene	Not recommended	Not recommended	Not applicable
Conical		Molars without esthetic requirements	Good access for oral hygiene	Poor esthetics	Posterior areas where esthetics is of minimal concern	Poor oral hygiene	Metal-ceramic All resin All ceramic
Modified ridge-lap		High esthetic requirement (i.e., anterior teeth and premolars, some maxillary molars)	Good esthetics	Moderately easy to clean	Most areas with esthetic concern	Where minimal esthetic concern exists	Metal-ceramic All resin All ceramic
Ovate		Very high esthetic requirement Maxillary incisors, canines, and premolars	Superior esthetics Negligible food entrapment Ease of cleaning	Necessitates surgical preparation Not for residual ridge defects	Desire for optimal esthetics High smile line	Patient's unwillingness to undergo surgery Residual ridge defects	Metal-ceramic All resin All ceramic
Modified ovate		Very high esthetic requirement Maxillary incisors, canines, and premolars	Superior esthetics Negligible food entrapment Ease of cleaning	Necessitates surgical preparation	Where horizontal ridge width is not sufficient for a conventional ovate pontic	Patient's unwillingness to undergo surgery	Metal-ceramic All resin All ceramic

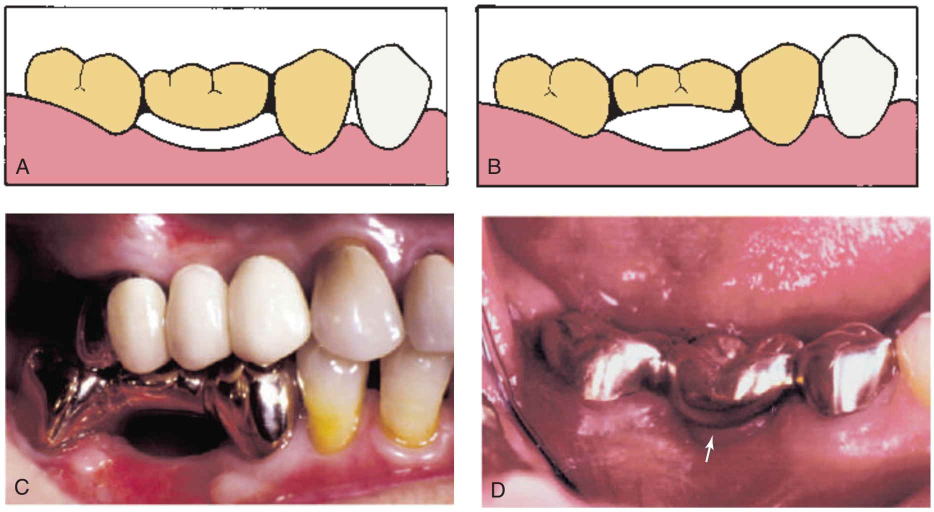


Fig. 20.13 (A) Illustration of sanitary pontic. Illustration (B) and appearance (C) of a modified sanitary pontic. (D) Placement of the pontic, close to the ridge, has resulted in tissue proliferation *(arrow)*.

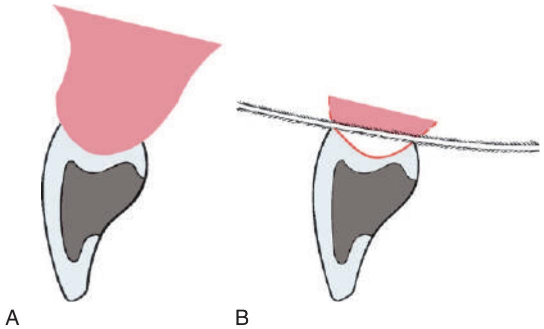


Fig. 20.14 (A) Cross-sectional view of ridge-lap pontic. (B) The tissue surface is inaccessible to cleaning devices.

Modified Ridge-Lap Pontic

The modified ridge-lap pontic combines the best features of the hygienic and saddle pontic designs, combining esthetics with easy cleaning. Demonstrated by Figs. 20.16 and 20.17, the modified ridge-lap pontic overlaps the residual ridge on the facial side (to achieve the appearance of a tooth emerging from the gingiva), but remains clear of the ridge on the lingual side. To enable optimal plaque control, the gingival surface must have no depression or hollow; rather, it should be as convex as possible from mesial to distal aspects (the greater the convexity, the easier the oral hygiene). Tissue contact should resemble a letter *T* (Fig. 20.18) whose vertical arm ends at the crest of the ridge. Facial ridge adaptation is essential for a natural appearance. Although this design was historically referred to as ridge-lap design,[25,26] the term ridge-lap is now used synonymously with saddle design. The modified ridge-lap design is the most common pontic form used in areas of the mouth that are visible during function (maxillary and mandibular anterior teeth, maxillary premolars, and first molars).

Conical Pontic

Often called *egg-shaped, bullet-shaped*, or *heart-shaped*, the conical pontic (Fig. 20.19) is straightforward for the patient to keep clean. It should be made as convex as possible and should have only one point of contact: at the center of the residual ridge. This design is recommended for the replacement of mandibular posterior teeth, for which esthetic appearance is a lesser concern. The facial and lingual contours are dependent on the width of the residual ridge; a knife-edged residual ridge necessitates flatter contours with a narrow tissue contact area. This type of design may be unsuitable for broad residual ridges because the emergence profile associated with the small tissue contact point may create areas of food entrapment (Fig. 20.20). The sanitary or hygienic pontic is the design of choice in these clinical situations.

Ovate Pontic

The ovate pontic is the pontic design that is most esthetically appealing. Its convex tissue surface resides in a soft tissue depression or hollow in the residual ridge, which makes it appear that a tooth is literally emerging from the gingiva (Fig. 20.21). Careful treatment planning is necessary for successful results. Socket-preservation techniques should be performed at the time of extraction to create the tissue recess from which the ovate pontic form will appear to emerge. For a preexisting residual ridge, surgical augmentation of the soft tissue is typically required. When an adequate volume of ridge tissue is established, a socket depression is sculpted into the ridge with surgical diamonds, electrosurgery, or a dental laser. With every option, meticulous attention to the contour of the pontic of the interim restoration is essential when the residual ridge that will receive the definitive prosthesis is conditioned and shaped.

The advantages of an ovate pontic include its pleasing appearance and its strength. When it is used successfully with ridge augmentation, its emergence from the ridge appears identical

Fig. 20.15 (A and B) Fixed partial denture (FPD) with a ridge-lap (concave) gingival surface. (C) When it was removed, the tissue was found to be ulcerated. The defective FPD was recontoured and used as an interim restoration while the definitive restoration was being fabricated. (D) Within 2 weeks, the ulceration had resolved.

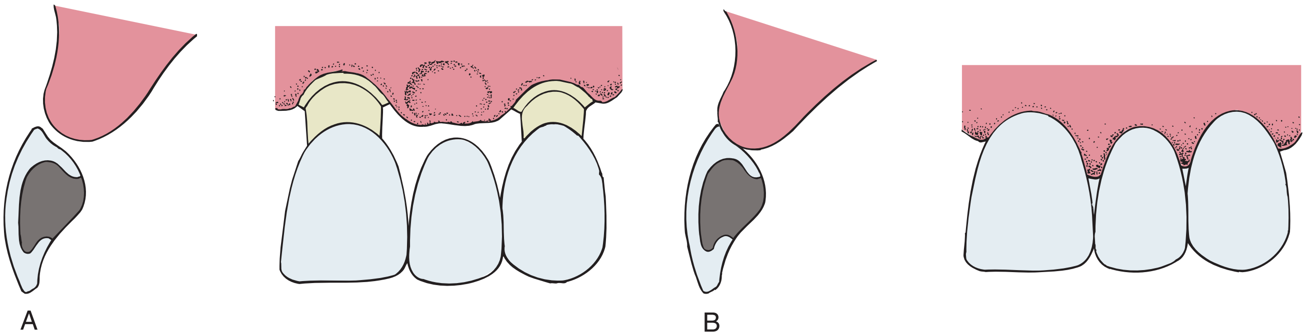


Fig. 20.16 Modified ridge-lap pontic. (A) Fixed partial denture (FPD) partially seated. (B) FPD seated.

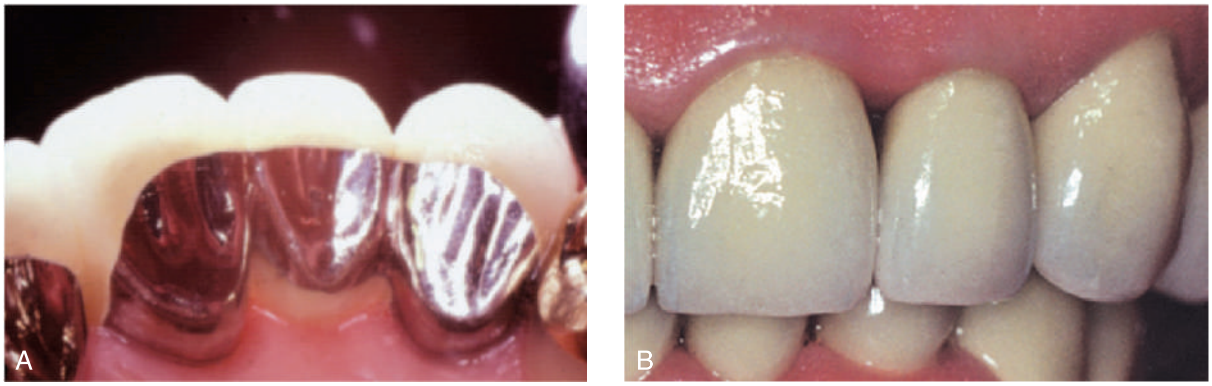


Fig. 20.17 Three-unit fixed partial denture replacing the maxillary lateral incisor. (A) To facilitate plaque control, the lingual surface is made convex. (B), The facial surface is shaped to simulate the missing tooth.

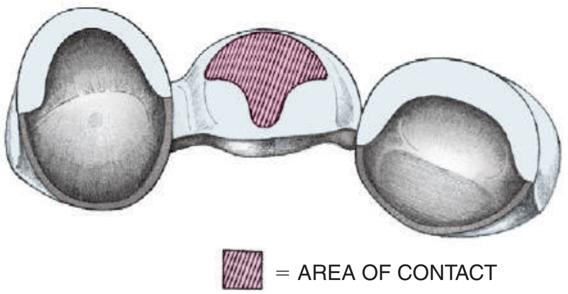


Fig. 20.18 Tissue contact of a maxillary fixed partial denture (FPD) should resemble the letter T. In this illustration, the FPD is viewed from the gingival aspect.

to that of a natural tooth. In addition, its recessed form is not susceptible to food impaction. The broad convex geometry is stronger than that of the modified ridge-lap pontic because the porcelain at the gingivofacial extent of a pontic is supported (Fig. 20.22). Because the tissue surface of the pontic is convex in all dimensions, it is accessible to dental floss; however, meticulous oral hygiene is necessary to prevent tissue inflammation resulting from the large area of tissue contact. Other disadvantages include the need for surgical tissue management and the associated cost. Furthermore, an additional evaluation appointment is typically necessary to achieve an esthetic result. The socket depression, with its pseudopapillae, requires the support of the interim ovate pontic and will collapse when the interim restoration is removed before an impression is made. To compensate for this three-dimensional change in the socket that occurs during the impression making, it is necessary to scrape the cast in this area to ensure positive contact and support of the pseudopapillae with the definitive pontic. Alternatively, special impression techniques can be used, such as the one described by de Vasconcellos et al.[27] Because these adjustments are made somewhat arbitrarily, it may also be necessary to make revisions to the tissue surface of the pontic (reshaping or porcelain additions) at the evaluation phase.

Modified Ovate Pontic

Liu[28] described a modified version of the ovate pontic that expands the clinical indications for the ovate pontic. The modified ovate pontic possesses an ovate form with the apex positioned more facially on the residual ridge, rather than at the crest of the ridge. This alteration allows the use of the pontic in clinical scenarios in which horizontal ridge width is not sufficient for a conventional ovate pontic. Cleansing of this pontic is also purported to be easiest of all pontic types.

BIOLOGIC CONSIDERATIONS

The biologic principles of pontic design pertain to the maintenance and preservation of the residual ridge, abutments, opposing teeth, and healthy supporting mucosa on the alveolar ridge at the pontic site. Factors of specific influence are pontic-ridge contact, amenability to oral hygiene, and the direction of occlusal forces.

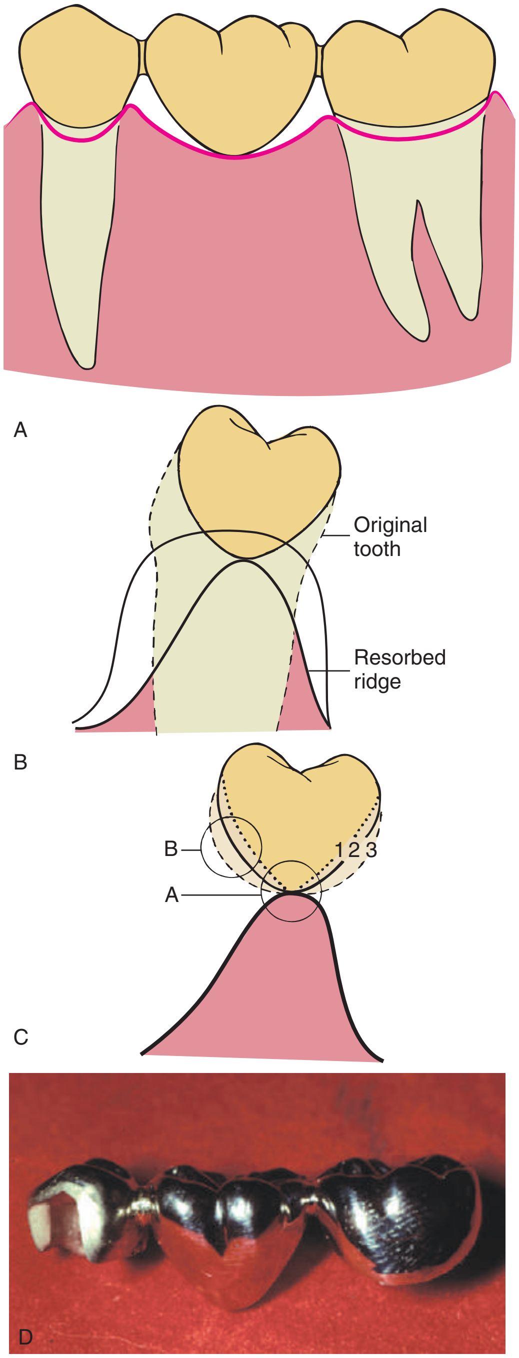


Fig. 20.19 (A and B) A pontic with maximum convexity and a single point of contact with the tissue surface is the design easiest to keep clean. (C) Evaluating the contour of three possible pontic shapes (*1*, *2*, and *3*). Contour *3* is the most convex in area *B* but is too flat in area *A*. Contour *1* is convex in area *A* but is too flat in area *B*. Contour *2* is the best. (D) A metal fixed partial denture with a conical pontic, suitable for replacement of a mandibular molar.

Alveolar Ridge Mucosal Lesions

Mucosa overlying the edentulous ridge is often not protected adequately after extraction with a removable or a fixed prosthesis. White lesions of the oral cavity are a common presentation

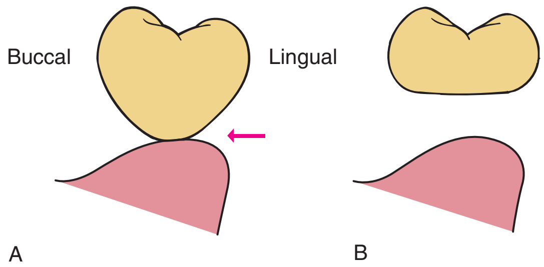


Fig. 20.20 (A) Conical pontics may be conducive to food entrapment on broad residual ridges *(arrow)*. (B) The sanitary pontic form may be a better alternative.

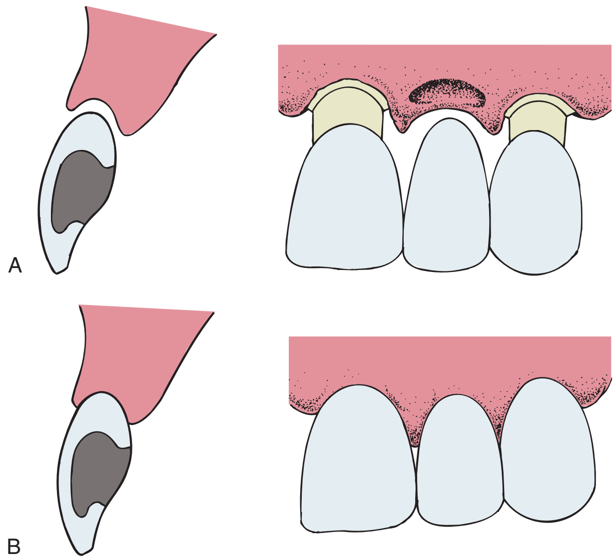


Fig. 20.21 Ovate pontic. (A) Fixed partial denture (FPD) partially seated. (B) FPD seated.

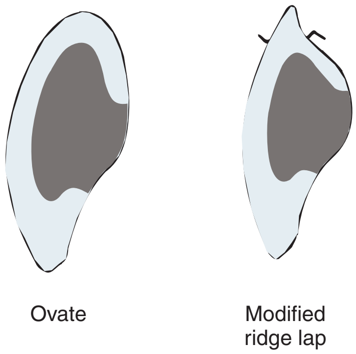


Fig. 20.22 The ovate pontic design eliminates the potential for unsupported porcelain in the cervical portion of an anterior pontic.

and can have a variety of etiologies, both benign and malignant.[29] Parafunctional habits such rubbing, chewing, or sucking on external objects, that is, ice chips, pencil, or any constant insult, can result in keratosis of the alveolar ridge mucosa. Woo and Lin evaluated histopathological findings of 584 patients with leukoplakia and reported that the most common age group to exhibit frictional keratosis were in the fifth and sixth decade.[30] Edentulous ridges and retromolar pads frequently exhibit benign keratosis as they are susceptible to both masticatory forces, occlusal trauma, ill-fitting removable denture, or other dental prosthesis. Most traumatized gingiva along the alveolar ridge show clinical signs of erythema, ulceration, edema, or other reactive lesions such as pyogenic granuloma.[31,32] A thorough evaluation of pontic site alveolar ridge tissue for any such white lesion, such as frictional keratosis and proliferative verrucous leukoplakia (PVL), should not be overlooked. PVL has shown to be associated with high recurrence and malignant transformation rates.[33,34] Once the fixed prosthesis is cemented the pontic can obstruct the occlusal view of the alveolar ridge, risking the chance of unnoticed progression of these lesions. Careful and vigilant evaluation and following the necessary protocols in evaluating the suspicious tissue, typically with a biopsy, is highly recommended. These special circumstances help to modify the design and selection of pontic types to aid in rigorous soft tissue monitoring.

Ridge Contact

Pressure-free contact between the pontic and the underlying tissues prevent ulceration and inflammation of the soft tissues.[1,35] If any blanching of the soft tissues is observed at evaluation, the pressure area should be identified with a disclosing medium (e.g., pressure-indicating paste) and the pontic should be recontoured until tissue contact is entirely passive. This passive contact should occur exclusively on keratinized attached tissue. When a pontic rests on mucosa, some ulceration may appear as a result of the normal movement of the mucosa in contact with the pontic (Fig. 20.23). Positive ridge pressure (hyperpressure) may be caused by excessive scraping of the ridge area on the definitive cast (Fig. 20.24). This was once promoted as a way to improve the appearance of the pontic-ridge relationship. However, because of the ulceration that inevitably results when flossing is not meticulously performed, the concept is not recommended[1,36,37] unless followed as previously described for an ovate pontic.[35,38] Although ovate pontics maintain positive tissue contact to support the pseudopapillae, healthy mucosa can be maintained if the contact to the mucosa is tight but noncompressive, and the gingival portion of the pontic is regularly cleaned.[39]

Fig. 20.23 Pressure of a pontic on the mucosa inevitably leads to ulceration.

Fig. 20.24 Blanching of soft tissue at evaluation indicates pressure of the pontic on the mucosa.

Fig. 20.25 The patient must be instructed in how to clean the gingival surface of a pontic with floss.

Oral Hygiene Considerations

The chief cause of ridge irritation is the toxins released from microbial plaque, which accumulate between the gingival surface of the pontic and the residual ridge, causing tissue inflammation and calculus formation.

Unlike removable partial dentures, FPDs cannot be taken out of the mouth for daily cleaning. Patients must be taught efficient oral hygiene techniques, with particular emphasis on cleaning the gingival surface of the pontic. The shape of the gingival surface, its relation to the ridge, and the materials used in its fabrication influence ultimate success.

Normally, where tissue contact occurs, the gingival surface of a pontic is inaccessible to the bristles of a toothbrush. Therefore, the patient must develop excellent hygiene habits. Devices such as proxy brushes, pipe cleaners, Oral-B Super Floss (Oral-B, Procter & Gamble), and dental floss with a threader are highly recommended (Fig. 20.25). Gingival embrasures around the pontic should be wide enough to allow oral hygiene aids. However, to prevent food entrapment, they should not be opened excessively. To enable passage of floss over the entire tissue surface, tissue contact between the residual ridge and pontic must be passive.

If the pontic has a depression or concavity in its gingival surface, plaque accumulates because the floss cannot clean this area and tissue irritation[40] follows. This is usually reversible; when the surface is subsequently modified to eliminate the concavity, inflammation disappears (see Fig. 20.15). Therefore, an accurate description of pontic design should be submitted to the laboratory and the prosthesis should be checked and corrected if necessary before cementation. Prevention is the best solution for controlling tissue irritation.

Pontic Material

Any material chosen to fabricate the pontic should provide good esthetic results where needed; biocompatibility, rigidity, and strength to withstand occlusal forces; and longevity. FPDs should be made as rigid as possible because any flexure during mastication or parafunction may cause pressure on the gingiva and cause fractures of the veneering material. Occlusal contacts should not fall on the junction between metal and porcelain during centric or eccentric tooth contacts, nor should a metal-ceramic junction be in contact with the residual ridge on the gingival surface of the pontic.

Investigations into the biocompatibility of materials used to fabricate pontics have centered on two factors: (1) the effect of the materials and (2) the effects of surface adherence. Glazed porcelain is generally considered the most biocompatible of the available pontic materials,[41–43] and clinical data[36,44] tends to support this opinion, although the crucial factor seems to be the material's ability to resist plaque accumulation[45] (rather than the material itself). Well-polished gold is smoother, less prone to corrosion, and less retentive of plaque than unpolished or porous casting.[46] However, even highly polished surfaces accumulate plaque if oral hygiene measures are ignored.[47,48]

Glazed porcelain looks very smooth, but when viewed under a microscope, its surface shows many voids and is rougher than that of either polished gold or acrylic resin (Fig. 20.26).[49] Nevertheless, highly glazed porcelain is easier to clean than are other materials. For easier plaque removal and biocompatibility, the tissue surface of the pontic should be made in glazed porcelain. However, ceramic tissue contact may be contraindicated in edentulous areas where there is minimal distance between the residual ridge and the occlusal surface. In these instances, placing ceramic on the tissue side of the pontic may weaken the design of the metal substructure, particularly with porcelain occlusal surface (Fig. 20.27). If metal is placed in tissue contact, it should be highly polished. Zirconia has been shown to be a biocompatible material. The soft tissue response to this material is superior to other porous materials because of its low bacterial colonization potential.[50] The absence of plaque produces clinically insignificant inflammatory responses to oral tissues.[51] Regardless of the choice of pontic material, patients can prevent inflammation around the pontic with meticulous oral hygiene.[52]

Occlusal Forces

Reducing the buccolingual width of the pontic by as much as 30% has been suggested[53,54] as a way to lessen occlusal forces on, and thus the loading of, abutment teeth. This practice continues today, although it has little scientific basis. Critical analysis[55] has revealed that forces are lessened only when food of uniform consistency is chewed and that a mere 12% increase in chewing efficiency can be expected from a one-third reduction of pontic width. Potentially harmful forces are more likely to be encountered if an FPD is loaded by the accidental biting on a hard object or by parafunctional activities such as bruxism, rather

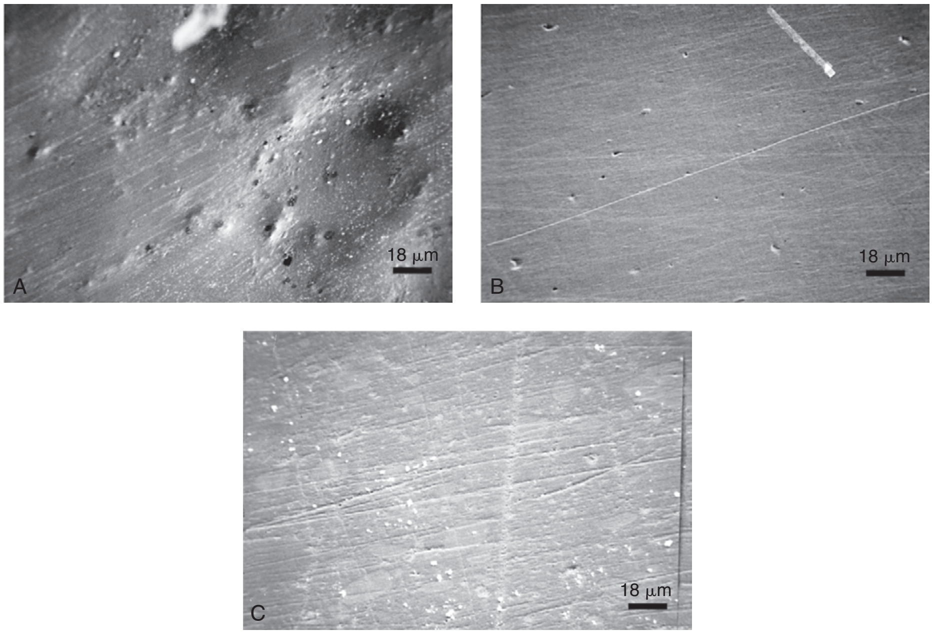


Fig. 20.26 Scanning electron micrographs of glazed porcelain (A), polished gold (B), and polished acrylic resin (C). (Microscopy by Dr. J.L. Sandrik.)

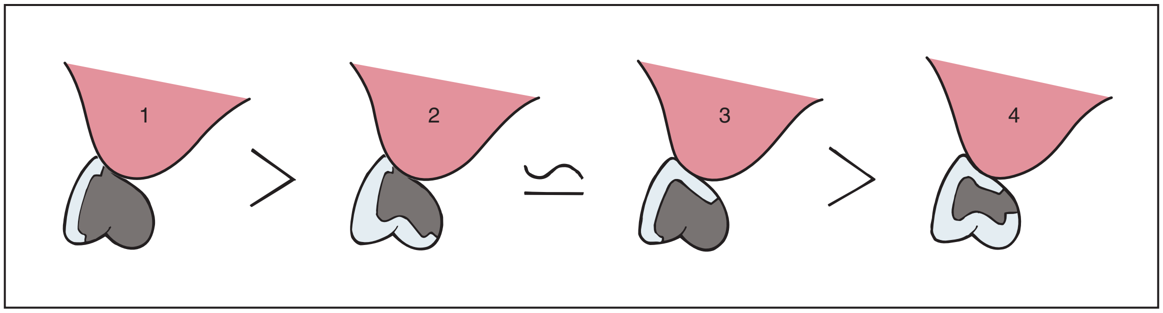


Fig. 20.27 Four pontic designs in descending order of strength, according to cross-sectional diameter of the metal substructure. When vertical space is minimal, the fourth design (porcelain tissue and occlusal coverage) may be contraindicated.

than by chewing foods of uniform consistency. Narrowing the occlusal surface does not reduce these forces.

In fact, narrowing the occlusal surface may actually impede or even preclude the development of a harmonious and stable occlusal relationship. Like a malposed tooth, it may cause difficulties in plaque control and may not provide proper cheek support. For these reasons, pontics with normal occlusal widths (at least in the occlusal third) are generally recommended. One exception is the situation in which the residual alveolar ridge has collapsed buccolingually. Reducing pontic width may then be desired and would thereby lessen the lingual contour and facilitate plaque-control measures.

MECHANICAL CONSIDERATIONS

The prognosis of FPD pontics is compromised if mechanical principles are not followed closely. Mechanical problems may be caused by improper choice of materials, poor framework design, poor tooth preparation, or poor occlusion. These factors can lead to fracture of the prosthesis or displacement of the retainers. Long-span posterior FPDs are particularly susceptible to mechanical problems. Inevitably, significant flexing occurs as a result of high occlusal forces and because the displacement effects increase with the cube of the span length (see Chapter 3). Therefore, evaluating the likely forces on a pontic and designing accordingly are important. For example, a strong metal or zirconia pontic, rather than a metal-ceramic pontic (Fig. 20.28), may be needed in high-stress situations, in which it would be more susceptible to fracture. When metal-ceramic pontics are chosen, extending porcelain onto the occlusal surfaces to achieve better esthetics should also be carefully evaluated. In addition to its potential for fracture, porcelain may abrade the opposing dentition if the occlusal contacts are on enamel or metal.

Fig. 20.28 Failure of a long-span metal-ceramic fixed partial denture subjected to high stress.

Fig. 20.29 Pontic failure resulting from improper laboratory technique.

Available Pontic Materials

Some FPDs are fabricated entirely of metal, lithium disilicate, acrylic resin, or zirconia, but most consist of a combination of metal and porcelain. The acceptance of acrylic resin–veneered pontics has been limited because of their reduced durability (wear and discoloration). The newer indirect composite resins, which are based on high inorganic content–filled resins and fiber-reinforced materials (see Chapter 15), have revived some interest in composite resin and resin-veneered pontics. Composite resin and resin-veneered pontics are seldom used as newer materials such as zirconia have better physical properties.

Zirconia Pontics

Zirconia has become a popular material for fixed implants and natural teeth restorations. Use of zirconia dictates the need to utilize computer-aided design and computer-aided manufacture (CAD-CAM) technology. Zirconia restorations can be milled from fully sintered, semi-sintered, or unsintered zirconia blanks.[56] Fully sintered zirconia is very high in strength and can wear out the milling equipment rapidly. Most restorations are milled in the non-sintered or green stage. At this stage, the restorations are about 20% to 30% larger to accommodate for the shrinkage of the material during the sintering process. The CAD technology determines and calculates this value during the planning and designing stage.

A unique property of yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP) is, *'transformation toughening'* by which it prevents crack propagation by increasing the localized fracture resistance (see Chapter 25). The high fracture resistance makes it suitable to be used for long-span, fixed restorations with multiple pontics and abutments provided adequate connector dimension can be achieved.

Esthetics can be improved with zirconia pontics as it is a tooth colored material. With advancements, multiple shades of zirconia are now available to best color match with the adjacent teeth. A thin layer of porcelain can be added on the facial surface to improve the esthetics (porcelain fused to zirconia). One of the disadvantages of this material is the large connector size required between pontics and abutments,[57] for adequate strength, which can compromise the gingival and occlusal/incisal embrasures (see Chapter 27). Large connectors can diminish the natural appearance of the restoration and compromise the ability for oral hygiene maintenance under zirconia pontics.

Fig. 20.30 Failure of unsupported gingival porcelain.

Metal-Ceramic Pontics

Most pontics are fabricated by the metal-ceramic technique. If properly used, this technique is helpful in solving commonly encountered clinical problems. A well-fabricated, metal-ceramic pontic is strong, easy to keep clean, and natural-looking. However, mechanical failure (Fig. 20.29) can occur and is often attributable to inadequate framework design. The principles of framework design are discussed in Chapter 19, but the following points are emphasized in this chapter:

- The framework must provide a uniform veneer of porcelain (approximately 1.2 mm). Excessive thickness of porcelain contributes to inadequate support and predisposes to eventual fracture (Fig. 20.30). This is often true in the cervical portion of an anterior pontic. A reliable technique for ensuring uniform thickness of porcelain is to wax the fixed prosthesis to complete anatomic contour and then accurately cut back the wax to a predetermined depth (Fig. 20.31).
- The metal surfaces to be veneered must be smooth and free of pits. Surface irregularities cause incomplete wetting by the porcelain slurry, which leads to voids at the porcelain-metal interface that reduce bond strength and increase the possibility of mechanical failure.
- Sharp angles on the veneering area should be rounded. They produce increased stress concentrations that can cause mechanical failure.
- The location and design of the external metal-porcelain junction require particular attention. Any deformation of the

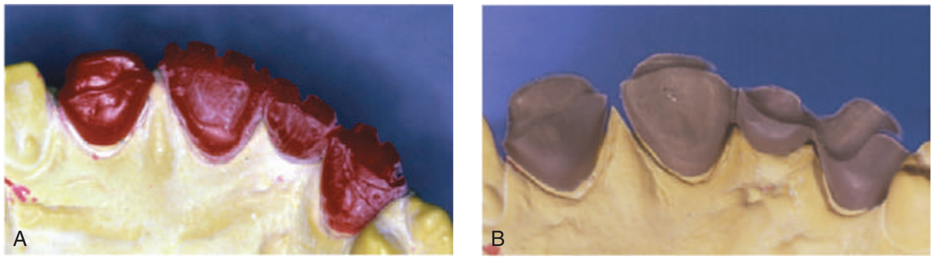


Fig. 20.31 Waxing to anatomic contour and controlled cutback (A) are the most reliable approaches to fabricating a satisfactory metal substructure (B).

Fig. 20.32 Porcelain chipping caused by occlusal contact across the metal-ceramic junction.

metal framework at the junction can lead to chipping of the porcelain (Fig. 20.32). For this reason, occlusal centric contacts must be placed at least 1.5 mm away from the junction. Excursive, eccentric contacts that might deform the metal-ceramic interface must be evaluated carefully.

ESTHETIC CONSIDERATIONS

No matter how well biologic and mechanical principles have been followed during fabrication, the patient evaluates the result by how it looks, especially when anterior teeth have been replaced. Many esthetic considerations that pertain to single crowns also apply to pontics (see Chapter 23). Several problems unique to pontics may be encountered in the attempt to achieve a natural appearance.

The Gingival Interface

An esthetically successful pontic replicates the form, contours, incisal edge, gingival and incisal embrasures, and color of adjacent teeth. The pontic's simulation of a natural tooth is most often betrayed at the tissue-pontic junction. The greatest challenge in this situation is to compensate for anatomic changes that occur after extraction. To achieve a “natural” appearance, special attention should be paid to the contour of the labial surface as it approaches the tissue-pontic junction. This cannot be accomplished by mere duplication of the facial contour of the missing tooth; after a tooth is removed, the alveolar bone undergoes resorption, remodeling, or both. If the original tooth contour were followed, the pontic would look unnaturally long incisogingivally (Fig. 20.33). For an esthetic pontic to achieve the illusion of a natural tooth, observers must think that they are seeing a natural tooth.

Fig. 20.33 Correct incisogingival height is critical in esthetic pontic design. (A) Esthetic failure of a four-unit fixed partial denture (FPD) replacing the right central and lateral incisors. The pontics have been shaped to follow the facial contour of the missing teeth, but because of bone loss, they look too long. (B) The replacement FPD. Note that the gingival half of each pontic has been reduced. Esthetic appearance is much improved. (C) This esthetic failure is the result of excessive reduction. The central incisor pontics look too short.

The modified ridge-lap pontic is recommended for most anterior situations; it compensates for lost buccolingual width in the residual ridge by overlapping what remains. Rather than emerging from the crest of the ridge as a natural tooth would, the cervical aspect of the pontic sits in front of the ridge, covering any abnormal ridge structure that results from tooth loss.

Fortunately, because most teeth are viewed from only two dimensions, this relationship remains undetected. A properly designed, modified ridge-lap pontic provides the required convexity on the tissue side with smooth and open embrasures on the lingual side for ease of cleaning. This is difficult to accomplish. Clinically, many pontics have suboptimal contour, resulting in an unnatural appearance. This can be avoided with careful preparation at the diagnostic waxing stage (see Chapter 3). Sometimes the ridge tissue must be surgically reshaped to enhance the result.

In normal situations light falls from above and an object's shadow is below it. Unexpected lighting or positioned shadows (Fig. 20.34) can be confusing to the brain. Because of past experience, the brain "knows" that a tooth grows out of the gingiva and it therefore "sees" a pontic as a tooth unless telltale shadows suggest otherwise. The dentist must carefully study where shadows fall around natural teeth, particularly around the gingival margin. If a pontic is poorly adapted to the residual ridge, an unnatural and odd-looking shadow exists in the cervical area and spoils the illusion of a natural tooth (Fig. 20.35). In addition, recesses at the pontic-gingival interface collect food debris, further ruining the illusion of a natural tooth.

When appearance is of utmost concern, the ovate pontic, used in conjunction with alveolar preservation or soft tissue ridge augmentation, can provide an appearance at the gingival interface that is virtually indistinguishable from that of a natural tooth. Because it emerges from a soft tissue recess, this pontic is not susceptible to many of the esthetic pitfalls applicable to the modified ridge-lap pontic. However, in most circumstances, the patient must be willing to undergo the additional surgical procedures that are necessary for placement of an ovate pontic.

Incisogingival Length

Correctly sizing a pontic simply by duplicating the original tooth is not possible. Ridge resorption makes such a pontic look too long in the cervical region. The height of a tooth is immediately obvious when the patient smiles and shows the gingival margin (Fig. 20.36). An abnormal labiolingual position or cervical contour is not immediately obvious. This fact can be used to produce a pontic of good appearance by recontouring the gingival half of the labial surface (see Fig. 20.35). The observer sees a normal tooth length but is unaware of the abnormal labial contour, meaning the illusion is successful.

Even with moderately severe bone resorption, obtaining a natural appearance by exaggerated contouring of the pontics may still be possible. In areas where tooth loss is accompanied by excessive loss of alveolar bone, however, a pontic of normal length would not touch the ridge at all.

One solution is to shape the pontic to simulate a normal crown and root with emphasis on the cementoenamel junction. The root can be stained to simulate exposed dentin (Fig. 20.37). Another approach is to use pink porcelain to simulate the

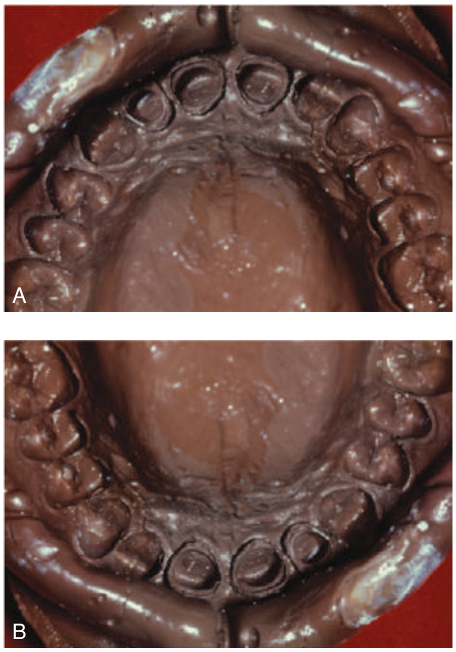


Fig. 20.34 Optical illusion. The two images (A) and (B) are identical except that one image is upside down. Most people make different three-dimensional interpretations of each photograph, interpreting one as a negative impression and the other as a positive cast. (Verify the illusion by turning the book.) The interpretation is based on how shadows fall; in normal situations, objects are seen illuminated from above.

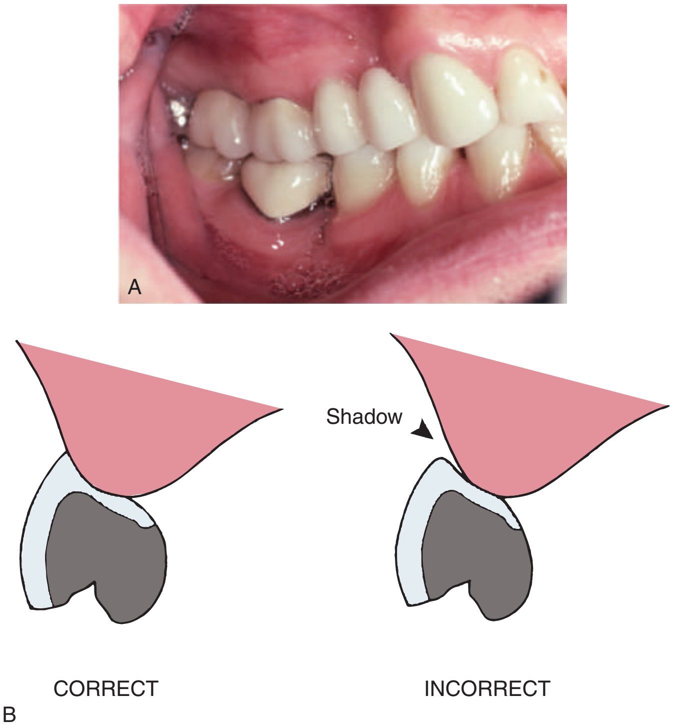
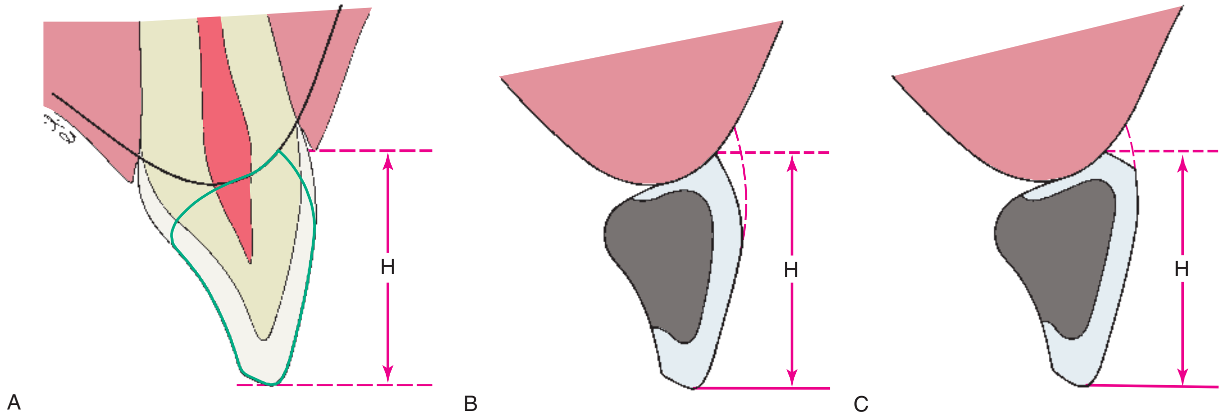


Fig. 20.35 A pontic should be interpreted as "growing" out of the gingival tissue. The second premolar pontic in this four-unit fixed partial denture (A) is successful because it is well adapted to the ridge; however, it is evident that the first premolar a pontic because of its poor adaptation to the ridge, which creates a shadow. (B) Shadows around the gingival surface *(arrowhead)* spoil the esthetic illusion.



It is often necessary to recontour a substantial portion of the facial surface (**B**) to minimize a shadow or food trap at the cervical of the pontic (**C**).

Fig. 20.36 (A) A pontic should have the same incisogingival height *(H)* as the original tooth. (B) Correctly contoured pontic. (C) Incorrectly contoured pontic. (The *dashed lines* in B and C represent the original tooth contour.) The shelf at the gingival margin may trap food and create an esthetically unacceptable shadow.

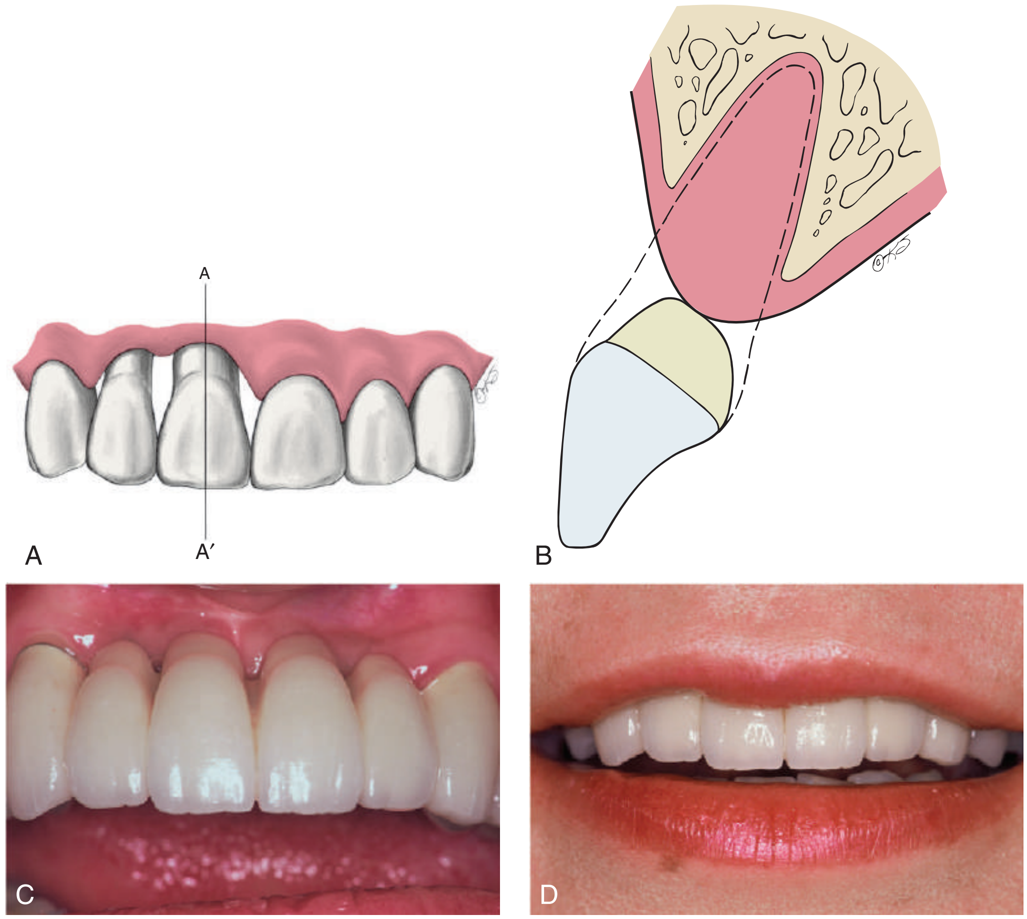


Fig. 20.37 It is difficult without surgical augmentation to fabricate an esthetic fixed prosthesis for a patient with extensive alveolar bone loss. (A–D) One approach is to contour the crowns normally and to shape and stain the apical extension to simulate exposed root surface. (A and B, Redrawn from Blancheri RL. Optical illusions and cosmetic grinding. *Rev Assoc Dent Mex*. 1950;8:103.)

Fig. 20.38 Fixed partial denture replacing maxillary left central and lateral incisors. The patient had lost significant bone from the edentulous ridge. (A and B) Appearance of the prosthesis was enhanced with the use of pink porcelain between the pontics to simulate gingival tissue. The patient has been able to maintain excellent tissue health through the daily use of Oral-B Super Floss.

gingival tissues (Fig. 20.38). However, such pontics then have considerably increased tissue contact and require scrupulous plaque control to achieve long-term success. Ridge augmentation procedures have been successful in correcting areas of limited resorption. When bone loss is severe, the esthetic result obtained with a removable partial denture is often better than that obtained with an FPD.

Mesiodistal Width

Frequently, the space available for a pontic is greater or smaller than the width of the contralateral tooth. This is usually because of uncontrolled tooth movement that occurred when a tooth was removed and not replaced.

If possible, such a discrepancy should be corrected by orthodontic treatment. If this is not possible, an acceptable appearance may be obtained by incorporating visual perception principles into the pontic design. In the same way that the brain can be confused into misinterpreting the relative sizes of shapes or lines because of an erroneous interpretation of perspective (Fig. 20.39), a pontic of abnormal size may be designed to give the illusion of being a more natural size. The width of an anterior tooth is usually identified by the relative positions of the mesiofacial and distofacial line angles, the overall shape by the detailed pattern of surface contour, and light reflection between these line angles. The features of the contralateral tooth (Fig. 20.40) should be duplicated as precisely as possible in the pontic and the space discrepancy can be compensated by alteration in the shape of the proximal areas. The retainers and the pontics can be proportioned to minimize the discrepancy. (This is another situation where a diagnostic waxing procedure helps solve a challenging restorative problem.)

Space discrepancy presents less of a problem when posterior teeth are being replaced (Fig. 20.41) because their distal halves are not normally visible from the front. A discrepancy here can be managed by duplicating the visible mesial half of the tooth and adjusting the size of the distal half.

PONTIC FABRICATION

Available Materials

Over time, several techniques for pontic fabrication have evolved. Prefabricated porcelain facings were traditionally very popular for use with conventional gold alloys. As use of the metal-ceramic technique increased during the 1970s, prefabricated facings lost their popularity and essentially disappeared. Although custom-made, metal-ceramic facings were an acceptable substitute, they never gained widespread acceptance. The various techniques are summarized in Table 20.3 (Fig. 20.42).

Most pontics are now made with metal-ceramic or zirconia, which provides the best solution to the biologic, mechanical, and esthetic challenges encountered in pontic design. Their fabrication, however, differs slightly from the fabrication of individual crowns. These differences are emphasized in the following paragraphs.

Metal-Ceramic Pontics

A well-designed, metal-ceramic pontic allows for easy plaque removal and has good strength, wear resistance, and esthetics (see Fig. 20.42D). Its fabrication is relatively simple if at least one retainer is also metal-ceramic. The metal framework for the pontic and one or both of its retainers is then cast in one piece. This facilitates pontic manipulation during the successive laboratory and clinical phases. In the following discussion, it is assumed that either one or both of the retainers are metal-ceramic, complete crowns. When this is not the case, an alternative approach is necessary.

Anatomic Contour Waxing

For strength and esthetics, the thickness of porcelain must be controlled accurately in the finished restoration. To ensure this, a wax pattern is made to the final anatomic contour. This also enables the dentist to assess connector design adequacy and the relationship between the connectors and the proposed configuration of the ceramic veneer (see Chapter 27).

Armamentarium. The following equipment is needed (Fig. 20.43):

- Bunsen burner
- Inlay wax
- Sticky wax
- Waxing instruments
- Cotton cleaning cloth
- Die-wax separating liquid
- Zinc stearate or powdered wax

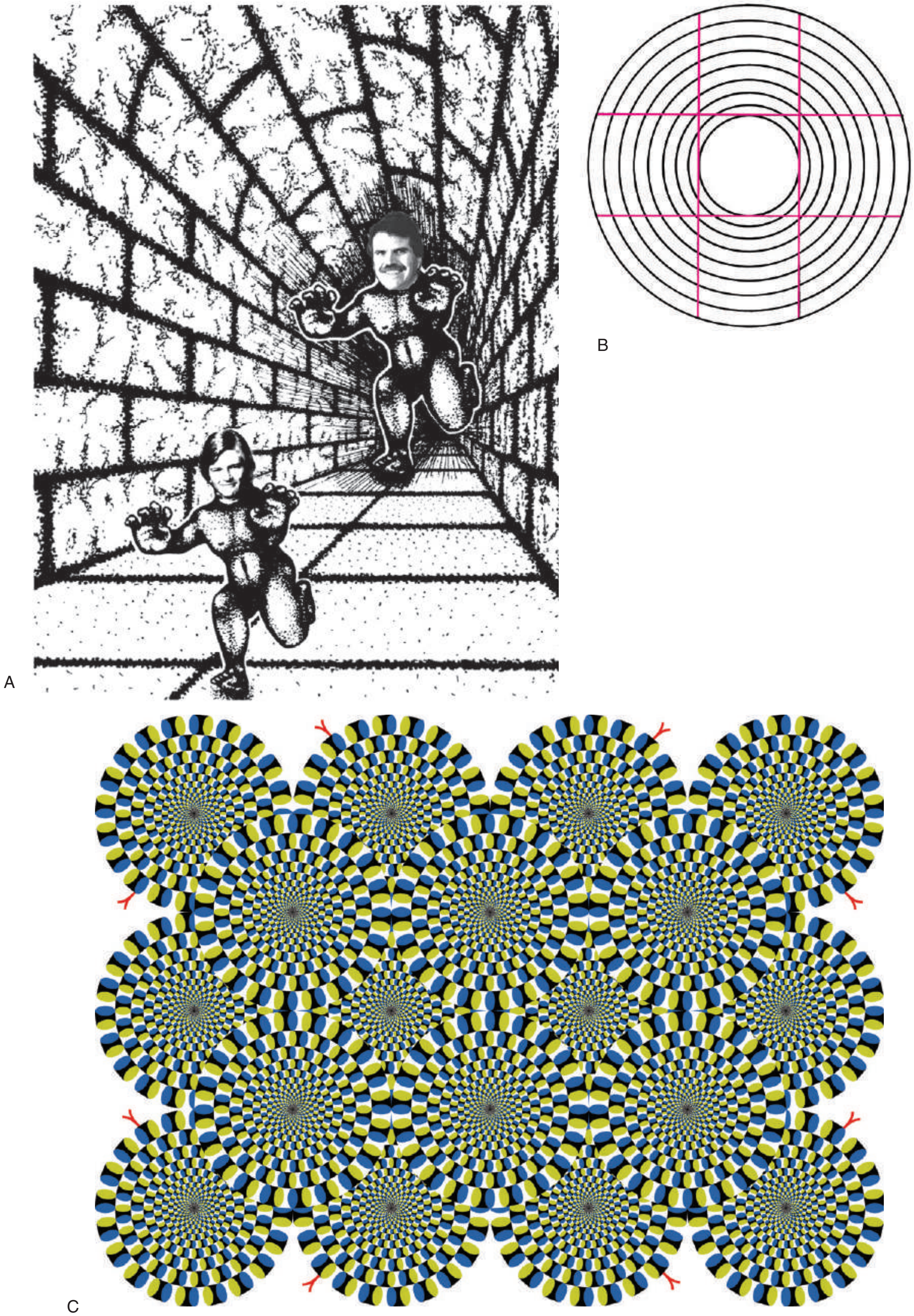


Fig. 20.39 Optical illusions. (A) The people are the same size. (B) The lines are straight. (Tilt the book to verify this.) (C) Kitaoka's "rotating snake" illusion. Rotation of the "wheels" occurs in relation to eye movements. On steady fixation close up, the effect vanishes.[65] (A, Modified from Shepard RN. *MindSights*. New York, WH: Freeman; 1990. C, Copyright Akiyoshi Kitaoka, 2003; reproduced with permission.)

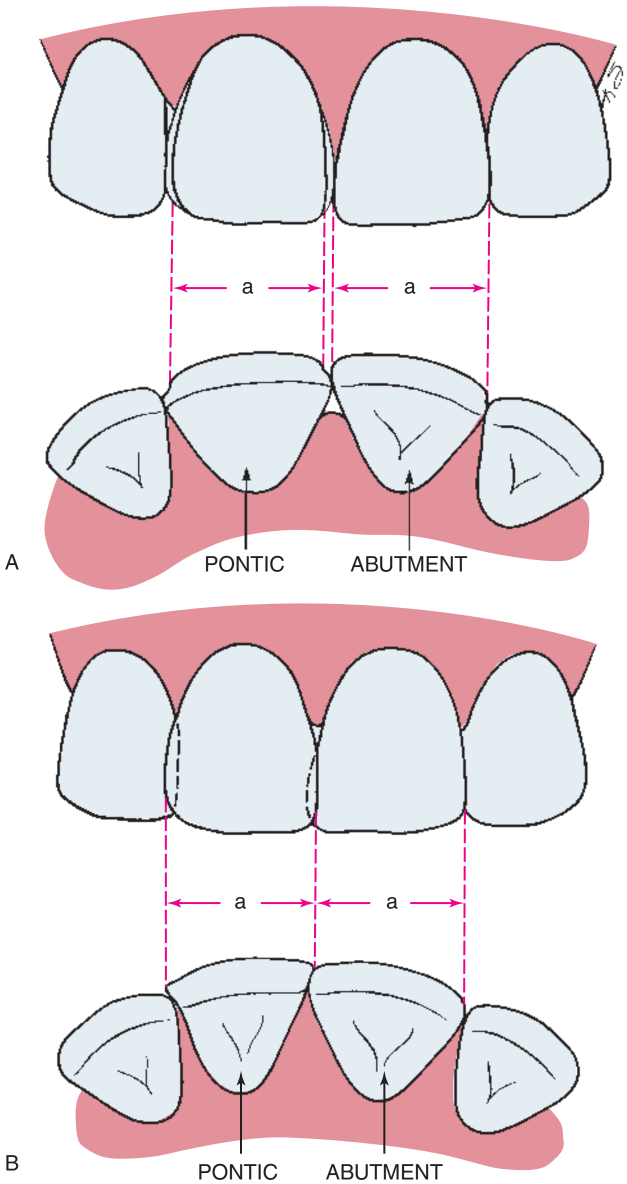


Fig. 20.40 An abnormally sized anterior pontic space can be restored esthetically by matching the location of the line angles and adjusting the interproximal areas. Large (A) and small (B) pontic spaces. Dimension *a* should be matched in the replacement. (Redrawn from Blancheri RL. Optical illusions and cosmetic grinding. *Rev Asoc Dent Mex.* 1950;8:103.)

- Double-ended brushes
- Cotton balls
- Fine-mesh nylon hose

Step-by-step procedure

1. Wax the internal, proximal, and axial surfaces of the retainers as described in Chapter 18.
2. Soften the inlay wax, mold it to the approximate desired pontic shape, and adapt it to the ridge. This is the starting point for subsequent modification. An alternative (and perhaps preferable) method is to make an impression of the diagnostic waxing or interim restoration. Molten wax can then be poured into this to form the initial pontic shape. Prefabricated pontic shapes are also available (Fig. 20.44).

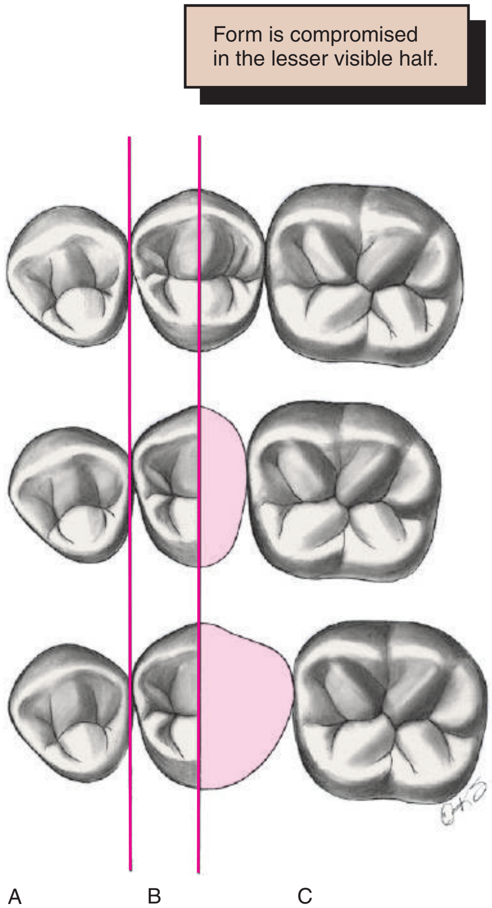


Fig. 20.41 When a posterior tooth is replaced (A), the dimension of the more visible mesial half of the adjacent tooth should be duplicated. Narrow (B) and wide (C) pontic spaces. (Redrawn from Blancheri RL. Optical illusions and cosmetic grinding. *Rev Asoc Dent Mex.* 1950;8:103.)

3. If a posterior tooth is being replaced, leave the occlusal surface flat because the occlusion is best developed with the wax addition technique outlined in Chapter 18.
4. Lute the pontic to the retainers and for additional stability, connect its cervical aspect directly to the definitive cast with sticky wax. Then wax the pontic to proper axial and occlusal (or incisal) contour (Fig. 20.45).
5. Complete the retainers and contour the proximal and tissue surfaces of the pontic for the desired tissue contact. The pontic is now ready for evaluation before cutback.

Evaluation. The form of the wax pattern is evaluated (Fig. 20.46), and any deficiencies are corrected. Particular attention is given to the connectors, which should have the correct shape and size. The connectors provide firm attachment for the pontic so that it does not separate from the retainers during the subsequent cutback procedure.

Cutback

Armamentarium

- Bunsen burner
- Waxing instruments
- Cut back instrument

TABLE 20.3 **Available Pontic Systems**

Material	Advantages	Disadvantages	Indications	Contraindications
Metal-ceramic	Esthetics Biocompatible	Difficult to fabricate if an abutment is not metal-ceramic Weaker than metal	Most situations	Long spans with high stress
Metal	Strength Straightforward procedure	Nonesthetic	Mandibular molars, especially under high occlusal force	Where esthetics is important
Ceramic	Best esthetics Biocompatible	Risk of fracture Unable to be sectioned and reconnected Large connectors needed	High esthetic demand	Long spans with high stress

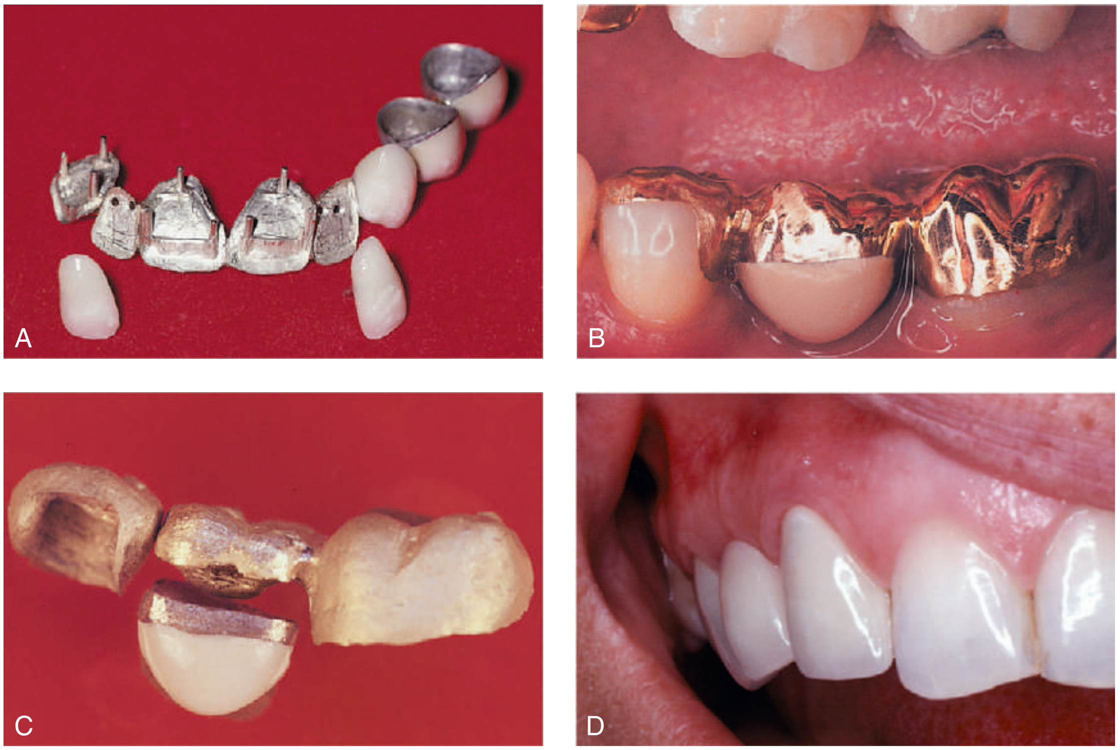


Fig. 20.42 (A) Eight-unit fixed partial denture (FPD) with porcelain facings. (B and C) A three-unit posterior FPD that was fabricated by post-ceramic soldering of a metal-ceramic facing to conventional gold. (D) Metal-ceramic FPD with a modified ridge-lap pontic (canine) that appears to emerge from the gingiva.

Fig. 20.43 Waxing armamentarium.

Fig. 20.44 Prefabricated wax pontics.

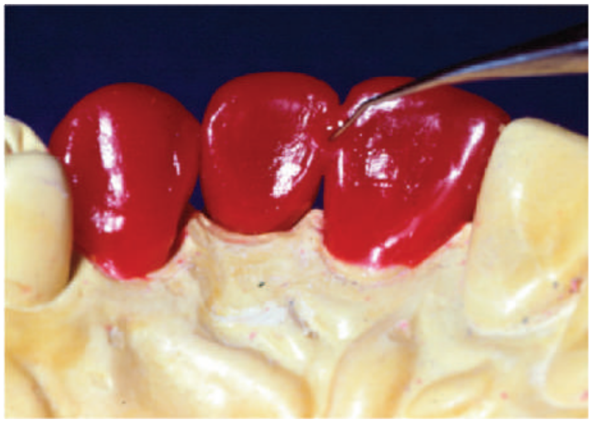


Fig. 20.45 Luting the pontic to the retainers.

Fig. 20.46 Anatomic contour wax patterns.

- Scalpel
- Thin ribbon saw blade or sewing thread
- Explorer

Step-by-step procedure

1. Use a sharp explorer to outline the area that will be veneered with porcelain (Fig. 20.47A). The porcelain-metal junction must be placed sufficiently lingually to ensure good esthetics.
2. Make depth cuts or grooves in the wax pattern (see Chapter 19 and Fig. 20.47B).
3. Complete the cutback as far as access allows with the units connected and on the definitive cast.
4. Section one wax connector with a thin ribbon saw (sewing thread is a suitable alternative) and remove the isolated retainer from the definitive cast (see Fig. 20.47C).
5. Finish the cutback of this retainer. Ensure there is a distinct 90-degree, porcelain-metal junction.
6. Reflow and finalize the margins. The pontic is held in position by the other retainer during this procedure.
7. Refine the pontic cutback where access is improved by removal of the first retainer.
8. Reseat the first retainer, reattach it to the pontic, section the other connector, and repeat the process.
9. Sprue the units and do any final reshaping as needed.
10. Invest and cast in the manner described in Chapter 22.

When one connector of a three-unit FPD is to be cast and the other soldered, the cast connector should be sectioned first when the foregoing procedure is followed. The gingival surface of the pontic should be cut back in the metal rather than in the wax because the tissue contact helps stabilize the pontic. Access is difficult and it is easy to break the fragile wax connector.

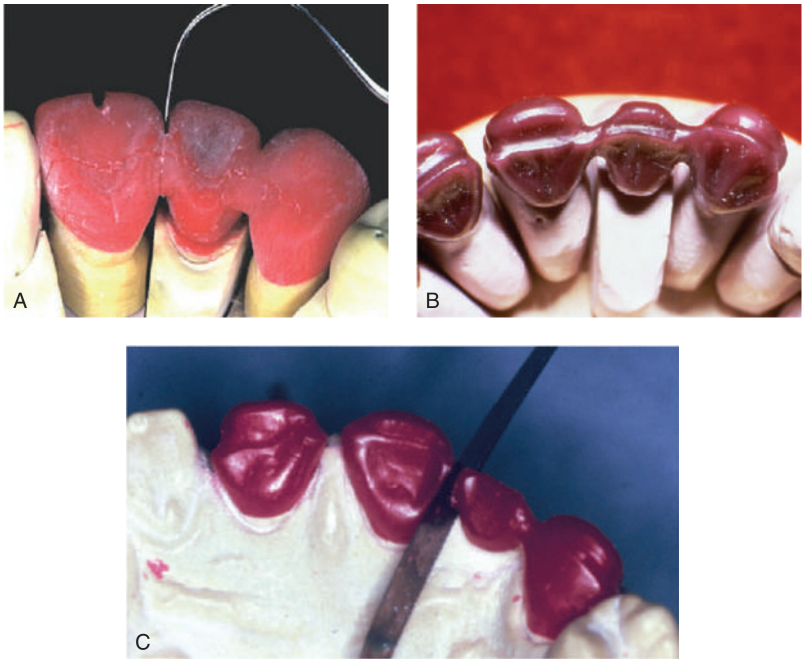


Fig. 20.47 Cutback procedure for a three-unit anterior fixed partial denture. (A) Delineating the porcelain-metal junction. (B) Wax patterns cut back for porcelain application. (C) A ribbon saw is used to section the connector.

Metal Preparation

Armamentarium

- Separating disk
- Ceramic-bound finishing stones
- Sandpaper disks (nonveneered surfaces only)
- Rubber wheel (nonveneered surfaces only)
- Round tungsten carbide bur (No. 6 or 8)
- Airborne-particle abrasion unit (with 25-µm aluminum oxide)

Step-by-step procedure

1. Recover the castings from the investment and prepare the surfaces to be veneered as described in Chapter 19 (Fig. 20.48).
2. Finish the gingival surface of the pontic. Do not over reduce this area.

Evaluation. Less than 1 mm of porcelain thickness is needed on the gingival surface because once it is cemented the restoration is seen from the facial side, rather than from the gingival side. Excessive gingival porcelain is a common fault in pontic framework design and may lead to fracture and poor appearance (see Fig. 20.30).

To facilitate plaque control, the metal-ceramic junction should be located lingually. Then tissue contact is on the porcelain and not on metal, which retains plaque more tenaciously.[58]

Porcelain Application

Many of the steps for porcelain application are identical to those in individual crown fabrication (see Chapter 24). There are some features peculiar to pontic fabrication, however, and these are emphasized.

Armamentarium. The following equipment is needed (Fig. 20.49):

- Paper napkin
- Glass slab
- Tissues or gauze squares
- Distilled water
- Glass spatula
- Serrated instrument
- Porcelain tweezers or hemostat
- Ceramist's brushes (No. 2, 4, or 6)
- Whipping brush
- Razor blade
- Cyanoacrylate resin
- Colored pencil
- Articulating tape
- Ceramic-bound stones
- Diamond stones
- Diamond disk

Step-by-step procedure

1. Prepare the metal and apply opaque as described in Chapter 24 (Fig. 20.50).
2. Apply cervical porcelain to the gingival surface of the pontic and seat the castings on the definitive cast. A small piece of tissue paper adapted to the residual ridge on the cast, moistened with a brush, prevents porcelain powder from sticking to the stone. (Cyanoacrylate resin or special separating agents can be used for the same purpose.)

Fig. 20.48 Metal substructure ready for airborne particle abrasion and oxidation.

Fig. 20.49 Armamentarium for porcelain application.

3. Build up the porcelain (as described in Chapter 24) with the appropriate distribution of cervical, body, and incisal shades. The tissue paper acts as a matrix for the gingival surface of the pontic.
4. When the porcelain has been condensed, section between the units with a thin razor blade. This prevents the porcelain from pulling away from the framework as a result of firing shrinkage. A second application of porcelain is needed to correct any deficiencies caused by firing shrinkage. Such additions usually are needed proximally and gingivally on the pontic.
5. Apply a porcelain separating liquid (e.g., VITA Modisol, Vita Zahnfabrik 5; VITA North America, Yorba Linda, CA) to the stone ridge so that the additional gingival porcelain can be lifted directly from the cast as in the fabrication of a porcelain labial margin (see Chapter 24).
6. Mark the desired tissue contact and contour the gingival surface to create as convex a surface as possible. The pontic is now ready for clinical evaluation, soldering procedures, characterization, glazing, finishing, and polishing (see Chapters 27–29).

Evaluation. The porcelain on the tissue surface of the pontic should be as smooth as possible (Fig. 20.51). Pits and defects

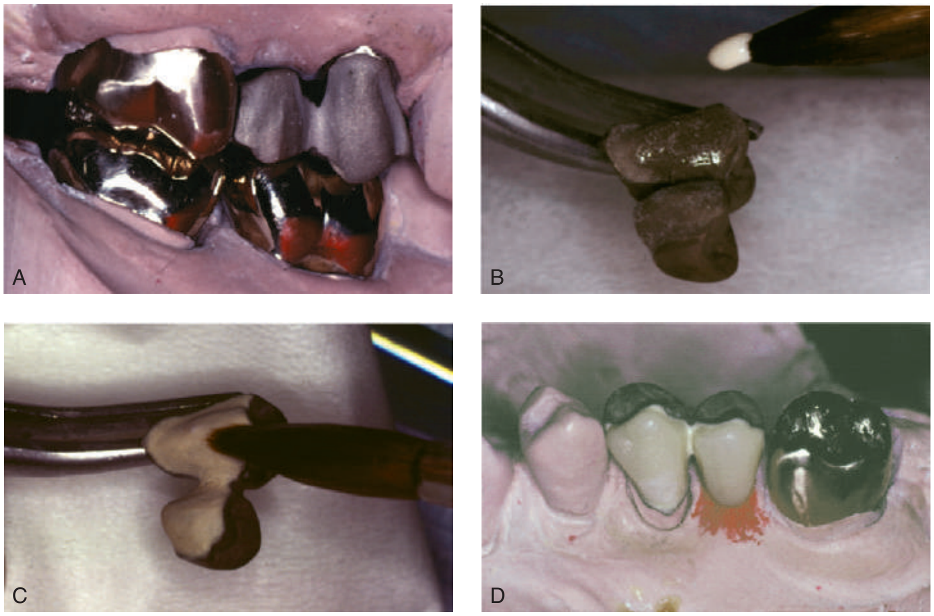


Fig. 20.50 Porcelain application. (A) Substructure ready for opaque application. (B) Opaque application. (C) Body porcelain application. (D) The porcelain after the first firing.

Fig. 20.51 Metal-ceramic pontic replacing a lateral incisor.

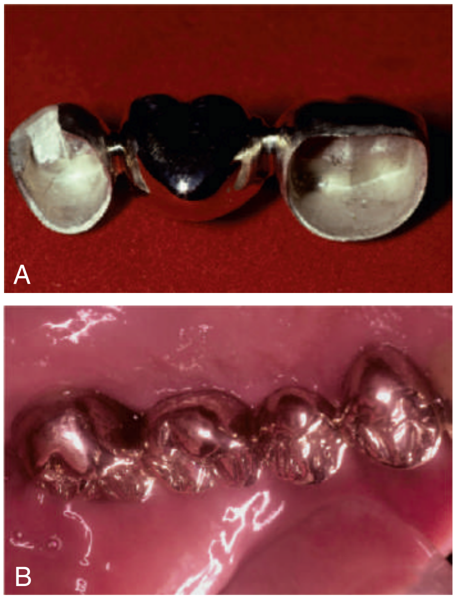


Fig. 20.52 Metal fixed partial dentures.

hamper plaque control and promote calculus formation. The metal framework must be highly polished with special care directed to the gingival embrasures (where access for plaque removal is more difficult).

Metal Pontics

Pontics made from metal (Fig. 20.52) require fewer laboratory steps and are therefore sometimes used for posterior FPDs. However, they have some disadvantages (e.g., their appearance). In addition, investing and casting must be done carefully because the mass of metal in the pontic is prone to porosity as the bulk increases. A porous pontic retains plaque and tarnishes and corrodes rapidly.

ZIRCONIA PONTICS

The number of materials available for fabrication of FPD has increased in the recent years.[59] CAD-CAM technology has gained popularity due to the lower cost of materials and faster processing times, increasing the overall efficiency.[60,61] Zirconia is one such material that is now being utilized for single and multi-unit FPDs on natural teeth and on dental implants. Although in the anterior zone, the zirconia FPDs may need to be veneered with feldspathic porcelain for superior esthetic results and to color match with the adjacent teeth. The fracture (chipping) of the porcelain layer in zirconia-porcelain restorations is one of the most commonly observed clinical complication,[62,63] although improved laboratory processing with slow cooling has greatly reduced this complication.[64]

Zirconia pontics are digitally planned and designed. All traditional principles of pontic design should be strictly adhered to maintain adequate hygiene and strength. The restorations can be milled after capturing the tooth preparations with an intraoral scanner. The teeth preparations can also be recorded with an elastomeric impression material, which is then digitized with a laboratory scanner.

Armamentarium

- Intraoral scanner
- The milling unit
- Furnace
- Round tungsten carbide bur (No. 6 or 8)

Step-by-step procedure

1. Once you have an intra oral scan of the preparations, follow the steps on the software for designing the prosthesis.
2. Mark the finish lines on the screen. Most software autogenerate a proposed prosthesis design.
3. Verify the pontic design: the shape, size, width, and tissue contact. All the surfaces can be adjusted as per your preference.
4. Verify the occlusal contacts and increase or decrease the contact area.
5. Follow the consecutive steps on the design software. Once designing is complete, the software will send the file to the milling unit.
6. Screw in the block of zirconia in the milling unit and start the milling process.
7. Once the zirconia prosthesis is milled, it is still in the presintered stage and appears much larger than the actual FPD.
8. Remove the FPD and grind the sprue with the help of a round tungsten carbide bur (No. 6 or 8).
9. Place the FPD in the furnace and let it sinter as per manufacturer's instructions.
10. Once the sintering process is completed and the FPD has cooled, it is ready for insertion.

Pontics in Fixed Implant Restorations

Pontics for implant restorations is similar to natural teeth restorations and should serve four important purposes: function, esthetics, mechanical, and hygiene maintenance.[6] The pontic design depends on many factors including the residual alveolar ridge anatomy with or without grafting. Developing adequate soft tissue contours under pontic spaces is somewhat challenging in resorbed or atrophic residual ridges and could lead to mechanical, esthetic, functional, and phonetic challenges. This may require addition of pink porcelain in severe situations to camouflage defects. Gingival tissue molding or manipulation around the pontic area would require at least 2 to 3 mm of attached gingiva thickness for compressibility.[38] If the gingival thickness is less than 1 mm, alveolar bone ridge reduction will be necessary to gain space, and also to preserve the residual alveolar ridge anatomy and interproximal papilla after extraction. Typically, esthetic implant restorations are restored immediately with interim restorations. The architecture of the pontic provides support and shapes the soft tissue during the healing process. It also prevents loss of interproximal papilla, leading to a dark interproximal space appearance called 'black triangle.'

Intimate contact between the pontic and the gingival tissue has to be evaluated before definitive insertion of the prosthesis. The pontic will exert some amount of pressure on the tissues but the ischemia (blanching) should disappear in 3 to 5 minutes. If the tissues continue to be blanched and displaced for prolonged periods of time, the prosthesis should be removed and adjusted for tissue contact under the pontic. Low viscosity elastomeric disclosing agents can be useful for accessing tissue contact, displacement, and patient comfort.

A thin layer of the disclosing agent is placed on the undersurface of the pontic. The prosthesis is seated intraorally and the screws are tightened until there is resistance. Patient discomfort may prevent the complete seating of the prosthesis. After the material has set, it is evaluated for any areas that have completely been wiped. Those heavy contact areas are adjusted with a diamond rotary instrument until the soft tissue ischemia is reduced and the prosthesis is seated completely.

SUMMARY

Designs that allow easy plaque control are especially important to the long-term success of a pontic. Minimizing tissue contact by maximizing the convexity of the pontic's gingival surface is essential. Special consideration is also needed to create a design that combines easy maintenance, natural appearance, and adequate mechanical strength. When the appropriate design has been selected, it must be accurately conveyed to the dental technician.

There are subtle differences between metal-ceramic pontic fabrication and the fabrication of other types of pontics. Under most circumstances, the metal-ceramic technique is used because it is straightforward and practical. However, it requires careful execution for maximum strength, esthetic appearance, and effective plaque control. Alternative procedures are sometimes helpful, particularly when gold alloys are used for the retainers. Resin-veneered pontics should be restricted to use as longer-term interim restorations and metal pontics may be the restoration of choice in non-esthetic situations, particularly those in which forces are high. Zirconia pontics can be used in esthetic and non-esthetic areas because of their high strength and esthetic properties. Every material has some limitations and the decision of the choice of pontic material should be based on each individual clinical scenario.

STUDY QUESTIONS

1. Outline and discuss a logical classification of pontics.
2. How does pontic design change as a function of location in the dental arch?
3. What are the materials available for pontic fabrication? What are their respective advantages, disadvantages, indications, and contraindications?
4. Discuss the factors that govern the shaping of the facial and lingual surfaces of a modified ridge-lap pontic.

5. What common clinical problems might be encountered if a pontic is improperly shaped or fabricated?
6. Discuss the various techniques for soft tissue augmentation and the residual ridge defects that these techniques are designed to resolve.
7. What factors should be considered in the selection of the pontic material that will be in contact with the residual ridge?

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21

Retainers for Removable Partial Dentures

Montry Suprono, Contributing Author

Different philosophies exist regarding the need to fabricate cast restorations for abutment teeth before a removable partial denture (RPD) is made. Successful removable prostheses can be made with minimal need for fixed prosthodontic preparatory treatment. Instead of the routine use of cast restorations to achieve optimal contours on the abutment teeth that will support the removable prosthesis, the remaining natural dentition may be modified through enameloplasty or the addition of restorative material such as composite resin, or both. This has the obvious advantage of reducing both treatment time and expense. However, the use of cast restorations on abutment teeth enables precise shaping of the axial contours of such restorations, which allows the masticatory and retentive forces to be directed more favorably through the appropriate use of occlusal rest seats and precisely shaped guide planes. Also, cast retainers enable the incorporation of intracoronal rest seats or precision attachments, which can offer significant esthetic advantages over clasp-retained RPDs. The use of cast crowns also allows splinting of abutment teeth with resultant reduction of mobility (Fig. 21.1).[1]

The correct treatment choice for any patient depends on the findings in a thorough history and examination and an accurate diagnosis and prognosis (see Chapters 1 and 3). Decisions concerning restoring RPD abutment teeth involve many

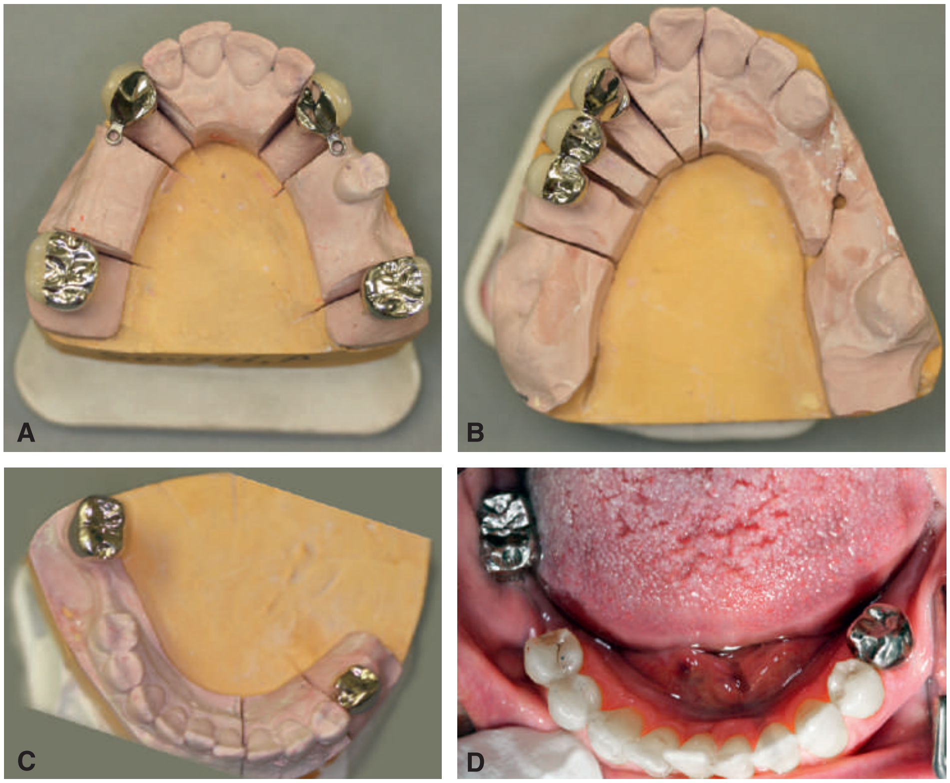

Fig. 21.1 Survey crowns are useful to create desired coronal contours to optimally support a removable partial denture (RPD). (A) Four survey crowns used to support a planned RPD. Occlusal rests were created on the mesial of the posterior crowns, with appropriate buccal undercuts and lingual reciprocal guide planes. The anterior crowns incorporate cingulum rests and extracoronal attachments. (B) It is generally not desirable to retain a lone standing tooth (pier abutment) in the middle of a modification space. In the preferred approach, the dentist eliminates a modification space by fabricating a fixed dental prosthesis. Note the cingulum rest on the canine, and the mesial occlusal rest on the posterior retainer. (C) Two complete cast crowns used to obtain improved contours for a partial mandibular RPD. (D) Clinical view.

factors—caries, existing restorations, tooth vitality, shape and angulation, oral hygiene, and cost and experience—that must be assessed and evaluated. Only then is the selected treatment likely to achieve the planned outcome based on the patient's functional and esthetic requirements.

TREATMENT PLANNING

The fabrication of a precisely fitting RPD is challenging. Without a careful, comprehensive diagnostic evaluation and a well-designed treatment plan, the chances of success are minimal. Most patients who require an RPD have sustained extensive damage because of caries, periodontal disease, or trauma and may have extensive prosthodontic treatment needs. They may also exhibit acquired or congenital intraoral defects. As a result of prolonged loss of arch integrity, there may be drifting or tipping of teeth, and the occlusion is often less than ideal.

Treatment plans that include an RPD may necessitate additional diagnostic procedures besides those described in Chapters 1 and 2. Accurate diagnostic casts mounted in centric relation are important. When teeth are missing, and a tripod effect cannot be achieved, stable record bases should be made to relate opposing diagnostic casts (Fig. 21.2). The necessary degree of stability can be obtained only if such record bases are fabricated on the cast that is to be articulated.

The use of a dental surveyor (Fig. 21.3) is essential during treatment planning for the following reasons:

- To evaluate tissue undercuts and their influence on RPD design
- To evaluate the relative alignment of the long axes of teeth that support the RPD
- To determine the optimum path of placement and removal of the RPD (and, by inference, its effect on the geometry of crown preparations)

The most appropriate anteroposterior and mediolateral tilt of the cast must be selected. Careful analysis is essential because a compromise between the requirements of ideal tooth preparation (see Chapter 7) and the requirements for a particular tooth to be used as an abutment to support and retain an RPD is often necessary. The path of placement of the RPD is the most important factor in determining how much tooth reduction is needed to meet both mechanical and esthetic requirements (Fig. 21.4).

Surveying diagnostic casts should be completed after a thorough oral examination and review of radiographs. When the diagnostic cast is surveyed, the anteroposterior tilt is established first. The lateral inclination is determined next. The operator should focus on any tissue undercuts, the relative alignment of selected abutment teeth, and the available occlusocervical dimension for planned proximal and reciprocal guide planes. The feasibility of recontouring axial walls and the possible consequences of such recontouring must also be considered. Teeth with short clinical crowns are often poor candidates for survey restorations.

Fig. 21.3 A dental surveyor is essential during treatment planning and in designing retainers for partial removable dental prostheses.

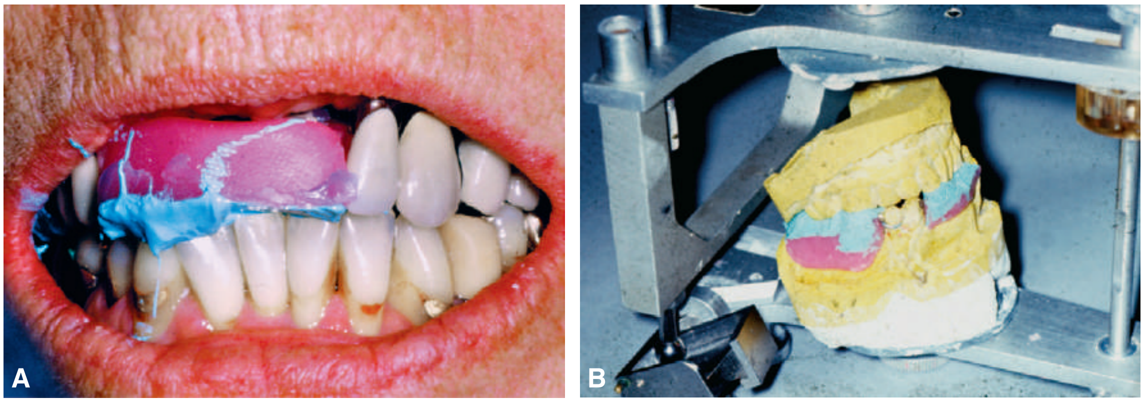

Fig. 21.2 When multiple teeth are missing (A), a clasp-retained record base with wax rims (used here with zinc oxide–eugenol paste) should be used to ensure accurate articulation (B). This minimizes the risk of tipping of the casts in relation to one another.

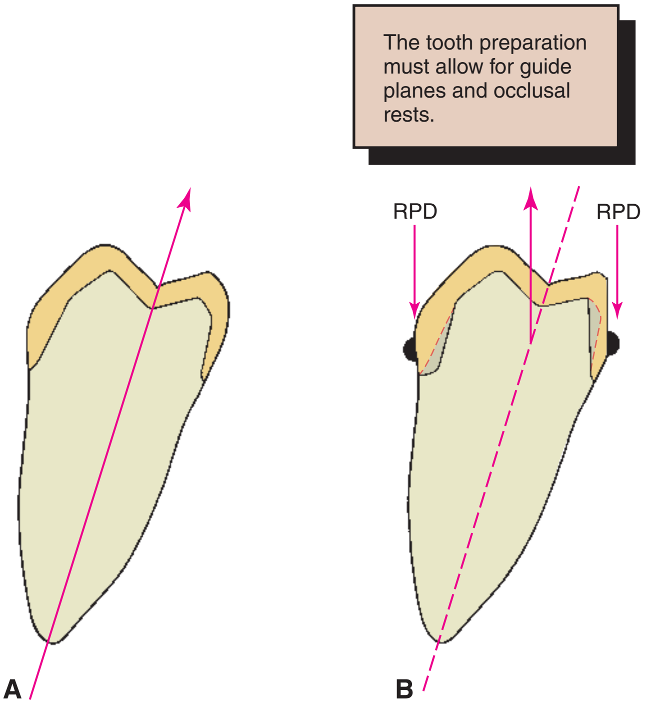

Fig. 21.4 (A) Normal tooth preparation for a complete cast crown. The path of placement is on the long axis of the tooth. (B) Modified tooth preparation for a removable partial denture (RPD) retainer with lingual guide planes. This preparation has a more buccal path of placement.

Fig. 21.5 The appearance of an anterior removable partial denture is improved by careful selection of the path of placement.

Favorable tooth alignment in relation to the planned path of placement of the RPD is critical, and unfavorable tooth position may warrant adjunctive treatment. For instance, it may be necessary to treat a malposed tooth orthodontically or endodontically if recontouring alone will not produce the desired geometry. Similarly, removing a tooth that unnecessarily complicates RPD design should be considered and weighed carefully against the effect of that decision on RPD stability. Compromised teeth need to be assessed carefully in terms of their prognosis. If future loss of such a tooth would render the RPD useless, it may be better to remove that tooth than to resort to heroic efforts to preserve it for the short term.

When anterior teeth have been lost, the path of placement of an RPD should parallel the proximal surfaces of the abutment teeth adjacent to the space (Fig. 21.5). This results in superior esthetics because it minimizes the space between the artificial and natural teeth. Sometimes esthetics can be improved using a rotational placement path.[2]

Complex decisions about the best combination of tooth preparation and placement path can be greatly simplified through diagnostic tooth preparation, waxing, and denture tooth arrangement (Figs. 21.6 and 21.7). These trial procedures on diagnostic casts help determine how to achieve the best mechanical and esthetic result without deviating from the principles of occlusion or making excessively bulky restorations that inevitably cause periodontal complications. The concept is to use interchangeably articulator-mounted casts of the pretreatment and posttreatment condition before treatment is initiated to determine the precise goals for occlusion and appearance. The use of such cross-mounted casts (see also Chapter 3) helps simplify the treatment sequence by allowing one arch to be treated at a time. The restorations on the first arch to be restored are fabricated against the diagnostically waxed opposing cast (Fig. 21.8; see also Fig. 3.33).

Prerequisites for Success

The clinician and dental laboratory technician must understand RPD design (Fig. 21.9). An in-depth discussion of the approaches to framework design is beyond the scope of this text. Instead, the modifications that must be incorporated in the cast restoration to accommodate an RPD are considered.

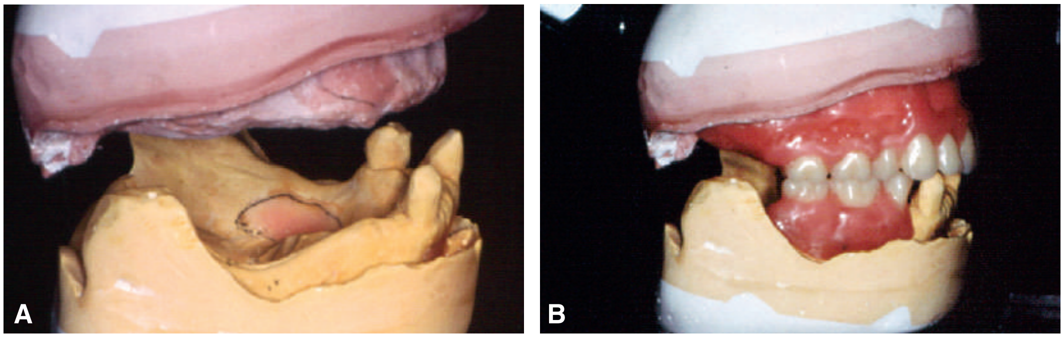

Fig. 21.6 Diagnostic mounted casts and waxing are essential prerequisites for extensive prosthodontic care. (A) Diagnostically mounted casts. (B) Diagnostic tooth arrangement. (Courtesy Dr. N.L. Clelland.)

Fig. 21.7 Diagnostic tooth preparation and waxing are especially valuable in treating patients who require a combination of fixed and removable prostheses. (A to D) Diagnostic waxing. (E and F) Fixed prostheses. (G and H) Completed restorations. Mandibular removable partial denture has cast metal occlusal surfaces. (Courtesy Dr. J.H. Bailey.)

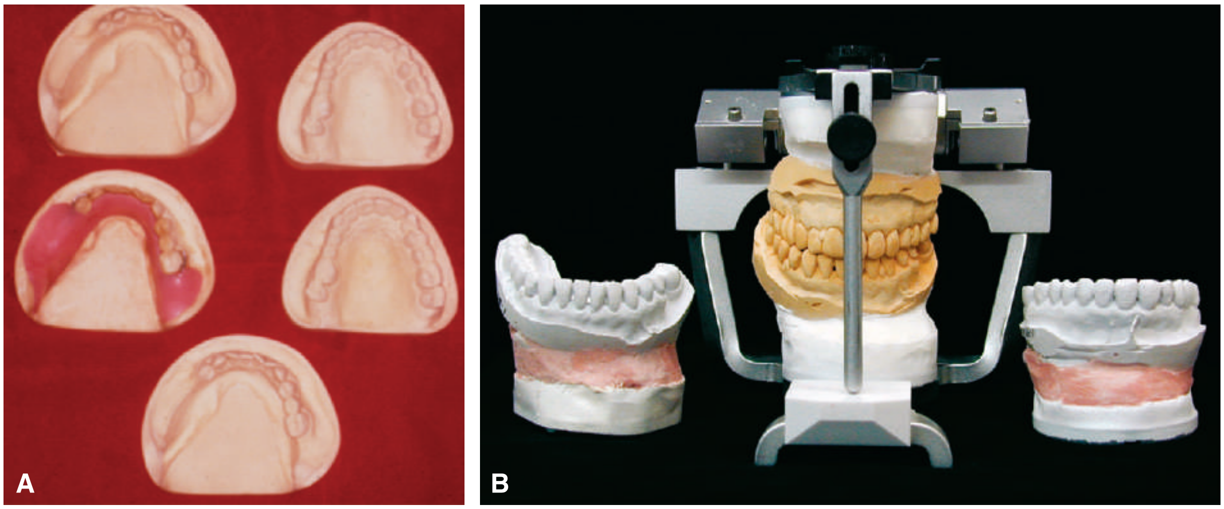

Fig. 21.8 Cross-mounted casts are used to simplify complex prosthodontic treatments. One set of casts is waxed to reflect the end-point of treatment, whereas the other set is left unaltered to enable mounting of the definitive casts. An additional cast is needed for surveying a removable dental prosthesis. (A) Casts needed for treating a patient who required a maxillary fixed prosthesis opposed by mandibular fixed and removable prostheses (see Fig. 21.7). (B) The duplicated casts are mounted in the identical relationship on an articulator. Treatment can then be undertaken in phases. First the mandibular teeth are prepared, and a definitive cast is obtained. This is mounted against the maxillary unaltered cast, which is then replaced by the identically oriented, diagnostically waxed cast for the laboratory fabrication of the mandibular fixed prosthesis. (See also Fig. 3.33.) (A, Courtesy Dr. J.H. Bailey.)

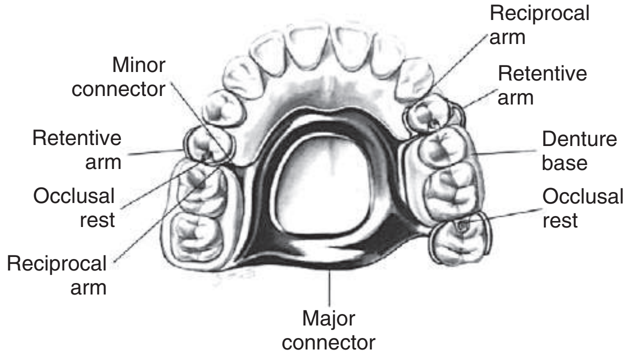

Fig. 21.9 Design of a removable partial denture. The component parts are labeled.

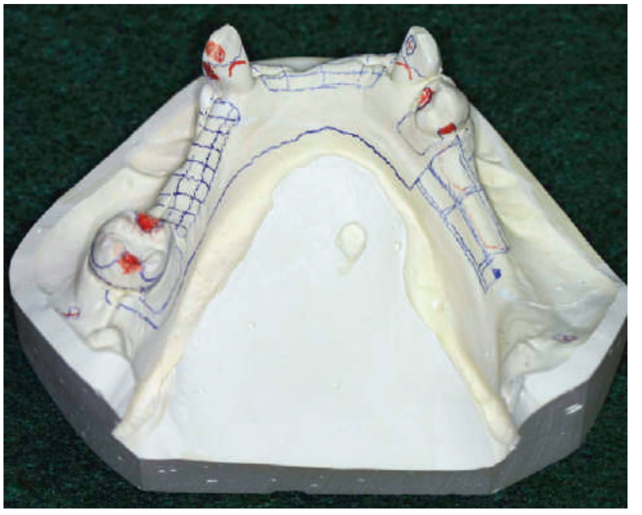

Fig. 21.10 Initial removable partial denture design sketched on the diagnostic cast. From Carr AB, Brown DT. *McCracken's Removable Partial Prosthodontics*. 13th ed. St. Louis: Mosby; 2016.

Design

Multiple concepts of RPD design have been advocated. Regardless of the concept chosen, a keen understanding of the requirements placed on fixed retainers is essential to success. Their design should allow the forces developed during placement, removal, and function of the RPD to be directed to cause the least harm to the remaining dentition. The proposed design (Fig. 21.10) should be carefully sketched at the initial treatment planning stage. In general, this effort will reveal any existing problems. Each fixed restoration should be designed to be fully compatible with the RPD while concurrently meeting all criteria to properly fulfill the functional requirements of mastication, esthetics, and facilitating oral hygiene performance. Decisions made about the path of placement of the RPD often necessitate the removal of additional tooth structure to maintain the minimally required material thickness for the fixed prosthesis (see Fig. 21.4).

Denture bases. The denture base areas are shaped to avoid interference with the abutment retainer during placement and removal. Therefore, the fixed prosthesis affects denture base configuration rather than vice versa.

Occlusal rest seat. The rest seat (Fig. 21.11) is the prepared recess in a tooth or restoration created to receive the RPD framework's occlusal, incisal, cingulum, or lingual rest. The occlusal rest of the RPD is the rigid extension that contacts the occlusal surface or restoration. The occlusal rest of an RPD should fit precisely into the corresponding rest seats on the retainers. To reduce laterally directed forces, the rest seats should be spoon-shaped. The junction between the internal aspect of the rest seat and the proximal guide plane should be rounded to minimize stress on the RPD framework and thereby reduce the chance of fracture at the interface between the occlusal rest and the minor connector.

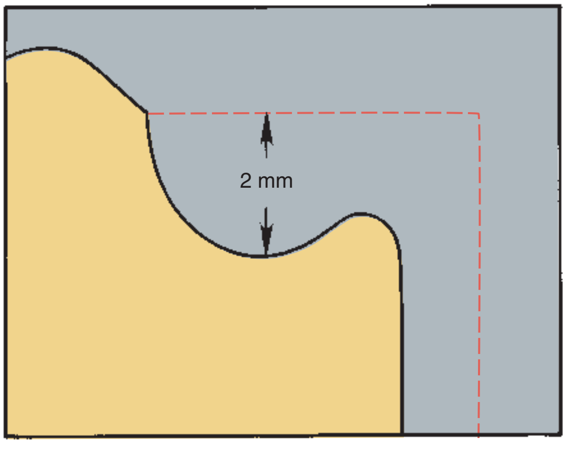

Fig. 21.11 Cross-sectional view through an occlusal rest seat. Note the rounded junction between the rest seat and the proximal guiding plane.

Occlusal rest seats are most predictably placed in healthy enamel or cast metal. If they are placed in weaker materials such as amalgam, composite resin, or dental porcelain, fracture, wear, or distortion is likely to result. Although the size of the rest seats remains a matter of controversy, a balance between conservative tooth preparation and respect for the material strength is suggested. Ordinarily, when crowns are made, the use of a No. 8 round bur to remove wax from an anatomic contour wax pattern produces an adequately sized rest seat (Fig. 21.12). On

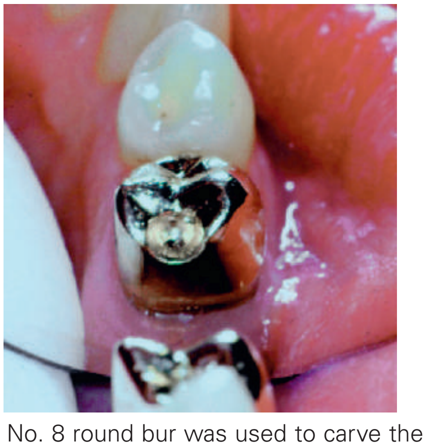

Fig. 21.12 A No. 8 round bur was used to carve the distal rest seat for this mandibular second premolar into the wax pattern.

small teeth (e.g., mandibular premolars), a No. 6 round bur can provide adequate space if functional loading is normal. A cingulum rest seat may be created on anterior teeth to support the removable prosthesis (Fig. 21.13). Rests that are convex mesiodistally and resemble a V-shaped groove labiolingually have proved successful in clinical practice. This configuration prevents displacement of the abutment while simultaneously assisting in directing forces more parallel to its long axis.

Unfortunately, a distinct cingulum rest of adequate size can rarely be placed in the cingulum of an unrestored tooth without penetration through the enamel.[3] Sometimes, a resin-bonded restoration[4] is used to provide a cingulum rest (Fig. 21.14). Porcelain labial veneers (see Chapter 25) and composite resin have also provided undercuts for RPD retention.[5,6] An incisal rest may be used on unrestored mandibular canines (Fig. 21.15). This provides good support for the RPD but may be esthetically unacceptable. When a rest is placed on a metal-ceramic restoration, adequate metal thickness must remain between the lateral walls of the occlusal rest seat and the porcelain-metal junction. About 1 mm is sufficient. Similarly, a minimal metal thickness of 1 mm between the rest seat and the occlusal aspect of the prepared tooth is advisable (see also Fig. 21.26). To reduce the risk of porcelain fracture, an occlusal rest seat should not be placed directly on porcelain.

Minor connectors. The minor connectors of a RPD (Fig. 21.16) are the connecting link between the major connector or base of a RPD and the other units of the prosthesis, such as the clasp assembly, indirect retainers, occlusal rests, and cingulum rests. They join the rest seats and the clasps to the major connector and should fit intimately against the proximal guide plane on the cast restoration. Within the tenets of RPD design, guide planes should be as tall as possible occlusocervically and should follow the normal configuration of the tooth buccolingually. All proximal and reciprocal guide planes should parallel each other.

Fig. 21.15 Incisal rest on a mandibular canine. (Courtesy Dr. M.T. Padilla.)

Fig. 21.13 A mandibular cast with anterior diagnostic wax patterns for survey crowns with cingulum rests and posterior denture teeth set up in wax.

Fig. 21.16 Minor connector *(arrow)*, lingual view. Note the close adaptation of the distal proximal plate, the minor connector, and the retentive clasp arm to the survey crown.

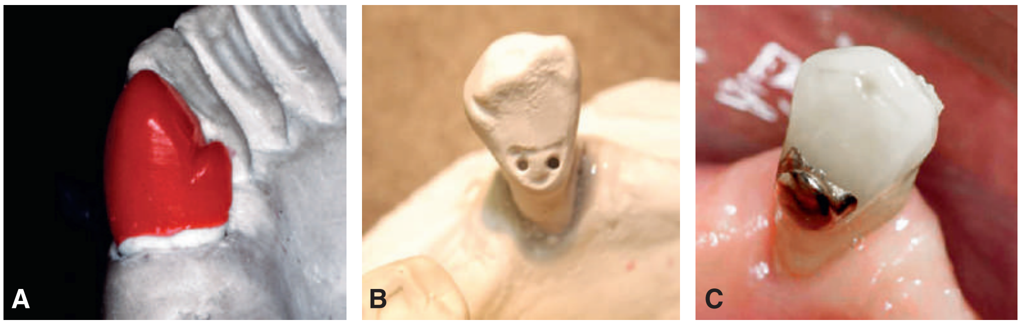

Fig. 21.14 (A) V-shaped cingulum rest seat in wax pattern. (B and C) Minimal tooth preparation accommodates a pin-retained casting to create a cingulum rest. Similar designs can be resin-bonded (see Chapter 26).

Clasp Retention

The clasp engages a portion of the tooth surface and either enters an undercut for retention or remains in contact with the reciprocal guide plane to function as a reciprocating (bracing) element. In general, clasps stabilize and retain an RPD. The amount of retention is related to, among other things, the configuration of the retentive arm, the material from which the clasp is made, and the extent of the undercut into which it is placed and from which it is dislodged when the RPD is removed from the mouth.

RPD frameworks are usually fabricated from base metal alloys, although some dentists prefer titanium or an American Dental Association type IV gold alloy. In addition to conventional cast clasps, wrought retention clasp arms can be made from platinum-gold-palladium or nickel-chromium alloy wires.

The modulus of elasticity of the base metals is considerably higher than that of a type IV gold alloy. Hence, shallower retentive undercuts, approximately 0.12 to 0.25 mm (0.005 to 0.010 inch), can be used with the former. Undercuts of 0.25 to 0.50 mm (0.010 to 0.020 inch) can routinely be used with clasps made of either type IV gold or wire.

When a clasp is in its normal position with the RPD fully seated, it should fit passively against the retainer; a clasp should be at least 2 mm occlusal to the crest of the free gingiva so that it does not interfere with the maintenance of periodontal health. This means that the survey line—a line produced on a cast by a surveyor marking the greatest prominence of contour in relation to a restoration's planned path of placement—must not be placed too far cervically.

Likewise, the height of contour must not be placed too far occlusally; otherwise, binding of the retentive arm may occur during RPD placement. Ideally, this height should be within the middle third of the retentive surface of the retainer. A properly contoured surface enables the retentive arm to flex gradually along the path of placement. Only the terminal third of the retentive arm for cast clasps should be placed gingival to the survey line. If a wrought clasp is used, the height of contour can be modified to engage the terminal half of the clasp in the undercut (Fig. 21.17). If more than the terminal third of the retentive arm is placed cervical to the height of contour, placement, and removal of the RPD may be impeded.

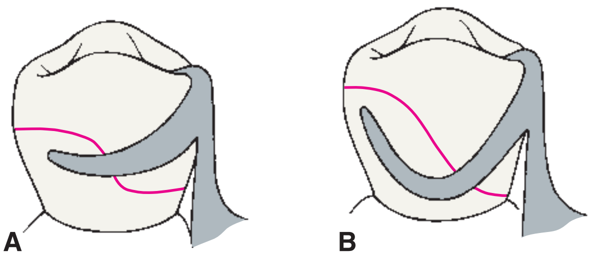

Fig. 21.17 The shape of the survey line is influenced by the material selected for the clasp. (A) Cast clasp. Only the terminal third engages the undercut. (B) Wrought clasp. The terminal half is retentive.

A typical survey line for occlusally approaching clasps has an undulating configuration somewhat reminiscent of the letter *S*, with its most gingival portion adjacent to the minor connector. The undercut may be immediately adjacent to the proximal guide plane if a gingivally approaching clasp is used. However, with the popular rest, proximal plate, and I-bar (RPI) design, it is placed at or mesial to the midline of the tooth.[7] Several factors—rest seat location, the origin of the clasp, tissue undercuts, and degree of clasp encirclement—influence the actual configuration of the survey line for individual retainers.

Reciprocation

Reciprocation is the mechanism by which lateral forces generated by a retentive clasp passing over a height of contour are counterbalanced (Fig. 21.18). This is usually done by a reciprocal clasp or plate that engages a reciprocal guiding plane. Reciprocal clasps have two functions: (1) They guide the prosthesis into place on insertion and (2) support the abutments against horizontal forces exerted by the flexing retentive arms during placement. The retentive arms should flex rather than displace the abutments laterally. Guide planes are needed on the teeth or crowns to allow for successful reciprocation. These should extend from the proximal guide plane to an area directly opposite the terminal position of the retentive clasp. Reciprocal clasps must contact the guide plane before the retentive arms start to flex so that the periodontium is protected against excessive lateral loading.

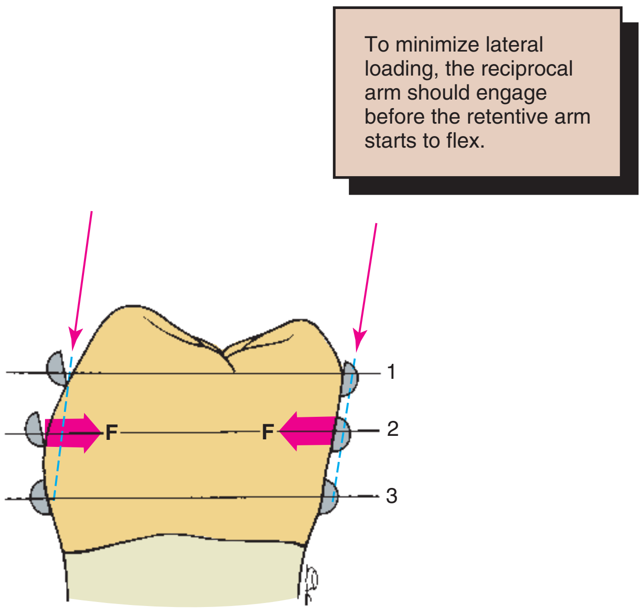

Fig. 21.18 Reciprocal arms prevent harmful lateral forces from being generated by the retentive arms during placement of a removable partial denture (RPD). *1*, Initial contact of the retentive arm; the reciprocal arm is in passive contact. *2*, Maximum flexure of the retentive arm; the forces exerted *(F)* are resisted by the reciprocal clasp. *3*, The RPD fully seated; both the retentive and the reciprocal clasps should be in passive contact.

TOOTH PREPARATION

Once the proposed placement path for the RPD has been determined and any necessary enamel modifications made to the natural teeth, those teeth that require abutment crowns can be prepared (Fig. 21.19). Making complete crowns is often necessary, but partial coverage is sometimes possible when the buccal contour does not require modification.

Path of Placement

Careful planning is required when the placement path of tooth preparations for RPD retainers is selected. Although conventional crowns generally have a path in the long axis of the tooth RPD retainers may not. Surfaces on which both guide planes and reciprocal planes are planned and areas that require survey lines in the gingival third typically require an additional reduction compared to an optimal conservative technique used on individual teeth. Because of the lingual inclination of mandibular molars, reducing them slightly more in the occlusal two-thirds of the lingual axial surface is often necessary to develop lingual guide planes that parallel each other across the dental arch.

Similarly, the axial reduction of surfaces adjacent to an edentulous RPD modification space often involves removing additional tooth structure to enable the development of the proximal plate parallel to the path of placement of the RPD. These modifications must not lessen the retention form excessively because, during prosthesis removal, the retainers are often subjected to forces parallel to their placement path, and retention becomes even more important. Additional features (e.g., grooves, boxes, pinholes) are frequently needed. It is certainly not mandatory that all retainers for an RPD have identical paths of placement.

Rest Seats

An adequate amount of tooth structure must be removed to allow for the minimally required metal thickness of 1 mm in the area of an occlusal rest seat. Some dentists prepare a rest seat in the tooth to achieve adequate reduction before starting the retainer preparation. They then use 1-mm reduction grooves to ensure adequate thickness. Although this approach can work well, problems may occur if it becomes necessary to alter the position of the rest seat during the laboratory phase. Therefore, preference should be given to the slightly less conservative approach seen in Fig. 21.20 because having the flexibility to move the rest seat during the laboratory phase can be extremely helpful. It also allows for adequate thickness for both restorative and RPD materials. Esthetic needs, such as the necessary interproximal extent of a cutback for a metal-ceramic restoration, are often evaluated best in the laboratory during waxing procedures.

Axial Contours

When a crown serves as an RPD abutment, modifications may be necessary in the normal axial reduction. The extent of additional axial reduction depends on the RPD design (see Fig. 21.9).

Additional tooth reduction is necessary if a retainer must be undercontoured with regard to the original tooth form to accommodate proximal or reciprocal guide planes and to allow the non-retentive part of an occlusally approaching clasp to be positioned as far gingivally as possible. (This is another situation

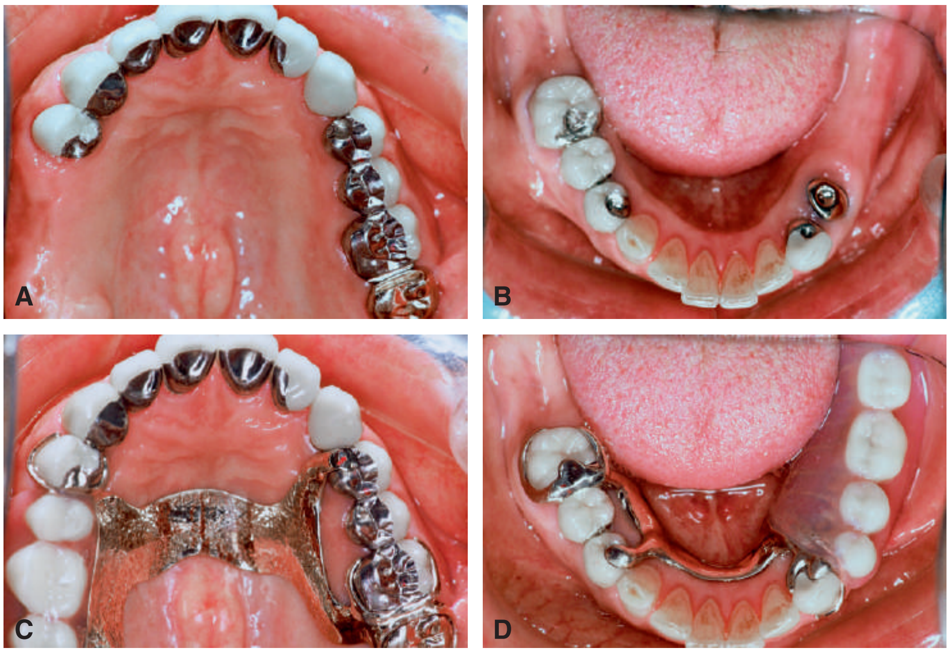

Fig. 21.19 Integration of fixed and removable prosthodontic treatment. (A) All teeth in this maxillary arch have been restored with fixed prostheses to accommodate the planned removable partial dental prosthesis. (B) This mandibular arch has been restored with a simple three-unit fixed dental prosthesis, a single crown, and a gold dome that will provide support for the removable prosthesis. (C and D) Maxillary and mandibular arches with the removable prostheses in place.

in which diagnostic preparations and diagnostic waxing procedures often prove very helpful in assessing the need for additional axial reduction.)

Another possible advantage of providing an abutment crown is the opportunity to shape the axial contours to accommodate the RPD clasps within the normal crown contours (Fig. 21.21). Although this allows for a less bulky removable prosthesis contour, it requires additional axial reduction. The use of a precision machine-tool milling device (see Fig. 21.29) is essential for these restorations.

IMPRESSION MAKING

Because of the relative interdependence of RPD abutment preparations, a diagnostic impression should be made after the preparations have been completed. This is poured in accelerated-setting stone or plaster. The resulting cast is then surveyed, and the need for any further modifications is determined; such modifications can then be incorporated with minimum loss of chair time. The same cast can also be used for fabricating the interim restorations (see Chapter 15). As described for

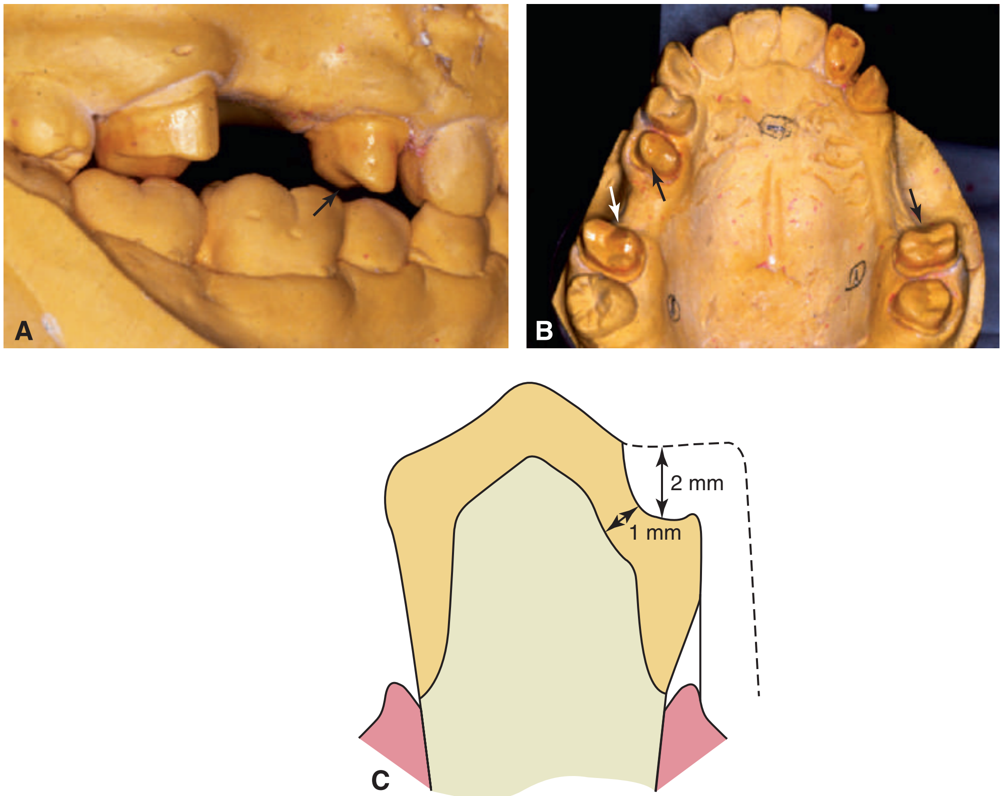

Fig. 21.20 Retainer preparation. (A and B) The rest seat preparation *(arrows)* allows some adjustment of rest seat location during the waxing phase. (C) Cross-section view through survey crown. Occlusal rest and minor connector with minimum dimensions.

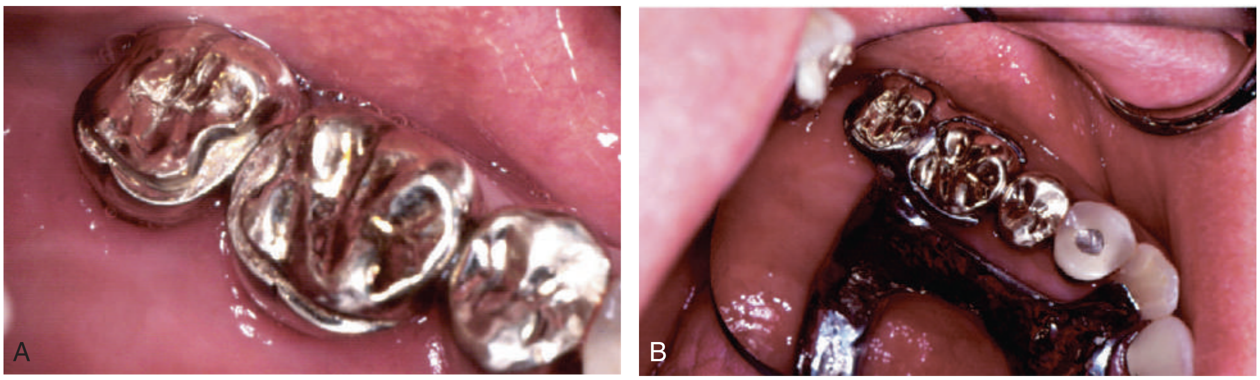

Fig. 21.21 Abutment crowns contoured to receive the removable partial denture (RPD) clasp precisely. (A) The cast crowns have received milled-in shelves that enable the RPD clasp to settle into the coronal form of the restored tooth. (B) RPD in place. (Courtesy Drs. K. Seckler and J. Jankowski.)

conventional restorations, a definitive impression is obtained with either an elastomeric or a reversible hydrocolloid impression material (see Chapter 14). When multiple teeth in an arch require crowns to provide proper support for a RPD, they are captured in a single elastomeric impression. In the maxillary arch, this usually can be accomplished without too much difficulty. However, in the mandibular arch, bilateral posterior impressions may present great difficulty. A practical solution is to make separate impressions and, at the evaluation appointment, to make a pickup impression over the top of the separately fabricated restorations. A new cast is then generated (see the remount technique in Chapter 29; Fig. 29.17). This cast is then used to refine the axial contours through milling procedures.

Intraoral recording for RPD frameworks and teeth preparations can also be made digitally. RPD frameworks fabricated from digital scans have demonstrated good accuracy and fit when compared with conventional impression methods.[8]

Occlusal Records

A record base with wax rims is needed to articulate the casts unless an adequate number of teeth are present to relate and stabilize the opposing casts with a conventional centric relation record.

Because a record base is stable only on the cast from which it was made, it should not be fabricated in advance. Therefore, an additional patient visit must be planned to obtain an interocclusal record. The maxillary cast orientation is transferred using a facebow to the articulator, and the mandibular cast is then articulated in the usual manner.

WAX PATTERN FABRICATION

Waxing partial denture abutments to optimally meet all requirements can be difficult, even for experienced operators. It is common to encounter crowns with guide planes that are significantly overcontoured. Overcontouring adversely affects the long-term prognosis, as plaque control measures are compromised. To the novice operator, the need for good occlusion, anatomic form, and proper contours for plaque control often appears to conflict with the need for guide planes and retentive undercuts. Careful analysis is essential at the treatment planning stages when a diagnostic waxing procedure can prove helpful. An organized approach to waxing RPD retainers must be maintained. The operator makes the wax patterns in the usual way (see Chapter 18), creating normal axial form and embrasures and allowing for optimum distribution of the forces of occlusion. This is followed by adjustment of the axial walls to accommodate the survey line and guide planes. The resulting occlusal table is typically smaller than a pattern that is shaped to optimal anatomic form. The rest seats are placed as the final step in this process, immediately before reflowing the margins and investing (see Chapter 22).

Survey Line

When normal axial coronal contour has been established in wax, the cast is removed from the articulator and placed on the surveyor (Fig. 21.22). The preliminary path of placement that was established during the treatment planning and tooth preparation phases may require slight modification. However, only a minor alteration should be necessary, and it often compensates for small, previously unrecognized errors that may have occurred at the tooth preparation stage.

The first step in generating the desired heights of contour is to generate a nearly cylindrical pattern that, when viewed from the occlusal side, corresponds with the normal outline form of the tooth being restored (see Fig. 21.22A). A straightforward way this can be accomplished is to slightly overcontour the wax coping and then use the carving attachment of the surveyor to create the cylindrical shape (see Fig. 21.22B). Once normal outline form has been established satisfactorily (or the outline form may be slightly undercontoured, depending on the path of placement of the RPD), the carved band can be coated with waxing powder, and the desired height of contour is scribed directly on the pattern with any suitable waxing instrument (see Fig. 21.22C and D). Excess wax above and below the desired height of contour is carved away, and an undercut gauge is used to evaluate the undercut (see Fig. 21.22E). All surfaces are then blended through selective reflowing (see Fig. 21.22F). Because the definitive size of the occlusal surface is now known, occlusal detail is added, and the occlusal rest seat can be carved in with a round bur of a suitable size (see Fig. 21.22G and H). A discoid-cleoid instrument may also be used to carve and finish rest seats.

The operator can relocate a survey line by tilting the cast (e.g., enlarging a mesial undercut by increasing the mesial tilt, moving a buccal survey line farther occlusally by increasing the tilt toward the buccal surface). When the cast tilt for the final placement path has been selected, the cast is marked at three points (some technicians also mark the side of the cast). This "tripodizing" allows the selected path to be reestablished with minimum inconvenience (Fig. 21.23). The surveyor carving attachment is then used. Some dental surveyors have a movable arm, which makes carving the wax easier. Identical results can usually be obtained with the rigid-arm type, but more care is necessary to prevent fracture of the wax pattern or tilting of the surveyor table. The final evaluation of the survey contour consists of dusting the pattern with zinc stearate or waxing powder, marking the height of contour with the analyzing rod, and measuring with the undercut gauge.

Guide Planes

The operator forms the proximal and reciprocal guide planes (Fig. 21.24) by trimming all excess wax from the patterns. Cervico-occlusally, the typical guide plane should remain within normal contours. Cervical to the guide plane, the form of the wax pattern should follow the configuration of the remaining tooth structure at the margin.

The minimum cervico-occlusal length for guide planes allows the reciprocal arms of the clasps to make initial contact and remain in contact during seating of the RPD (see Fig. 21.18).

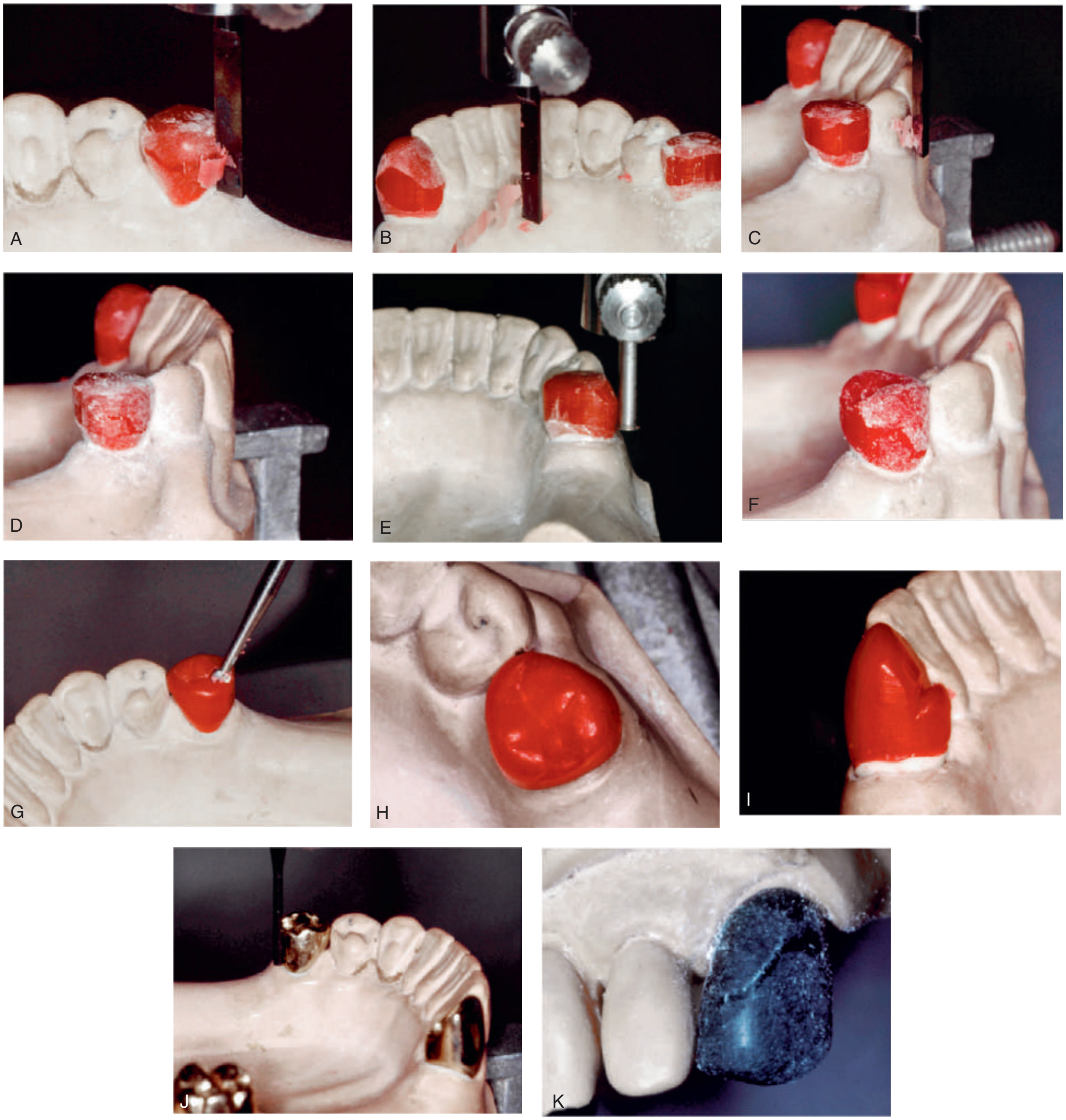

Fig. 21.22 Waxing removable partial denture retainers. (A) After the path of placement has been established, the carving attachment of the surveyor is used to make a 2- to 4-mm-wide band on the wax pattern. (B) Note that the band includes the proximal and lingual walls of the pattern where the proximal and reciprocal guide planes, respectively, will be established. (C) The band is carried onto the buccal surface, where the retentive clasp is to be placed. Viewed from the occlusal aspect, when complete, the band remains within the normal anatomic contour. (D) The pattern is dusted with zinc stearate or powdered wax, and the desired survey line is scribed. (E) After excess wax has been carved away occlusally and gingivally to create the desired contour, the undercut gauge is used to verify that the proper amount of wax has been removed. (F) After smoothing and blending of the various surfaces, the pattern is again dusted with powder, and the configuration of the final survey line is verified. (G) Then a round bur is used to place the occlusal rest seat. On premolars, a No. 6 round bur is adequate; on molars, a No. 8 round bur may be used. (H) At least 1 mm of wax is maintained around the perimeter of the rest seat. (I) A cingulum rest seat on a canine pattern can be carved with conventional waxing instruments. The lingual aspect of the rest seat must withstand lingual displacement. Mesiodistally, the rest seat is slightly curved, with the highest point in the middle of the pattern. (J) After casting, the crowns are evaluated, and any adjustments are made to refine the height of contour, guide planes, and occlusal rest seats. (K) Typical survey line for a wrought clasp. Note that the distal half of the clasp can easily be placed above the height of contour. The terminal half engages the undercut. A sufficiently long trajectory must remain incisal to the height of contour to allow gradual flexing of the clasp.

Occlusal Rest Seats

Occlusal rest seats (Fig. 21.25) are most commonly located in the interproximal marginal ridge area and can easily be cut into the wax patterns with a hand-held round bur or discoid-cleoid hand instrument (see Fig. 21.22). When metal-ceramic restorations are the retainers, the rest seat should be in metal at least 1 mm from the metal-ceramic junction (Fig. 21.26). When a rest is to be placed in a wax pattern for a metal-ceramic restoration, this is best done after the pattern has been cut back for the metal-ceramic veneer. It can prove helpful to displace occlusal rests on metal ceramic crowns slightly lingually: This enables maintaining adequate metal thickness between the rest and the area that has been cut back for the ceramic veneer, and it is often easier to ensure continuity between the minor connector of the RPD and the occlusal rest.

Cingulum rest seats (Fig. 21.27; see also Fig. 21.14) are placed with a carver. Buccolingually, they have a *V*-shaped configuration in cross section; mesiodistally, they are slightly curved, with the highest point in the center of the tooth.

Fig. 21.23 A mandibular cast with diagnostic wax patterns and denture teeth set up. The cast has been marked as tripod for repositioning according to the planned path of insertion of the removable partial denture.

SPECIAL FINISHING PROCEDURES

After the wax patterns have been invested and the retainers have been cast, the restorations are carefully seated onto the dies. When the fit is satisfactory, the casting is transferred to an indexed cast for milling. The survey table is adjusted so that the cast is oriented at the correct angulation, and cylindrical rotary instruments are used to refine the guide planes and to make any needed corrections.

Milling

Many precision parallel milling devices are available commercially. The simplest consists of a clamp that holds a conventional straight handpiece parallel to the shaft of the surveyor (Fig. 21.28). This works satisfactorily when used carefully. There are also expensive machine-tool milling devices that can be

Fig. 21.24 (A) A proximal guide plane and the correct axial survey lines are incorporated in the anatomic contour wax pattern. (B) The contours are duplicated in porcelain. (C) The fixed prostheses are cemented. (D) An accurately contoured retainer provides proper support for the removable partial denture.

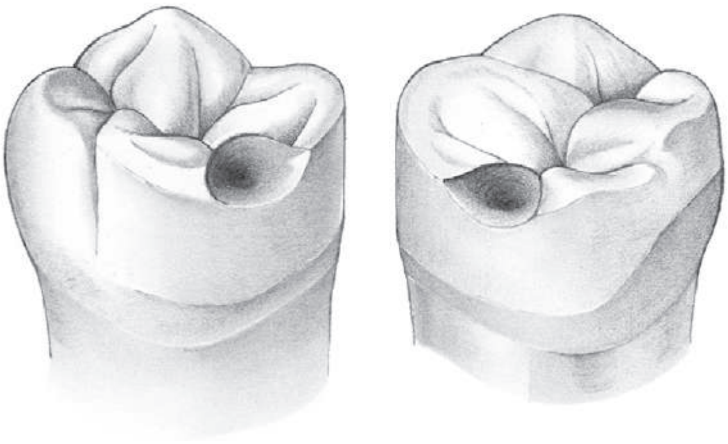

Fig. 21.25 Completed wax pattern for a removable partial denture retainer with occlusal rest seat, distobuccal retention, and proximal and lingual guide planes.

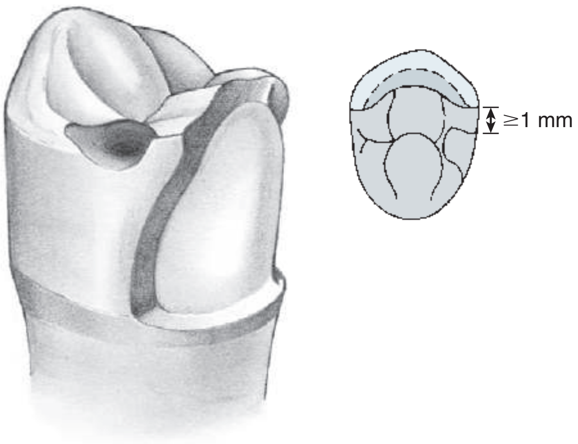

Fig. 21.26 Maxillary premolar wax pattern after cutback for the porcelain application. The rest seat should be at least 1 mm from the metal-ceramic junction. The guide plane continues in the porcelain.

Fig. 21.27 Cingulum rest seat on a mandibular canine. Note its mesiodistal curvature (compare with Fig. 21.22I). (Courtesy Dr. X. Lepe.)

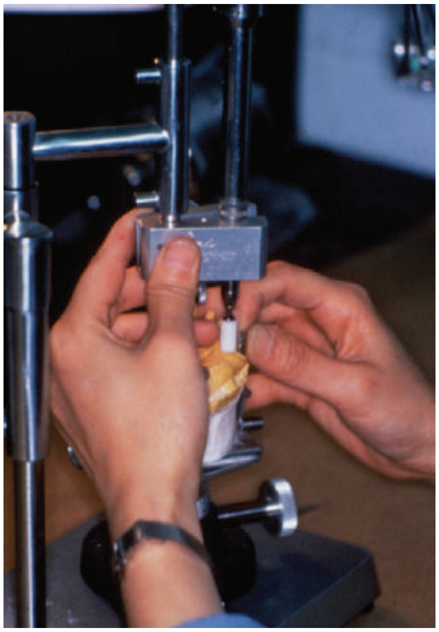

Fig. 21.28 Handpiece holder for milling guide planes. The holder attaches a conventional straight handpiece parallel to the shaft of a dental surveyor.

controlled with great precision and are particularly useful for extensive attachment prostheses (Fig. 21.29).

Cylindrical tungsten carbide burs without crosscuts are recommended for refining metal proximal and reciprocal guide planes. Light pressure should be used throughout the milling procedure. Once the desired contour has been obtained, only minimum finishing with paper disks or rubber wheels is necessary. A complete- or partial-coverage crown is finished through the normal sequence of abrasives until a high polish has been attained. If the retainer is a metal-ceramic crown, the veneering surface is prepared after completing the milling procedure. Then the desired survey line and retentive undercuts are established

Fig. 21.29 Machine-tool milling device allows precise control of the milling process.

in porcelain. The porcelain can then either be glazed or polished while care is taken to maintain the desired heights of contour throughout the polishing procedures.

Caution is needed when survey lines are scribed on a bisque bake of porcelain. Red or green pigments must be used because they do not cause contamination after firing. Graphite from a soft lead pencil produces discoloration in the fired porcelain, and such pencils must not be used (see Fig. 21.24B).

EVALUATION AND CEMENTATION

The clinical evaluation of the prosthesis proceeds as for any restoration. The RPD retainer should have good marginal integrity and proper axial contour, and it should be stable with accurate occlusal and proximal contact (see Chapters 29 and 30).

When these criteria have been met, a precementation irreversible hydrocolloid impression is poured in a fast-setting stone, and the resulting cast is analyzed on the surveyor. Any change in contour that may have occurred during finishing is easily detected at this time when corrective action is still possible. For a metal-ceramic restoration, recontouring, repolishing, reglazing, or a combination of these may be necessary.

Cementation procedures for survey crowns are identical to those for conventional restorations (see Chapter 30). When multiple restorations involving prefabricated attachments are to be cemented, postponing cementation of the retainers until after the completion of the RPD can sometimes prove advantageous.

FABRICATION OF A CROWN FOR AN EXISTING REMOVABLE PARTIAL DENTURE

Occasional patients have a defective abutment crown under an otherwise satisfactory RPD. Although a new RPD is often the more appropriate choice, at least 15 methods have been described for making a crown fit an existing RPD.[9,10] These can be classified as direct, direct-indirect, or indirect procedures.

When a direct-indirect procedure is used, a pattern is fabricated from autopolymerizing acrylic resin and wax. The resin is applied onto the tooth preparation, and resin is added until it contacts the internal aspect of the RPD clasps, thus duplicating the axial contours of the original abutment crown. This resin pattern is repositioned on a die on which the margins and shape of the restoration are refined by wax. The combined resin-wax pattern is invested, and after wax and resin elimination, the crown or coping is cast.

The indirect procedure consists of a “pickup” impression of the prepared tooth and the seated RPD. This is poured conventionally after any undercuts in the RPD have been waxed out. The crown is fabricated conventionally, the RPD being removed and replaced on the cast to establish appropriate contours. Additional wax (or porcelain for a metal-ceramic crown) is added where the retentive undercut is needed (Fig. 21.30). A disadvantage of this technique in comparison with the direct approach is that the RPD is required in the laboratory throughout the crown fabrication. This may not be acceptable to the patient, particularly if the patient’s appearance is affected.

With all these techniques, extra care is necessary for finishing the areas of the crown where contact with the RPD occurs. Small clasp-adaptation imperfections often result, but with some practice, it is possible to routinely fabricate quite acceptable restorations that eliminate the need to fabricate a new RPD.

If the contours of the existing but defective retainer are acceptable, it is possible to obtain an optical scan of the desired contours and the occlusal surfaces of the adjacent teeth. After the defective crown has been removed and the tooth preparation completed, a conventional or optical impression can be made. In the dental laboratory, the software is manipulated to merge the information previously captured during the design phase of the new crown, which is then fabricated in the specified material. If finishing procedures are performed in a cautious manner, this approach is successful in fabricating crowns that offer reasonable RPD stability on delivery (Fig. 21.31).[11]

ATTACHMENTS

A wide range of prefabricated attachments is available for use with RPDs.[12,13] Most of these consist of two components: one that is incorporated in the crown and one that becomes part of the RPD. Both extracoronal and intracoronal designs are available (Fig. 21.32).

In general, the use of attachments, whether extracoronal or intracoronal, should be limited. Attachments add to the complexity and cost of the restorative service and often necessitate remaking the fixed retainers when the attachments wear out. In one study, only 22 of 57 prostheses were free of complications during the first 2 years.[14] When used with distal extensions, attachments lead to higher stresses in the abutment teeth.[15] When the teeth that will support an RPD are located

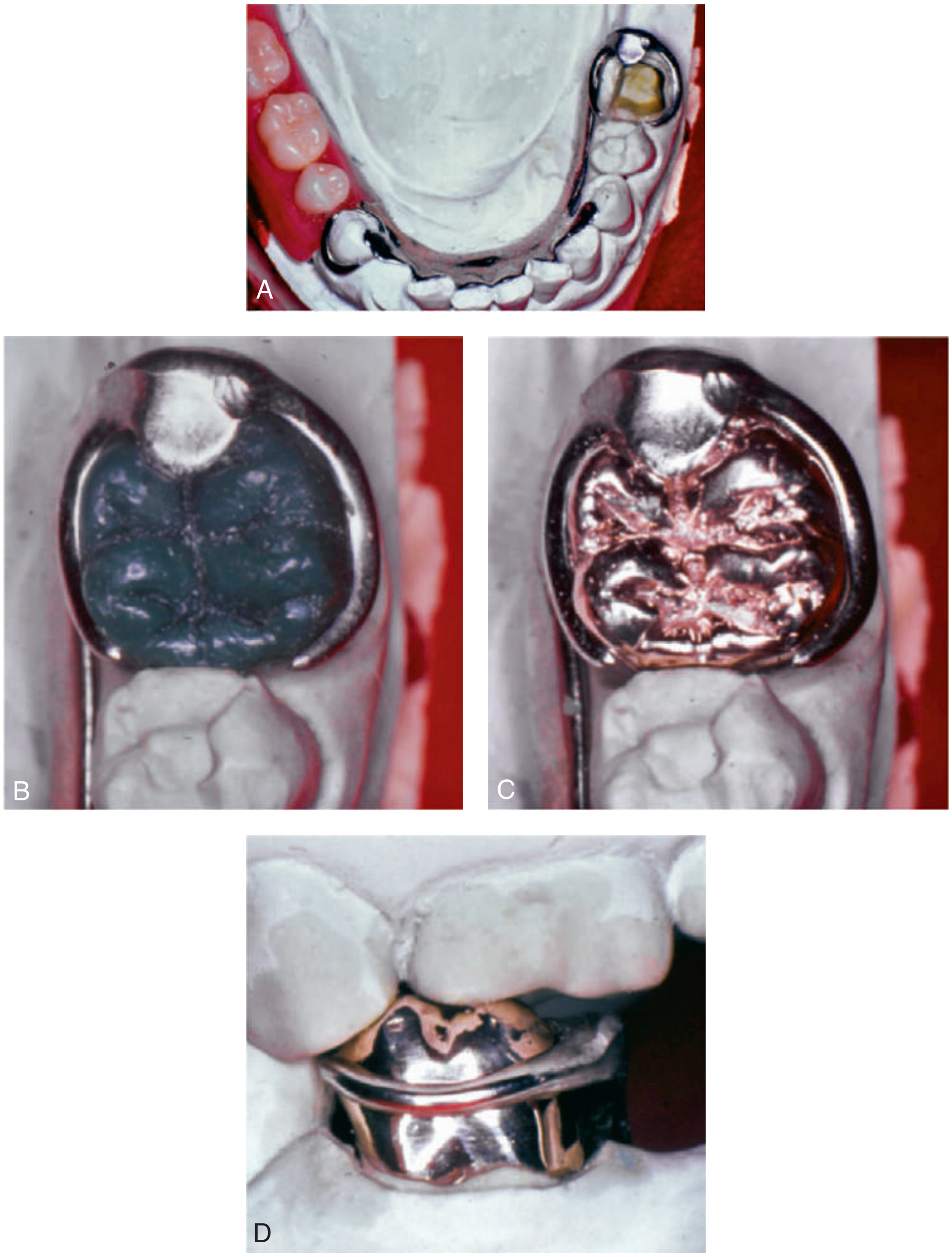

Fig. 21.30 Crown fabricated to fit an existing removable partial denture (RPD) through the indirect procedure. (A) After a pickup impression, the RPD is fitted to the definitive cast. (B) Wax pattern. (C and D) Completed crown. (Courtesy Dr. M.T. Padilla.)

in the esthetic zone, the use of attachments can be justified to enhance appearance since they can offer a means to avoid visible unsightly clasps.

Extracoronal Attachments

Any prefabricated attachment for support and retention of an RPD in which the "male" and "female" components are positioned outside the normal contour of the abutment tooth is considered an extracoronal attachment (Fig. 21.33). Careful judgment is needed in deciding when to use such attachments (e.g., ERA [Sterngold Dental, LLC], Ceka [AlphaDent NV], Dalbo [Cendres & Métaux SA], or Dawson [Comdent, Inc.]) because they place unfavorable stresses on the abutment teeth, similar to the stresses exerted by a cantilever. In addition, they make oral hygiene more difficult. In some instances, however, extracoronal attachments offer esthetic advantages that may outweigh their biologic and mechanical disadvantages (Fig. 21.34). Resin bonding has been used to retain extracoronal attachments directly to the teeth using the same principles as for resin-bonded prostheses (see Chapter 26).[16] It is doubtful, however, that the retention obtained in that manner is adequate to prevent eventual dislodgment of the attachment.

Fig. 21.31 (A) Scanned image of maxillary right second premolar from existing diagnostic cast. (B) Scanned image of prepared maxillary right second premolar from definitive cast after impression. (C) Duplicated image of maxillary right second premolar crown from diagnostic cast is superimposed on prepared tooth of definitive cast. (D) Computer-aided design and computer-aided manufacturing (CAD/CAM) milled ceramic crown is adjusted and cemented. (E) Retrofit ceramic crown is well adapted under patient's existing removable partial denture. (From Yoon TH, Chang WG: The fabrication of a CAD/CAM ceramic crown to fit an existing partial removable dental prosthesis: a clinical report. *J Prosthet Dent.* 2012;108:143.)

Fig. 21.32 An intracoronal and an extracoronal attachment were used in this anterior fixed dental prosthesis. (Courtesy Dr. F.F. Hsu.)

Intracoronal Attachments

Intracoronal attachments have "male" and "female" components positioned within the abutment tooth's normal contour. These can be prefabricated or made in the dental laboratory.

Prefabricated Attachments

The more commonly used prefabricated intracoronal attachments (e.g., Stern Latch, The C&M McCollum [Sterngold Dental, LLC] or Ney-Cheyes No. 9 [Ney Dental International]) typically consist of a precision-milled "male-female" assembly (Fig. 21.35) similar to the dovetail configuration described for nonrigid connectors (see Chapter 3).

The precision of the fit between components of an intracoronal precision attachment is so fine that retention results from friction. An intracoronal precision attachment RPD is

Fig. 21.33 Prefabricated extracoronal attachments. (A) The ERA. These attachments are designed to be resilient and to direct stress to both the abutment teeth and edentulous ridges when supporting a distal extension of a removable partial denture (RPD). The color-coded "male" components are processed directly into the acrylic denture base and have different levels of retention. (B) Abutment crowns incorporating ERA attachments. (C) Completed prostheses. (D) The Dalbo Mini. This attachment provides some movement between "male" and "female" components. (E) The Ceka: *1*, "female" component; *2*, "male" component; *3*, spacer; *4*, "male" RPD connector; *5*, positioning mandrel; *6*, adjustment tool. (F) The 2.7 Dawson: *1*, "male" component; *2*, "female" component, which has a built-in replaceable plunger for retention; *3*, the 2.7 Dawson attachment assembled. (A and D, Courtesy Sterngold Dental, LLC, Attleboro, Massachusetts. B, C, and F, Courtesy Dr. W.V. Campagni.)

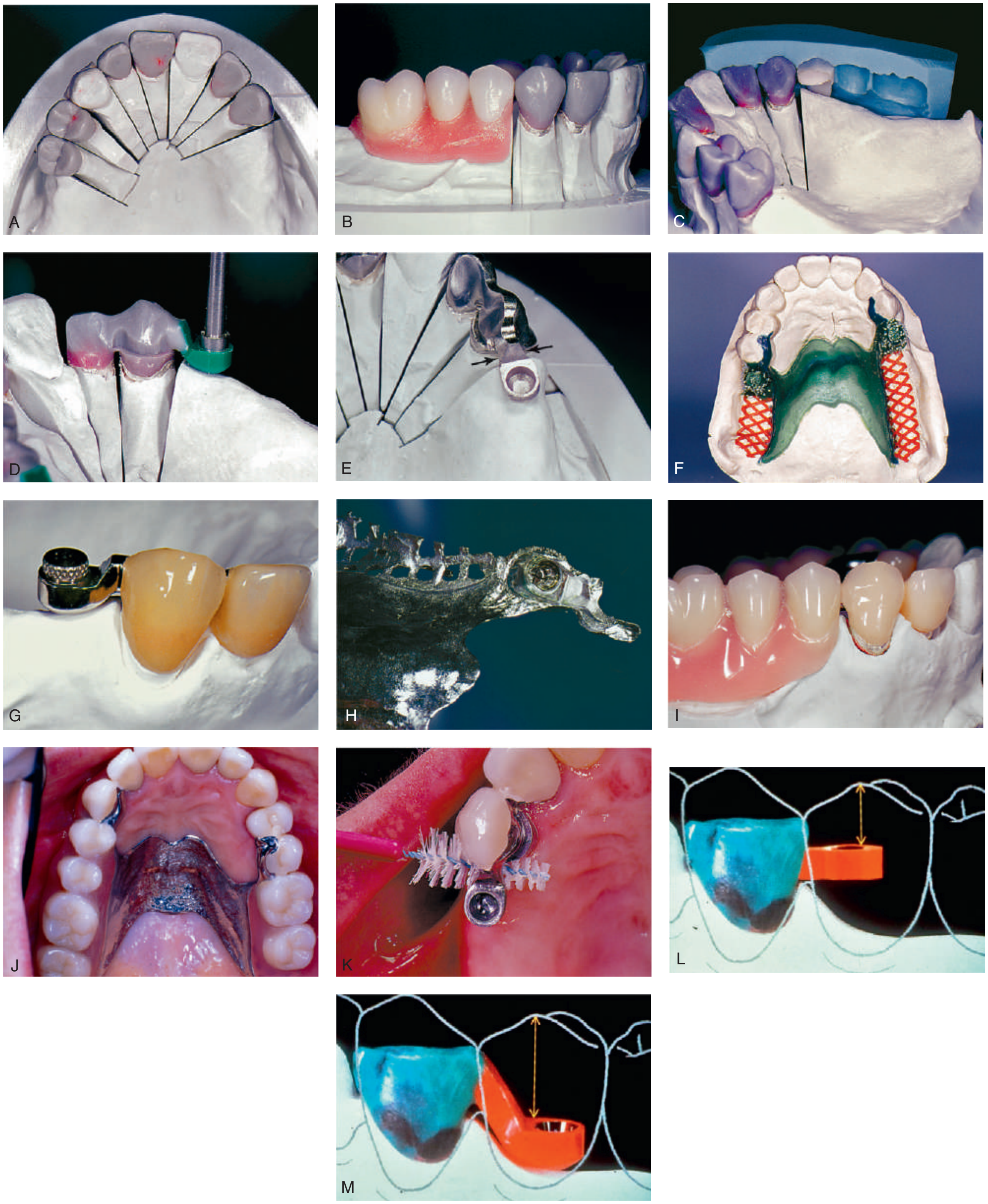

Fig. 21.34 Use of Ceka extracoronal attachments to retain a distal extension of a removable partial denture (RPD). (A and B) Anatomic contour waxing and occlusal plane development. (C) A buccal index is used to allow repositioning of the denture teeth to help identify correct attachment placement. (D) The "female" attachment pattern is positioned in relation to the wax pattern by means of a special mandrel in the dental surveyor. (E) The substructures have been cast. Adequate strength is present where the extracoronal "female" attachment joins the retainer *(arrows)*. (F) Refractory cast with RPD wax pattern. (G) "Male" component positioned in the "female" attachment. (H) Attachment picked up. (I) The completed prosthesis hides the attachment from sight. (J) The RPD in place. (K) Proxy brush enables appropriate plaque control around the attachment. (L and M) "Female" patterns are available in different angulations to provide optimal access for oral hygiene and adequate space for the RPD. (A to K, Courtesy Dr. S. Freijlich and Mr. T. Behaeghel. L and M, Courtesy Preat Corporation, Grover Beach, CA.)

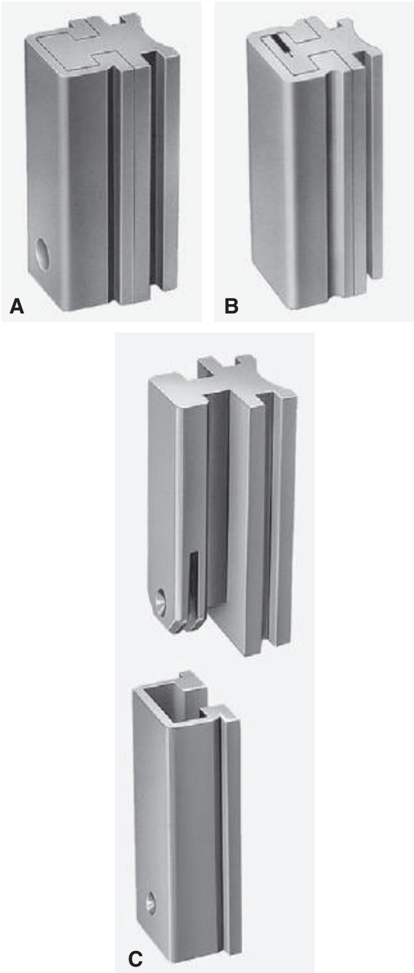

Fig. 21.35 Prefabricated intracoronal attachments. (A and B) The Stern Latch. (C) The C&M McCollum. (Courtesy Sterngold Dental, LLC, Attleboro, MA.)

not readily dislodged because it can be removed only in a single direction, which may present difficulties for patients with limited dexterity. However, retention can be significantly reduced after wear of the retentive surfaces. Most precision attachments are made of platinum-palladium alloys, necessary to withstand the high temperature associated with the casting of metal-ceramic alloys directly onto the attachment.

The "female" attachment is incorporated in the retainer wax pattern, and the assembly is invested. After wax elimination, the attachment is retained inside the investment, and the restoration is cast directly onto the attachment. Although multiple parallel attachments can be fabricated in this manner, most technicians prefer to solder a second or third attachment to the respective retainers. This allows the technician to verify alignment with the attachment in the first retainer.

Alternatively, a metal tray may be incorporated in the secondary retainer for added flexibility during the positioning of the second attachment parallel to the first attachment. The secondary retainer is luted into place, invested, and soldered. "Male" components can then be inserted. After the RPD framework has been made, the "male" attachments are either soldered to the frame or attached to the acrylic resin denture base with autopolymerizing resin (Figs. 21.36 and 21.37).

The preceding paragraph condenses an intricate sequence of technically highly demanding steps. The less experienced operator is strongly cautioned not to underestimate the high level of skill and meticulous attention to detail that are required.

The best advantage of intracoronal attachments is that they eliminate the need for an often unesthetic facial clasp. Simultaneously, however, the size of most intracoronal precision attachments limits their application, especially on vital teeth. To maintain the health of supporting tissues, the proximal surface of the restoration should not be overcontoured. Therefore, the optimum placement of attachments is within the normal contours of the tooth and thus the restoration. However, this is usually possible only on large teeth. On small teeth, few intracoronal precision attachments can be kept within the confines of normal tooth contour without endodontic treatment. In addition, clinical crown height must be sufficient for adequate cervico-occlusal length to allow a positive friction fit (a minimum attachment height of 4 mm or more is recommended).

Laboratory-made Attachments

Many laboratory-made (semiprecision) attachments are also available. They are referred to as *dovetails* because of the shape of their interlocking components. They can be made by incorporating a prefabricated plastic insert in the wax pattern; the pattern is then invested, the insert is eliminated, and the pattern is cast (Fig. 21.38). The "female" dovetail can also be milled, after which the "male" component is waxed and cast.

An alternative fabrication method is to use a tapered metal mandrel (e.g., Ticon [CMP Industries LLC]) that is heated and inserted in the wax pattern. When the wax is eliminated after investing, the exposed portion of the mandrel in the mold oxidizes. The crown is then cast directly onto the mandrel, which is later removed (see Fig. 21.38). A "male" attachment can be waxed and cast separately. After seating, the attachment is then soldered or welded to the RPD framework.

Because of the inaccuracies inherent in their fabrication, most laboratory-made attachments have a limited amount of frictional retention in comparison with the commercially available precision attachments. The majority are tapered for ease of fabrication and therefore necessitate the use of lingual retentive clasps for positive retention.

When attachments are used with a metal-ceramic restoration, adequate metal must remain between the "female" component and the facial veneer of dental porcelain. As for occlusal rests, a minimum metal thickness of 1 mm is recommended between any intracoronal attachment and the metal-ceramic interface (Fig. 21.39).

Bars, Studs, and Magnets

Stud attachments[17] and magnets[18] (Fig. 21.40) are sometimes used to retain overdentures. They are incorporated in post-retained castings or implant abutments and offer the advantage of allowing increased occlusal force and improved denture stability (Fig. 21.41).[19] To have adequate room for all attachment

Fig. 21.36 Use of Stern Latch intracoronal attachments to support and retain a maxillary removable partial denture (RPD). The Stern Latch attachment has frictional retention augmented by an internal gingival spring latch. The matrix may be waxed and then cast directly to the metal components. The "male" component may be soldered to the framework or embedded in the resin of the finished RPD. (A and B) Extensive periodontal disease and caries necessitated the loss of several teeth with a hopeless prognosis. (C) The resin-reinforced definitive cast with the finished fixed prostheses and RPD framework. (D) Restorations and framework removed from the cast. (E) Cemented fixed restorations without the RPD. (F) Intraoral view of finished prostheses. (G) Anterior view of completed prosthesis. (Courtesy Dr. W.V. Campagni.)

Fig. 21.37 Use of the Dawson 2.7 extracoronal attachment to support and retain a maxillary removable partial denture (RPD). This precision attachment comprises an extracoronal patrix, which is waxed into the fixed abutment prosthesis and then cast directly to the metal components. The matrix comprises a housing with a spring-loaded plunger for retention. The plunger engages a dimple on the distal side of the patrix. The plunger and spring can be removed from the housing for replacement with a special U-shaped pin. (A) Definitive cast with finished crowns on resin replica dies for fabrication of RPD framework. (B) Framework on definitive cast. The matrix will be luted to the frame with resin for the try-in. (C) View of finished RPD, showing matrix processed in place. (D) Occlusal view of RPD intraorally. (E) Anterior view of completed prosthesis. (Courtesy Dr. W.V. Campagni.)

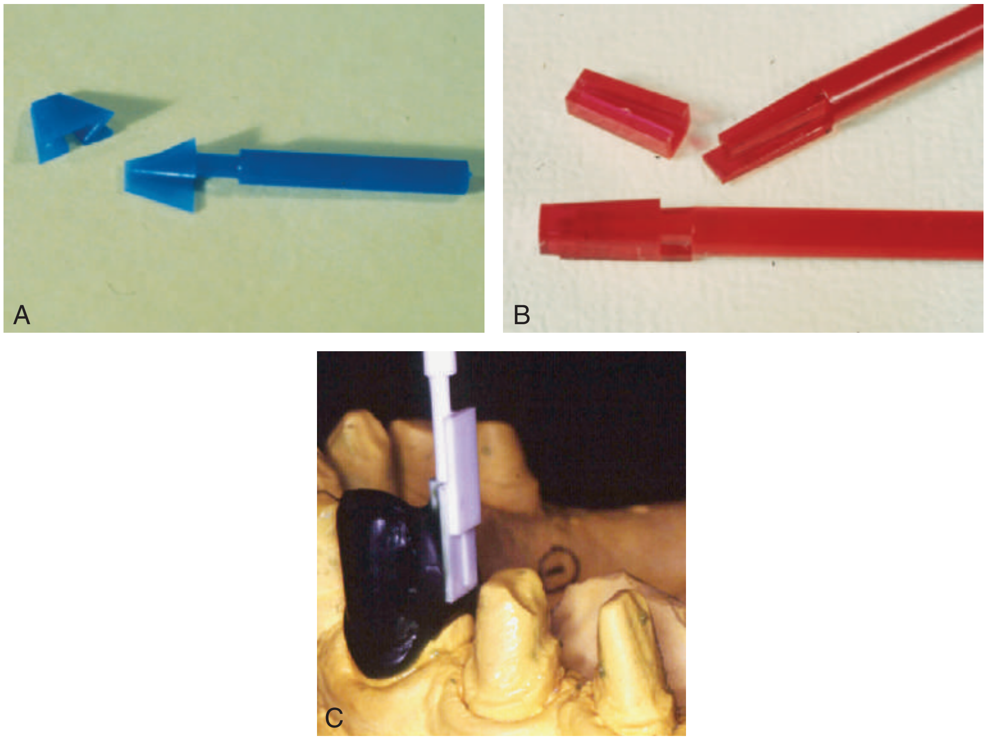

Fig. 21.38 (A to C) Plastic preformed patterns for an intracoronal rest. (C, Courtesy Dr. F.F. Hsu.)

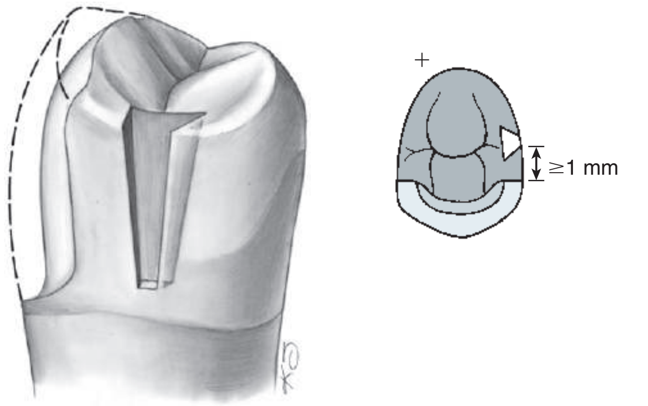

Fig. 21.39 "Female" intracoronal rest incorporated in a metal-ceramic restoration. The attachment should be at least 1 mm from the metal-ceramic junction. Retention is provided by a lingual undercut into which a clasp engages. Reciprocation is provided internally by the rest seat.

components, the denture resin, and a hollowed-out shell of a denture tooth (see Fig. 21.40B), a minimal vertical space of 7 to 9 mm is recommended.

A bar-retained RPD or overdenture can be very stable while it braces individual abutment teeth. The bar should attach to the retainer without interfering with oral hygiene.

In general, this means that considerable coronal length is necessary for the bar to produce an acceptable result. The bar should not be placed in contact with an edentulous ridge; it should be positioned about 2 mm away from the soft tissues (Fig. 21.42).

Implant-Assisted RPD

Dental implants are another viable option that will help improve esthetics, comfort, support, and retention of RPDs.[20] At times, it can be a more conservative treatment option as significant teeth preparations and restorations may be avoided. Low profile stud attachments (e.g., LOCATOR Attachment System [Zest Dental

Fig. 21.40 (A and B) The ERA stud attachment. Like the ERA extracoronal attachment (see Fig. 21.33A to C), this resilient attachment is available in different sizes (Stern ERA and Micro ERA) and color-coded retention levels. (C and D) The Stern Root Anchor. This stud attachment comprises an intraradicular ball-and-socket joint. The nylon "male" part (C) is processed into the denture acrylic. The titanium "female" part (D) is cemented directly into the prepared root. (E) The Dalla Bona Spherical attachment, a gold alloy stud attachment with adjustable frictional resistance. (F and G) The Hader bar. In this bar system, a plastic bar is incorporated into the fixed prosthesis before casting. Color-coded nylon rider clips are incorporated into the denture and are available with varying retention. Alternatively, a gold rider can be used for greater strength. (H) The Dolder bar. This gold alloy bar is available in rigid *(1)* and resilient or hinging *(2)* configurations. (I) Parts of the Dolder bar: *1*, sleeve; *2*, spacer; *3*, bar. (A to H, Courtesy Sterngold Dental, LLC, Attleboro, MA.)

> Considerable vertical space is needed for stud attachments and bar-supported RPDs.

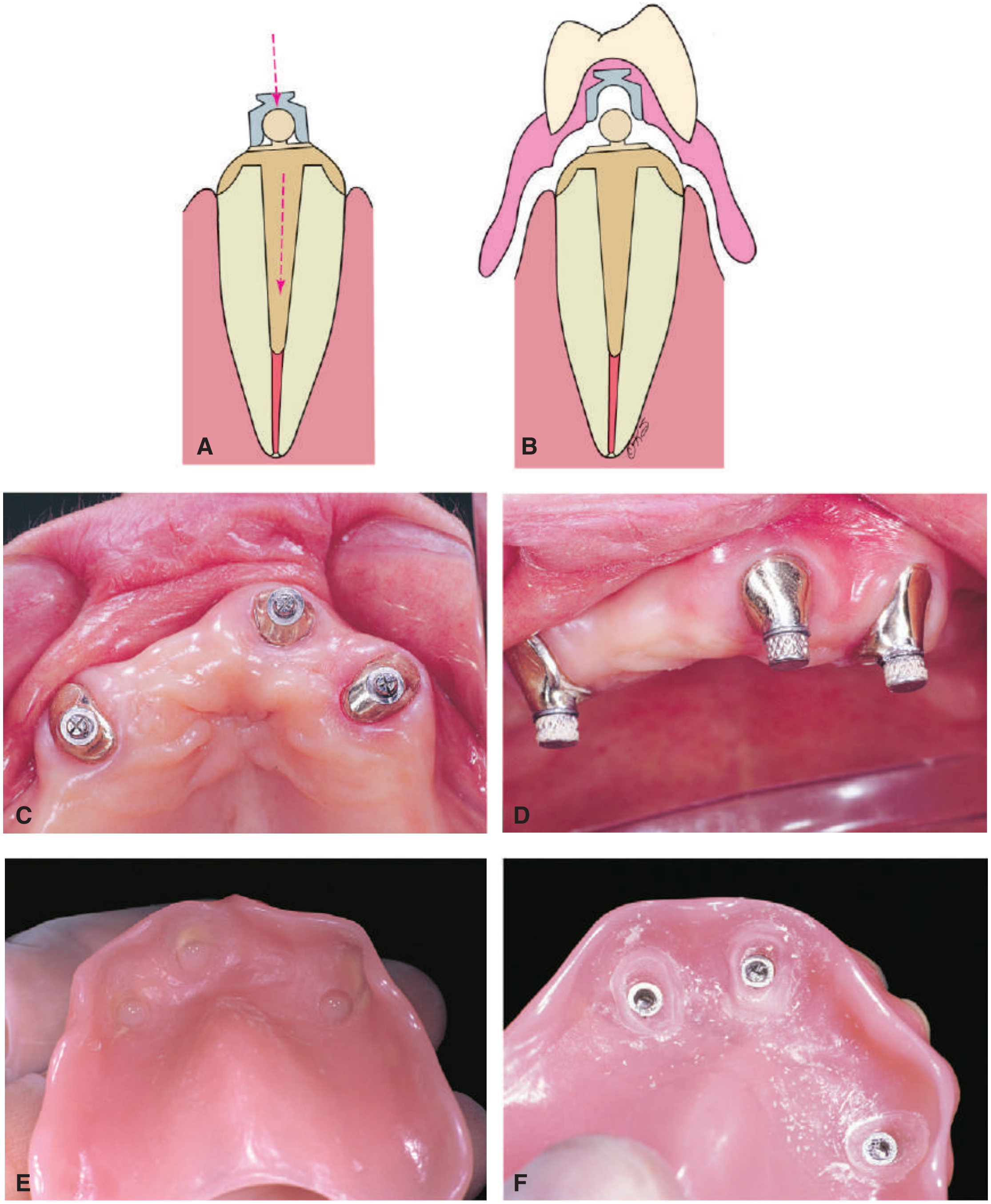

Fig. 21.41 (A) Illustration of post-retained casting incorporating the "male" component of a stud attachment. The design allows for slightly different paths of insertion *(arrows)* of the post and overdenture. (B) Illustration of the "female" component attached to the overdenture with acrylic resin. *RPDs*, Removable partial denture, (C) Occlusal view of three cemented copings with the "male" components in place. (D) "Female" attachments have been positioned over the "male" attachments. (E) Resin is applied to the internal surface of the prosthesis immediately before the denture is inserted. (F) Denture immediately after removal of excess resin around the "female" components, which are now mechanically retained in the prosthesis. (Courtesy Dr. M.A.S. Freijlich and Mr. T. Behaeghel.)

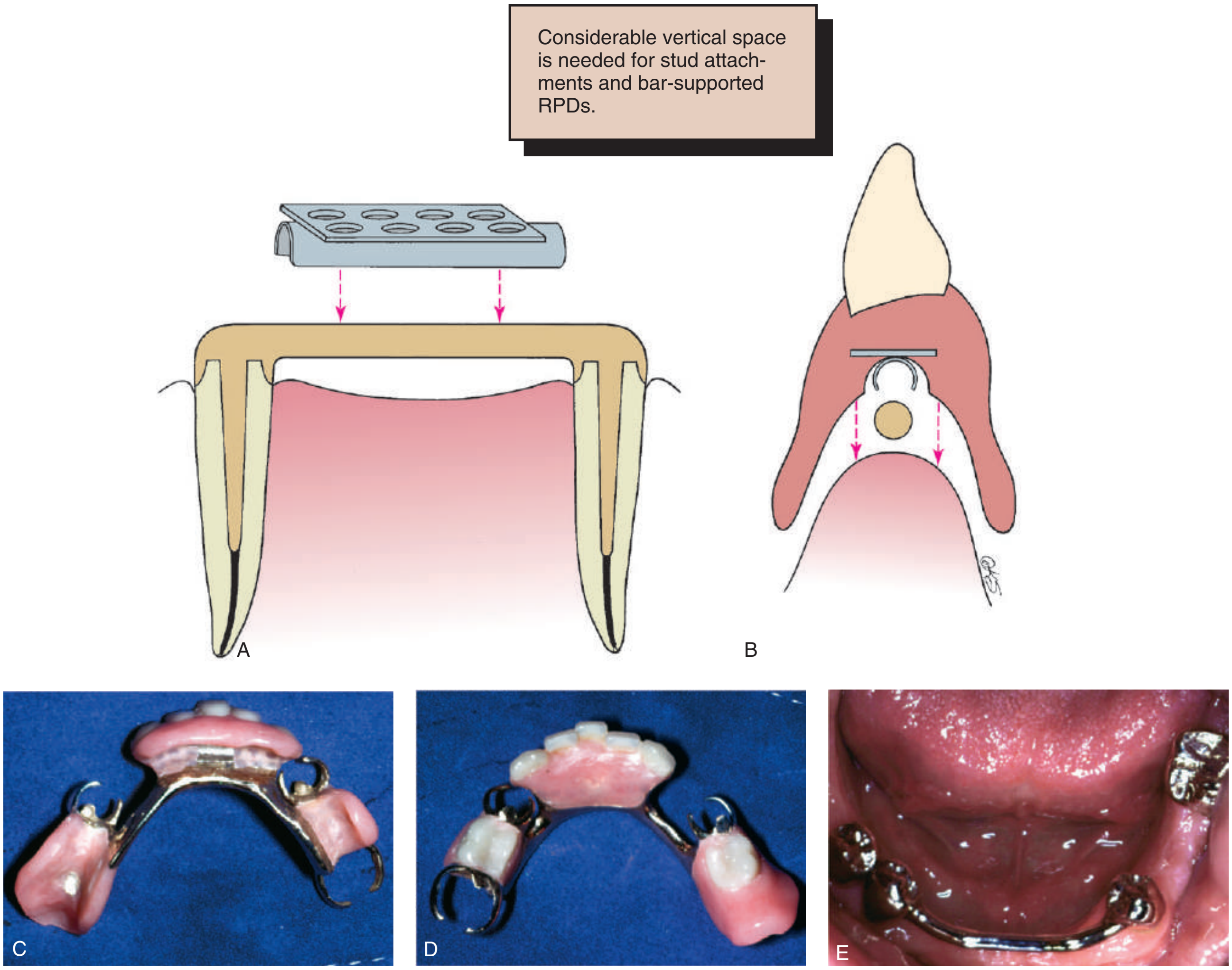

Fig. 21.42 Bar attachment. (A) The bar is retained by posts on conventional fixed restorations. The clip provides support and retention for the removable partial denture (RPD) (B) Incisogingival height must be sufficient to accommodate a bar prosthesis. (C) Internal view of the bar-retained RPD. (D) Occlusal view. (E) Cemented fixed prosthesis with a bar to accommodate an RPD.

Solutions]) are an option that provides additional support and retention to RPDs (Fig. 21.43). It also helps alleviate stress with remaining teeth in distal extension situations (e.g., Kennedy Class I) and can help guard periodontally or restoratively compromised teeth.

SUMMARY

Along with conventional diagnostic procedures, an in-depth survey of the diagnostic cast must be performed for any patient requiring an RPD. The coronal surfaces of the abutment teeth should be shaped to allow for optimum retention and stability of the RPD during function. Proximal and reciprocal guide planes should be established simultaneously to guide and stabilize the prosthesis during placement and minimize horizontal forces on the abutment teeth.

To achieve harmony with the necessary RPD design, making cast restorations on otherwise intact and caries-free teeth is sometimes necessary. The contours or axial configuration of unaltered crowns of natural teeth may not be suitable for the best clasp design.

The amount of tooth reduction needed to fabricate restorations with the desired survey contours is often slightly greater than that needed if the respective abutment teeth are prepared for conventional restorations. Allowances must be made for occlusal rest seats and guide planes. Precision and semiprecision attachments can offer esthetic and retentive advantages (Fig. 21.44).

Intracoronal attachments are often more esthetic than are conventional clasps. They work well if kept within the normal contours of the teeth.

Extracoronal attachments should be used sparingly because of their unfavorable loading of abutment teeth and the associated problems in maintaining oral hygiene.

Attachments and occlusal rest seats in metal-ceramic restorations should be placed at least 1 mm from the metal-ceramic interface.

Survey crowns necessitate finishing procedures for which special milling equipment is needed.

A precementation impression should be obtained for verifying that the best coronal contours have been created in harmony with the RPD.

Fig. 21.43 (A) Intraoral photograph of a mandibular Kennedy Class I situation with two implant abutments in the posterior areas. (B) Intaglio surface of an implant assisted removable partial denture (RPD) with low profile stud attachments. (C) Placement of the implant assisted RPD in the mandible.

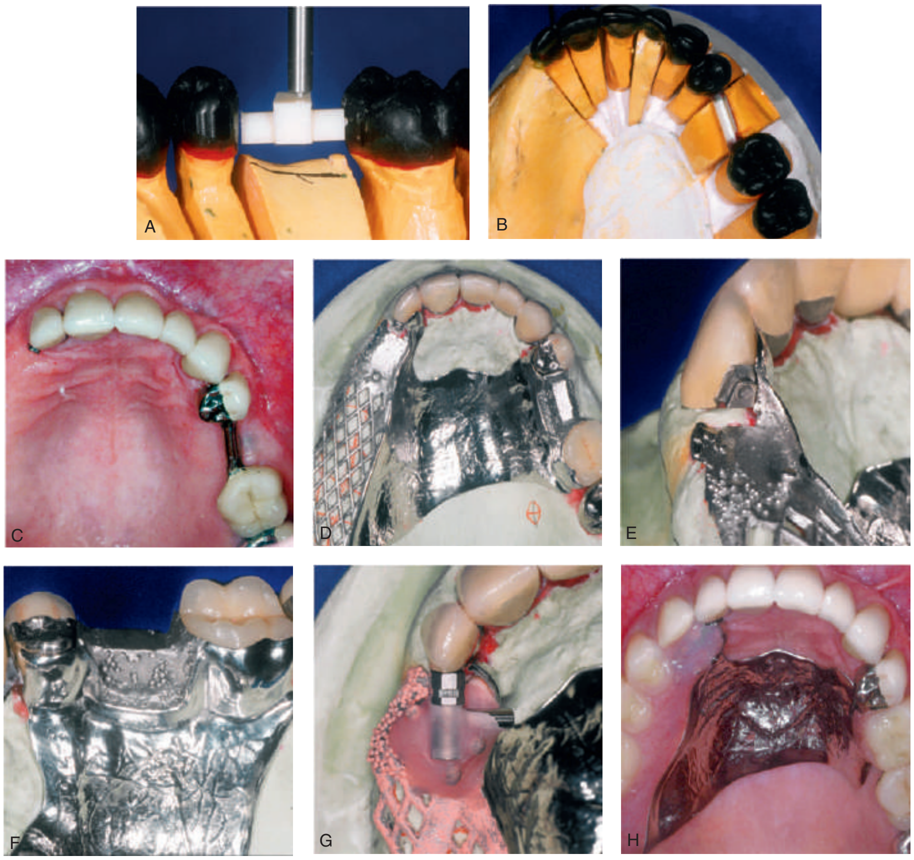

Fig. 21.44 Use of a combination of bar and extracoronal attachments for support and retention of a maxillary removable partial denture (RPD) according to the rotational path concept. The COMPAS attachment system was chosen as the extracoronal attachment. This system was designed by Dr. Peter Dawson and is an evolution of the D 2.7 attachment (see Fig. 21.37), which was also designed by Dr. Dawson. It includes preformed plastic parts that are placed by mandrels and waxed into the crown forms for cutback and casting. It also includes a spring-loaded plunger that is incorporated into the matrix, which is luted to the RPD framework by being embedded into the resin. Preformed plastic bar and matrix forms were used and were incorporated into the fixed prostheses wax patterns. (A) Curved bar is positioned and waxed for placement. (B) Anatomic contour waxing with bar on left and extracoronal attachment on right abutment. (C) Evaluation of completed crowns. The fixed restorations were picked up in an impression that was used to fabricate the definitive cast for the RPD framework. (D) Framework and restorations on definitive cast. (E) Attachment on distal side of abutment. (F) Framework cast to fit over curved bar. (G) Plunger assembly luted to framework for evaluation. (H) Intraoral view of completed prostheses. (Courtesy Drs. W.V. Campagni and F. Munguia.)

STUDY QUESTIONS

1. Explain the principles underlying reciprocation and their effect on the coronal contour of individual retainers.
2. Discuss the principles that govern the determination of the location of the height of contour and the survey line on the retentive surface of a retainer that is to support a removable partial denture (RPD).
3. How does tooth preparation for a retainer for an RPD differ from conventional tooth preparation for the same tooth? What are the various factors that must be considered, and how do they influence the result?
4. What is the recommended fabrication sequence of a wax pattern for a retainer for a an RPD?
5. Discuss the classification of attachments and the respective indications, contraindications, advantages, and disadvantages.
6. Discuss the shape, size, and design of occlusal rest seats.
7. State the advantages and disadvantages of extracoronal and intracoronal attachments.
8. Discuss the importance of wax rims and occlusal records.
9. State the general steps in a survey of partially edentulous casts.
10. Discuss situations where stud attachments on dental implants would be preferred over teeth retained stud attachments.

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22

Metal Restoration Fabrication

Metal restorations have traditionally been made by lost-wax casting, a process known since ancient times. In this technique, wax patterns are converted to cast metal. It was first described[1,2] at the end of the 19th century as a means of making dental castings.

The process consists of surrounding the wax pattern with a mold made of heat-resistant investment material, then eliminating the wax by heating, and introducing molten metal into the mold through a channel called the *sprue*. In dentistry, the resulting casting must be a highly accurate reproduction of the wax pattern both in surface details and in overall dimensions. Small variations in investing or casting can significantly affect the quality of the definitive restoration. Routine success in making castings depends on attention to detail and consistency of technique.

An in-depth understanding of the precise influence of each variable in the technique is necessary to be able to make rational decisions to adjust specific steps in the technique as needed for a given procedure.

PREREQUISITES

When the wax pattern has been completed and its margin has been reflowed (see Chapter 18, the section on Margin Finishing), it is carefully evaluated for smoothness, finish, and contour (see Chapter 18). The pattern is inspected under magnification, and any residual flash (wax that extends beyond the preparation margin) is removed. A sprue is attached to the pattern, and the pattern is then removed from the die and attached to a crucible former (Fig. 22.1). The wax pattern must be invested immediately because any delay leads to distortion of the pattern as a result of stress relief of the wax.[3]

Sprue

Sprue design (Fig. 22.2) varies depending on the type of restoration being cast, the alloy used, and the casting machine. There are three basic requirements, as follows:

- The sprue must allow the molten wax to escape from the mold.
- The sprue must enable the molten metal to flow into the mold with as little turbulence as possible.
- The metal within it must remain molten slightly longer than the alloy that has filled the mold. This provides a reservoir to compensate for the shrinkage that occurs during solidification of the casting alloy.

The shape of the channel in the refractory mold is determined by the sprue that connects the wax pattern to the crucible former. The sprue can be made from wax, plastic, or metal. Wax sprues are preferred for most castings because they melt at the same rate as the pattern and thus allow easy escape of the molten wax. Solid plastic sprues soften at a higher temperature than does the wax pattern and may block the escape of wax, which results in increased casting roughness. However, plastic sprues can be useful when fixed dental prostheses are cast in one piece because their added rigidity minimizes distortion. Also, hollow plastic sprues that allow the escape of wax are available.

If a metal sprue is used, it should be made of noncorroding metal to avoid possible contamination of the casting. Many metal sprues are hollow, so as to increase contact surface area and strengthen the attachment between the sprue and pattern. They are usually separated from the investment at the same time the crucible former is. The dental laboratory technician must then examine the orifice very carefully for small particles of investment that may break off when such a sprue is removed because these can cause incompleteness of the casting if they are undetected (see the section on Incompleteness later in this chapter).

Diameter

In general, a sprue with a relatively large diameter is recommended because this improves the flow of molten metal into the mold and ensures a reservoir during solidification.[4,5]

A 2.5-mm (10-gauge) sprue is recommended for molar and metal-ceramic patterns. A smaller 2.0-mm (12-gauge) sprue is adequate for premolar castings and most partial-coverage restorations.

In some casting techniques other than the commonly used centrifugal technique, a narrow sprue, or a sprue design that narrows at the point of attachment to the wax pattern, is essential. For instance, with air-pressure machines, the melting occurs directly in the depression created by the crucible former and the metal then is forced into the mold by the sudden change in air pressure. With this technique, a narrow sprue that necks in prevents the molten metal from flowing into the mold prematurely.

Location

The sprue should be attached to the bulkiest, noncritical part of the pattern, away from margins and occlusal contacts. Normally, the largest nonfunctional cusp is used (Fig. 22.3). The point of attachment should allow a stream of metal to be directed to all

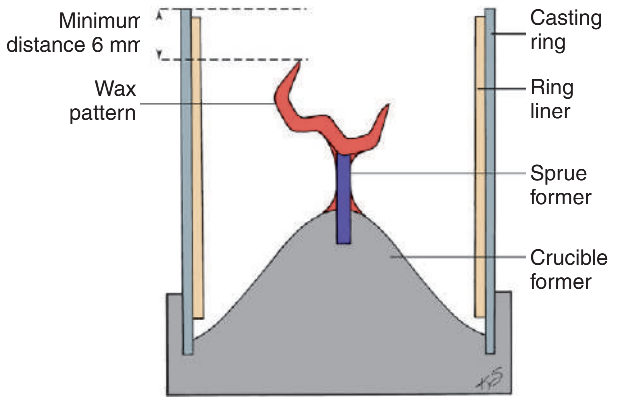


Fig. 22.1 Wax pattern attached to the crucible former with a sprue ready for investing. A ring liner is in place.

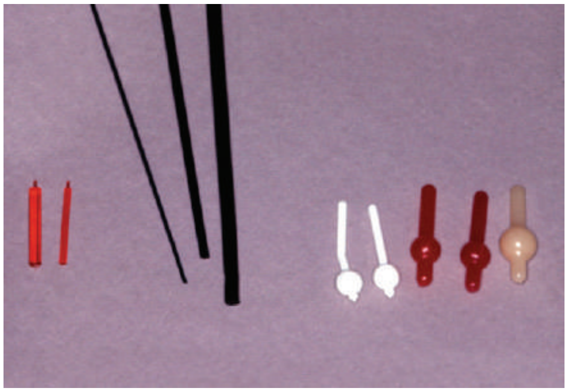


Fig. 22.2 Prefabricated plastic and wax sprues. These are preferred over metal sprues because plastic and wax are eliminated during the heating cycle.

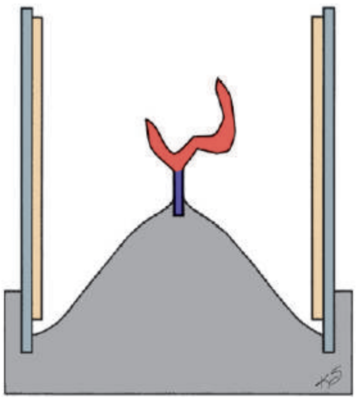


Fig. 22.3 Correct sprue placement on the bulkiest nonfunctional cusp allows molten alloy to flow to all parts of the mold.

parts of the mold without having to flow in an opposite direction to the casting force (Fig. 22.4).

The sprue must also allow for proper positioning of the pattern in the ring. The objective is to center the pattern. This can be crucial because expansion within the mold is not uniform.[6,7] For example, positioning the sprue on the cusp tip can yield good results, but positioning it on the proximal contact may

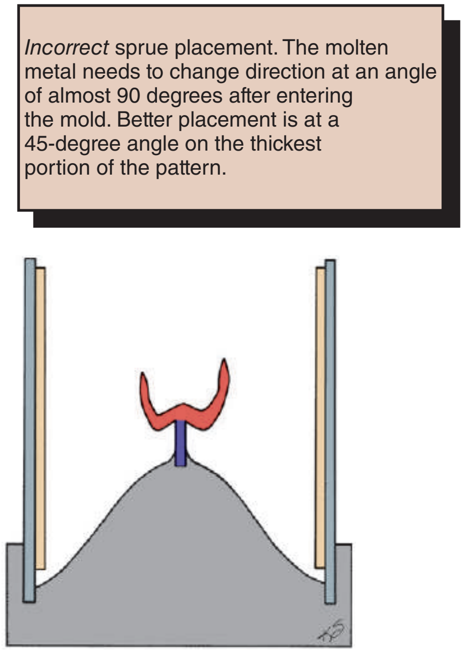


Fig. 22.4 Incorrect sprue placement in the central fossa obliterates occlusal anatomy and may result in poor mold filling because the molten metal is not pushed into the cusp tips by centrifugal force.

produce a casting that is too wide mesiodistally and too short occlusocervically.

Attachment

The sprue's point of attachment to the pattern should be carefully smoothed to minimize turbulence. For the centrifugal casting technique, the attachment area should not be restricted because necking increases casting porosity and reduces mold filling.[8] Similarly, excessively widening the attachment can cause this part of the cooling melted portion to solidify last, causing a void on the internal aspect of the casting, known as *shrink-spot porosity*.

Venting

Small auxiliary sprues or vents have been recommended to improve casting of thin patterns. Their action may help gases escape during casting[9] or may ensure that solidification begins in critical areas by acting as a heat sink (Fig. 22.5).[10]

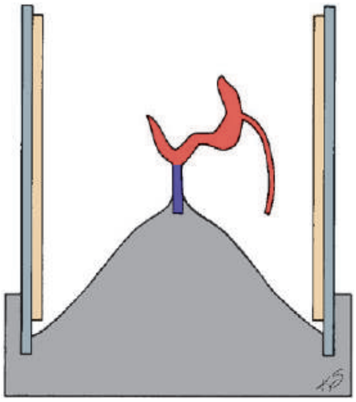
Crucible Former

The sprue is attached to a crucible former (sometimes referred to as a *sprue former*; Fig. 22.6), usually made of rubber, which serves as a base for the casting ring during investing. The exact shape of the crucible former depends on the type of ring and casting machine used. With most modern machines, the crucible former is tall, allowing use of a short sprue and enabling the pattern to be positioned near the end of the casting ring.

Casting Ring and Liner

The casting ring serves as a container for the investment while it sets and restricts the setting expansion of the mold. Normally, a liner is placed inside the ring to allow for more expansion

A



B

Fig. 22.5 (A and B) Thin auxiliary sprues may help gases escape and ensure that casting solidifies in a critical area.

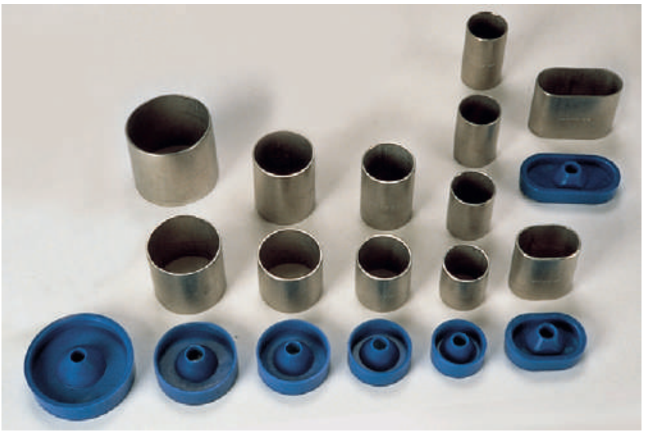


Fig. 22.6 Rubber crucible formers and corresponding casting rings. (Courtesy Whip Mix Corporation, Louisville, Kentucky.)

because the liner is somewhat compressible. Use of two liners allows for additional compression and enables increased setting expansion of the investment material. At one time, asbestos was used as the liner; to avoid the health risks associated with asbestos fibers, cellulose paper liners or refractory ceramic fiber liners are now used. Like many other factors that come into play in achieving consistent casting with the proper quality of fit, changes in the liner are important. Wetting the liner increases the hygroscopic expansion of the mold and should be carefully

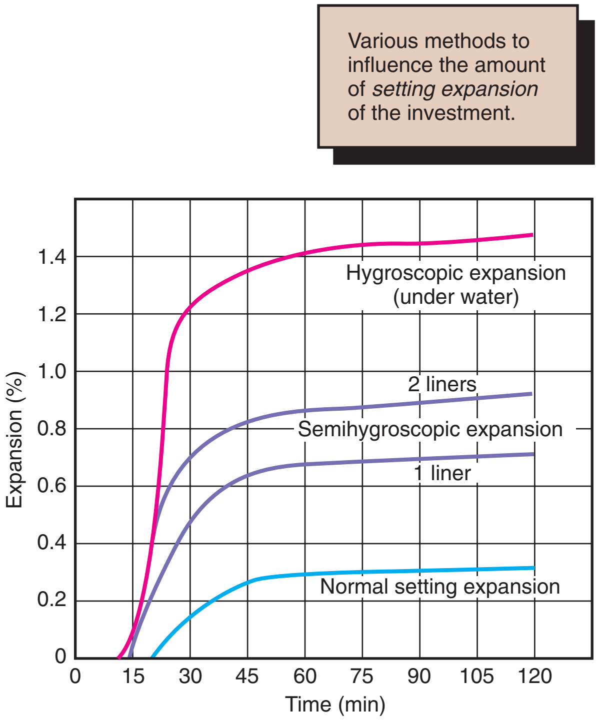


Fig. 22.7 Setting expansions of dental casting investments. Note that expansion can be increased by a hygroscopic technique, as well as by the particular type of ring liner used. (Courtesy Whip Mix Corporation, Louisville, Kentucky.)

controlled. An absorbent dry liner removes water from the investment and causes the mix to become thicker, which leads to increase in the total expansion.[11,12] To prevent expansion restriction, care must be taken not to squeeze the liner against the ring. Expansion can be increased if the mold is placed in a water bath, causing hygroscopic expansion (Fig. 22.7). The position of the pattern in the casting ring also affects expansion. For consistent results, a single crown should be centered in the ring, equidistant from its walls. When fixed prostheses are cast as one piece, accuracy is better if the pattern is placed near the center of a large or special oval ring, rather than if a portion of a multiunit wax pattern is only partially centered and partially near the edge of a smaller ring.[6]

Ringless Investment Technique

With the use of higher strength, phosphate-bonded investments, the ringless technique has become quite popular (Fig. 22.8).[13] This method entails the use of a paper or plastic casting ring and is designed to allow unrestricted expansion.[14] This can be useful with higher melting alloys that shrink more because of a longer cooling trajectory.

Sprue Technique

Armamentarium

The following equipment is needed (Fig. 22.9):

- Sprue
- Sticky wax
- Rubber crucible former
- Casting ring

Fig. 22.8 Crucible formers and cone-shaped plastic rings for a ringless investment technique in casting. The crucible former and plastic ring are removed before wax elimination, which leaves the invested wax pattern. The systems are designed to achieve expansion that is unrestricted by a metal ring. (Courtesy Whip Mix Corporation, Louisville, Kentucky.)

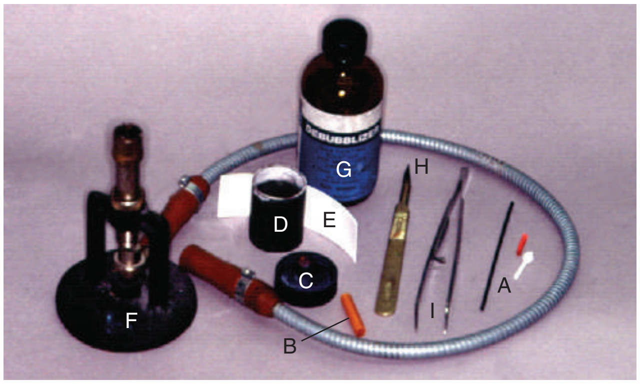


Fig. 22.9 Armamentarium for sprue technique with the wax pattern. *A*, Sprue; *B*, sticky wax; *C*, rubber crucible former; *D*, casting ring; *E*, ring liner; *F*, Bunsen burner; *G*, pattern cleaner; *H*, scalpel blade; *I*, forceps.

- Ring liner
- Bunsen burner
- Pattern cleaner
- Scalpel blade
- Forceps

Step-by-Step Procedure for a Single Casting

A 2.5-mm (10-gauge) sprue form is recommended for molar crowns or metal-ceramic castings, and a 2-mm (12-gauge) sprue for premolar and partial-coverage restorations. The procedure is as follows:

1. Attach a 12-mm wax sprue to the bulkiest, nonfunctional cusp of the wax pattern and position it to form an obtuse angle with the adjacent axial walls and occlusal surface (Fig. 22.10A). This angle is usually about 135 degrees to the axial walls, and it facilitates filling of the mold.
2. Add wax to the point of attachment and smooth it to prevent turbulence during casting.
3. Remove the pattern from the die, using extreme caution not to distort it (see Fig. 22.10B).
4. Holding the sprue with forceps, insert it into the hole in the crucible former (see Fig. 22.10C). It should now be luted into place with wax, and the junction between sprue and crucible should be smoothed. Use of a surfactant enhances wetting of the pattern during investing (see Fig. 22.10D).
5. Line the casting ring, keeping it flush with the open end, and moisten the liner (see Fig. 22.10E and F).
6. Place the ring over the pattern to ensure that it is long enough to cover the pattern with about 6 mm of investment (see Fig. 22.10G). If necessary, the sprue may be shortened, or a longer ring may be chosen.

Procedure for Multiple Castings

When more than two units are being cast together, each is joined to a runner bar (Fig. 22.11). A single sprue is used to feed the runner bar. Two units may be cast with a runner bar, or each unit may be fed from a separate sprue.

MATERIALS SCIENCE

M.H. Reisbick

Several investment materials are available for fabricating a dental casting mold. These typically consist of a refractory material (usually silica) and a binder material, which provides strength. Additives are used by the manufacturer to improve handling characteristics.

When investments are classified by binder, three groups are recognized: gypsum-bonded, phosphate-bonded, and silica-bonded investments. Each has specific applications. The gypsum-bonded investments are used for castings made from lower melting range alloys. The phosphate-bonded materials are recommended for metal-ceramic frameworks. The silica-bonded investments are for high-melting base metal alloys used in casting partial removable dental prostheses. However, because of their limited application in fixed prosthodontics, silica-bonded investments are not included in the following discussion.

Gypsum-Bonded Investments

Gypsum is used as a binder, along with cristobalite or quartz as the refractory material, to form the mold. The cristobalite and quartz are responsible for the thermal expansion of the mold during wax elimination. Because gypsum is not chemically stable at temperatures exceeding 650°C (1202°F), these investments are typically restricted to castings of conventional types II, III, and IV gold alloys.

Expansion

Three types of expansion can be manipulated to obtain the desired size of casting: setting, hygroscopic, and thermal.

Setting expansion. As the gypsum investment sets after mixing, it expands and slightly enlarges the mold. The pattern, metal casting ring, and compressibility of the ring liner all influence this expansion.

The water-to-powder ratio can be altered to reduce or increase the amount of setting expansion. Less water increases the setting expansion and results in a slightly larger casting. Using an additional ring liner increases the setting expansion, as does a slight increase in mixing time. If a smaller casting is desired, more water can be used or the liner can be eliminated,

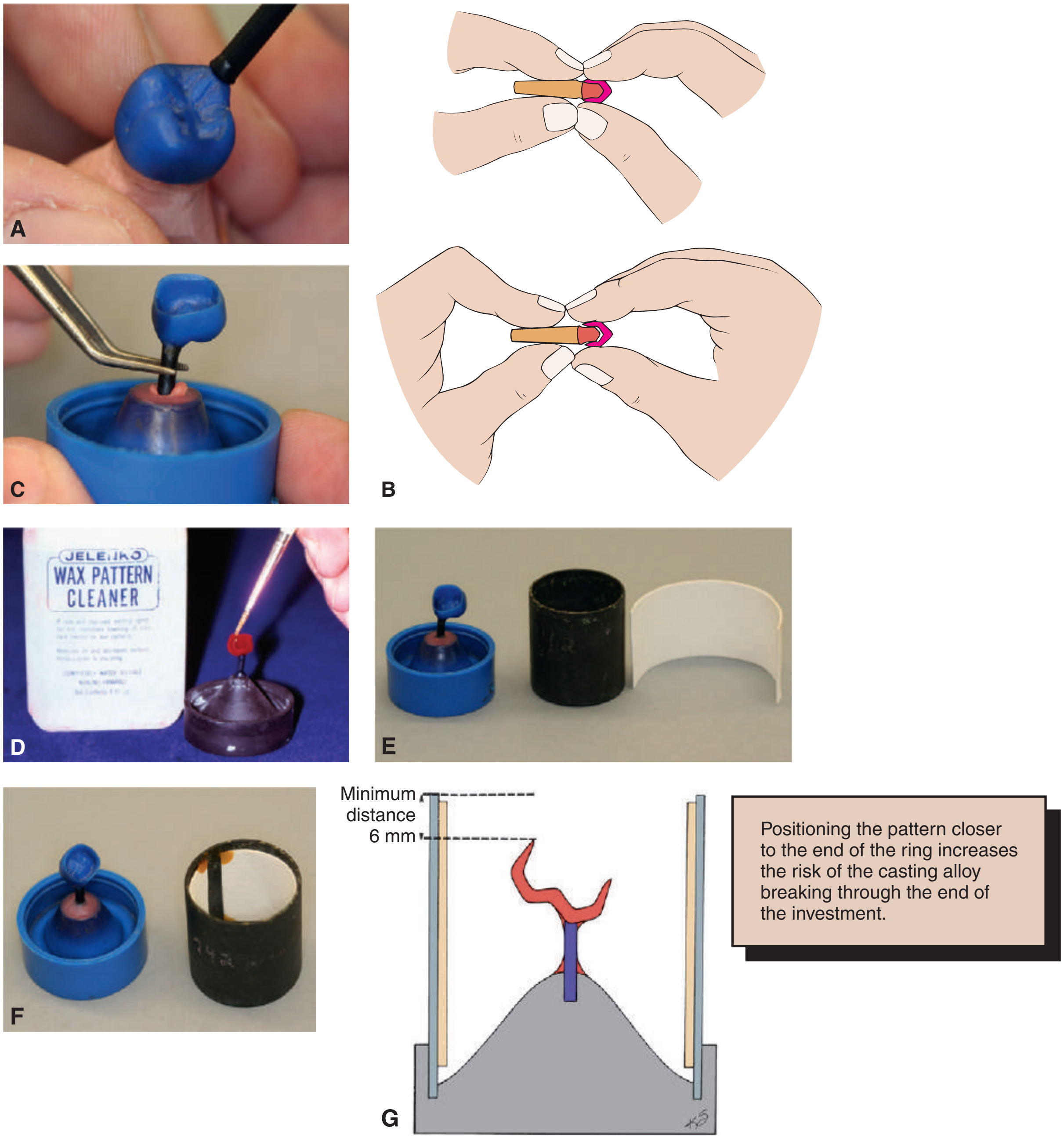


Fig. 22.10 Sprue technique for a single casting. (A) Attaching the sprue to the pattern. (B) Removing the pattern from the die. (C) Positioning the pattern on the crucible former. (D) Application of surfactant. (E) A ring liner increases the setting expansion. (F) The ring liner has been stabilized with sticky wax. (G) The pattern must be positioned a sufficient distance from the end of the ring.

both of which curtail the amount of expansion. In attempts to alter setting expansion, the changes should not deviate more than minimally from the manufacturer's recommendations, to ensure that there are no changes in the essential properties of the investment.

Hygroscopic expansion. Hygroscopic expansion occurs when water is added to the setting gypsum investment immediately after the ring has been filled. To accomplish this, the ring is usually submerged in a water bath at 37°C (100°F) for up to 1 hour immediately after investment. A significant amount of additional setting expansion results, enabling the use of a slightly lower wax elimination temperature. A wet ring liner also contributes hygroscopic expansion to the portion of the mold it is in contact with (see Fig. 22.7).

Thermal expansion. As the mold is heated to eliminate the wax, thermal expansion occurs (Fig. 22.12). The silica refractory material is principally responsible for this because of solid-state phase transformations. Cristobalite changes from the α (low-temperature) to the β (high-temperature) form between 200°C (392°F) and 270°C (518°F); quartz transforms at 575°C (1067°F). These transitions involve a change in crystal form, an accompanying change in bond angles and axis dimension, and

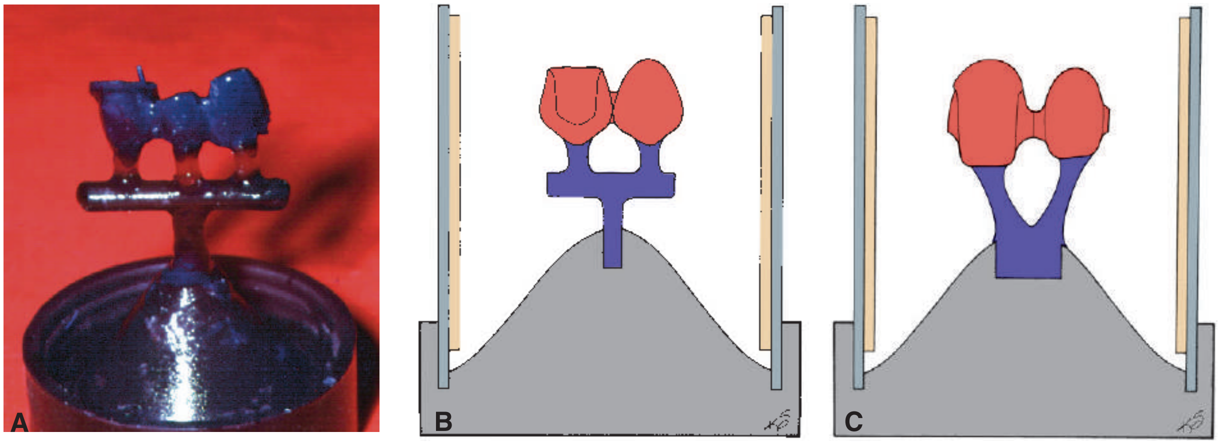


Fig. 22.11 Sprue technique with multiple units. For more than two castings, a runner bar is used (A). For two castings, a runner bar may be used (B), or each casting may be fed through separate sprues (C).

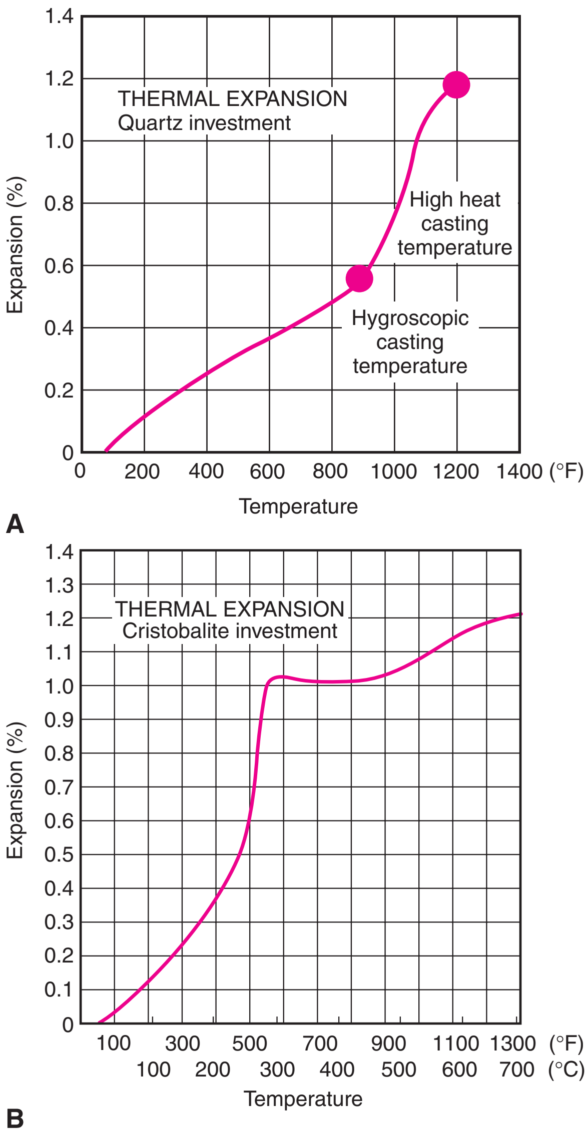


Fig. 22.12 Thermal expansions of quartz-based (A) and cristobalite-based (B) investments. (Courtesy Whip Mix Corporation, Louisville, Kentucky.)

a decrease in density, which produce a volume increase in the refractory components.

Phosphate-Bonded Investments

Because most metal-ceramic alloys fuse at approximately 1400°C (≈2550°F) (as opposed to conventional gold alloys at 925°C (≈1700°F), additional shrinkage occurs when the casting cools to room temperature. To compensate for this, a larger mold is necessary. The added expansion can be obtained with phosphate-bonded investments.

The principal difference between gypsum-bonded and phosphate-bonded investments is the composition of the binder and the relatively high concentration of silica refractory material in the latter. The binder consists of magnesium oxide and an ammonium phosphate compound. In contrast to gypsum-bonded products, this material is stable at burnout temperatures above 650°C (1202°F) (Fig. 22.13), which allows for additional thermal expansion. Investment strength increases with increasing temperature (see Fig. 22.13C). Most phosphate-bonded investments are mixed with a specially prepared suspension of colloidal silica in water. (Some, however, can be mixed with water alone.)

Some phosphate-bonded investments contain carbon and therefore are gray in color. Carbon-containing materials should not be used for casting base metals because the carbon residue affects the final alloy composition. However, they may be used for casting alloys with high gold or palladium content.

Expansion

In comparison with gypsum-bonded investments, phosphate-bonded investments offer greater flexibility in controlling the amount of expansion. The liquid-to-powder ratio needs only slight modification to effect a significant change in setting expansion. Increasing the proportion of special liquid (colloidal silica) also increases expansion.

Working Time

Phosphate-bonded investments have a relatively short working time in comparison with gypsum materials. Their exothermic setting reaction accelerates as the temperature of the mix rises

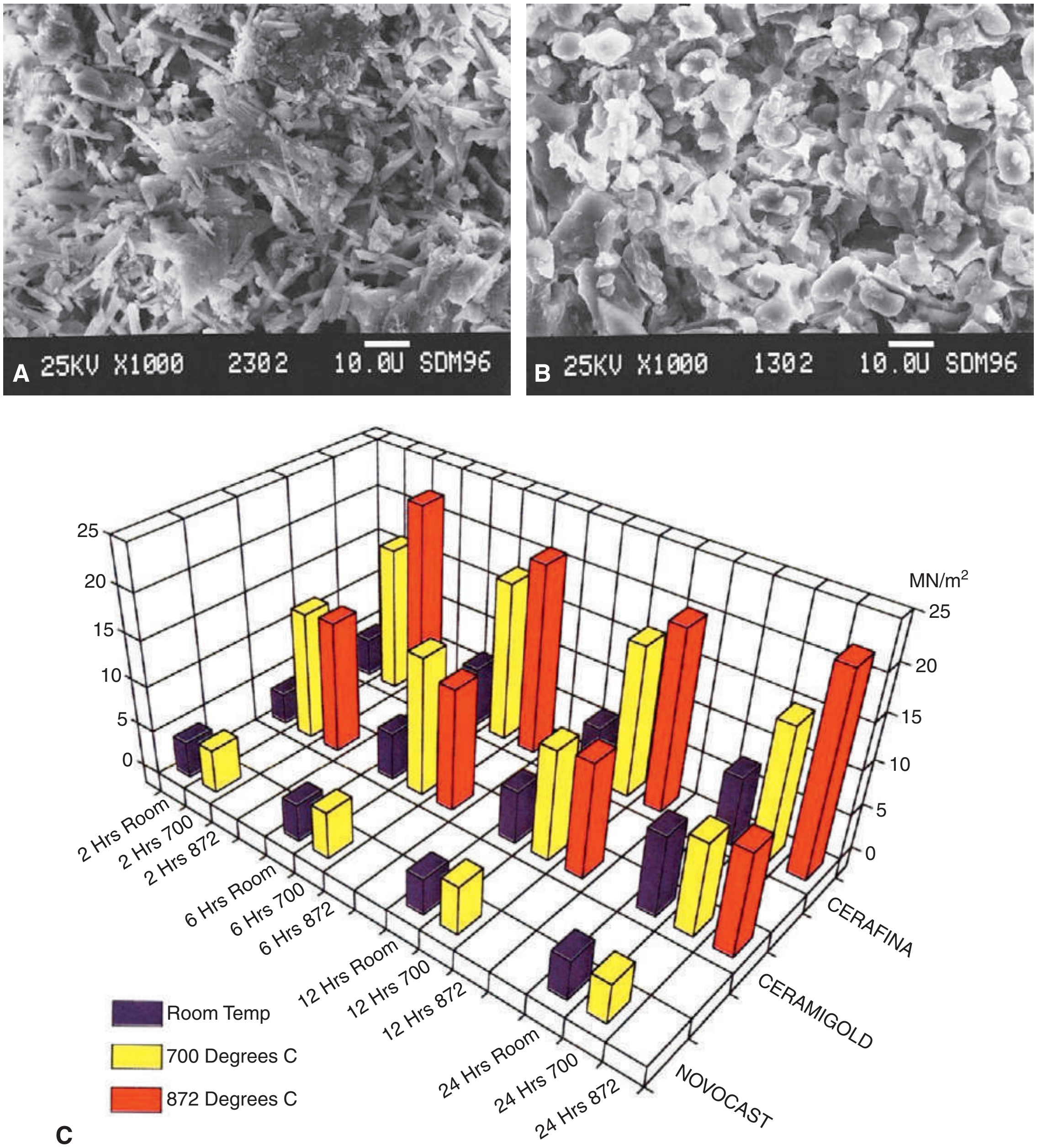


Fig. 22.13 Scanning electron micrographs of a gypsum-bonded investment (A) and a phosphate-bonded investment (B), each heated to 700°C (1292°F). (C) Relationship between investment temperature and strength. (C, From Chew CL, Land MF, Thomas CC. Investment strength as a function of time and temperature. *J Dent.* 1999;27:297.)

during manipulation. The filled ring feels warm to the touch even shortly after it has been filled. A longer mixing time significantly accelerates the setting reaction and temperature, reducing the working time even further. The addition of water to the colloidal silica suspension increases the working time, with some loss of setting expansion. Therefore, many technicians vary the quantity of special liquid and water between batches, making trial mixes for each new shipment. This has been a reliable means of adjusting expansion.[15]

Gas is formed during the reaction and must be removed for a sufficiently long period to minimize nodules on the casting.[16] Maintaining a vacuum for about 60 seconds appears to be adequate.

■ ■ ■

SELECTION OF MATERIALS

Selecting a Casting Alloy

William Brantley

The choice of casting alloy largely determines the selection of investment and casting techniques and therefore is discussed first.

The number and variety of alloys suitable for casting have expanded dramatically, largely because of changes in the price of gold. Many alloys are available, especially for metal-ceramic restorations (see Chapter 19). The dentist must be able to make a rational choice on the basis of current information.

Factors to Be Considered

Intended use. Alloys for casting were traditionally classified on the basis of their intended use, as follows:

- Type I: simple inlays
- Type II: complex inlays
- Type III: crowns and fixed dental prostheses
- Type IV: partial removable dental prostheses and pinledges
- Porcelain: metal-ceramic alloys

Physical properties. In 1965, the ADA adopted the specifications of the Fédération Dentaire Internationale (FDI), which classified casting alloys according to their physical properties (specifically their hardness), as follows:

- Type I: soft
- Type II: medium
- Type III: hard
- Type IV: extra hard

Porcelain-type alloys with a high noble metal content were found to have hardness similar to that of type III alloys, and base metal alloys were found to be harder than type IV alloys (see Chapter 19).

The historic ADA Specification No. 5 for these four types of gold casting alloys has been replaced by ISO 22674:2016,[17] which expanded this classification to six types. Similar to their Roman number counterparts in the old ADA Specification No. 5, the new classification type 2 is recommended for single-tooth fixed restorations, type 3 is recommended for multiple-tooth fixed restorations, and type 4 is recommended for restorations/appliances with thin cross sections that are subjected to very high forces. The new type 0 is recommended for small veneered one-surface inlays and veneered crowns, and also applies to metallic materials for metal-ceramic crowns produced by electroforming or sintering. The new type 6 is recommended for thin removable partial dentures, parts with thin cross sections, and clasps.

Color. Manufacturers place considerable emphasis on the color of their alloys, and color preference is often for gold over silver. The patient's views on the subject should be sought if the metal will be visible in the mouth; otherwise, the color of the dental alloy is irrelevant.

Color is not a good guide to gold content: 9-carat jewelry alloy with only 37.5% gold looks considerably more yellow than does a metal-ceramic dental alloy with 85% gold but no copper.

Composition. For an alloy to be accepted by the ADA as suitable for dental restorations,[18] the manufacturer must list the percentage composition by weight of the three main ingredients and any noble metal percentage. The functional characteristics of corrosion resistance and tarnish resistance were traditionally predicted on the basis of gold content. In general, if at least half the atoms in the alloy are gold (which would be 75% by weight), good resistance to corrosion and tarnish can be predicted. Nevertheless, clinical evaluations have failed to show statistically significant differences in the tarnish resistance of high-gold (77%) and low-gold (59.5% to 27.6%) alloys.[19] However, a poorly formulated alloy, even of high gold content, can rapidly tarnish intraorally.

Cost. Treatment plans are often modified to suit the financial capabilities of the patient or a third party. Base metal alloys have found favor principally because of their low cost. Similarly, alloys containing approximately 50% gold have been found to offer some economic advantage (although the savings are not proportional to the reduced gold content of the alloy). Alloys primarily contain palladium, and while only a small percentage of gold is an alternative for use in the metal-ceramic technique, soldering procedures may be less predictable.

When the intrinsic metal cost of a restoration is calculated, the volume of the casting, rather than its weight, should be determined. Dental casting alloys can vary considerably in density from below 8 g/mL to over 18 g/mL (see Table 19.2). An "average" restoration has a volume of 0.08 mL; an all-metal pontic may have a volume reaching 0.25 mL.[20] Therefore, it is conceivable that the cost of a large pontic cast in a low-density alloy would be equal to, or less than, the cost of a complete cast crown fabricated from a high-density alloy. When noble metal prices are high, more sophisticated techniques of scrap recovery are economically attractive. These can range from installing conventional metal catchers in all areas, where castings are finished, to equipping all workstations with filtered suction machines.

Clinical performance. In most respects, clinical performance (biologic and mechanical) is more important than cost. Biologic properties that can be evaluated include gingival irritation, recurrent caries, plaque retention, and allergies. Mechanical properties include wear resistance and strength, marginal fit, ceramic bond failure, connector failure, and resistance to tarnish and corrosion.

A risk in choosing a new alloy is that defective clinical performance may fail to be evident in laboratory testing or in short-term animal and clinical trials. For example, manufacturers introduced copper-based casting alloys with very poor corrosion resistance[21] when the price of gold was rapidly rising (these formulations were very similar to those for aluminum-bronze alloys sold as dental gold in the 1920s). Although the clinically established alloys all have disadvantages, their performance is likely to have been well documented, and the quality of restorative treatment can be more accurately predicted.

Laboratory performance. Sound laboratory data are essential in selecting a casting alloy. Important areas of consideration are casting accuracy, surface roughness, strength, sag resistance, and metal-ceramic bond strength. Currently available data suggest that nickel-chromium alloys have lower casting accuracy[22] and greater surface roughness[23] than do gold alloys (Fig. 22.14) but higher strength and sag resistance because of their higher melting ranges.[24]

Handling properties. The ease with which an alloy can be manipulated may influence its selection. An alloy that produces satisfactory clinical results, but only under extremely critical conditions or with expensive equipment, may be rejected in favor of one that produces acceptable results with less critical manipulation.

The ability to burnish an alloy and reduce marginal gap width to reduce the exposed thickness of the luting agent is important,[25] although the areas where marginal adaptation is clinically most important (interproximally and subgingivally) are usually not very accessible for such manipulation.

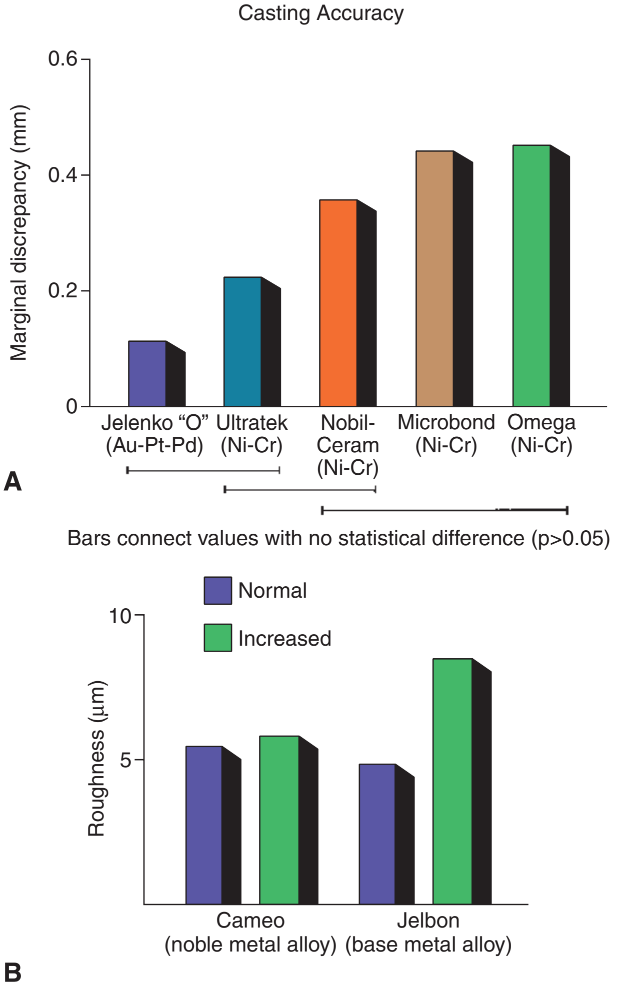


Fig. 22.14 (A) Comparison of casting accuracies with different alloys. Au-Pt-Pd, gold-platinum-palladium; Ni-Cr, nickel-chromium. (B) Influence of metal casting temperature and alloy selection on casting roughness. (A, From Duncan JD. The casting accuracy of nickel–chromium alloys for fixed prostheses. *J Prosthet Dent.* 1982;47:63. B, From Ogura H, Raptis CN, Asgar K. Inner surface roughness of complete cast crowns made by centrifugal casting machines. *J Prosthet Dent.* 1981;45:529.)

Biocompatibility. All materials for intraoral use should be biocompatible. In addition, it should be possible to handle them safely in the office or laboratory. Many hazardous materials—such as mercury, chloroform, silver cyanide, and hydrofluoric acid—are commonly used in dentistry. Consequently, restrictions have been imposed on their shipping and use. For instance, asbestos is no longer used in casting ring liners and uranium salts in dental porcelain. There is also concern[26] for the possible health hazards (see Chapter 19) associated with alloys containing nickel and beryllium. Although no definite conclusions can be drawn, appropriate safety precautions are advisable when these alloys are being ground. Filtered suction units and appropriate barriers (masks) should be used. The ADA[27] requires nickel-containing alloys to carry a precautionary label stating that their use should be avoided in patients with a known nickel allergy (Fig. 22.15).

■ ■ ■

Fig. 22.15 (A and B) Dramatic gingival reactions to nickel-containing metal-ceramic restorations. (Courtesy Dr. W.V. Campagni.)

Selecting an Investment Material

After the choice of casting alloy has been made, the investment material can be selected.

Ideal Properties

An ideal investment should incorporate the following features:

- Controllable expansion to compensate precisely for shrinkage of the cast alloy during cooling
- The ability to produce smooth castings with accurate surface reproduction and without nodules
- Chemical stability at high casting temperatures
- Adequate strength to resist casting forces
- Sufficient porosity to allow for gas escape
- Easy recovery of the casting

Gypsum-bonded investments. Gypsum-bonded investments satisfy most of the requirements for an ideal material, although they are not suitable for casting metal-ceramic alloys because the gypsum is unstable at the high temperatures required and sulfide contamination of the alloy can occur. In addition, with some materials, obtaining adequate expansion may be difficult. This is critical in casting complete crowns. A casting that is slightly oversized (in a controlled manner) is advantageous for accurate seating (see Chapters 7 and 28). Factors that increase expansion[28] of gypsum-bonded investments include the following:

- Use of a full-width ring liner
- Prolonged spatulation
- Storage at 100% humidity
- Lower water-to-powder ratio
- Use of a dry liner
- Use of two ring liners
- Hygroscopic technique with the pattern in the upper part of the ring[29]

Phosphate-bonded investments. Phosphate-bonded investment materials offer certain advantages over gypsum-bonded investments. They are more stable at high temperatures and thus are the material of choice for casting metal-ceramic alloys. They expand rapidly at the temperatures used for casting alloys, and their expansion can be conveniently and precisely controlled. The expansion is increased as a result of a combination of the following factors:

- Heat from the setting reaction softens the wax and allows freer setting expansion.
- The increased strength of the material at high temperatures restricts shrinkage of the alloy as it cools.
- The powder mixed with colloidal silica reduces the surface roughness of the castings and also increases expansion. Thus, expansion can be conveniently controlled by slightly diluting the colloidal silica with distilled water.

However, castings made with phosphate-bonded investments are rougher than those made with gypsum-bonded investments[30] and are more difficult to remove from the investment.[31] Because phosphate-bonded investments have lower porosity,[32] complete mold filling is more difficult. Castings also are more likely to have surface nodules, which must be removed. (Vacuum mixing and a careful investing technique help reduce, but do not eliminate, the occurrence of nodules.)

INVESTING

Vacuum mixing of investment materials (Fig. 22.16) is highly recommended for consistent results in casting with minimal surface defects, especially when phosphate-bonded investments are used. Good results are possible with brush application of vacuum-mixed investment or when the investment is poured into the ring under vacuum pressure. Vacuum mixing with brush application of the investment is the suggested mode. To expedite the procedure and minimize distortion, all necessary items and materials should be prepared before the wax pattern is reflowed and removed from the die.

Armamentarium

The following equipment is needed (Fig. 22.17):

- Vacuum mixer and bowl
- Vibrator
- Investment powder (gypsum or phosphate bonded)
- Water or colloidal silica
- Spatula
- Brush
- Surfactant graduated cylinder
- Crucible former
- Casting ring and liner

Step-by-Step Procedure

Brush Technique

In this technique, the pattern is first painted with surface tension reducer; the surface must be wet completely. The procedure is as follows:

1. Select the correct program on the mixing unit in accordance with the manufacturer's instructions (Fig. 22.18A). The mixing bowl can be either wiped completely dry or shaken dry. If it is shaken dry, remember that the residual water adds about 1 mL to the mix. Add investment powder to the liquid in the mixing bowl (see Fig. 22.18B).
2. Attach the bowl to the mixer, and mechanically spatulate (see Fig. 22.18C and D).
3. Coat the entire pattern with investment, pushing the material ahead of the brush from a single point (see Fig. 22.18E). Gently vibrate throughout the application of investment, being especially careful to coat the internal surface and the margin of the pattern (see Fig. 22.18F). A finger positioned under the crucible former on the table of the vibrator minimizes the risk of excessive vibration and possible breaking of the pattern from the sprue. After the pattern has been completely coated, attach the ring and immediately fill by causing the remaining investment to vibrate out of the bowl.
4. Place the lined casting ring over the pattern (see Fig. 22.18G) and, with the aid of vibration, pour the investment down the

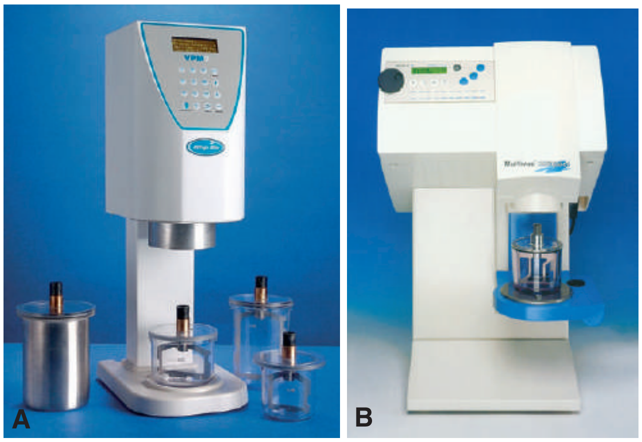


Fig. 22.16 Vacuum investing machines. (A) The Whip Mix combination unit. (B) The Multivac Compact. (A, Courtesy Whip Mix Corporation, Louisville, Kentucky. B, Courtesy Dentsply Sirona, York, Pennsylvania.)

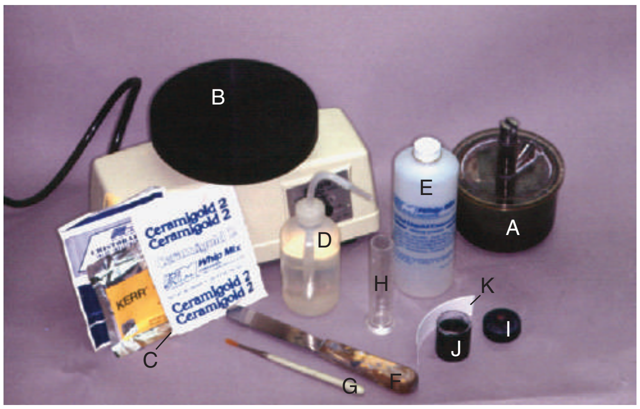


Fig. 22.17 Investing armamentarium. *A*, Vacuum mixer and bowl; *B*, vibrator; *C*, investment powder (gypsum or phosphate bonded); *D*, water; *E*, colloidal silica; *F*, spatula; *G*, brush; *H*, surfactant graduated cylinder; *I*, crucible former; *J*, casting ring; *K*, ring liner.

side of the ring (see Fig. 22.18H). Fill the ring slowly, starting from the bottom and moving up (see Fig. 22.18I).

5. When the investment reaches the level of the pattern, tilt the ring several times to cover and uncover the pattern, thereby minimizing the possible entrapment of air. Investing must be performed quickly within the working time of the investment. If the investment begins to set too soon, rinse it off quickly with cold water. The wax pattern can then be replaced on the die, and material can reflow into its margins again.

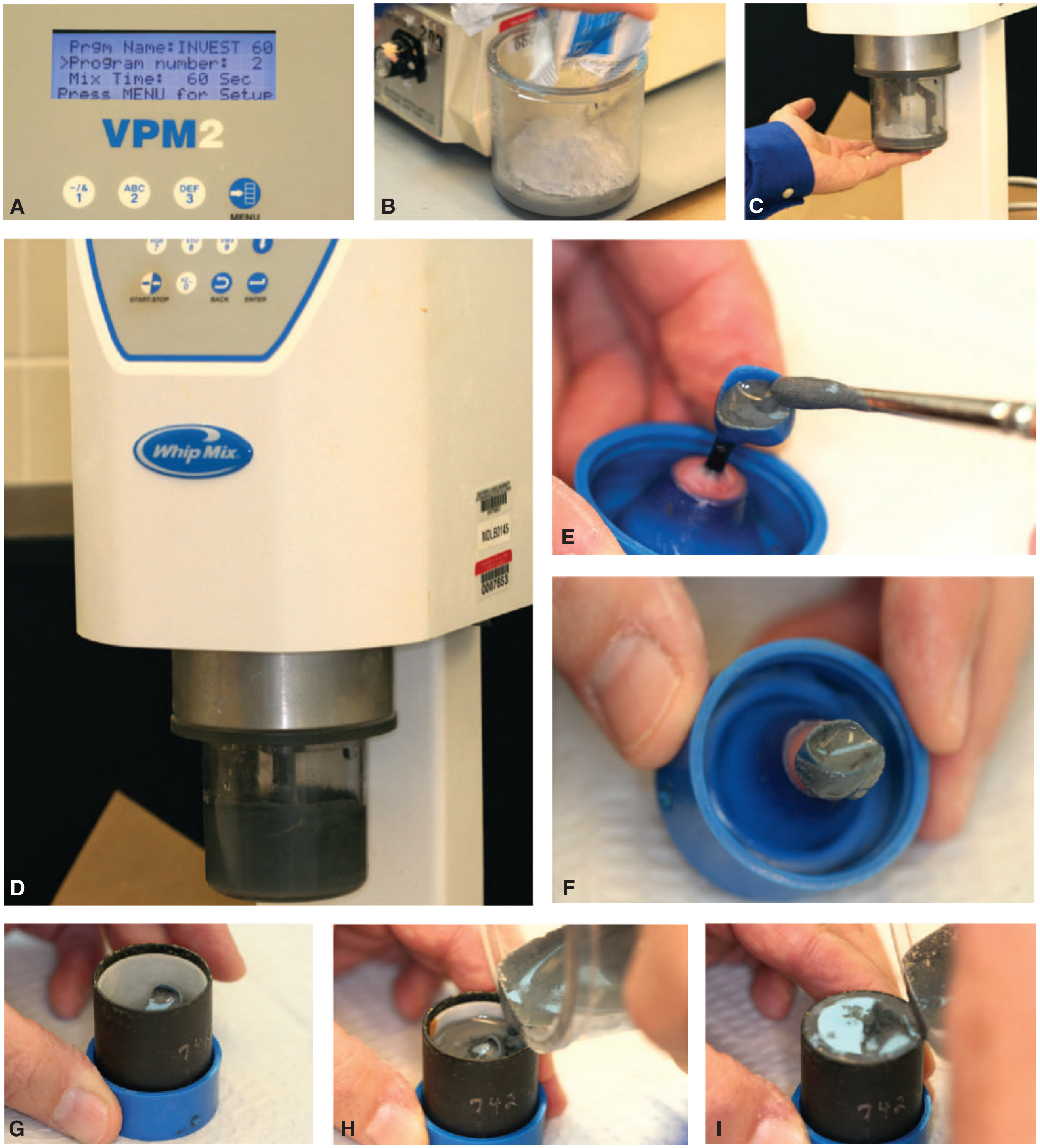


Fig. 22.18 Investing procedure: brush technique. (A) The correct program on the mixing unit is selected. (B) Investment is added to precisely measured-out liquid. (C) The chuck of the mixing bowl is inserted into the slot of the vacuum mixer. (D) The bowl is stabilized by the vacuum created between its lid and the base of the unit as mixing progresses. (E) A No. 6 or No. 8 brush is used to coat the pattern. (F) The pattern is completely coated, and the casting ring can now be attached. (G) Casting ring with liner affixed to the crucible former. (H) The bowl is vibrated, and the ring is filled. When the investment reaches the level of the wax pattern, the ring must be tilted to reduce the risk of trapping air inside the pattern. (I) The ring is completely filled.

6. After the ring is filled to the rim, allow the investment to set.
7. If the hygroscopic technique is used, place the ring in a 37°C (100°F) water bath for 1 hour.

Wax Elimination

Wax elimination, or wax burnout, consists of heating the investment in a thermostatically controlled furnace (Fig. 22.19) until all traces of the wax are vaporized. The temperature reached by the investment determines its thermal expansion.

All water in the investment must be driven off during wax elimination. The temperature to which the ring is heated during wax elimination must be sufficiently high. It should be maintained long enough ("heat soak") to minimize a sudden drop in temperature upon removal from the furnace. Such a drop may result in an incomplete casting because of excessively rapid solidification of the alloy as it enters the mold. Once the investment is heated during the wax-elimination procedure, heating must be continued, and casting must be completed. Cooling and reheating of the investment can cause casting inaccuracy because the refractory mold and binder do not revert to their original forms (hysteresis). Inadequate expansion and cracking of the investment are typical results.

Step-by-Step Procedure

1. Allow the investment to set for the recommended time (usually 1 hour), and then remove the rubber crucible former (Fig. 22.20). If a metal sprue is used, remove it as well. The ring should be placed in a humidor if stored overnight. The smooth "skin" that forms on the ring with phosphate-bonded investments should be removed with a plaster knife, and any loose particles of investment should be blown off with compressed air.
2. Reexamine the ring for any residual particles, and then place it with the sprue facing down in the furnace on a ribbed tray. The tray allows the molten wax to flow out freely.
3. Heat the furnace to 200°C (392°F) and hold this temperature for 30 minutes. Most of the wax is by then eliminated.
4. Increase the heat to the final burnout temperature (generally 650°C (1202°F) or 480°C (896°F) if a hygroscopic technique is used; follow the manufacturer's instructions) and hold that temperature for 45 minutes. Because the heating rate affects expansion,[33] it also should be standardized as part of the investing and casting protocol in order to routinely obtain accurately fitting castings. The mold is now ready for casting, although a large casting ring requires increased heating time. If preferred, two burnout furnaces can be set at 200°C and 650°C, respectively, 480°C for both, or a programmable two-stage furnace can serve equally well. However, the investment should not be overheated or kept at the chosen temperature too long. Gypsum-bonded investments are not stable above 650°C. Also, some carbon in carbon-containing investments burns off, which causes increased surface roughness of the casting.[23]

When the casting ring is transferred to the casting machine, a quick visual check of the sprue in shaded light is helpful to see whether it is properly heated. It should be a cherry-red color.

ACCELERATED CASTING METHOD

Conventional casting techniques require considerable time, typically 1 hour for bench setting (generally judged as the time taken for the investment to reach its maximum exothermic setting reaction temperature) for the investment, and 1 to 2 hours for the wax elimination. An accelerated casting procedure that reduces this time to 30 to 40 minutes has been proposed.[34–37] Initially suggested as a way to make cast post and core restorations in a one-visit procedure (also for castings made for dental licensure examinations), the procedure has been found to produce castings with accuracy and surface roughness similar to those produced by traditional methods.[38,39] The technique entails the use of a phosphate-bonded investment in which approximately 15 minutes is needed for bench set and 15 minutes for wax elimination by placement of the ring in a furnace preheated to 815°C (1500°F).

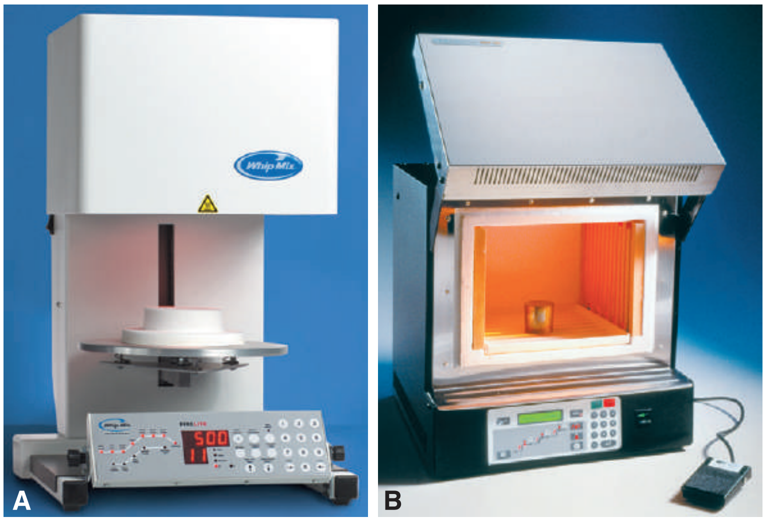


Fig. 22.19 Burnout ovens are available with manual, semiautomatic, or fully programmable controls. (A) FIRELITE. (B) Ney Vulcan. (A, Courtesy Whip Mix Corporation, Louisville, Kentucky. B, Courtesy Dentsply Sirona, York, Pennsylvania.)

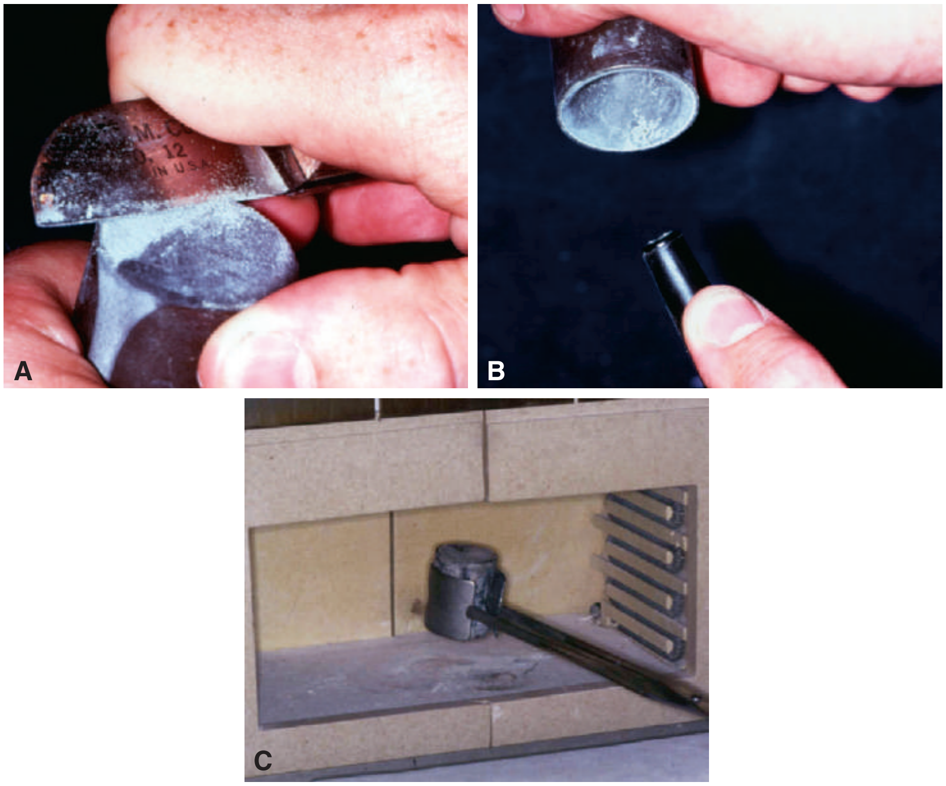


Fig. 22.20 (A) When the investment has set, the "skin" at the top of the ring is trimmed off. (B) The rubber crucible former is removed, and any loose particles of investment are blown off. (C) The ring is then placed in the furnace for the recommended burnout schedule.

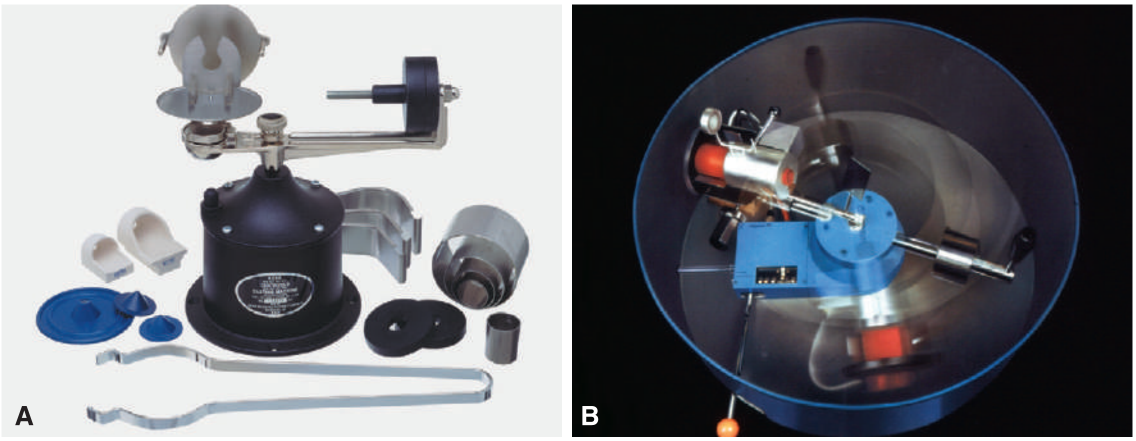


Fig. 22.21 Casting machines. (A) Kerr Broken-Arm. (B) Degussa Model TS-1. (A, Courtesy Kerr Corporation, Orange, California. B, Courtesy Dentsply Sirona, York, Pennsylvania.)

CASTING

Casting Machines

A casting machine (Fig. 22.21) requires a heat source, to melt the alloy, and a casting force. For a complete casting, the casting force must be high enough to overcome the high surface tension of the molten alloy,[40] as well as the resistance of the gas within the mold.

The heat source can be either the reducing flame of a torch or electricity. Conventional alloys can be melted with a gas-air torch (Fig. 22.22A and B), but for the metal-ceramic alloys in a higher melting range, a gas-oxygen torch (see Fig. 22.22C) is needed. For base metal alloys, a multiorifice gas-oxygen torch (see Fig. 22.22D) or an oxyacetylene torch is needed. Electric heating can occur by convection from a heating muffle or by generation of an induction current in the alloy (Fig. 22.23). Advocates of the latter[41] maintain that heating can be more evenly controlled, which prevents undesirable changes in alloy composition caused by volatilization of the elements with lower melting points. In general, the electric machines are expensive and more appropriate for larger dental laboratories, whereas a torch may be the equipment of choice for smaller laboratories

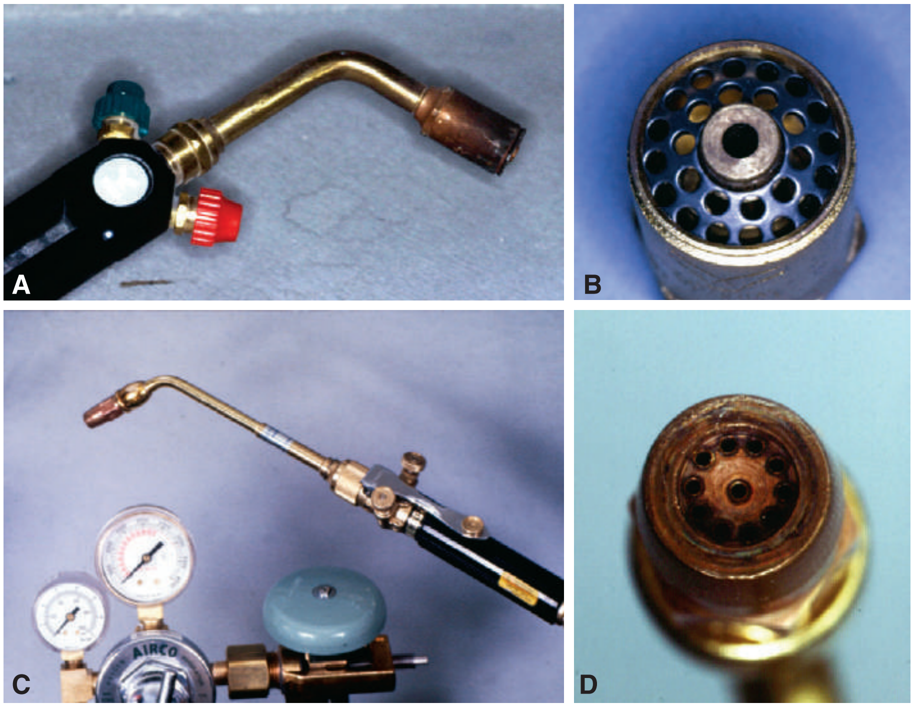


Fig. 22.22 (A) Gas-air casting torch. (B) Gas-air tip. (C) Gas-oxygen casting torch. (D) Multiorifice tip.

and dental offices. The combination of alloy and casting technique influences the marginal fit of the restorations.[42,43]

In present-day casting machines, either air pressure or centrifugal force is still used to fill the mold; both were first proposed in the early days of lost-wax castings.[2,44] Some machines evacuate the mold before it is filled with metal, and vacuum has been shown to improve mold filling,[45] although it is not clear whether the difference is clinically significant.[46]

Casting Technique

The ring is not removed from the burnout furnace until the alloy has been melted and is ready to cast.

Cleaning a previously cast alloy is necessary to remove investment debris and oxides before its reuse. Noble metal alloys can be melted on a charcoal block with a gas-air torch, which provides a reducing atmosphere. Remaining impurities are removed through pickling and ultrasonic or steam cleaning. Alloys from different manufacturers should not be mixed, even if they are similar. According to one report, recasting nickel-containing alloys with 65% surplus metal addition significantly increased the cytotoxic activity.[47]

Similarly, a dedicated crucible should be used for each alloy. Overheated or otherwise abused alloys, as well as grindings and old restorations, should be returned to the manufacturer as scrap materials, rather than being reused.

Armamentarium

The following equipment is needed (Fig. 22.24):

- Broken-arm (Kerr) centrifugal casting machine
- Crucible
- Blowtorch
- Protective colored goggles
- Tongs
- Casting alloy
- Flux

Procedure

The casting machine is given three clockwise turns (four if metal-ceramic alloys are used) and is locked in position with the pin. The cradle and counterbalance weights are checked for the appropriate size of the casting ring. A crucible for the alloy being cast is placed in the machine. The torch (gas-air for regular alloys, gas-oxygen for metal-ceramic) is lit and adjusted. For metal-ceramic alloys, the clinician should wear a pair of colored goggles to protect the eyes and also to enable direct viewing of the melt.

The crucible is preheated (Fig. 22.25A), particularly over the trajectory that will be in contact with the alloy, and the alloy is added. Preheating avoids excessive slag formation during casting. Also, when metal-ceramic alloys are cast, a crucible that is too cool can "freeze" the alloy, which results in an incomplete casting. The mass of the alloy must be sufficient to sustain adequate casting pressure. With a high-density noble metal alloy, 6 g (4 dwt[a]) is typically adequate for premolar and anterior castings, 9 g (6 dwt) is adequate for molar castings, and 12 g (8 dwt) is adequate for pontics.

The alloy is heated in the reducing part of the flame until it is ready to cast. A little flux can be added to conventional gold alloys (not to metal-ceramic alloys). Gold alloys ball up and have a mirror-like shiny surface that appears to be spinning. Nickel-chromium and cobalt alloys are ready to cast when the sharp edges of the ingot round over. The mold is placed in the

[a]Pennyweight (*d* is an abbreviation for *denarius*, a Roman silver coin).

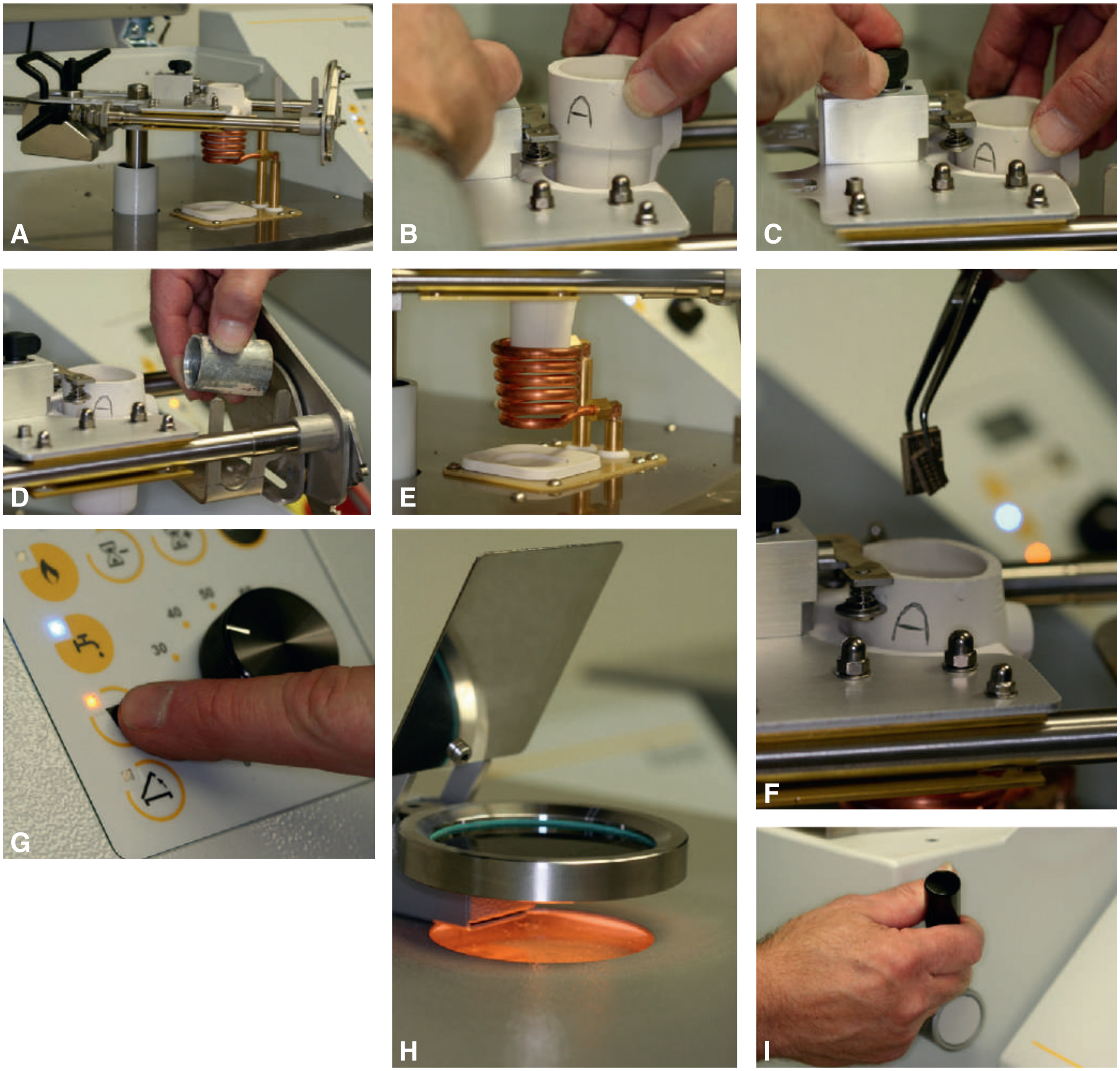


Fig. 22.23 Induction casting. (A) The motorized casting machine consists of a quartz crucible that is surrounded by a water-cooled copper induction coil that serves as the heat source. The counterweight (on left) can be adjusted as a function of the size of the casting ring. The quartz crucible is inserted (B) and secured (C). (D) An unused casting ring is used to verify alignment of the cradle (and the ring) with the crucible opening through which the gold alloy will enter the investment mold. (E) The induction coil is raised until it surrounds the crucible. (F) The alloy is inserted in the crucible. Depending on alloy type, a carbon insert may be placed inside the quartz crucible. (G) The necessary current intensity for the alloy is set. (H) Visual confirmation of the melt being ready for casting is possible through the closed lid of the casting machine. A dark filter offers eye protection. (I) The operator initiates the casting procedure by throwing the lever on the side of the unit. Casting pressure is sustained by the electric motor in the base of the unit and switches off automatically after 30 seconds, at which time the lid is unlatched automatically.

cradle of the casting machine (see Fig. 22.25B) and kept on the alloy with the reducing flame until the crucible is moved into position (see Fig. 22.25C–G). The casting machine arm is then released to make the casting (see Fig. 22.25H). The machine is allowed to spin until it has slowed enough that it can be stopped by hand, and the ring is removed with casting tongs.

Recovery of the casting. After the red glow has disappeared from the button, the casting ring is plunged under running cold water into a large rubber mixing bowl (Fig. 22.26).

Gypsum-bonded investments disintegrate quickly, and residue is eliminated easily with a toothbrush. Final traces can be removed ultrasonically. Oxides are removed by pickling in

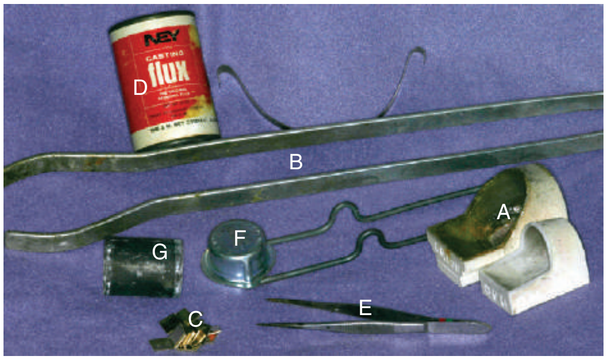


Fig. 22.24 Casting armamentarium. *A*, Crucibles; *B*, tongs; *C*, casting alloy; *D*, flux; *E*, tweezers; *F*, lighter; *G*, casting ring.

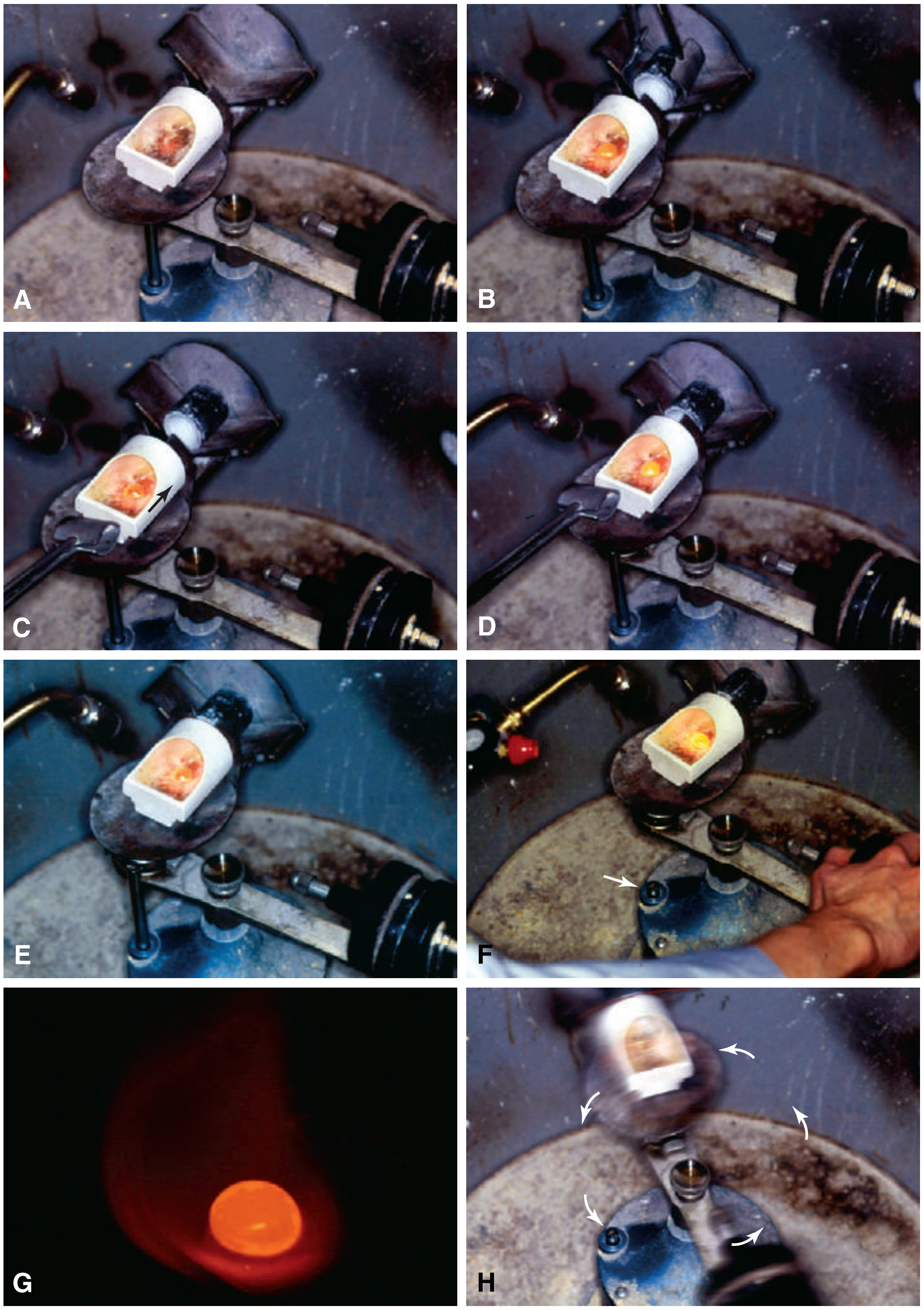


Fig. 22.25 Casting technique. (A) The crucible is preheated. (B) The alloy is melted. When the alloy is molten, the casting ring is removed from the furnace and placed in the cradle. (C) Tongs are used to slide the crucible platform into contact with the casting ring *(arrow)*. (D) The orifice of the crucible aligns with the sprue. (E) Heating continues for a few seconds so that the melting is complete and casting can proceed. (F) The casting arm is pulled forward until the pin drops *(arrow)*. (G) The melted alloy, seconds before casting. (H) Centrifugal force carries the melted alloy into the mold cavity *(arrows* show the direction of spin).

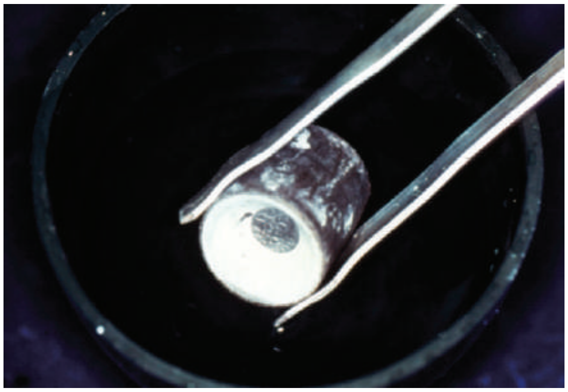


Fig. 22.26 The ring is quenched in cold water in a plaster bowl. Gypsum-bonded investments readily disintegrate; phosphate-bonded investments are much stronger and the castings need to be devested carefully.

Fig. 22.27 Nonfuming pickling acid can be used in conjunction with this covered pickling unit.

50% hydrochloric acid (or, preferably, a nonfuming substitute; Fig. 22.27). Phosphate-bonded investments do not disintegrate equally well, and some must be removed forcibly from the casting ring. They can be handled as soon as they have been sufficiently cooled under running water.

A knife is used to trim the investment at the button end of the ring (Fig. 22.28A). The other end is not trimmed because of the risk of damaging the margin. When the ring liner is exposed, the investment can be pushed out of the ring (see Fig. 22.28B). It is then broken apart under running water (because it is still hot; see Fig. 22.28C). The remaining investment is carefully removed with a small blunt instrument (see Fig. 22.28D), and any traces are dissolved in hydrofluoric acid or a less caustic substitute. Care must be taken to prevent scratching of the internal surface of the casting or damage to the margins.

Evaluation. The casting is never fitted on the die until the intaglio surface has been carefully evaluated under magnification; even tiny imperfections can cause damage to the stone die. A die may be rendered useless in a matter of seconds if a casting is fitted prematurely.

Defects in the casting. Investing and casting require meticulous attention to detail in order to obtain a successful, properly fitting casting. Table 22.1 summarizes and provides examples of the more common causes of various problems.

Roughness. The surface of a casting should be smooth, although finishing and polishing are still required (see Chapter 28). Lines or grooves in the casting are usually present but overlooked in the wax pattern. They may necessitate a remake, particularly if they were positioned near the margin or on the fitting surface. Generalized casting roughness may indicate a breakdown of the investment from excessive burnout temperature.

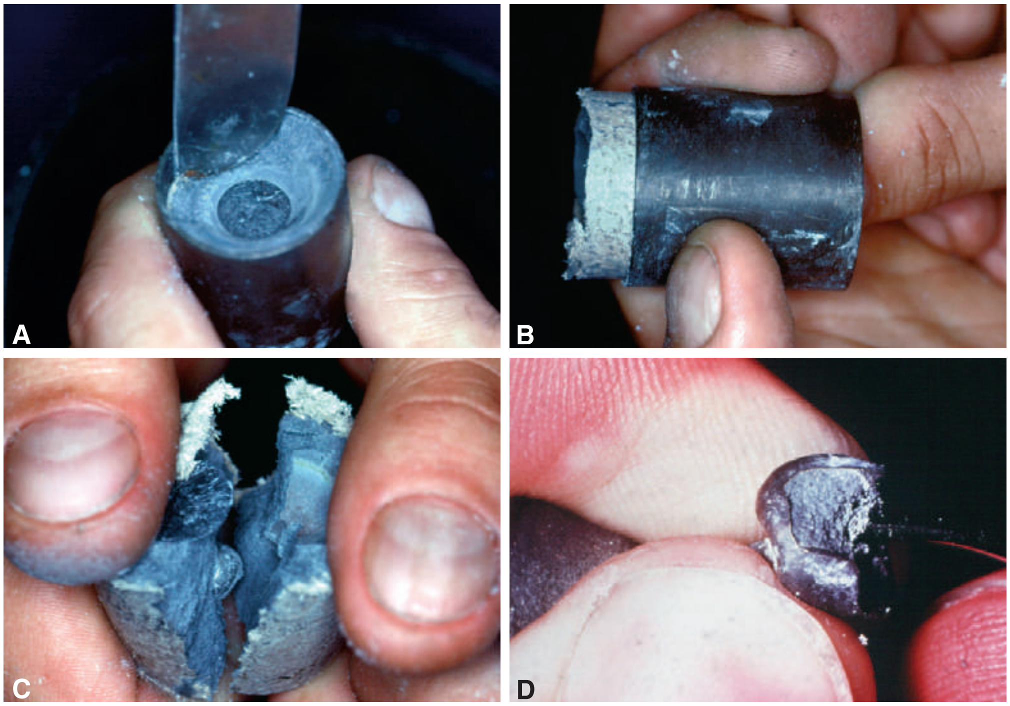


Fig. 22.28 Recovery of a casting from phosphate-bonded investment. (A) Trimming is done from the button end of the ring. (B) Investment is being pushed out of the casting ring. (C) The mold is broken open. (D) Investment is removed from the casting. Care must be taken to avoid damaging the margin.

TABLE 22.1 Common Causes of Casting Failure

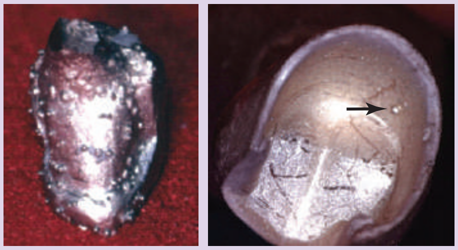
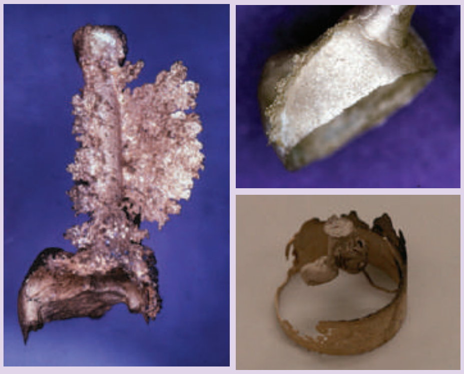
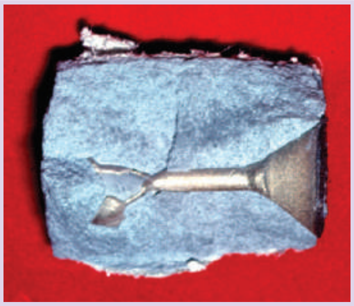
Problem	Possible Causes	Appearance
Rough casting	Excess surfactant Improper water-to-powder ratio Excessive burnout temperature	
Large nodule	Air trapped during investing procedure	
Multiple nodules	Inadequate vacuum during investing Improper brush technique Lack of surfactant	
Nodules on occlusal surface	Excessive vibration	
Fins	Increased water-to-powder ratio Pattern too near edge of investment Premature heating (mold still wet) Too-rapid heating Dropped mold	
Incomplete casting	Wax pattern too thin Cool mold or melted alloy Inadequate metal	

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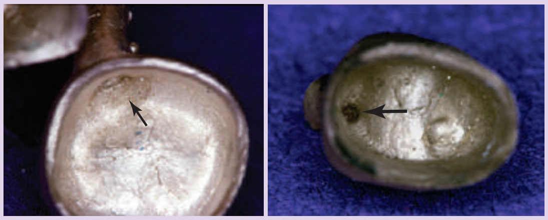
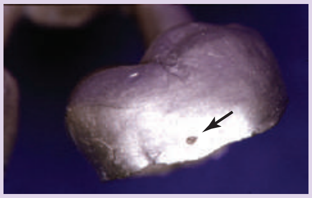
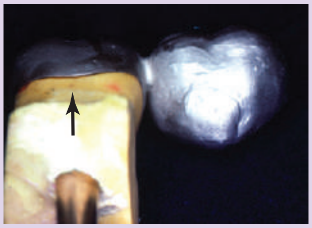
TABLE 22.1 Common Causes of Casting Failure—Cont'd

Problem	Possible Causes	Appearance
Incomplete casting with shiny, rounded defect	Incomplete wax elimination	
Solidification shrinkage ("suck-back") porosity	Improper pattern position Narrow, long sprue	
Inclusion porosity	Particle of investment dislodged during casting	
Marginal discrepancy	Wax pattern distortion Uneven expansion	
Inadequate or excessive expansion	Improper water-to-powder ratio Improper mixing time Improper burnout temperature	

Nodules. Bubbles of gas trapped between the wax pattern and the investment produce nodules on the casting surface. Even minute nodules can limit the seating of the casting to a considerable degree. When they are large or situated on a margin, they usually necessitate remaking of the restoration. When small, they can often be removed with a No. ¼ or No. ½ round bur (Fig. 22.29). A binocular microscope is extremely helpful for detecting and removing nodules. A slight excess of metal should be removed to ensure that the nodule does not interfere with complete seating.

Keys to avoiding nodules include a careful investing technique, use of a surfactant, vacuum spatulation, and careful coating of the wax pattern with investment. Castings made with phosphate-bonded investment are especially prone to imperfections, and experience and care are necessary to routinely produce castings that are free of nodules.

Fins. Fins are caused by cracks in the investment that have been filled with molten metal. These cracks can result from a weak mix of investment (high water-to-powder ratio), excessive casting force, steam generated from too-rapid heating, reheating an invested pattern, an improperly situated pattern (too close to the periphery of the casting ring), or even premature or rough handling of the ring after investing.

Incompleteness. If an area of wax is too thin (less than 0.3 mm), which occurs occasionally on the veneering surface of a metal-ceramic restoration, an incomplete casting may result. Thickening of the wax in these areas is recommended. Incomplete casting of normal-thickness wax patterns may result from inadequate heating of the metal, incomplete wax elimination, excessive cooling ("freezing") of the mold, insufficient casting force, not enough metal, or metal spillage.

Voids or porosity. Voids in the casting (in particular in the margin area) may be caused by debris trapped in the mold (usually a particle of the investment undetected before wax elimination). A well-waxed smooth sprue helps prevent this. Porosity resulting from solidification shrinkage ("suck-back") occurs if

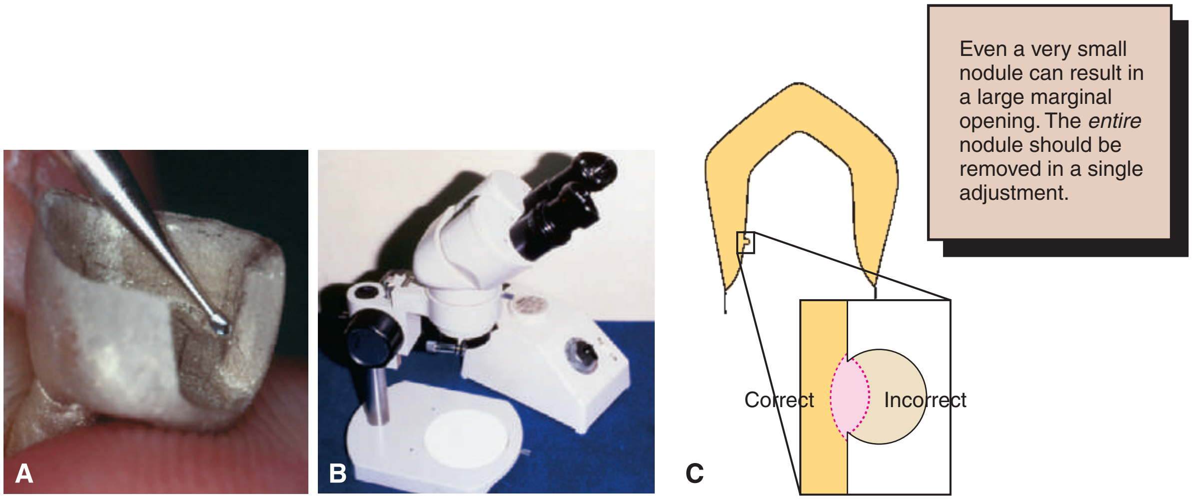


Fig. 22.29 Removing casting nodules. Small nodules are frequently present, particularly with phosphate-bonded investments. They interfere with seating and must be identified before the casting is placed on the die. (A) Once they are identified, a small round bur can be used to remove them. (B) Magnification is helpful for this. (C) Slightly more, rather than less, metal than the size of the nodule should be removed to ensure that the casting does not bind during seating.

the metal in the sprue solidifies before the metal in the mold, as may happen when a sprue is too narrow, too long, or incorrectly located or when a large casting is made in the absence of a chill vent. Gases may dissolve in the molten alloy during melting and leave porosity.

Back-pressure porosity[48] may be caused by air pressure in the mold as the molten metal enters. Its occurrence is reduced through the use of a more porous investment, location of the pattern near the end of the ring (6 to 8 mm), and casting with a vacuum technique.

Marginal discrepancies. Inaccuracies of fit at the margin can be caused by distortion during removal of the wax pattern from the die. They may also result from increased setting expansion (hygroscopic technique) after uneven expansion of the mold.

Dimensional inaccuracies. The casting can be either too small or too large. Attention to detail is essential for an accurately expanded mold. A standardized procedure is needed in regard to liquid-to-powder ratio, spatulation, the ring liner, the amount of liquid added, and mold heating.

Special Considerations for Titanium and Titanium Alloys

William Brantley

The casting of titanium and titanium alloys for prosthodontic applications can be performed only at specially equipped dental laboratories. Because of the high melting point and highly reactive nature of titanium at elevated temperatures, special expensive casting machines are needed since a vacuum or inert atmosphere environment must be employed, along with arc-melting and special casting investments. For metal-ceramic applications, special low-fusing, low-expansion porcelains are required. Reaction of the cast titanium or titanium alloy with the investment and residual air in the casting machine results in formation of a very hard near-surface region termed α-case, which requires special laboratory effort for removal. While marginal discrepancy values for cast titanium were originally excessive (well over 100 µm), continued development of new investments and casting protocols have led to clinically acceptable results for cast titanium and titanium alloys. However, the foregoing problematic considerations have prevented the worldwide adoption of cast titanium and titanium alloys for prosthodontics. Selected references[49–51] show the advances in research on titanium casting and porcelain bonding. There has also been interest in titanium casting alloys such as Ti-6Al-7Nb for prosthodontics that are more biocompatible than Ti-6Al-4V.

The new technology of additive manufacturing (AM) (to be discussed later) can capably handle the fabrication of prostheses from CP (unalloyed) titanium and titanium alloys, provided suitable fine particle-size powders are used. Although the three-dimensional printing apparatus is also expensive, this factor becomes less problematic when the cost per individual unit is considered. The evolution of printing titanium and titanium alloys for prosthodontic applications (removable partial denture frameworks,[52] removable partial denture clasps,[53] and copings for metal-ceramic restorations[54]) is shown in the references. Many future developments are expected for this highly active area of research.

■ ■ ■

REVIEW OF TECHNIQUE

The following list summarizes the steps involved in investing and casting (Fig. 22.30) and should prove helpful in reviewing the material covered in this chapter:

1. A sprue 2 or 2.5 mm in diameter (10- or 12-gauge) is attached to the bulkiest, nonfunctional cusp (the larger size for molar and metal-ceramic patterns, the smaller size for premolar and partial coverage). Sprues can be attached to multiple units with a runner bar (see Fig. 22.30A).
2. The pattern is carefully removed from the die and attached to a crucible former (sprue length should be 6 mm or less; see Fig. 22.30B).

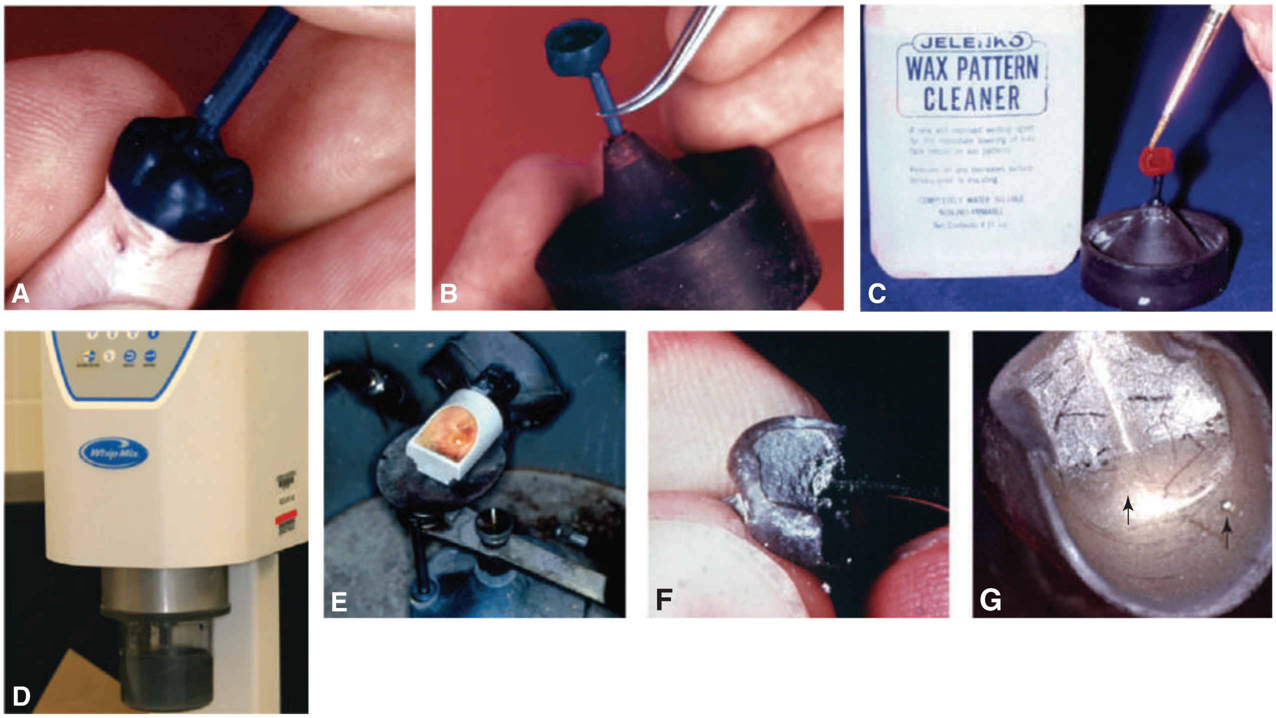


Fig. 22.30 Technique review. (A) A sprue 2 or 2.5 mm in diameter (10- or 12-gauge) is attached to the bulkiest nonfunctional cusp; sprues can be attached to multiple units with a runner bar. (B) The pattern is carefully removed from the die and attached to a crucible former. (C) The pattern is painted with surface tension reducer. (D) The pattern is then carefully coated with vacuum-mixed investment. (E) After wax elimination, the casting machine is prepared, and the crucible is preheated. The alloy is melted, the ring is transferred, and the casting is made promptly. (F) The casting is recovered from the investment. (G) Defects *(arrow)* are identified and corrected if possible.

3. The pattern is painted with surface tension reducer (see Fig. 22.30C) and then carefully coated with vacuum-mixed investment (see Fig. 22.30D).
4. The ring is filled, and the investment is allowed to bench set for a minimum of 1 hour.
5. After wax elimination, the casting machine is prepared, and the crucible is preheated. The alloy is melted, the ring is transferred, and the casting is made promptly (see Fig. 22.30E).
6. The casting is recovered from the investment (see Fig. 22.30F).
7. Defects are identified and corrected if possible (see Fig. 22.30G).

TRADITIONAL LOST WAX PROCESS SUMMARY

Investing and casting comprise a series of highly technique-sensitive steps in which the wax pattern is converted into a metal casting. Accurate and smooth restorations can be obtained if the operator pays special attention to each step in the technique. When initial attempts at casting produce errors or defects, appropriate corrective measures must be taken so that they do not recur.

Digital Workflows

Geoffrey A. Thompson • Adel Almaaz • Hongseok An

Metal restorations and frameworks can be manufactured by using computer-aided design and computer-aided manufacturing (CAD-CAM) technology. In preparation for manufacturing using a digital workflow, the acquisition of digital files is necessary for restoration design and for operation of the automated CAM machinery.

Digital Data Acquisition

When a prosthetic restoration is planned, there are several means to enter a digital workflow. If the tooth receiving treatment is anatomically suitable, an intraoral scan of the tooth, or laboratory scan of a pretreatment stone cast, or an elastic impression should be acquired before its preparation. Alternatively, when the tooth morphology is unsuitable for planning the definitive restoration, the ipsilateral tooth, particularly in the esthetic region, can be scanned and used to create a mirror image from it. A scan of a diagnostic waxing, or trial restoration that has been verified in the patient's mouth for esthetics and phonetics, can also serve as a starting point in a digital workflow (Fig. 22.31A). The digital acquisition of an esthetic interim restoration on a prepared tooth is another method and lastly, many digital dental planning software programs include a digital tooth library, providing an additional way to create a digital design file.

Following definitive tooth preparation, a second digital file is acquired by using a chairside scanner, or, alternatively, from a conventional definitive impression, or a stone cast that is scanned with a laboratory scanner (see Fig. 22.31B). Merging of the tooth preparation file with a digital file of the unprepared tooth (see Fig. 22.31C), obtained as explained previously, will

Fig. 22.31 (A) Digital image of diagnostic waxing. (B) Digital image of prepared teeth. (C) The diagnostic waxing is merged with prepared teeth by using unprepared teeth and attached gingiva as references.

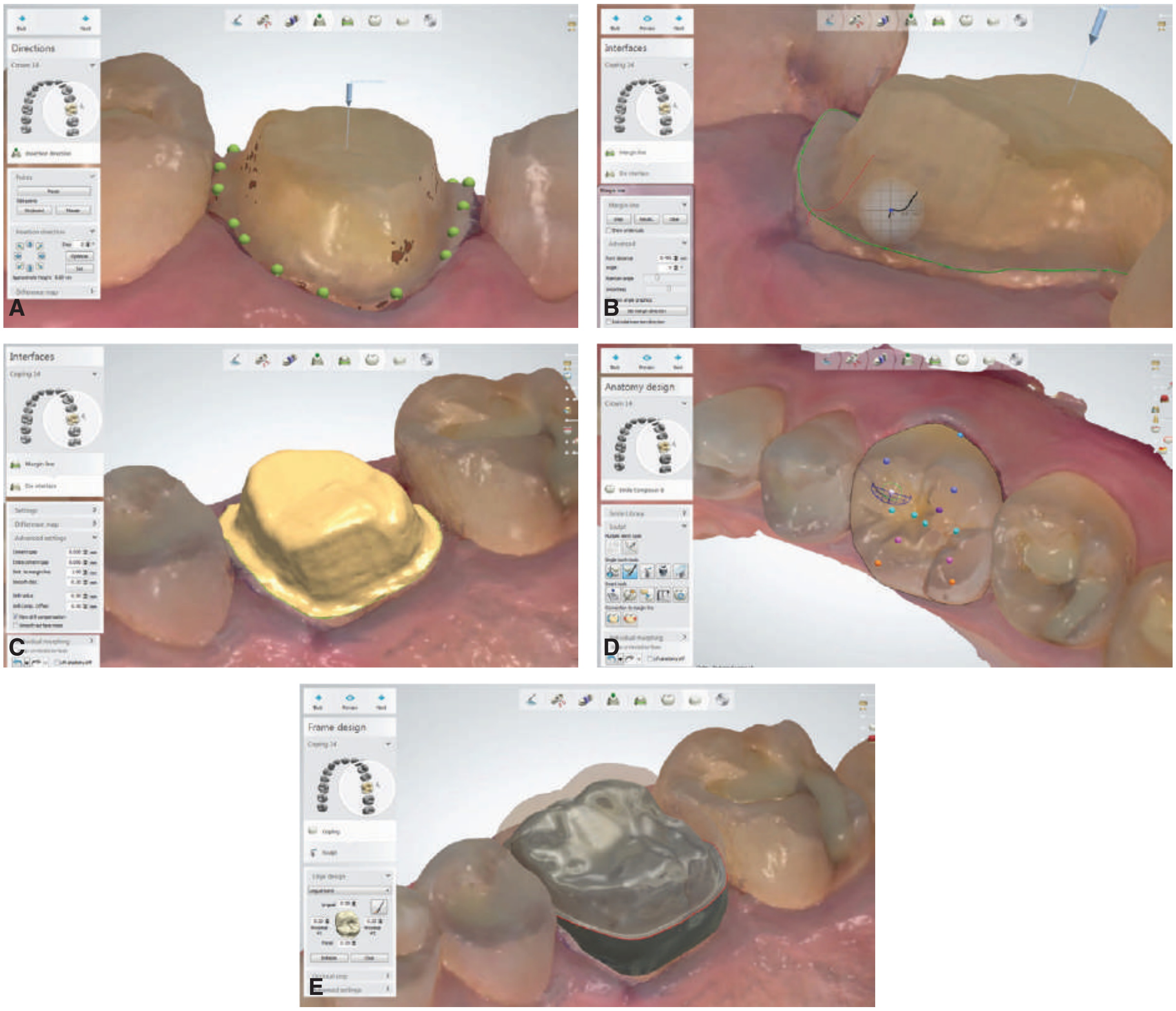


Fig. 22.32 (A) Margin tracing. (B) Insertion direction. (C) Virtual die spacer. (D) Anatomic contour design. (E) Cut back and framework design.

provide the clinician or dental laboratory technician the boundaries by which to design the new restoration. Merging of different digital files is accomplished by using anatomic landmarks, or by using commercially available add-on reference points common to both digital scans; therefore, it is important that scans contain enough information so that merging of digital files is reliable. It is from these scans that the metal coping design files are created for use with the CAM instrument.

Computer-Aided Design

After importing all necessary digital files into the planning software program, design can be performed by the restorative dentist or a dental laboratory technician. The first step is to determine the location of the prepared margin (Fig. 22.32A). This step may be automatically determined by the planning software program, manually or through a combination method. A good way to approach this is to let the software program determine the margin location followed by manually adjusting the margin in areas that require some improvement. It is good practice to look at the margins from both a vertical and horizontal perspective so that the height of contour of the prepared margin can be more easily identified.

Determining the insertion axis is an especially important step when planning multiple adjacent restorations or a fixed partial denture (see Fig. 22.32B). The planning software program can automatically determine an insertion axis; however, it should be assessed for correctness and it may require adjustment. Like most software planning tools, the axis can be manually determined with the goal of having the least amount of undercut possible.

The new prosthesis can be designed using the tooth library found in the planning software program or by using a digital file acquired from pretreatment records. Assess the default positioning of a crown or merged image by using auto-positioning. Manually adjust the size, rotations, and heights of contour. Then, check for the thickness, location, and intensity of the occlusal contact points. Also, under control of the operator is the occlusal offset, positive or negative, and it is the amount the restoration will be in hyperocclusion or out of occlusion. Other factors under control of the operator are the amount and location of the die spacer (see Fig. 22.32C and D) and the location and intensity of the interproximal contacts.

For a metal-ceramic framework, adherence to recommendations for metal support of the veneering porcelain should conform to recommended prosthodontic principles. Cutback design may be performed in a couple of ways: (1) by shrinking the digitally created complete-contour restoration by a specified dimension, or (2) manually (see Fig. 22.32E). With the manual method, a designer can shrink specific areas while leaving other areas alone. In that way, margins, collars, proximal contacts, or occlusal surfaces may be designed in metal.

Drill compensation refers to a feature of a CAD software program that adjusts the surface of a design to allow for the diameter of the drill to be used for milling. A typical effect would be the removal of extra material around a sharp or irregular line, angles, or edges. The amount of drill compensation is mainly determined by the diameter of the smallest milling tool used for the milling process. The diameter of milling tools varies depending on prosthetic material and milling machine. Typically, harder materials such as glass-ceramics require milling tools with greater diameter. The designer has control over the horizontal and vertical compensation and the angulation at the restoration margin (Fig. 22.33). A standard tessellation language (STL) file of the planned design is exported for use with the CAM machinery.

Computer-Aided Manufacturing

Since the development of dental CAD-CAM technology in the early 1970s, the precision and accuracy of fabricated dental restorations has increased while the cost per unit has decreased.[55] Whether the digital workflow begins in the dental clinic or a dental laboratory, CAM technology can be divided into two main categories, subtractive and additive, for manufacturing dental prostheses.[56–58]

Fig. 22.33 Excessive cement space because of drill compensation. The sharp line angle areas *(arrows)* are over-relieved to allow the round-ended milling tool with 1 mm diameter. All line angles and sharp edges on tooth preparation should be rounded to avoid this issue.

Subtractive Manufacturing Technologies for Metal

Most CAD-CAM workflows[56–58] are based upon a subtractive manufacturing or milling process.[59] Subtractive manufacturing is when a bulk material is machined or cut away in a controlled process until the desired final shape is attained. The bulk material can be a metal, polymer, ceramic or a composite.

Older milling machines were simple and operated in three axes to produce the prosthesis. Three-axis milling machines are challenged by the complex shapes of dental restorations, in part, because of limited access to undercuts or the size of its cutting tools. To overcome some of the limitations of three-axis machines, four- and five-axis milling machines have been developed which operate around the x-axis, y-axis, and z-axis and with rotation about the x- or the y-axis or both (Fig. 22.34A).

Dental restorations can be milled from a spectrum of metal alloys including high noble, noble, and base metals. Cobalt-chromium (Co-Cr) and titanium alloys are some of the commonly used base metal alloys (Fig. 22.34B and C).[59,60] Advantages include the capability to mill from a large selection of materials and the surface finish is under the machine operators control.[59,60] A disadvantage of this technology is the millings are usually discarded as waste and may increase production costs.[61] The scientific literature does not support CAD-CAM milling technology over analog procedures for obtaining a metal coping, and both workflows can result in clinically acceptable restorations.[62,63] Selection for a millable dental alloy is based, in part, on material cost and mechanical properties.[59,64]

Additive Manufacturing Technologies for Metals

A comparatively newer technology, called AM, was developed in response to a need for rapid manufacturing, or prototyping. The leading advantage of AM is that waste may be reduced in comparison to subtractive manufacturing methods. In addition, AM is not limited by milling tools or the number of milling machine axes; therefore, very complex dental restorations may be manufactured. The biggest disadvantage of AM may be the cost of initial equipment acquisition.

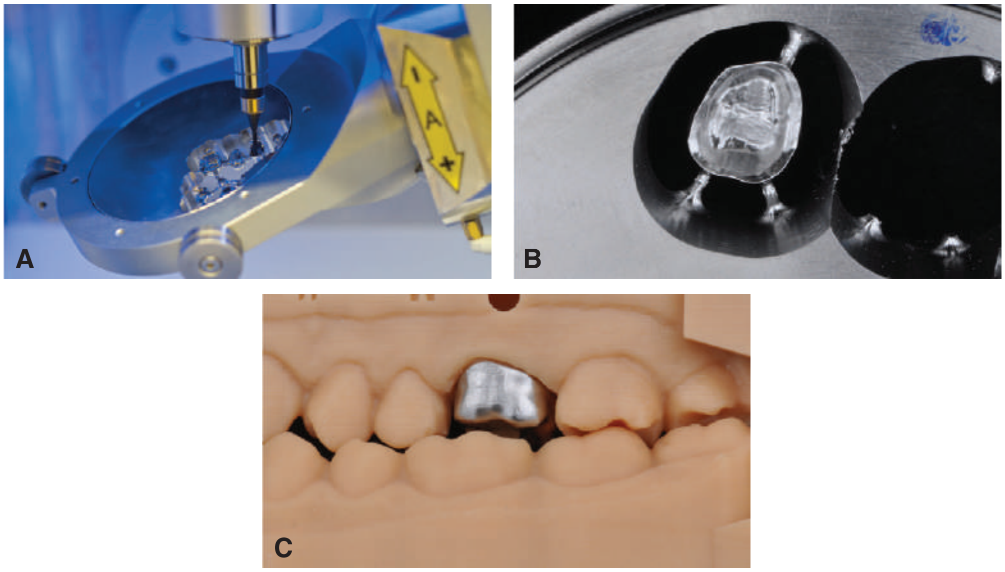


Fig. 22.34 (A) 5-axis milling machine. (B) Milled Co-Cr framework. (C) Milled Co-Cr framework separated from disk and seated on the 3D-printed resin cast.

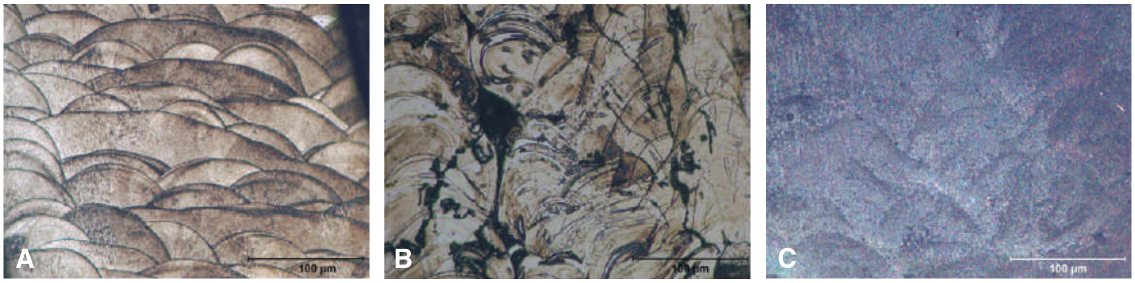


Fig. 22.35 (A) Selective laser melting (SLM) Co-Cr alloy, magnification ×20. (B) SLM noble palladium-cobalt alloy, magnification ×20. (C) SLM high noble gold-palladium-silver alloy, magnification ×20. (From Al Maaz A, et al: Effect of finish line design and metal alloy on the marginal and internal gaps of selective laser melting printed copings. *J Prosthet Dent.* 2019;122:143.)

AM systems operate on the principle that an STL file of the desired dental restoration is created and subsequently divided into multiple vertical or horizontal layers using a slicer program.[65] The slicer program converts the STL file into G-code, which can control automated machines.[65]

There is no universally accepted classification of AM technologies; however, a common classification for AM metals includes sheet lamination, powder bed fusion (PBF), stereolithography, direct energy deposition, metal filament extrusion, and jetting.[66] As a result of the development of proprietary technologies by individual commercial manufacturers, each primary classification has subclassifications, and many of those possess their own unique acronym.

Powder Bed Fusion Technology

PBF is the most common AM technology used in industry and in dentistry. As a group, the technology includes selective laser melting (SLM) and electron beam melting (EBM) (Fig. 22.35).

Selective Laser Melting

SLM has been increasingly used for fabrication of printed metal dental restorations[1] made from Co-Cr or Au-Pt alloys.[67,68] SLM printers have three basic components, a movable build platform, a powerful laser and a powder bed.[65] The laser forms a part by localized melting of the powder, and as each layer is completed, the build platform moves down and a new powder layer is added.[65] The process is repeated one layer at a time until the part is completed.[65] While early SLM systems deposited layers of approximately 30 to 50 µm per pass,[69] progressive development of the process has led to better results, and several studies reported layer thicknesses of approximately 20 µm for dental applications.[69–72] The difference between SLM and selective laser sintering (SLS) is in the degree of fusion of the metal powders during manufacture. SLM printers completely melt the metal powders while SLS does not.[66]

Electron Beam Melting

EBM is another PBF technology and is similar in concept to SLM; however, the principal difference is in the energy source for manufacturing the prosthesis. Rather than a laser, EBM uses a high-power electron beam to additively manufacture metal objects. The build rate and the maximum build size make it suitable for producing small or large dental prostheses. Currently, EBM may only be used to manufacture restorations from titanium alloy powders.

Fig. 22.36 GE Additive Concept Laser Mlab 200 R system. (Used with courtesy of GE Additive, Cincinnati, OH.)

Properties of Additive Manufacturing Metals

Properties of metal alloy powders, such as composition, melting temperature, particle size distribution, energy absorption and reflection coefficient and thermal conductivity are important considerations to ensure desired results.[73,74] For example, average powder particle size can affect sintering kinetics during solidification and mechanical properties.[60,73,75] Printer settings, such as scanning speed, holding time, temperature of the preheated bed, and thickness of each layer have been reported to affect strength, density, and quality of finished parts (Fig. 22.36).[73,76–78] One important goal of all workflows is to minimize thermal distortion, which can be controlled by proper selection of the preheated bed temperature.[79] The build process occurs in an inert atmosphere to prevent reactivity of the molten metal alloys with the environment and the formation of impurities.

Accuracy

Precisely fitting margins are a prerequisite for long-lasting fixed prosthetic restorations, but determining the maximum acceptable marginal gap is challenging. McLean and von Fraunhofer examined more than 1000 crowns, and determined that a marginal gap of no greater than 120 µm was clinically acceptable. However, Christensen concluded 39 µm was the greatest acceptable marginal discrepancy.[63,80] Most CAD-CAM workflows can produce metal restorations with clinically acceptable internal[81] and marginal gaps.[62,81,82]

The research is inconclusive as to whether the marginal and internal fit of noble and base metal alloys fabricated with new technologies is affected by the type of alloy or technique. Although significant differences have been identified when using different alloys and techniques, almost all alloys and manufacturing processes exhibit clinically acceptable mean marginal openings.[83–86]

Microstructure and Mechanical Properties

The microstructure of materials can influence its mechanical properties and performance during function. Han et al.,[59] and Takaichi et al.,[60] studied the microstructure of Co-Cr alloy specimens manufactured by SLM, casting and milling technologies. The Co-Cr microstructure largely depended upon the fabrication method. Co-Cr specimens produced by SLM exhibited a fine grain structure and was dependent upon processing parameters, while the milled microstructure depended solely on the characteristics of the block used.[59,60] In another study, Al Maaz et al.,[84] compared the microstructure of Co-Cr, noble, and high noble alloy specimens manufactured by the same SLM laboratory. Differences were observed and were dependent on the type of alloy used.

Metal-ceramic dental restorations must possess adequate mechanical properties and metal-ceramic bond strength to ensure good clinical performance. Additively manufactured restorations can be as strong or stronger than conventionally fabricated restorations, depending on the technology used and production factors.[59] In a study that compared cast, milled, and SLM Co-Cr specimens all produced from the same alloy composition, it was found that SLM specimens possessed superior mechanical properties and metal-ceramic bond strength compared with milled and cast specimens, and may be superior to conventional techniques.[60]

Ceramic Veneering

A metal coping, or framework of metal-ceramic restorations, can be fabricated using a digital workflow, but manual veneering of ceramic is still required to complete a metal-ceramic restoration. Veneering ceramic can be applied by using either a conventional hand layering technique, or a waxing and pressing (press-over-metal) technique.

While it is possible to fabricate some monolithic ceramic or composite resin restorations without using a physical model, it is necessary to use a physical model when fabricating a metal-ceramic restoration in order to create ideal tooth morphology and occlusion on the ceramic part. The stone cast can be used for this purpose if a conventional impression technique is used, and a 3D-printed resin cast is typically used when a digital intraoral scan is used to fabricate the metal coping. Previous studies have shown that the accuracy of 3D-printed resin models is acceptable for a short span.[87,88] However, it should be used with caution as the accuracy of 3D-printed resin casts can vary depending on the printing machine.[89]

Bond strength between the veneering ceramic and the metal coping should be considered when selecting metal alloy for a metal-ceramic restoration. Titanium alloy has been a popular material of choice in dentistry because of its excellent mechanical and biological properties, as well as ease and rapidity of milling. However, milled titanium copings are rarely used for metal-ceramic restorations because of their low ceramic shear bond strength and poor clinical performance caused by frequent veneering ceramic problems.[90,91] Non-precious metal alloys, such as Co-Cr alloys, are more commonly used for CAD-CAM fabricated metal-ceramic restorations. Ceramic shear bond strength of Co-Cr alloys is known to be compatible with castable alloys whether it is fabricated by using a subtractive system or with AM.[92–94]

▪ ▪ ▪

SUMMARY

Traditionally, metal restorations have been made by lost-wax casting. In dentistry, castings must be a highly accurate reproduction of the wax pattern in surface details and overall dimensions. Small variations in technique can significantly affect the quality of the definitive restoration. Routine success depends on attention to detail and consistency of technique. Metal restorations and frameworks can also be manufactured by using CAD-CAM technologies. CAD workflow begins in the dental clinic or a dental laboratory, CAM technology can be divided into subtractive and additive categories.

STUDY QUESTIONS

1. Discuss the step-by-step process of preparing a wax pattern for investing.
2. Contrast the differences between gypsum and phosphate bonded investments. Why would you select one or the other?
3. Discuss different expansion techniques for casting investments.
4. What factors are considered in the selection of casting alloys? What are the classification of casting alloys?
5. Identify four types of casting failures and describe and discuss their respective causes.
6. Discuss the steps involved in digital acquisition of a tooth preparation, its antagonists and the interocclusal relationship.
7. Discuss three additive manufacturing technologies for metal restorations and their respective advantages and disadvantages.

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23

Color, the Color-Replication Process, and Esthetics

Alvin G. Wee, Contributing Author

To achieve an esthetic restoration, it is necessary to understand the process in which the color and translucency of fixed restorations are planned and obtained so as to replicate the color and contours of its adjacent teeth. Errors, especially in the color replication process, have been a problem and source of frustration for dentists and technicians, and they may lead to dissatisfaction for the patient. This chapter outlines some of the principles of color, light, and human perception as they relate to the color replication process and esthetics of fixed restorations.

DESCRIPTION OF COLOR

Just as a solid body can be described by three dimensions of physical form (length, width, and depth), color can be described with the same precision by three primary attributes. Describing these attributes, however, depends on the color system used. Two systems are explained: the more visually descriptive Munsell color order system and the more quantitative Commission Internationale de l'Éclairage L*a*b* (CIELab) color system.

Munsell Color Order System

This system was widely used in the dental literature and also used in the past to quantify color.[1–3] It is still a popular method of visually describing color. The three attributes of color in this system are called *hue, chroma*, and *value*. (When used in reference to the Munsell coordinates, these terms are capitalized.)

Hue

Hue is defined as the particular variety of a color. The hue of an object can be red, green, yellow, and so on, and is determined by the wavelength of the reflected or transmitted light observed. The place of that wavelength (or wavelengths) in the visible range of the spectrum determines the hue of the color. The shorter the wavelength, the closer the hue is to the violet portion of the spectrum; the longer the wavelength, the closer it is to the red portion. In the Munsell color system, Hues are arranged around a wheel (Fig. 23.1).

Chroma

Chroma is defined as the intensity of a hue. The terms saturation and chroma are used interchangeably in the dental literature; both mean the strength of a given hue or the concentration of pigment. A simple way to visualize differences in chroma is to imagine a bucket of water. When one drop of ink is added, a solution of low chroma results. Adding a second drop of ink increases the chroma, and so on, until a solution is obtained that is almost all ink and consequently of high chroma. In the Munsell color system, the intensity of Chroma of a particular Hue is more intense on the outer rim than near the hub of the wheel (Fig. 23.2).

Value

Value is defined as the relative lightness or darkness of a color or the brightness of an object. The brightness of any object is a direct consequence of the amount of light energy the object reflects or transmits (see Fig. 23.2).

It is possible for objects of different hues to reflect the same number of photons and thus have the same brightness or value. A common example is the difficulty experienced in trying to distinguish a green object from a blue object in a black and white photograph. The colors of the two objects reflect the same amount of light energy and therefore appear identical in the picture.

A restoration that has too high a value (is too bright) may be easily detected by an observer and is a common esthetic problem in metal-ceramic prosthodontics.

Color Difference Formulae

The CIELab color system has been used almost exclusively for color research in dentistry around the world.[4–7] It was introduced in 1976 and recommended by the International Commission on Illumination. This system, unlike the Munsell system, is easy to interpret clinically, as equal distances across the CIELab color space (color differences, or ΔE_{ab}) represent approximately uniform steps in human color perception, which improves the interpretation of color measurements. This means that it is possible to define the magnitude of perceptible or acceptable color difference between, for example, a porcelain crown and the adjacent natural dentition.

The CIELab color order system defines color space by three coordinates: L*, a*, and b*. L* is similar to the Munsell system's Value and represents the lightness, brightness, or black/white character of the color. The coordinates a* and b* describe the chromatic characteristics of the color. L* describes the achromatic character of the color. Colors with high value, or L* (such as tooth colors), are located near the top of the color space, as depicted in Fig. 23.3. The chromatic (non–black/white) characteristics of a

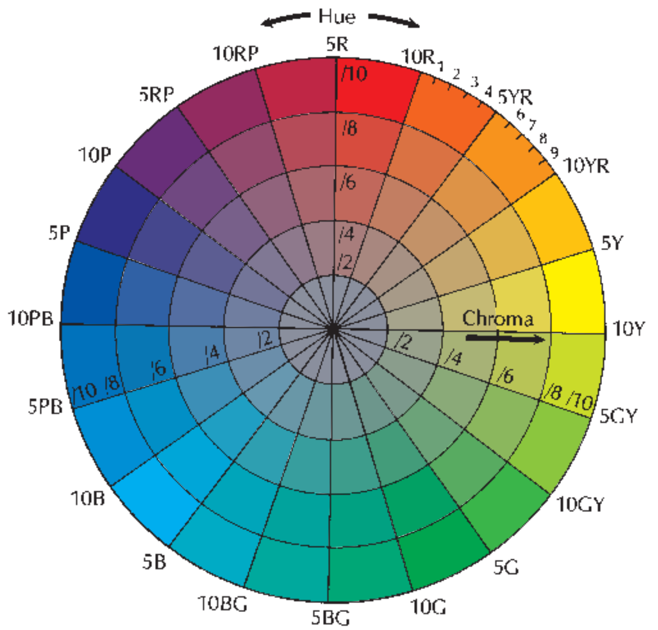


Fig. 23.1 Arrangement of Hue and Chroma in the Munsell system. Hue is represented by letters: *R*, Red; *YR*, yellow-red; *Y*, yellow; *GY*, green-yellow; *G*, green; *BG*, blue-green; *B*, blue; *PB*, purple-blue; *P*, purple; *RP*, red-purple. Chroma is represented by the numbers (see Fig. 23.2).

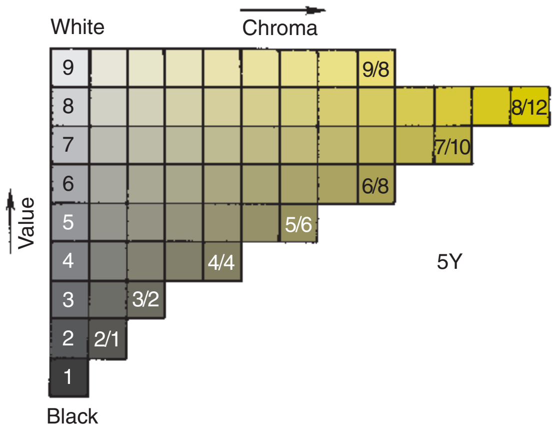


Fig. 23.2 Arrangement of Value and Chroma in the Munsell system. *Y*, Yellow.

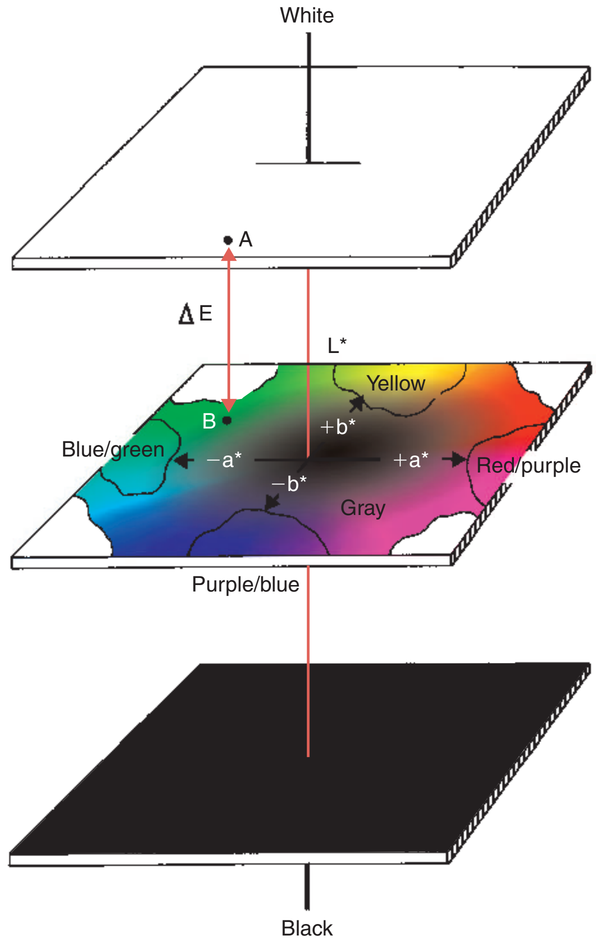


Fig. 23.3 Commission Internationale de l'Éclairage L*a*b* (CIELAB) color space. Any color can be defined in terms of these coordinates. L* (the vertical axis) defines the lightness or darkness of the color and corresponds to Value in the Munsell system; a* and b* define the chromatic characteristics. The color difference (ΔE) between two colors (A and B) can be calculated from the sum of the squares of the differences among the three coordinates. The system is arranged so that a color difference of 1 is perceivable by 50% of observers with normal color vision. (From Rosenstiel SF, Johnston WM. The effect of manipulative variables on the color of ceramic metal restorations. *J Prosthet Dent*. 1988;60:297. Dong JK, Jin TH, Cho HW, et al. The esthetics of the smile: a review of some recent studies. *Int J Prosthodont*. 1999;12:9.)

color are represented in the Munsell system by Hue and Chroma and in the CIELab system by a* and b*. In each system, these two coordinates define the location of color on a plane of given lightness, such as the one depicting color *B* in Fig. 23.3. In the Munsell system, the color is identified by one polar coordinate (Hue) and one linear, or Cartesian[a] coordinate (Chroma); in the CIELab system, both coordinates (a* and b*) are Cartesian. For an analogy, consider how the location of a house in a city might be described. It could be said that someone lived a distance of 11.85 miles (linear coordinate) in the north-northwest direction (polar coordinate) from downtown. This is analogous to describing a color in the Munsell system. The identical location could also be defined as being 10.6 miles north and 5.3 miles west of downtown (two Cartesian coordinates) (Fig. 23.4). This is analogous to a CIELab description of a color. The descriptions represent the same location in space. However, unlike the Munsell coordinates, the CIELab coordinates define the color space in approximately uniform steps of human color perception. This means that equal distances across the CIELab color space (color differences, or ΔE) represent approximately equally perceived shade gradations, an arrangement that makes interpretation of color measurements more meaningful.

[a] From the Latin form of René Descartes (1596–1650), the French philosopher and mathematician.

L*

L* is a lightness variable proportional to Value in the Munsell system. It describes the achromatic character of the color.

a* and b*

The a* and b* coordinates describe the chromatic characteristics of the color. Although they do not correspond directly to Munsell's Hue and Chroma, they can be converted by numerical parameters (see Fig. 23.3).[8] The a* coordinate corresponds to the red-purple/blue-green axis in the Munsell color space. A positive a* relates to a predominantly red-purple color, whereas a negative a* denotes a color that is more blue-green. Similarly, the b* coordinate corresponds to the yellow/purple-blue axis. ΔE for the CIELAB formula is defined by the following equation:

$$\Delta E_{ab} = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}$$

There have been recent research efforts to determine a more ideal color difference formula for use in dentistry to allow improved correlation of perceptibility and acceptability to instrumental color difference value. In 2001, a new CIE 2000 color difference formula was adopted as the new CIE color difference formula.[9] The new equation is based on the CIELab and also includes chroma, lightness, and hue weighting functions, as well as an interactive term between hue and chroma differences, for improving the performance for blue, and a scaling factor CIELab a* scale for improving the performance for gray. The equation is:

Fig. 23.4 Locations in space can be defined in polar *(dashed line)* or Cartesian *(solid lines forming right angle)* coordinates.

$$= \sqrt{\left(\frac{\Delta L}{k_L S_L}\right)^2 + \left(\frac{\Delta C}{k_C S_C}\right)^2 + \left(\frac{\Delta H}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C}{k_C S_C}\right)\left(\frac{\Delta H}{k_H S_H}\right)}.$$

The R_T, S_L, S_C, and S_H terms are weighting factors for this formula. The three K terms are additional weighting factors that were each set to 1 in this study. The CIEDE2000 formula has been shown to provide a better fit to the calculated color difference, therefore providing better indicators of human perceptibility or color difference between tooth color compared to the CIELab[10] (or the $CMC_{(l:c)}$)[b] color difference formulae.[11] Sharma et al.[12] and the associated website (http://www.ece.rochester.edu/~gsharma/ciede2000/) may be very helpful in calculating CIEDE2000 color differences and getting more recent information about this newly recommended formula.

COLOR REPLICATION PROCESS

In this chapter, the process in which the color of adjacent teeth is replicated in a metal-ceramic or ceramic crown is termed the *color replication process*. The color replication process for fixed restorations (Fig. 23.5) consists of the shade-matching phase, followed by a shade-duplication phase. Shade matching can be accomplished through either visual shade matching or the increasingly popular instrumental analysis. The shade duplication takes place in the dental laboratory, in which either the corresponding porcelain, selected in the shade-duplication phase, or more sophisticated porcelain mixtures are used to fabricate the fixed restoration. If differences between the definitive restoration and the originally matched restoration are visually perceptible, it is possible for the clinician to apply surface characterization porcelains to the restoration to adjust any color discrepancy.

SHADE-MATCHING PHASE

This phase occurs in the dentist's office, in which the information on the color and translucency of the adjacent teeth to be matched is recorded through either visual shade matching or instrumental color analysis.

[b] Named for the Colour Measurement Committee of the Society of Dyers and Colourists.

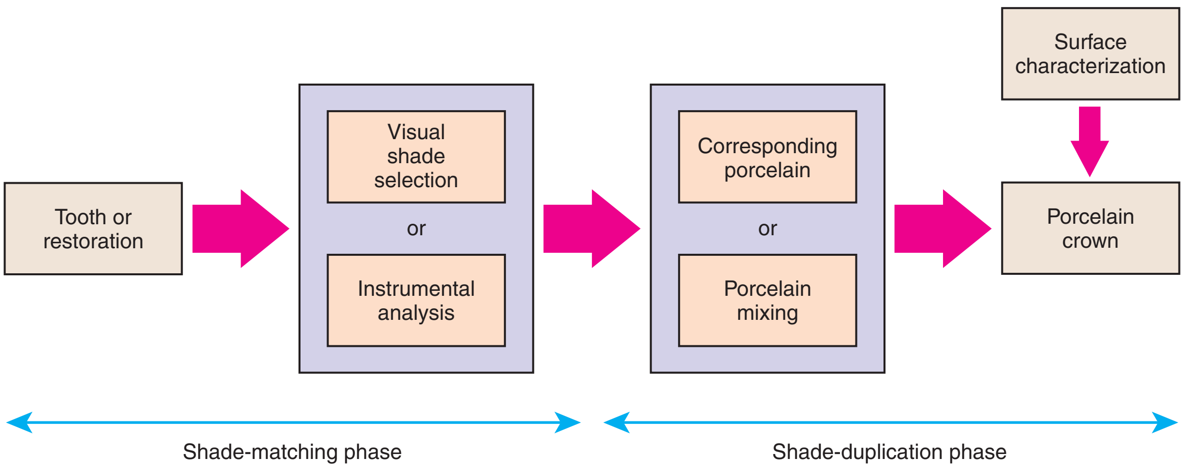


Fig. 23.5 Color replication process for fixed restorations.

Visual Shade Matching

Visual assessment of the shade and translucency is the method most frequently applied in dentistry.[13] Studies have shown that this often-used method is difficult to apply with accuracy and often yields unreliable and inconsistent results.[14,15] Fortunately, a lifelike and successful restoration does not have to be an exact duplicate of the color and translucency of the adjacent teeth. It should, however, blend with the teeth as a result of the distribution of ceramic materials in the restoration. The apparent color of an object is influenced by its physical properties, by the nature of the light to which the object is exposed, and by the subjective assessment of the observer; however, the variability of two of the three factors (e.g., lighting and subjectivity of the observer) can cause the same object (e.g., tooth) to look very different. By understanding the three main factors (lighting, subjectivity of human vision, and the object) that influence the outcome of visual shade matching, the dentist can improve the accuracy and reliability of this process.

Lighting

Light is necessary for color to exist. An object that is perceived as a certain color absorbs all light waves corresponding to other colors and reflects only the waves of the object's color. For example, an object that absorbs blue and green light and reflects red light appears red. The quality and quantity of the light source and the environment in which the teeth and shade guides are being visually matched are important.

Although daylight was initially thought to be the ideal light source for color matching,[14] its use is not recommended, in view of inconstant color characteristics. The color of daylight can vary from red-orange at sunset to blue when the sky is clear. The relative intensity of daylight also fluctuates with cloud cover.[16] An ideal light source for visual shade matching is one that is diffuse and comfortable for the eyes, allowing observers to assess the color accurately and comfortably.[16] In one study, evaluators obtained better visual shade matching in controlled stable, constant, and standard full-spectrum lighting than in daylight.[17]

Description of light. Scientifically, light is described as visible electromagnetic energy whose wavelength is measured in nanometers, or billionths of a meter. The eye is sensitive only to the visible part of the electromagnetic spectrum, a narrow band with wavelengths from 380 to 750 nm. At the shorter wavelengths are ultraviolet rays, x-rays, and gamma rays; at the longer wavelengths are infrared radiation, microwaves, and television and radio transmission waves (Fig. 23.6).

Pure white light consists of relatively equal quantities of electromagnetic energy over the visible range. When white light is passed through a prism (Fig. 23.7), it is split into its component colors because the longer wavelengths are bent (refracted) less than the shorter ones.

Quality of light source. A light source of the appropriate quality should be used during visual shade matching. The appropriate color temperature with appropriate spectral energy distribution and color-rendering index (CRI) must be considered in the selection of a light source.

A light source with a color temperature close to 5500 K (D55) that is spectrally balanced throughout the visible spectrum is ideal for color matching. Color temperature is related to the color of a standard black body when heated and is reported in degrees Kelvin (K; 0 = −273°C). Accordingly, 1000 K is red; 2000 K is yellow; 5555 K is white; 8000 K is pale blue. D65 (Fig. 23.8) is considered to be the true color temperature of white light as perceived by human observers.[18] D65 is commonly used in dental shade matching as the standard lighting for visual shade matching. A light source with a CRI greater than 90 is recommended for shade matching.[19] The CRI, on a scale of 1 to 100, indicates how well a particular light source renders color in comparison with a specific standard source. Dental personnel's shade-matching ability on a designed color test[20] was significantly better with a full-spectrum light source of

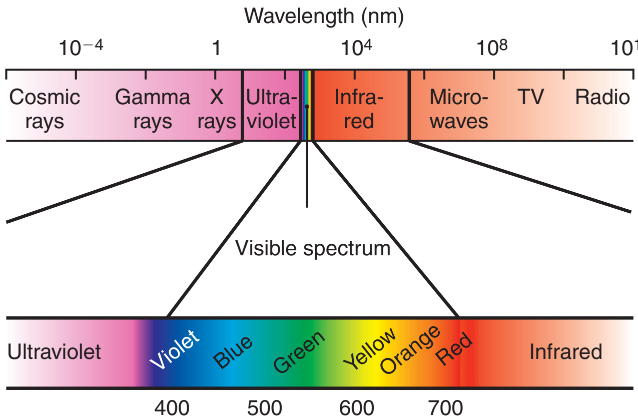


Fig. 23.6 Electromagnetic energy spectrum. One nanometer (nm) is 10^{-9} meter (m).

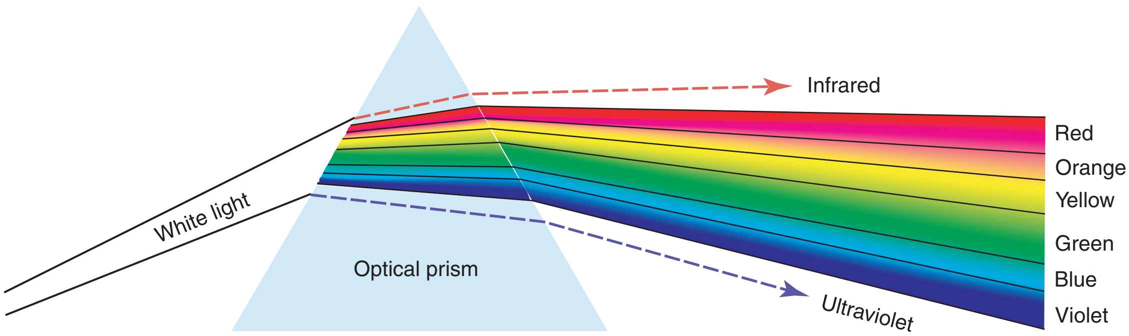


Fig. 23.7 A prism bends or refracts long wavelengths of light less than shorter wavelengths, thereby separating the colors.

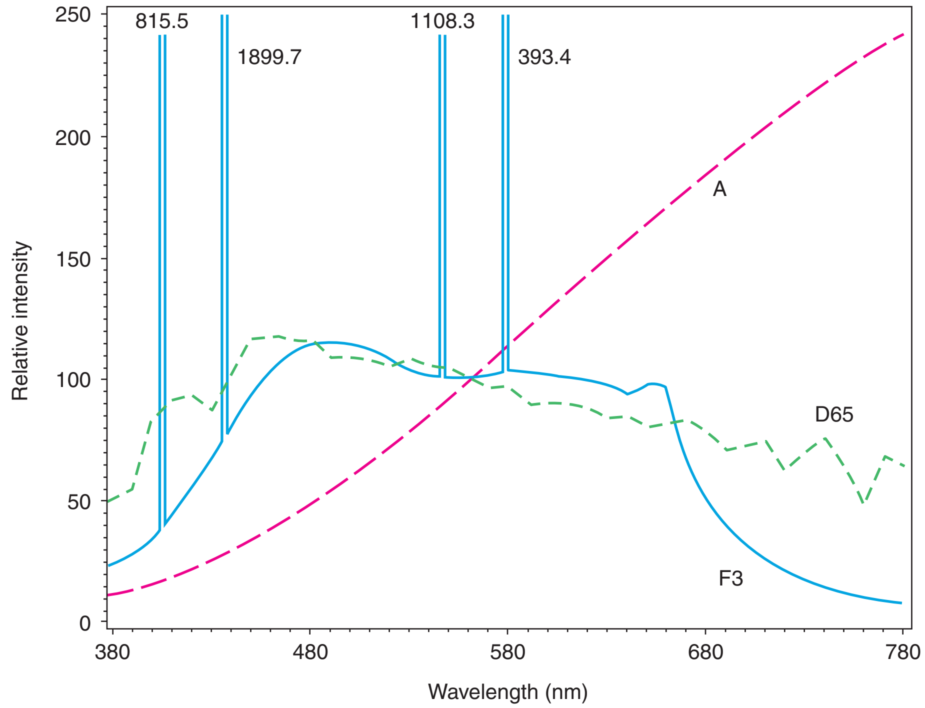


Fig. 23.8 Relative intensity versus wavelength of three light sources: D65 illuminant is relatively balanced; A illuminant (tungsten filament) has high amounts of orange and red wavelengths; F3 illuminant (fluorescent tube light) has peaks of blue and yellow wavelengths.

5700 K (CRI = 91) than with light sources of 6000 K (CRI = 93), 4200 K (CRI = 65), and 7500 K (CRI = 94).[21]

Unfortunately, the most common light sources in dental operatories are incandescent and fluorescent, neither of which is ideal for shade matching. An ordinary incandescent light bulb emits relatively higher concentrations of yellow light waves than of blue and blue-green light waves, whereas fluorescent ceiling fixtures give off relatively high concentrations of blue waves. The quality of the lighting used to carry out visual shade matching in 32 private dental practices in the Midwestern region of the United States were measured with an illuminance spectrophotometer (Konica Minolta CL-500A). The average color temperature and CRI was found to be 4089.3 K (SE = 131.66) and 82.8 K (SE = 1.39) respectively (unpublished data). Color-corrected fluorescent lighting is recommended because it approaches the necessary type of balance. Recommended commercial color-corrected ambient lighting, ideal for shade matching, for the dental operatory is described in Table 23.1.

Quantity of light source. Appropriate intensity of the ambient lighting in the dental operatory provides the dentist with visual comfort, particularly in terms of contrast. It is recommended that the light intensity be between 2000 and 3200 lux[c] for the dental operatory and 28 lux for the dental laboratory.[22] The intensity of the dental operatory lighting has not been found to be crucial for color matching when the light intensity ranges from 800 to 3200 lux.[23]

Auxiliary light sources. If ambient lighting in the dental operatory is not ideal in terms of quality and quantity for visual shade matching, the use of auxiliary lighting is recommended. The auxiliary light source for shade matching should be intense enough to overcome the influence of the ambient light. It has been recommended that the ratio of task (shade matching) to ambient light should not exceed 3:1; too much intensity does not allow discrimination of small color differences.[22] Commercial auxiliary lighting, such as the Demetron Shade Light (Kerr Corp.) or the Smile Lite (Smile Line), (Fig. 23.9) which comes with a polarizing filter to reduce specular reflectance, is recommended for shade matching (see Table 23.1).

Shade-matching environment. The ambient and direct lighting used for shade matching scatters and reflects from surfaces before reaching the structure that it illuminates. The colors of the dental operatory, the clothing of the dentist and dental assistants, the patient's clothing, and the dental drape may influence the perceived color of the patient's teeth and shade guide.[24] To maintain the necessary lighting quality for shade matching, the chroma of the environment should be carefully controlled. It is recommended that the walls, staff clothing, patient drape, and shade-matching environment have a Chroma of four Munsell units or less, which are the pastel[22] or the ideal neutral gray tones.[25] Among the further recommendations is that the ceiling have a Munsell Value of 9. All other major reflectors (e.g., walls, cabinets) should present at least a Munsell Value of 7 and a Munsell Chroma of no more than 4. Countertops not within the working area can have a Munsell Chroma of up to 6 but a Munsell Value retained at 7 or greater.[26]

[c] Lux is a unit of illumination, equal to 1 lumen per square meter; it was originally based on the illumination provided by a household candle at a distance of 1 m.

TABLE 23.1 Examples of Commercial Balanced Lighting Available

Product Name	Manufacturer	Type	CRI	CCT (°K)	Estimated Life (hours)
CRS Light	CRS Light, Cleveland, Ohio	Fluorescent tube	91	5750	20,000
Full Spectrum, Supreme	NaturalLighting.com, Houston, Texas	Compact fluorescent tube	96	5000	20,000
Lumichrome 1XX	Lumiram, White Plains, New York	48-inch fluorescent tube	98	6500	24,000
Lumichrome 1XZ	Lumiram, White Plains, New York	24-inch fluorescent tube	95	5700	24,000
Demetron Shade Light	Kerr Corporation, Orange, California	Handheld fluorescent tube (3 h battery life)	93	6500	20,000
Shade Wand	Authentic Products, Inc., San Antonio, Texas	Handheld fluorescent tube	—	5500	—
Hand Held	Great Lakes Lighting, Bay City, Michigan	Handheld fluorescent tube	94	—	9000
Base Light	Tri-Shade Matching Light, China	Handheld LED	92	5500 3200 3900	—
Smile Lite	Smile Line USA, Inc Wheat Ridge, CO	Handheld LED	—	5500	
Vita-Lite	Duro-Test Lighting, Inc., Philadelphia, Pennsylvania	Handheld fluorescent tube	91	5500	10,000–28,000
Light-A-Lux (40-watt T-12)	American Environmental Products, Fort Collins, Colorado	Compact fluorescent tube	90	5900	20,000
Super Daylite (32-watt T-8)	American Environmental Products, Fort Collins, Colorado	Compact fluorescent tube	98	6500	20,000
Super Daylite (40-watt T-12)	American Environmental Products, Fort Collins, Colorado	Compact fluorescent tube	96	5000	20,000
Super 10,000 Lux (40-watt T-10)	American Environmental Products, Fort Collins, Colorado	Compact fluorescent tube	91	5000	20,000
F40/C50/RS/WM	General Electric Company, GE Lighting, Cleveland, Ohio	48-inch fluorescent tube	90	5000	20,000

CCT, Correlated color temperature; *CRI*, color-rendering index.
Data from Wee AG. Color matching: color matching conditions. In: Paravina RD, Powers JM, eds. *Esthetic Color Training in Dentistry*. St. Louis: Mosby; 2004; and from Paravina RD. *Personal Communication*. 2004.

Fig. 23.9 The Smile Lite. (Courtesy Smile Line, Switzerland.)

Human Vision

Light from an object enters the eye and acts on receptors in the retina (rods and cones). Impulses from these are passed to the optical center of the brain, where an interpretation is made. Shade matching is therefore subjective: different individuals have different interpretations of the same stimulus.

The eye. Under low lighting conditions, only the rods are used (scotopic vision). These receptors allow the brightness (but not the color) of objects to be interpreted. The rods are most sensitive to blue-green objects. Color vision is dependent on the cones, which are active under higher lighting conditions (photopic vision). The change from photopic to scotopic vision is called *dark adaptation* and takes about 40 minutes.[27]

The area with the most cones is in the center of the retina, which is free of rods. The rods predominate toward the periphery. This means that the central field of vision is more color perceptive. Although the exact mechanism of color vision is not known, there are three types of cones—sensitive to red, green, and blue light[28]—that form an image in much the same way as the additive effect of the pixels in a television picture.

Color adaptation. Color vision decreases rapidly as a person stares at an object. The original color appears to become less and less saturated until it appears almost gray.

Deceptive color perception. The brain can be tricked in how it perceives color. A classic example of such a trick is the Benham disk (Fig. 23.10). When this black and white disk is illuminated and rotated at an appropriate speed, it appears to be highly colored.

Color is also influenced by surrounding colors, particularly complementary ones (those diametrically opposed in Fig. 23.1). For example, when blue and yellow are placed side by side, their chroma may appear to be increased. The color of teeth can also look different if the patient is wearing brightly colored clothing or lipstick (Fig. 23.11).

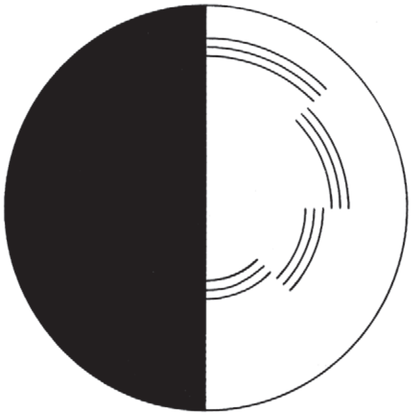


Fig. 23.10 The Benham disk. When it rotates, red, green, and blue rings are seen. The order of the colors is reversed if the disk rotates in the opposite direction. This is a purely sensory phenomenon caused by afterimages.

Metamerism. Two colors that appear to be a match under a given lighting condition but have different spectral reflectance (Fig. 23.12) are called *metamers*, and the phenomenon is

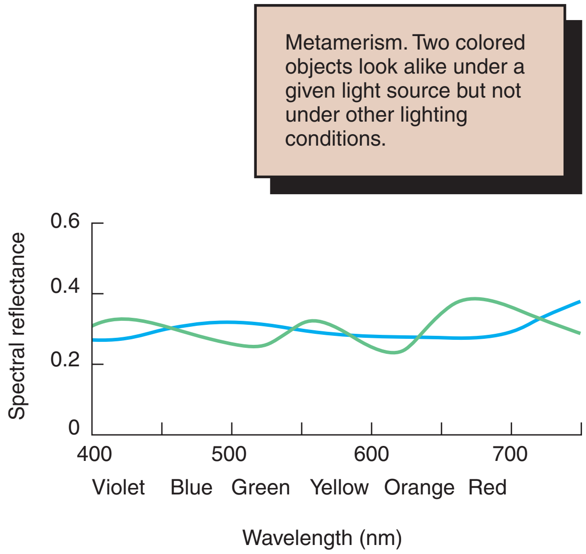


Fig. 23.12 Spectral reflectance curves of a metameric pair. The two objects represented appear to match under some lighting conditions but not under others.

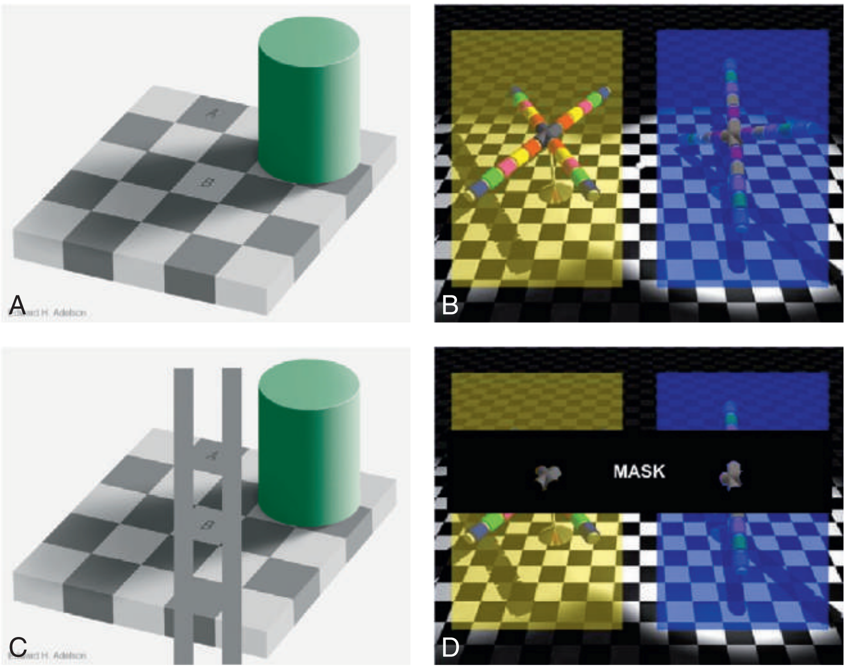


Fig. 23.11 (A) The checker shadow illusion. The squares marked *A* and *B* are the same shade of gray. For proof, see part (C). (B) The colored cross illusion. The central elements of the two *X*-shaped objects appear very different in color but are, in fact, exactly the same. For proof, see part (D). (C) The checker shadow Illusion. The original image in part (A) plus two stripes. When the squares marked *A* and *B* are joined with two vertical stripes of the same shade of gray, it becomes apparent that both squares are the same. (D) When a mask that isolates the central elements from the surrounding colors is placed, the illusion is revealed. As with many so-called illusions, both of these effects really demonstrate the success rather than the failure of the visual system. The visual system is not very good at being a physical light meter, but that is not its purpose. The important task is to break the image information down into meaningful components, thereby allowing the nature of the objects in view to be perceived. However, when appropriate tooth shades are selected, it is important not to be influenced by the surrounding colors. (A and C, Courtesy Dr. E.H. Adelson. B and D, Courtesy Dr. R.B. Lotto.)

known as *metamerism*. For example, two objects that appear to be an identical shade of yellow may absorb and reflect light differently. Yellow objects normally reflect yellow light, but some may actually absorb yellow light and reflect orange and green. To an observer, the orange and green combination looks yellow, although when the lighting is changed, the metamers no longer match. This means that a sample that appears to match under the operatory light, for example, may not be satisfactory in daylight. The dentist can avoid the problem of metamerism by selecting a shade and confirming it under different lighting conditions (e.g., color-corrected and fluorescent light).

Fluorescence. Fluorescent materials, such as tooth enamel, re-emit radiant energy at a frequency lower than that absorbed.[29] For example, ultraviolet radiation is re-emitted as visible light. In theory, a mismatch can occur if the dental restoration has different fluorescence than the natural tooth. In practice, fluorescence does not play a significant role in color matching dental restorations.[30]

Opalescence. Natural teeth, particularly at their incisal edges, exhibit a light-scattering effect[d] that creates the appearance of bluish-white colors as the teeth are seen at different angles. This is similar to the bluish-white background seen in opal gemstones (hence the term *opalescence*). Manufacturers try to match this effect when formulating dental porcelains.[31,32]

Color blindness. Defects in color vision (color blindness) affect about 8% of the male population and fewer in the female population.[33] Different types exist, such as achromatism (complete lack of hue sensitivity), dichromatism (sensitivity to only two primary hues; usually either red or green is not perceived), and anomalous trichromatism (sensitivity to all three hues with deficiency or abnormality of one of the three primary pigments in the retinal cones). Dentists should therefore have their color perception tested. If any deficiency is detected, the dentist should seek assistance when selecting tooth shades.[34]

Shade Selection Systems

The most convenient method for selecting a shade is a commercially available porcelain shade guide (Fig. 23.13). Table 23.2 presents color measurement values made from VITA classical (Lumin Vacuum), Ivoclar Vivadent Chromascop, and VITA Toothguide 3D-MASTER guides with a spectroradiometer. Each shade tab (Fig. 23.14) has an opaque backing color, a neck color, a body color, and an incisal color. Shade matching consists of selecting the shade tab that looks the most natural and reproducing this color in a laboratory with materials and techniques recommended by the manufacturer. The procedure is more straightforward if specimens of the same hue are grouped together in the shade guide. In the past, shade guides were produced in response to the demand for denture teeth rather than on the range of natural tooth color.[35] More recently, shade guides have covered the color space occupied by natural teeth,[e] such as the VITA Toothguide 3D-MASTER (see Fig. 23.13C). In one study, this shade guide resulted in the lowest coverage

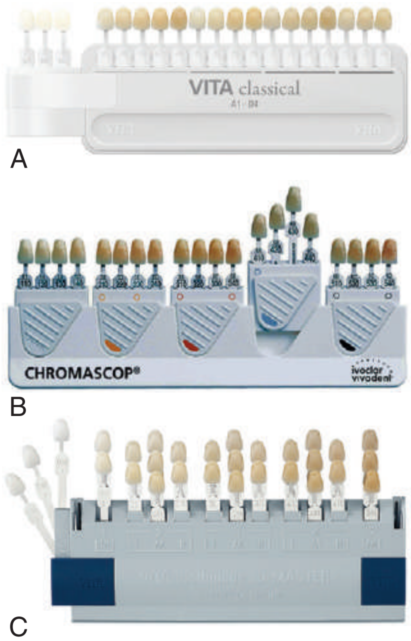


Fig. 23.13 Commercial shade guides. (A) The VITA classical (Lumin Vacuum) shade guide. (B) Ivoclar Vivadent Chromascop shade guide. (C) VITA Toothguide 3D-MASTER. (A and C, Courtesy VITA North America, Yorba Linda, California. B, Courtesy Ivoclar Vivadent, Amherst, New York.)

error ($\Delta E = 3.93$)[36] in comparison with VITA classical (Lumin Vacuum) ($\Delta E = 5.39$) or Chromascop shade guides ($\Delta E = 5.28$).[37] The VITA Toothguide 3D-MASTER did not differ significantly from the coverage errors of the combination of all three shade guides ($\Delta E = 3.69$).

VITA classical (Lumin Vacuum) shade guide: Hue matching. In the popular VITA classical (Lumin Vacuum) shade guide (see Fig. 23.13A), A1, A2, A3, A3.5, and A4 (Reddish Brown) are similar in hue, as are the B (Reddish Yellow), C (Grayish), and D (Reddish Gray) shades. Spectroradiometric measurement of 359 nonrestored vital unbleached dentition and the VITA classical (Lumin Vacuum) shade guide demonstrates the frequency distribution of the shade guide (Fig. 23.15).[37] One study revealed that A3 was the most common shade tab selected.[38] Choosing the nearest hue first and then selecting the appropriate match of chroma and value from the tabs available is the recommended technique.

If the chroma or intensity is low, accurately determining a given hue may be difficult. Therefore, the region with the highest chroma (i.e., the cervical region of canines) should be used for initial hue selection (Fig. 23.16A).

Chroma selection. Once the hue is selected, the best chroma match is chosen. For example, if a B hue is determined to be the best match for color variety, four gradations (tabs) of that hue are available: B1, B2, B3, and B4 (see Fig. 23.16B). Several comparisons are usually necessary for determining which sample best represents the hue and its corresponding chroma (saturation) level. Between comparisons, glancing at a gray object rests the operator's eyes and helps avoid retinal cone fatigue.

[d] Called *Mie scattering* after Gustav Mie (1868–1957), German physicist.

[e] Shades that match artificially bleached teeth are also available.

TABLE 23.2 CIELAB Values: Shade Guides Measured With Spectroradiometer With 45 Degree Illumination and 0 Degree Observer Without an Aperture

Shade Guide	Tab	L*	a*	b*
VITA Toothguide 3D-MASTER	1M1	83.1 (0.9)	−0.1 (0.3)	12.5 (0.4)
	1M2	84.0 (0.8)	−0.2 (0.5)	18.8 (0.9)
	2L1.5	79.0 (1.0)	0.0 (0.2)	18.5 (0.2)
	2L2.5	79.5 (0.8)	0.2 (0.2)	24.5 (0.7)
	2M1	78.0 (0.6)	0.8 (0.3)	14.0 (0.6)
	2M2	78.7 (0.6)	0.9 (0.4)	19.9 (0.5)
	2M3	79.2 (0.8)	0.7 (0.2)	25.3 (0.4)
	2R1.5	77.8 (1.0)	1.5 (0.2)	16.3 (0.7)
	2R2.5	79.5 (1.1)	1.7 (0.3)	23.3 (0.6)
	3L1.5	73.1 (0.9)	1.5 (0.2)	20.3 (0.4)
	3L2.5	73.9 (1.1)	1.9 (0.2)	26.2 (0.8)
	3M1	73.4 (0.6)	1.8 (0.3)	15.4 (0.5)
	3M2	74.6 (1.0)	2.0 (0.4)	21.5 (0.8)
	3M3	75.0 (1.4)	2.6 (0.2)	27.9 (0.8)
	3R1.5	73.4 (1.1)	2.7 (0.3)	17.9 (0.6)
	3R2.5	73.6 (1.0)	3.5 (0.3)	25.9 (0.7)
	4L1.5	69.2 (0.8)	2.8 (0.3)	21.7 (0.3)
	4L2.5	69.1 (0.8)	3.7 (0.4)	28.5 (0.7)
	4M1	68.3 (0.9)	2.9 (0.2)	17.0 (0.5)
	4M2	70.1 (1.4)	3.7 (0.4)	23.7 (0.6)
	4M3	69.5 (0.7)	4.8 (0.3)	30.7 (0.4)
	4R1.5	69.6 (0.6)	4.3 (0.2)	20.8 (0.3)
	4R2.5	69.2 (1.1)	5.1 (0.2)	26.3 (0.4)
	5M1	64.4 (0.6)	4.2 (0.2)	19.4 (0.5)
	5M2	65.1 (1.0)	5.7 (0.2)	26.3 (0.8)
	5M3	65.9 (0.5)	7.0 (0.4)	33.4 (1.3)
Ivoclar Vivadent Chromascop	110	82.5 (1.0)	0.1 (0.1)	18.3 (0.3)
	120	80.2 (1.8)	0.7 (0.1)	19.7 (0.6)
	130	78.2 (0.8)	0.1 (0.1)	20.2 (0.5)
	140	78.9 (1.1)	1.6 (0.2)	23.7 (0.5)
	210	77.4 (1.5)	1.8 (0.1)	25.6 (0.8)
	220	76.4 (2.5)	3.4 (0.0)	23.4 (0.7)
	230	74.7 (1.8)	3.7 (0.2)	25.6 (0.9)
	240	73.8 (0.6)	5.6 (0.1)	28.2 (0.5)
	310	73.6 (1.0)	1.2 (0.1)	28.1 (0.7)
	320	71.4 (1.6)	2.7 (0.1)	28.2 (0.8)
	330	71.5 (1.4)	3.4 (0.1)	31.1 (0.5)
	340	68.3 (2.0)	4.9 (0.2)	28.9 (0.8)
	410	73.5 (1.2)	2.2 (0.2)	20.2 (0.7)
	420	72.1 (0.9)	1.7 (0.1)	20.5 (0.3)
	430	72.2 (0.9)	0.6 (0.1)	20.8 (0.7)
	440	69.1 (1.0)	0.9 (0.1)	21.1 (0.3)
	510	69.9 (1.5)	1.9 (0.1)	22.5 (0.6)
	520	67.6 (1.0)	2.7 (0.2)	24.7 (0.9)
	530	67.2 (0.2)	3.4 (0.1)	26.8 (1.0)
	540	64.0 (1.2)	7.6 (0.1)	26.2 (0.6)

Continued

TABLE 23.2 CIELAB Values: Shade Guides Measured With Spectroradiometer With 45 Degree Illumination and 0 Degree Observer Without an Aperture—cont'd

Shade Guide	Tab	L*	a*	b*
VITA classical (Lumin Vacuum)	A1	82.4 (1.9)	−1.4 (0.4)	14.3 (0.7)
	A2	79.1 (1.1)	0.6 (0.3)	19.2 (0.5)
	A3	77.6 (0.9)	1.0 (0.3)	21.0 (0.9)
	A3.5	73.4 (1.2)	2.3 (0.1)	24.5 (0.6)
	A4	69.0 (0.9)	2.4 (0.6)	25.4 (0.8)
	B1	80.1 (2.3)	−1.9 (0.5)	12.6 (0.9)
	B2	80.1 (2.2)	−1.0 (0.5)	18.2 (1.0)
	B3	74.8 (1.4)	0.9 (0.5)	25.0 (0.9)
	B4	75.5 (2.7)	1.0 (0.2)	26.1 (1.8)
	C1	76.6 (0.9)	−0.7 (0.2)	14.2 (0.8)
	C2	72.7 (0.4)	0.2 (0.3)	20.0 (0.4)
	C3	70.5 (0.9)	0.8 (0.1)	19.1 (0.5)
	C4	64.2 (1.2)	2.6 (0.2)	22.1 (0.5)
	D2	74.9 (1.5)	−0.4 (0.4)	13.2 (0.8)
	D3	74.7 (2.6)	1.1 (0.4)	18.3 (0.9)
	D4	73.5 (0.7)	−0.6 (0.2)	21.1 (0.5)

From Bayindir F, Kuo S, Johnston WM, et al. Coverage error of three conceptually different shade guide systems to vital unrestored dentition. *J Prosthet Dent.* 2007;98:175.

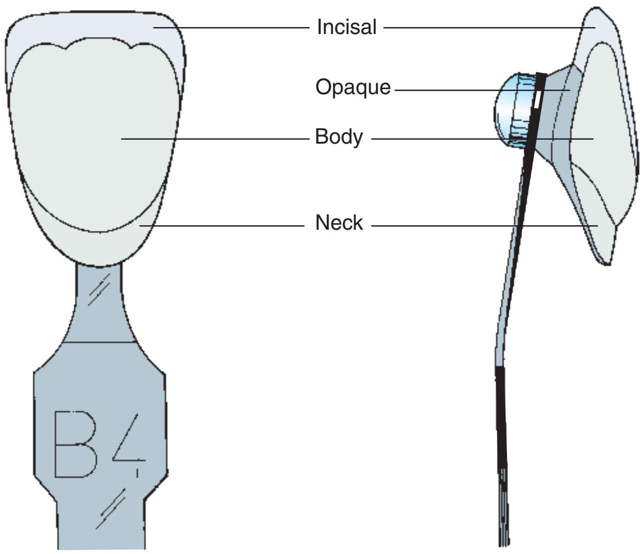


Fig. 23.14 Illustration of porcelain shade sample.

Value selection. Finally, value is determined with a second commercial guide whose samples are arranged in order of increasing lightness (see Fig. 23.16C). (The lightness readings—L* in Table 23.2—can be used as a guide to the sample sequencing.) By holding the second shade guide close to the patient, the operator should be able to determine whether the value of the tooth is within the shade guide's range. Attention is then focused on the range of shade that best represents the value of the tooth and how that range relates to the tab, matching for hue and saturation. An observer is able to assess the value most effectively by observing from a distance, standing slightly away from the chair, and squinting the eyes. By squinting, the observer can reduce the amount of light that reaches the retina. Stimulation of the cones is reduced, and a greater sensitivity to achromatic conditions may result.[39] While squinting, the observer concentrates on which disappears from sight first: the tooth or the shade tab. The one that fades first has the lower value.

When the proper value selection has been made, it is the exception rather than the rule for this to coincide with the determinations for hue and chroma. The operator must decide whether to change the previously selected shade sample. If the independent value determination is lower than the value of the sample selected for hue and chroma, a change is usually necessary because increasing the value of an object by adding surface stain (which always reduces brightness) is not possible. If the value determination is higher than the hue determination, the operator should decide whether this difference can be bridged through internal or surface characterization of the restoration. The final decisions about hue, chroma, and value are then communicated to the laboratory.

VITA Toothguide 3D-MASTER (VITA North America)

The manufacturer of this shade system (Fig. 23.17A) claims that it covers the entire tooth color space. The shade samples are grouped in six lightness levels, each of which has chroma and hue variations in evenly spaced steps (see Fig. 23.17B).

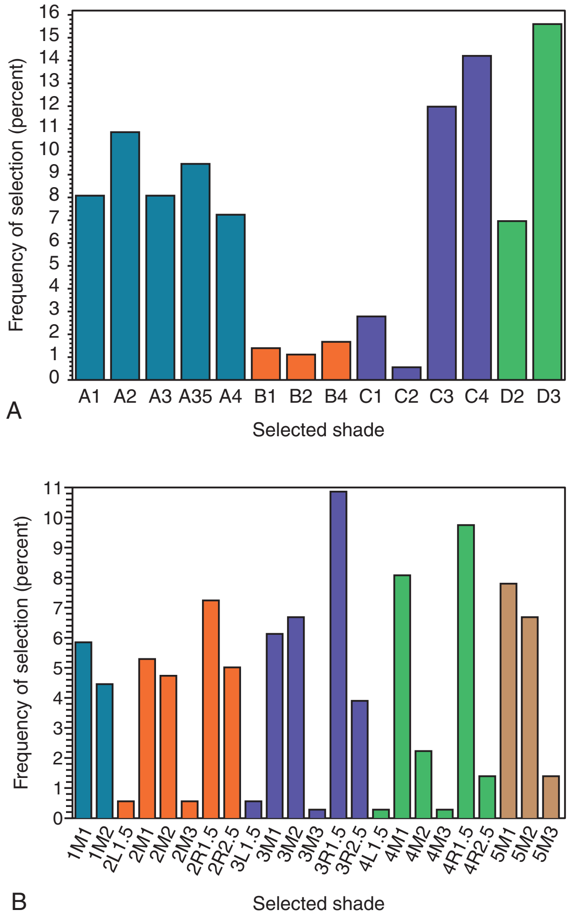


Fig. 23.15 (A) Frequency of selection for the VITA classical (Lumin Vacuum) shade guide. (B) Frequency of selection for the VITA Toothguide 3D-MASTER. (From Bayindir F, Kuo S, Johnston WM. Coverage error of three conceptually different shade guide systems to vital unrestored dentition. *J Prosthet Dent.* 2007;98:175.)

The shade guide is spaced in steps (ΔE) of four CIELab units in the lightness dimension and two CIELab units in the hue and chroma dimensions. The difference between lightness and color steps seems a logical approach to reducing the number of shade samples needed in the guide because of the way the CIELAB units are visually perceived. It seems to match the color difference formula of the Colour Measurement Committee of the Society of Dyers and Colourists.[40] Because the guide is evenly spaced, intermediate shades can be predictably formulated by combinations of porcelain powders.[41] Spectroradiometric measurement of 359 nonrestored vital unbleached dentition and the VITA Toothguide 3D-MASTER demonstrates the frequency distribution of the shade guide (see Fig. 23.15B).[37] This study revealed that 3R1.5 was the most common shade tab selected.

The manufacturer recommends selecting the lightness (see Fig. 23.17D) first, then chroma (see Fig. 23.17E), and finally the hue (see Fig. 23.17F). A form is available to facilitate the laboratory shade prescription, which can include intermediate steps

The VITA Linearguide 3D-MASTER was also introduced subsequently (see Fig. 23.17G); it has the same shade tab, but it is presented in a more simplified manner. This is a two-step process compared to a three-step process that was proposed for the VITA Toothguide 3D-MASTER. The VITA Linearguide 3D-MASTER contains one VITA Valueguide 3D-MASTER and five VITA Chroma/Hueguide 3D-MASTER. The first step is to use the VITA Valueguide 3D MASTER to select the value of the tooth to be matched (0M2, 1M2, 2M2, 3M2, 4M2 and 5M2). The second step would be to use the VITA Chroma/Hueguide 3D-MASTER (e.g., 2M1, 2L1.5, 2R1.5, 2M2, 2L2.5, 2R2.5 and 2M3) to select the actual shade. One study found the VITA Linearguide 3D-MASTER not only

Fig. 23.16 Shade matching with the use of the VITA classical (Lumin Vacuum) shade guide. (A) Selecting hue by matching samples with high chroma (e.g., A4, B4, C4, or D3) to a tooth with high chroma (i.e., canine). (B) Selecting chroma from within the hue group (e.g., B1, B2, B3, or B4). (C) Value-ordered shade guide is used to check lightness. (C, Courtesy VITA North America, Yorba Linda, California.)

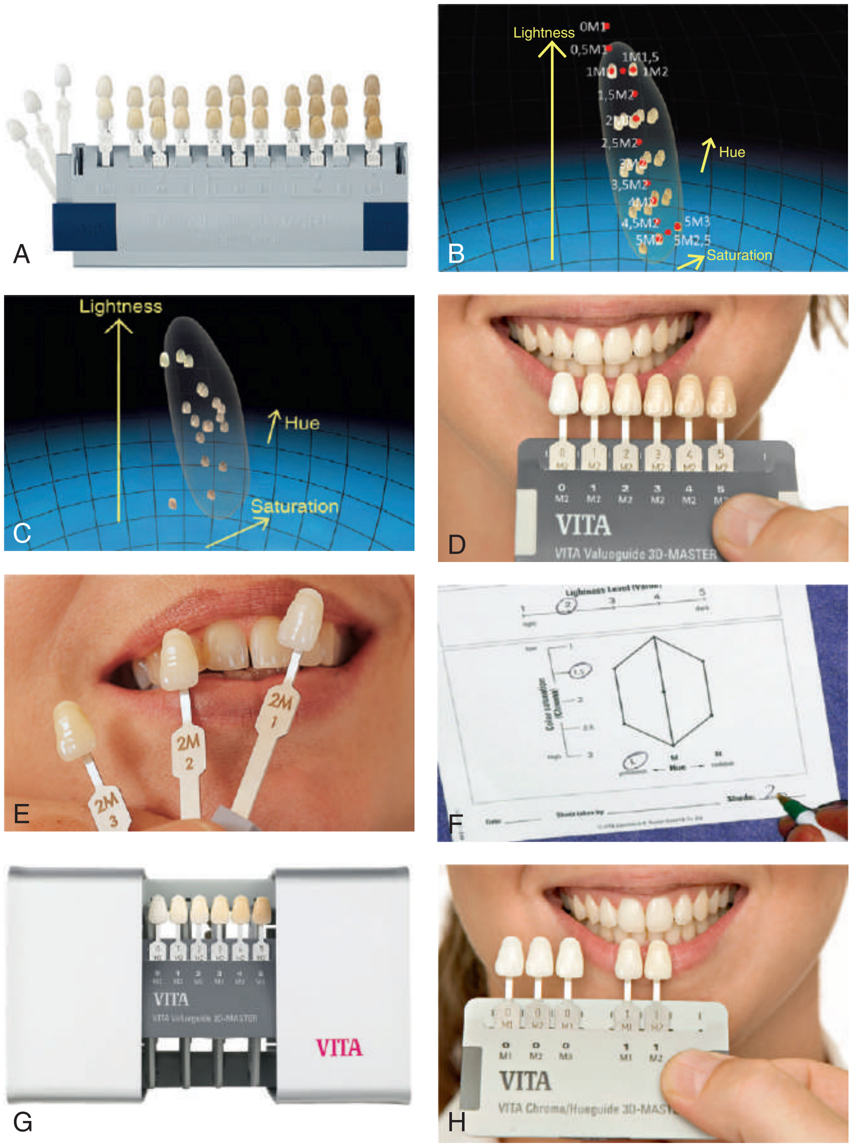


Fig. 23.17 Shade selection with the VITA Toothguide 3D-MASTER. (A) The shade guide is arranged in five lightness levels (plus an additional level for bleached teeth). (B) Each lightness level has sufficient variations in chroma and hue to cover the natural tooth color space. (C) This is in contrast to traditional shade guides, which are not uniformly spaced. Lightness is selected first (D), then chroma or saturation (E), and finally hue. (F) The color communication form allows convenient laboratory shade prescription and intermediate shades if necessary. (G) The system is also available in a linear arrangement. In this arrangement, the dentist first selects from five value tabs (H) and then chooses the appropriate mix of chroma and hue within the selected value range. (Courtesy VITA North America, Yorba Linda, California.)

had a better subjective evaluation compared to Toothguide 3D-MASTER and Vitapan Classical, but also enabled significantly better shade matching results than the Toothguide 3D-MASTER.[42]

Extended-Range Shade Guides

Most commercial shade systems cover a range more limited than the colors found in natural teeth, and the steps in the guide are greater than can be perceived visually.[43] Some porcelain systems are available with extended-range shade guides, and other manufacturers have extended their ranges over the years. The use of two or more shade guides is a practical way to extend the range of commercial guides.

Translucency

Assessment of the inherent translucency of the adjacent teeth[41] is important in determining whether the tooth or teeth need to be restored with which type of ceramic or a metal-ceramic system. In general, a ceramic crown system for anterior teeth is a more esthetic restoration, mainly because of the translucency match. Table 23.3 is useful for determining which system to use to improve translucency match for the fixed restoration.[44]

Dentin Shade Guides

When a translucent ceramic system for a crown or veneer is used (see Chapter 25), communicating the shade of the prepared dentin to the dental laboratory is helpful. One system

TABLE 23.3 Recommendations for Selection of Crown Material, Based on Translucency of Natural Teeth

Natural Teeth	In-Ceram Spinell	Empress	e-Max	Procera All-Ceram	In-Ceram Alumina	Zirconia	Metal Ceramic
Low value, high translucency	X	X	X				
Average value and translucency	X	X	X	X			
Opaque, high value					X	X	X

Adapted from Chu SJ, Trushkowsky RD, Paravina RD. Dental color matching instruments and systems. Review of clinical and research aspects. *J Dent*. 2010;38(suppl 2):e2.

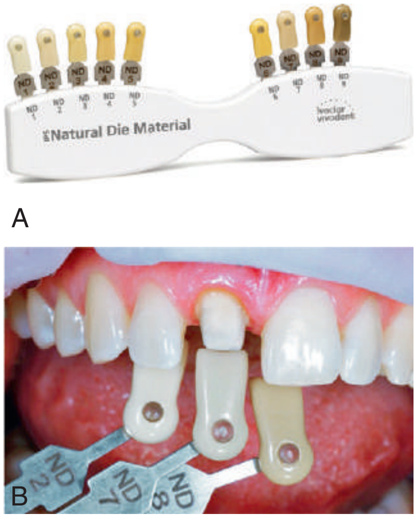


Fig. 23.18 Dentin shade guide (A) is used to communicate the color of the prepared tooth (B) to the technician when translucent ceramic systems are used. (Courtesy Ivoclar Vivadent, Amherst, New York.)

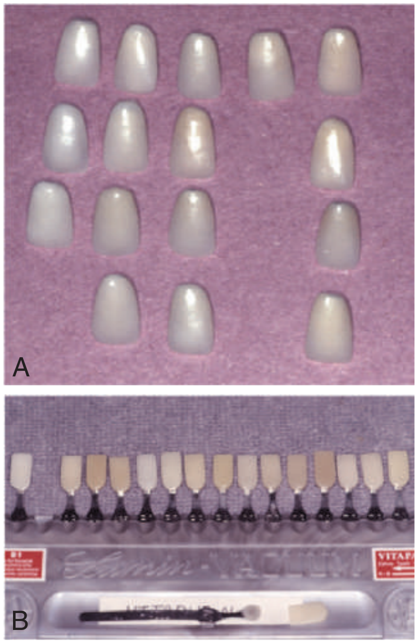


Fig. 23.19 (A) A custom shade guide. (B) Commercially available tabs for fabricating custom shade samples. (A, Courtesy Dr. A.M. Peregrina.)

(IPS e.max [Ivoclar Vivadent]) provides specially colored dye materials that match the dentin shade guide and enable the dental laboratory technician to judge restoration esthetics (Fig. 23.18).

Custom Shade Guide

Unfortunately, certain teeth cannot be matched to commercial shade samples. In addition, eliminating error in the shade duplication phase of the color replication process (see Fig. 23.5) may be encountered in reproducing the color of shade guides in the definitive restorations. The extensive use of surface characterization has severe drawbacks because the stains increase surface reflection and prevent light from being transmitted through the porcelain, which may result in an increase in metamerism.[45]

One approach to this problem is to extend the concept of a commercial shade guide by making a custom shade guide (Fig. 23.19). An almost infinite number of samples can be made with different combinations of porcelain powders in varying distributions. Alternatively, one can just fabricate porcelain tabs that correspond to the shade guides that are usually used by the clinician. (My Shade Guide, Smile Line—Recommended Fig: https://www.smileline.ch/de/produkte/my-shade-guide) However, the procedure is time consuming and is generally confined to specialty practice.

Another approach is to custom stain the closest matching selected shade guide, at chairside during the shade-matching phase, with a light polymerized porcelain staining system (GC Fuji ORBIT LC [GC America]). This system comes as a 14-stain kit or a 6-stain introductory kit. The shade tap can be custom-stained several times until it matches the adjacent teeth satisfactorily. This shade tab is then sent to the dental laboratory so that the crown can be fabricated identically in the required color.

Shade distribution chart or images. Shade distribution charting (Fig. 23.20) is a practical approach to accurate shade matching and is recommended even when a fairly good match is available from the commercial shade sample.

The tooth is divided into three regions: cervical, middle, and incisal. Each region is matched independently, either

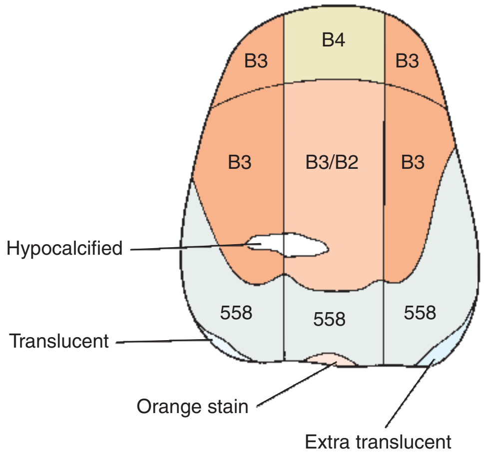


Fig. 23.20 Shade distribution chart.

to the corresponding area of a commercial shade sample or to a single-color porcelain chip. Because only a single color is matched, intermediate shades can usually be estimated rather easily and duplicated by means of mixing porcelain powders.[46] The junctions between these areas are normally distinct and can be communicated to the laboratory in the form of a diagram. The shade distribution and thickness of the enamel porcelain are particularly important.[47] Individual characteristics are marked on such a sketch and enable the ceramist to mimic details such as hairline fractures, hypocalcification, and proximal discolorations. Alternatively, the information on the individual characteristics can be transferred to the laboratory through a digital image with the close matching shade tab. Having the shade tab in the image allows the technician to calibrate the color of the digital image on the computer monitor.[48]

Summary of Guidelines for Visual Shade Matching

Regardless of which shade guide system is used, the following principles should be followed:

1. Shade matching should be made under balanced lighting and in an appropriate shade-matching environment with gray or pastel-colored walls and cabinets.
2. Anything on the patient that influences the shade matching, including brightly colored clothing, should be draped, and lipstick should be removed.
3. The teeth to be matched should be clean. If necessary, stains should be removed by prophylactic treatment.
4. Shade matching should be made at the beginning of a patient's visit. Tooth color increases in value when the teeth are dry, particularly if a dental dam has been used.
5. Cheek retractors should be used to provide an unhindered intraoral shade-matching area.
6. The dentist can expand the choices of shade tabs by using several shade guides or mentally noting that the shade of the tooth could be between two shade tabs. The technician should be asked to mix the porcelain in equal amounts to obtain an in-between shade.
7. The patient should be viewed at eye level so that the most color-sensitive part of the dentist's retina is used. The viewing working distance should be approximately 25 cm (10 inches).
8. If the tooth and shade tab have different surface characteristics, wetting the surface of both helps remove the differences.
9. Shade matching should be made quickly (less than 5 seconds), with the shade tab placed directly next to the tooth being matched. This ensures that the background of the tooth and the shade sample are the same, which is essential for accurate matching. The dentist should be aware of eye fatigue, particularly if very bright fiberoptic illumination has been used.
10. The dentist should rest his or her eyes between viewings by focusing on a neutral gray surface immediately before a matching; this balances all the color sensors of the retina. Resting eyes on a blue card was once advised, but it is no longer recommended because it results in blue fatigue.
11. To select the appropriate hue, the canine tooth is recommended for comparison because it has the highest chroma of the dominant hue.
12. The dentist can select an appropriate value by squinting.
13. The number of shade tabs should be reduced and separated to approximately three as quickly as possible. Then one or two of the shade tabs that match the best should be reselected.
14. Shade matching should be confirmed at one or two other visits and, if possible, confirmed with an auxiliary staff member. It is also recommended that shade selection be confirmed under several different lightings.
15. If an exact match cannot be selected, a shade tab with the lower chroma and highest value should be selected because extrinsic characterization can be used to increase chroma and reduce the value (see Chapter 29).
16. The dentist should map the polychromatic nature of the tooth being matched—its special characteristics (e.g., cracks, hypocalcification, and translucency of the incisal enamel of the tooth)—with one of the following: (1) a shade distribution chart, (2) a digital image with the closest shade tab beside the tooth, or (3) staining of the closest matching shade tab.

INSTRUMENTAL COLOR ANALYSIS

Color-Measuring Instruments

Color matching for dental restorative materials is generally done visually by matching with a shade sample. In the industry, electronic color-measuring instruments, such as spectrophotometers, spectroradiometers, and colorimeters, are used. Spectrophotometers and spectroradiometers measure light reflectance at wavelength intervals over the visible spectrum. Spectrophotometers differ from spectroradiometers primarily in that they have a stable light source and usually have an aperture between the detector and sample. Colorimeters provide direct color coordinate specifications without mathematical manipulation. This is accomplished by sampling of light reflected from an object through three color filters that simulate the response of the color receptors in the eye.

Color-measuring instruments with an aperture between the translucent object and the illumination and sensor have been shown to exhibit "edge loss" when carrying out measurements.[49,50] Edge loss is a phenomenon in which light scattered through a translucent material ordinarily would be seen by the eye but is simply not measured by the instrument. This happens when the light is scattered in the translucent object away from the aperture and does not return back through the aperture to the sensor; the phenomenon has been shown to be wavelength dependent. Thus, color-measuring instruments measuring translucent objects with an aperture assign incorrect color coordinates.[50] The phenomenon must be avoided if accurate color measurements of translucent objects, such as teeth and porcelain, are to be obtained, which is done with a combination of an external light source that does not cause shadowing and a spectroradiometer (Fig. 23.21). CIELab data measured with this arrangement for three different shade guides and 359 anterior teeth from 120 participants[51] are shown in Fig. 23.22.[37]

Various clinical color-measuring devices are available, either with or without a visual shape mapping. An example is the RayPlicker (Borea, the Shade Company) that is able to show the shade map of the adjacent teeth (Fig. 23.23). According to in vitro testing of some of these devices with various shade tabs, their reliability is approximately 90%, whereas their accuracy ranges from approximately 60% to 90%.[52,53] Initial clinical testing of some of these instruments shows similar clinical outcomes for visual matching.[54,55]

A different approach to the "hardware" method described previously is a software approach with image analysis. Images made with the shade reference are captured by a clinical digital camera or smartphone, and each is "calibrated" after the image is made (Fig. 23.24). The calibration entails mathematically adjusting known references in the image. ShadeWave (ShadeWave, LLC) has a library of shade guides with their corresponding shade tabs. This includes not only tabs for teeth but also tabs for gingiva and stump shades.

Once an image is calibrated, the unknown image components are discovered and segmented on the tooth. These include not only the shade but also translucency and value.

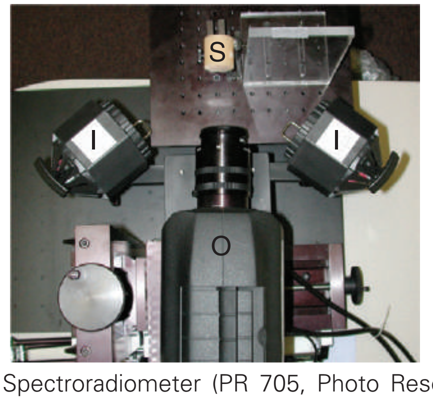


Fig. 23.21 Spectroradiometer (PR 705, Photo Research, Inc.) with an optical setup of 45 degrees illumination *(I)* and 0-degree observer *(O)* for measurements of a translucent material specimen *(S)*.

Images and processing are done in the cloud by Health Insurance Portability and Accountability Act (HIPAA)–compliant remote servers. The advantage of this is global communication of information to and from dentist, dental laboratory technician, and specialist in one location.

SHADE-DUPLICATION PHASE

Errors associated with the duplication of the selected shade with dental porcelain have been well documented. These errors are related to the underlying metal used,[56,57] the batch of porcelain powder,[58] the brand of porcelain,[6,59] and the number of times that glazing was performed.[60]

Visually detectable differences between the color of the shade tab and the fired porcelain are not uncommon.[59,61] Surface corrections of these errors include surface characterization, as discussed in Chapter 29. Another strategy that has been used is to include custom shade guides (see Fig. 23.18) in the shade-matching process. The custom shade guide should be from the same metal and porcelain type that will be used when the metal-ceramic crown is fabricated.

In summary, as shown in Fig. 23.25, the strategies for porcelain shade replication are as follows:

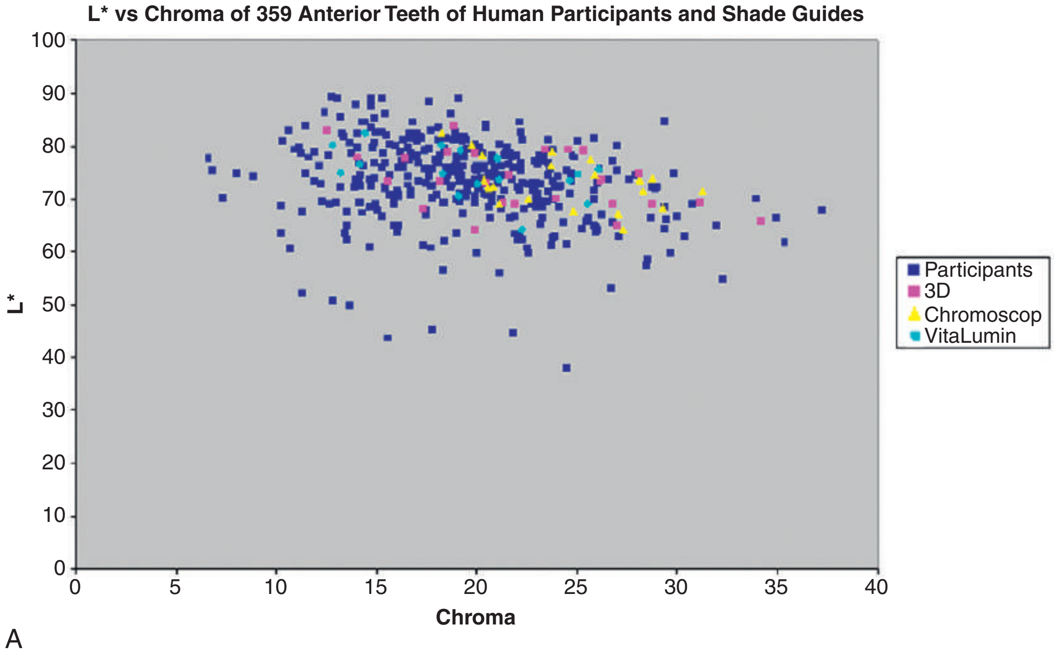
- Use fabricated custom shade tabs with ceramic materials that you commonly use for fixed restorations.
- If you are using instrumental color analysis, verify the selected shade visually at that appointment.
- Duplicate the polychromatic nature, translucency, and individual characteristics of the adjacent teeth.
- Mix porcelain to obtain in-between shades; this can be used to refine the shade duplication.

ESTHETICS

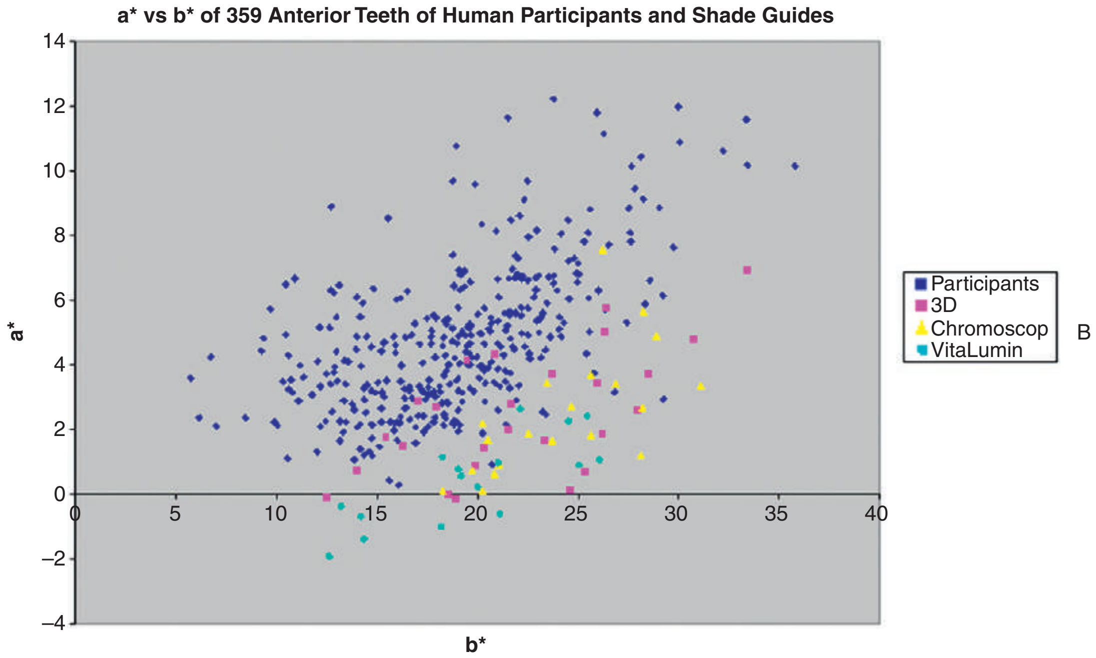
Esthetics is the study of beauty. Knowledge of esthetics helps the dentist achieve an appearance pleasing to the patient. A successful prosthodontic restoration provides the patient with excellent long-term function. It should also produce an attractive smile; esthetics is often the primary motivating factor for patients to seek dental care.[62] In fact, correction of esthetic problems has a positive effect on self-esteem.[63]

Anatomy of a Smile

Most people believe they can recognize an attractive smile, but individual opinion varies, particularly when cultural factors are considered. In research, investigators show participants photographs or computer-manipulated images of various smiles, and participants grade the images for attractiveness (Fig. 23.26).[64,65] Such research is quantified in the standard "dental aesthetic index" (DAI), an orthodontic treatment-need index based on perceptions of dental esthetics in the United States.[66] In general, an extensive smile that showed the complete outline of the maxillary anterior teeth and teeth posterior to the first molar was considered the most attractive and youthful (Fig. 23.27). (A smile in an aging individual shows less of the maxillary incisors and more of the mandibular incisors.)



A



B

Fig. 23.22 (A and B) Comparison between colors of 359 anterior teeth and three shade guides: VITA Toothguide 3D-MASTER, Ivoclar Vivadent Chromascop (Chromascop), and VITA classical (Lumin Vacuum) (VitaLumin). (A) L* versus chroma. (B) a* versus b*. (From Bayindir F, Kuo S, Johnston WM. Coverage error of three conceptually different shade guide systems to vital unrestored dentition. *J Prosthet Dent*. 2007;98:175.)

The *buccal corridor* refers to the amount of space between the cheeks and teeth in a smile and is related to the width of the dentition and the width of the mouth during a smile (Fig. 23.28).[67] The *smile arc* is the relative curvature of incisal edges of the maxillary teeth and the curvature of the lower lip. In smiles that were considered the most attractive, these curvatures were very similar,[68] a factor that should be considered when restorations are shaped.

Proportion

Esthetics depends largely on proportion. An object is considered beautiful if it is properly proportioned, and unattractive if it is top-heavy, squat, or out of proportion. Concepts of proportion are probably based on what is found in nature. Leaves, flowers, shells, and pinecones normally develop in proportion. Their growth is closely related to a mathematical progression

Fig. 23.23 The Rayplicker Quickshade. (A) The probe is placed on the tooth and the tooth shade is recorded in VITA classical (Lumin Vacuum) or VITA Toothguide 3D-MASTER units. (B) The device has a display that has options to either display the overall shade, shade of three or nine parts of the tooth, the detailed mapping, and also the incisal translucency of the teeth. (Courtesy of Borea, the Shade Company, Limoges, France.)

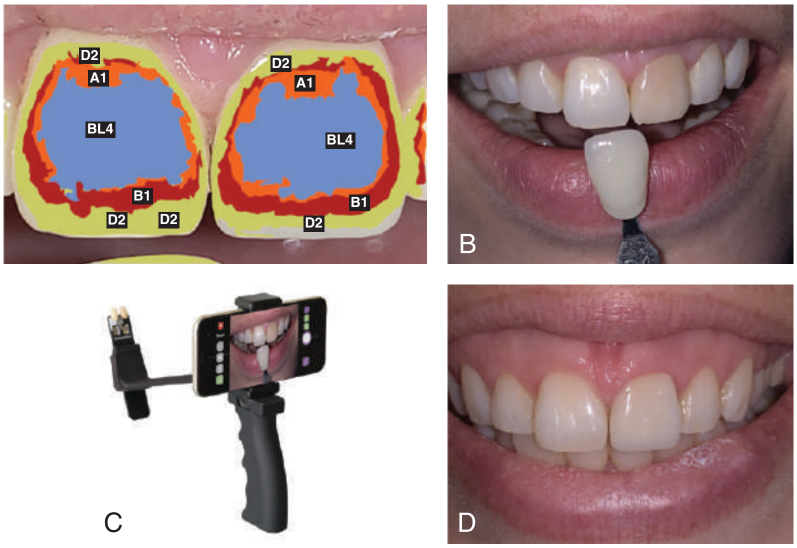
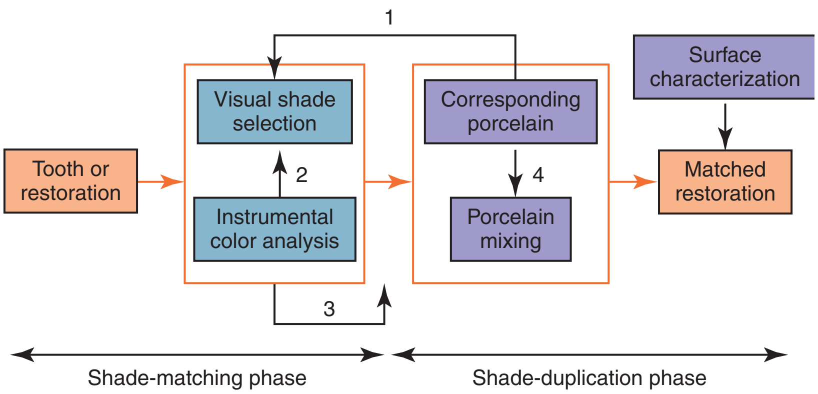


Fig. 23.24 The shade reference is placed beside the adjacent tooth (A), and a digital image is made (B). The image of the final restoration (C) is also taken, uploaded and viewed within the ShadeWave program (D). (Courtesy ShadeWave; Dr. Jill Smith, Boston, MA, dentist; Juan Escobar, AAACD, CDT ceramist.)

Fig. 23.25 Summary of the strategies for porcelain shade replication.



(the *Fibonacci series*[f]) in which each number is the sum of the two immediately preceding it (i.e., 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, and so on). The ratio between succeeding terms converges on approximately 1.618:1, known as the *golden proportion*. When a line is bisected in the golden proportion, the ratio of the smaller section to the larger section is the same as the ratio of the larger section to the whole line (Fig. 23.29). The golden proportion was used extensively in ancient Greek architecture and is exemplified in the Parthenon.

Claims have been made[69] that the golden proportion exists in natural dentitions in the ratio of the widths of incisors and canines, as seen from the front. Waxing guides, grids, or special calipers (Panadent Corp) that always extend to the golden proportion can be used, which may be helpful in designing a well-proportioned prosthesis (Fig. 23.30). However, studies of simulated smiles (Fig. 23.31) have revealed that designing prostheses to match the golden proportion is by no means optimal, except for patients in whom incisor length may be increased after periodontal disease.[70,71] Other investigators have attempted to apply mathematical concepts to dental esthetics.[72] Of particular importance to anterior tooth esthetics appears to be the ratio of height to width of the maxillary incisors. When dentists were asked to select the most attractive smile, they consistently chose the image in which the maxillary incisor height-to-width ratio was closest to the range of 75% to 78% (Fig. 23.32).[70,73] These findings are consistent with the preferences of the general population.

[f] After Leonardo Fibonacci (c. 1170–c. 1250), Italian mathematician, who devised it in the 13th century.

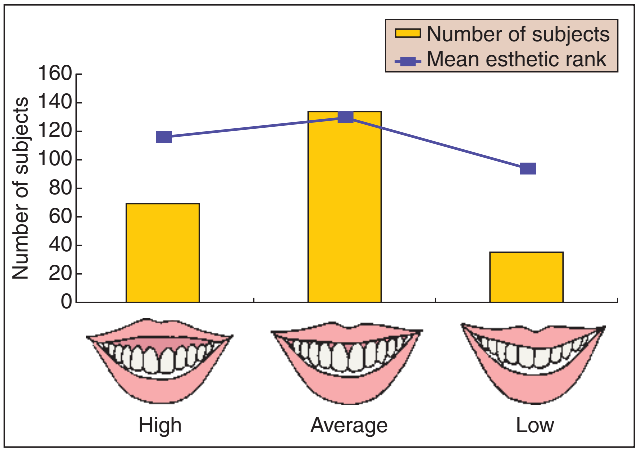


Fig. 23.26 Mean esthetic ranking of smiles with three upper lip positions. (From Dong JK, Jin TH, Cho HW. The esthetics of the smile: a review of some recent studies. *Int J Prosthodont*. 1999;12:9.)

Fig. 23.27 Computer image manipulation was used to determine the attractiveness of various smiles. Light colors and oval-shaped teeth in women (A–D) and rectangular teeth in men (E–G) were considered the most attractive. (Reprinted with permission of Decker Periodicals from Carlsson GE, Wagner IV, Odman P, et al. An international comparative multicenter study of assessment of dental appearance using computer-aided image manipulation. *Int J Prosthodont*. 1998;11:246.)

Fig. 23.28 Computer imaging illustrating variations in buccal corridor and smile arc. *Acc*, Accentuated. (Courtesy Dr. J. Parekh.)

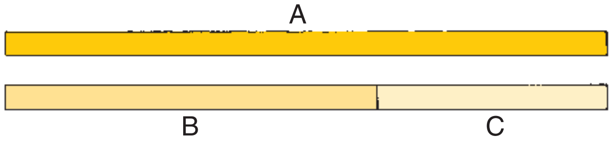


Fig. 23.29 The golden proportion. The ratio of *A* to *B* (1.618 to 1) is the same as that of *B* to *C*.

Fig. 23.30 The calipers always extend to the golden proportion.

Fig. 23.31 Computer-simulated smiles. (A) The anterior teeth are manipulated to give average proportion values. The lateral incisors are 66% the width of the central incisors, and the canines are 84% the width of the lateral incisors. (B) These anterior teeth have been manipulated to reflect the golden proportion. The lateral incisors are 62% the width of the central incisors, and the canines are 62% the width of the lateral incisors. In an Internet survey, only 8% of general public respondents preferred or much preferred the golden proportion image. (From Rosenstiel SF, Rashid RG. Public preferences for anterior tooth variations: a Web-based study. *J Esthet Restor Dent*. 2002;14:97.)

Balance

Balance, including the location of the midline (Fig. 23.33), is an important prosthodontic concept.[74] The observer expects the left and right sides of the mouth to balance out, if not to match precisely. An obvious restoration on one side may be balanced if there is a diastema or a large tooth on the other side. If something is out of balance, the brain infers that there is an unreciprocated force and an unstable arrangement; a balanced arrangement implies stability and permanence.

Fig. 23.32 Computer-simulated smiles in which the central incisors had different height-to-width ratios: 89% (A), 85% (B), 77% (C), and 73% (D). (C) was chosen as best by 65% of dentists responding, followed in popularity by (B), (D), and (A). (From Rosenstiel SF, Rashid RG. Dentists' perception of anterior esthetics: a Web-based survey [Abstract no. 1481]. *J Dent Res*. 2004;83[Special Issue A].)

Midline

Coincidence of facial and incisal midlines is stressed when orthodontic treatment planning is assessed and should be carefully evaluated in the planning of prosthodontic treatment. Studies have shown that the mean threshold for acceptable dental midline deviation is 2.2 ±1.5 mm[75] and that there was no difference in the perception of midline discrepancies between orthodontists and young laypeople; differences in this perception increased with the size of the discrepancy but not by sex.[71,76]

Fig. 23.33 Poor esthetics resulting from a lack of balance. The differences in central incisor and canine heights and misaligned midline contribute to lack of symmetry.

Incisal Embrasure Form

The shape of incisal embrasures can have a dramatic effect on dental esthetics (Fig. 23.34). Embrasure form is increased in young dentition, and a restoration with unnaturally reduced embrasures can appear unattractive. However, some patients demand reduced embrasures, seeking “perfectly” even incisal edges, although this appearance was “preferred” or “strongly preferred” by fewer than 30% of respondents to an Internet survey.[71] As with all aspects of personal esthetics, the patient’s opinion is paramount; the dentist provides expert knowledge. In restoring with multiple ceramic restorations, a sensible approach to achieving optimal incisal embrasure form is to instruct the dental laboratory to return restorations with reduced embrasure form. During the evaluation procedure, the embrasures can be carefully increased intraorally according to the patient’s wishes.

Incisor Angulation

The mesial or distal angulation of the maxillary incisor teeth can have a dramatic effect on esthetics (Fig. 23.35). In general, slight mesial angulation is acceptable, but distal angulation should be avoided.[73] Knowledge of these principles and attention to detail in designing anterior restorations is the key to highly esthetic restorations.

Virtual Patient

The creation of a 3D representation of a virtual patient can be a valuable method for patient communication so that the dentist’s development of a treatment plan can be shared with the patient (see Chapter 2). A representative technique is presented in Figs. 23.36–23.43. The use of a virtual patient developed from computed tomography (CT), extraoral, and intraoral scans has been shown to provide an accurate representation of the patient’s situation.[77]