

CAD/CAM Systems, Materials, and Clinical Guidelines for All-Ceramic Crowns and Fixed Partial Dentures

Abstract: *Advances in dental ceramic materials and the development of computer-aided design/computer-aided manufacturing (CAD/CAM) and milling technology have facilitated the development and application of superior dental ceramics. CAD/CAM allows the use of materials that cannot be used with conventional dental processing techniques. This article reviews the main techniques and new materials used in dentistry for CAD/CAM-generated crowns and fixed partial dentures. Also covered are the clinical guidelines for using these systems.*

New materials and techniques continue to be developed in the quest for the ultimate esthetic restorative material.^{1,2} The use of all-ceramic crowns has increased in recent years.^{3,4} The reason for this increase is the ease with which a ceramist can mimic the optical properties of natural teeth; specifically, the optical properties of value and translucency, which cannot be met with an opaque metal substrate. Requirements for use of any restoration include the natural manipulation of light, strength, user friendliness, long-term clinical success, application in varied clinical situations, and biologic compatibility.

Interest in all-ceramic crowns has been driven by concerns of the biocompatibility of dental alloys and by the perception that improved esthetics can be obtained by removing the dark and opaque metallic substructure.^{1,4} Although all-ceramic crowns have been used for more than a century, many of the materials have been fraught with problems such as early failure resulting from catastrophic fracture. More recently, glass ceramics have been developed with increased crystalline filler content, providing a more even distribution and finer particle size of the crystals within the glass matrix than conventional feldspathic ceramics. This has yielded significantly improved flexural strengths for this class of ceramic materials.^{5,6} Unfortunately, strength improvements are limited by the inherent weakness of the glass matrix because all-ceramic material fails as a result of crack propagation at a critical strain of 0.1%.⁷ Applied stresses can cause crack growth through the glass matrix resulting in the ultimate failure of the restoration. Acid etching and adhesive luting can greatly limit this process,⁸ most likely as a result of a process of crack bridging at the bonded interface of the porcelain by the luting composite.⁹ Recently developed ceramics with minimal or no glassy phase have demonstrated increased physical properties.¹⁰ An ideal all-ceramic restoration should be able to be used in a multitude of clinical situations and not be limited to the incisor region. Accordingly, optimal ceramics should resist the forces of mastication and parafunctional behavior, duplicate the color seen in natural teeth (eg, increasing chroma combined with increasing translucency), and withstand the mechanical and chemical attacks perpetuated on it in the oral environment for an extended period of time. Further, the location of the restoration will affect the clinical predictability of a particular restorative material. Increased strength requirements are necessary as

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Learning Objectives:

After reading this article, the reader should be able to:

- identify recent advances in dental ceramic materials, processing techniques, and milling technology.
- list the strategies that have been developed for using different CAD/CAM processes to generate high-strength all-ceramic frameworks.
- identify the advantages and disadvantages of several different currently available CAD/CAM systems.

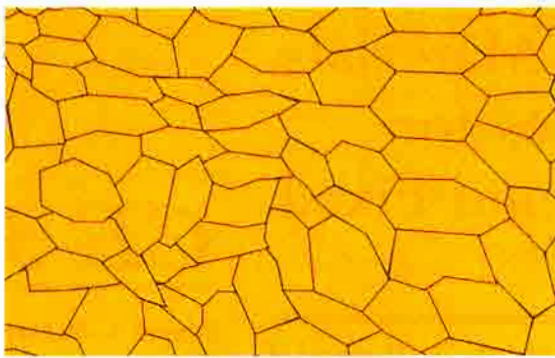


Figure 1—A schematic of solid sintered monophase materials. These materials are polycrystalline solids with complete fusion of the crystals at all grain boundaries with no intervening glass phase.



Figure 2—A schematic of interpenetrating phase materials. There is a partial junction or necking of particles in the crystalline phase. The interstitial spaces between the particles are filled with glass.

esthetic restorative procedures are performed in the posterior areas of the dentition.^{11,12}

CAD/CAM Technologies

Advances in dental ceramic materials and processing techniques; specifically, computer-aided design (CAD)/computer-aided manufacturing (CAM) and milling technology, have facilitated the development and application of superior dental ceramics. CAD/CAM allows the use of materials that cannot be used by conventional dental processing techniques. Tightly controlled industrial ceramic processing can produce increased microstructural uniformity, higher density, lower porosity, and decreased residual stresses. Such improvements have the potential to improve clinical predictability.

In the author's experience, problems and complaints with early systems focused on the machining accuracy of the particular system and not with the materials used with the systems. Initial CAD/CAM systems produced restorations that had poor marginal fidelity with a general lack of internal adaption to the

die resulting from low resolution scanning devices and inadequate computing power. Technological advances in new systems and software development have minimized or eliminated these problems so that marginal integrity can be excellent.¹³

Recently, two strategies using different CAD/CAM processes to generate high-strength all-ceramic frameworks have been developed. One strategy uses materials that completely eliminate the glassy phase by directly sintering the crystals together without any intervening matrix.¹⁴ This strategy is referred to as solid sintered ceramics (Figure 1). There are several different processing techniques that allow the fabrication of either solid sintered aluminum oxide or zirconia oxide frameworks.

The second strategy allows the reinforcing component to form a continuous skeletonlike meshwork of either alumina or spinell (a magnesium oxide/aluminum oxide mixture) or an alumina/zirconia mixture that is subsequently infiltrated with a low viscosity lanthanum glass. This class of materials is referred to as interpenetrating phase network compounds (Figure 2). This strategy was used in the development of In-Ceram^{®a} for the CEREC inLab system^b.¹⁵ In-Ceram[®] differs from glass-ceramics in which reinforcing particles are completely surrounded by their glassy matrices (Figure 3).

High-Strength Ceramic Materials

Solid Sintered Monophase Ceramics

Solid sintered ceramics have the highest potential for strength and toughness but, because of high firing temperatures and sintering shrinkage techniques, were only recently made available to use as high-strength frameworks for crowns and fixed partial dentures (FPDs). There are three basic techniques for fabricating solid sintered monophase ceramic frameworks for porcelain application. One system (DCS^c) machines the final desired framework shape from a solid sintered block of material. This system is expensive and has not been proven cost effective because of excessive machining time and the amount of manual labor necessary to adjust and fit the coping. The Procera^{®d} system (Figure 4), which is an example of the second method, uses an

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^bSirona USA, Charlotte, NC 28273; (800) 659-5977

^cAustenal, Chicago, IL 60632-4287; (800) 621-0381

^dNobel Biocare, Yorba Linda, CA 92887; (800) 993-8100

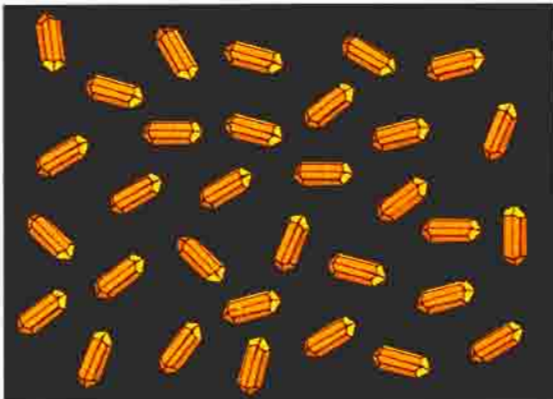


Figure 3—A schematic of glass ceramic materials. The matrix is glass with a separate and discrete crystalline phase.

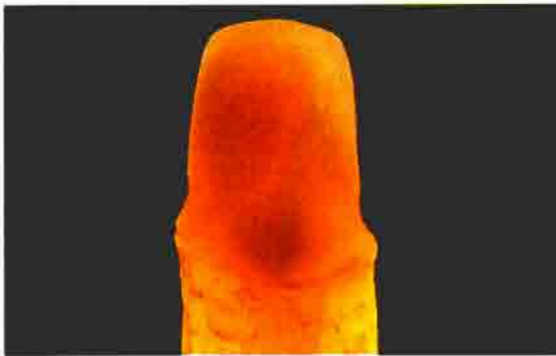


Figure 5—The more translucent alumina Procera® coping that has been transilluminated.

oversized die where a slurry of either aluminum oxide or zirconia oxide is applied so that when it is subsequently fired, the slurry fully sinters and shrinks to fit the scanned die.

The third method was recently developed, and machines an oversized coping from a partially sintered block of zirconia oxide material, which is then fired to full sintering temperature during which it shrinks to fit the die. There are two systems in this category. One system, the Degussa Cercon[®], requires a wax-up of the desired bridge framework. This wax-up is then scanned and, through software manipulation and CAM processing, an oversized framework is generated, which is fired to allow full sintering. The second system, the Lava[®], system, creates virtual dies and frameworks, thus eliminating the need for a wax-up. An oversized framework is created through a CAM process, which is then fully sintered. This system also allows for shading of the core material. These systems have only recently been introduced to the marketplace.

Zirconia oxide, sometimes called zircon,

¹Dentsply Ceramco, Burlington, NJ 08016; (800) 487-0100
²3M ESPE, St. Paul, MN 55144-1000; (800) 634-2249

Figure 4—The scanning device for the Procera® system.



has unique physical characteristics that makes it twice as strong and twice as durable as alumina-based ceramics. Although reported values for flexural strength for this new material range from 900 MPa to 1100 MPa,^{10,16} there is no direct correlation between flexural strength (modulus of rupture) and clinical performance. A more important physical property is fracture toughness, which has been reported to be between 8 MPa and 10 MPa for zirconia.¹⁰ This is significantly higher than any previously reported ceramic, and roughly twice the amount reported for the alumina materials. Fracture toughness is a measure of a material's ability to resist crack growth (ie, a measure of the amount of energy necessary to cause crack growth). Clinically, restorations are not loaded to failure as is done in a flexural strength test. Instead, millions of subcritical loads (eg, chewing) are applied. Materials ultimately fail because of this cyclic fatigue by crack propagation. Therefore, materials with higher fracture toughness are more ideal clinically because it takes more energy to cause crack growth. Other factors such as stress corrosion (ie, *chemically assisted crack growth*) and residual flaws in the material greatly affect the final strength of a finished material.^{17,18}

Increased physical properties can be partially attributed to a process called phase transformation.¹⁹ Partially stabilized zirconia exists in a tetragonal crystal configuration. When an external energy source is applied to the zirconia, as in mechanical finishing (cold working), the zirconia material can undergo a phase transformation to a different crystal (monoclinic form) configuration. The monoclinic form of crystal is 3% to 5% larger than the

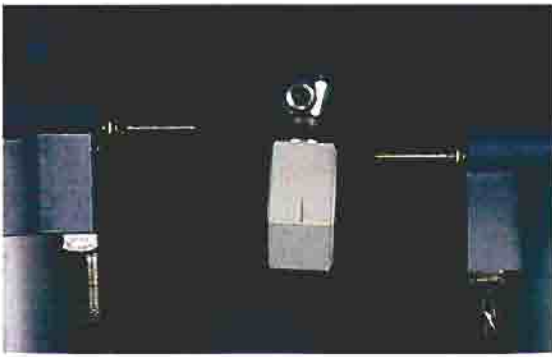


Figure 6—A block of spinell placed in the milling chamber of the CEREC® inLab system.

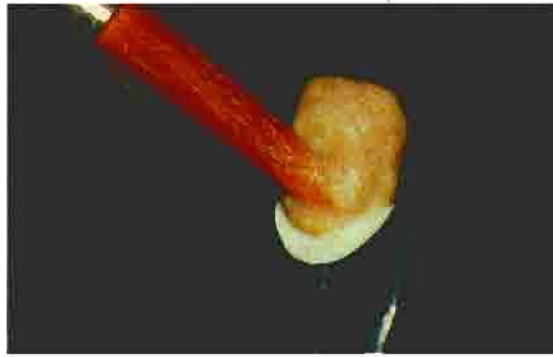


Figure 7—Infiltration glass of the chosen shade being applied to a machined spinell coping.

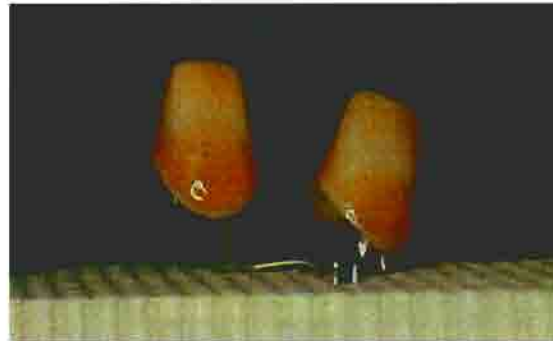


Figure 8—Spinell copings after glass infiltration. The excess glass is subsequently removed with aluminous oxide air abrasion.

tetragonal crystal. In areas where there are microscopic flaws in the material, as there are in all-ceramic materials, this phase transformation has the potential to heal microscopic cracks by closing them off because of the increased volume of the monoclinic form of crystal. Also, as energy is absorbed at a crack tip from an externally applied source, the phase transformation absorbs some of the stress, minimizing the potential for crack propagation. Zircon has the apparent physical properties for use in posterior three-unit FPDs. Unfortunately, no clinical data exists to support their use for posterior FPDs.

An early problem encountered with solid sintered ceramics was their opacity. More recent versions of the alumina and spinell materials provide more translucency to accommodate the clinical situation (Figure 5). It is possible to make alumina and zirconia materials very translucent and almost clear (eg, a false diamond is made of zircon and is quite clear). Translucency relates to many factors, which include refractive index, relative refractive index of phases, grain size, configuration, and orientation, all of which can be manipulated to increase or decrease translucency. At the present time, only a white and moderately opaque form of zircon is available except for the Lava® system, which allows colored versions.

Interpenetrating Phase Compounds

Interpenetrating phase materials were adapted for dental use by Sadoun.¹⁵ The system uses a partially sintered crystalline matrix of a high-modulus material in which there is a junction of the particles in the crystalline phase (Figure 2). The crystalline phase consists of alumina, an alumina/magnesia mixture (spinell), or an alumina/zirconia mixture. The material is

supplied in a block form (Figure 6), which is milled in the CEREC® inLab system. The framework (made from any of the three materials) is then infiltrated with a low viscosity lanthanum glass at high temperature (Figures 7 and 8). Extremely high flexural strengths have been reported for this new class of dental ceramic, which is three to four times greater than conventional or glass ceramics.^{2,6,10,16} It is theorized that this high strength is the result of the primarily crystalline nature of this material and minimal glassy phase, in which a flaw would have to propagate through the high-modulus material to cause ultimate failure.

CAD/CAM Systems

The Procera® System

Anderson¹⁴ was the first to use CAD/CAM technology to enlarge refractory dies to compensate for sintering shrinkage with a proprietary high temperature and pressure firing to produce almost pure alumina copings (the Procera® system) (Figure 9). The system has been recently expanded to include the ability to generate solid sintered zirconia oxide copings (Figures 10 through 14). Dies are generated in the conventional manner and then placed in

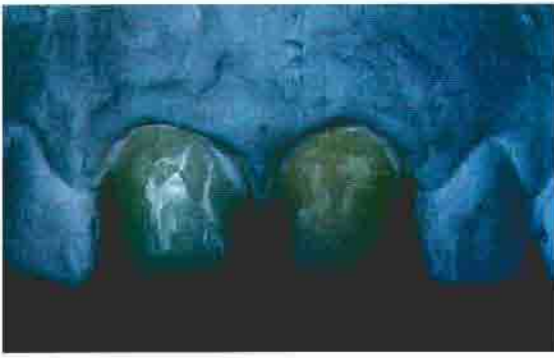


Figure 9—Procera® alumina copings ready for porcelain application.



Figure 11—Preoperative view of an anterior case requiring restoration. (Image courtesy of Dr. Eric van Dooren, Belgium, and Ernst Hegenbarth, MDT, Germany.)



Figure 13—Postoperative view of completed crowns made with zirconia copings using the Procera® system. (Image courtesy of Dr. Eric van Dooren, Belgium, and Ernst Hegenbarth, MDT, Germany.)

the scanner (Figure 14). The die is scanned and a three-dimensional image is displayed on the computer screen. The coping is then designed on the computer and the information is transferred electronically to one of the milling centers around the world. At the milling center, a refractory die is produced that is exactly oversized to the amount necessary to compensate for the sintering shrinkage of the material. A slurry paste of either aluminous oxide or zirconia oxide is applied to the die. It is then carved to the shape of the CAD-designed framework. The die is placed in a special furnace and fired to the

Figure 10—A
Procera® zircon
coping.



Figure 12—Final preparation of the anterior case for Procera® crowns. (Image courtesy of Dr. Eric van Dooren, Belgium, and Ernst Hegenbarth, MDT, Germany.)

full sintering temperature. The framework is then divested. It is now ready for porcelain application (Figure 9). Excellent esthetic results can be obtained with this system with proper coping design and porcelain application techniques (Figures 15 through 17). The Procera® system also has the ability to fabricate custom abutments for regular platform Brånemark® implants^d (Figure 18). This system has proven to be the most economical and universally accepted system for generating crowns. The capital investment is for only a scanner and the cost of each coping is approximately the cost of a noble metal coping. This system has proven effective with a 5-year study by Oden demonstrating a failure rate of only 1% per year.²⁰ Similarly, in a study sample by the authors of 128 crowns with an average time in the mouth of 36 months, 2 restorations failed by core fracture and 1 by porcelain delamination. This compares favorably with the study by Oden.

The CEREC® inLab System

The CEREC® inLab system (Figure 19) is an evolution from the dentist-based CEREC® III system^b that is used for generating one-visit inlays and onlays. The system is a self-



Figure 14—A die fixed in the scanner with the contact digitizer preparing to digitize the die.



Figure 16—Postoperative view of the single central incisor restored with a Procera® crown.

contained scanning and milling unit designed to fabricate single copings and three-unit FPD frameworks using interpenetrating phase compounds. The die to be scanned is placed in the system and is optically scanned (Figure 20). A virtual die is then displayed on the monitor and the coping is designed through the software. The die is then replaced with a block of the desired material (Figure 6) and the coping or framework is machined. The coping is then removed from the system and some fitting to the die is usually required. A special glass of the appropriate shade is chosen and placed over the coping. This is then placed in a furnace and fired to 1100° C where the glass melts and, by capillary action, fills the interstitial spaces between the grains of the partially sintered block material (Figure 8). The ceramic phase and the glassy phase form a continuous interconnecting meshwork. These frameworks are then ready for esthetic porcelain application (Figures 21 and 22). This system has demonstrated excellent marginal integrity with proper training and experience using the system in initial trials (McLaren EA, unpublished data, 2001). The type of materials used in this system has demonstrated excellent clinical success used for single anterior and posterior units.²¹



Figure 15—Preoperative clinical case of a single central incisor that needs to be replaced.

Clinical Indications

There have been relatively few clinical studies reporting on CAD/CAM-generated all-ceramic crowns that have included large sample sizes or long follow-up periods. Ideally, follow-up periods would be ≥ 5 years with sample sizes of several hundreds of units. Long follow-up periods are necessary because it takes several years for fatigue to cause failure. Two studies of reasonable sample size and study duration reported excellent success rates for both solid sintered alumina and interpenetrating phase alumina materials.^{20,21} In both studies, an annual failure rate of about 1.2% was reported, which compares favorably with metal ceramics. The authors have placed more than 1,500 restorations with these materials with an annualized fracture rate of $< 2\%$. Thus, the materials generated with CAD/CAM technology have physical properties that make it ideally suited for single-crown restorations anywhere in the mouth, assuming design and accepted clinical protocol are respected.

Fixed Partial Dentures

In a clinical study by Sorensen, In-Ceram® alumina anterior three-unit FPDs were 100% successful at 3 years.²² In the authors' experience, three-unit FPDs replacing an incisor have demonstrated success (1 failure of 17 FPDs resulted from fracture with an average clinical service of 4 years) (Figures 23 and 24). Additional clinical data have been short term but promising. Many anecdotal reports of success would indicate that high-strength ceramic frameworks subsequently veneered with porcelain would be clinically acceptable for three-unit anterior FPDs as long as accepted guidelines are maintained. Although several studies are being initiated or are ongoing, no long-term

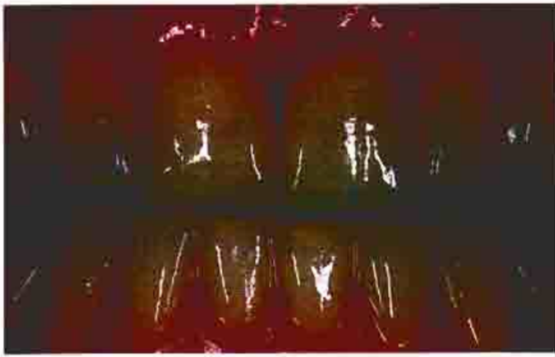


Figure 17—Postoperative view of two maxillary central incisors with Procera® alumina copings.

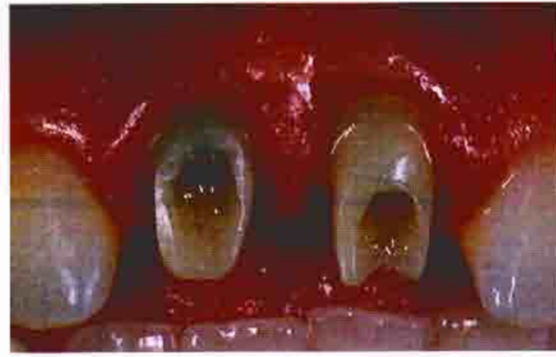


Figure 18—Procera® alumina custom implant abutments.



Figure 19—The CEREC® inLab system.

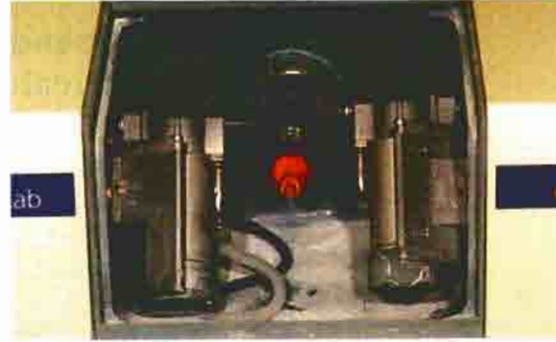


Figure 20—The die to be scanned is fixed in the milling chamber.

data yet exist to justify the use of CAD/CAM technology for the fabrication of posterior FPDs. Early results look extremely promising but the effects of fatigue and chemical corrosion take time to manifest. Clinical use of these materials for posterior FPDs should still be considered experimental at this point and patients should be fully informed of possible effects.

Clinical Guidelines

Preparations

The correct reduction for the space necessary for the esthetic fabrication of a Procera® or CEREC® inLab system is the same as for esthetic porcelain-fused-to-metal (PFM) restorations. Evaluation of restorations in which the authors performed all of the clinical and ceramic procedures has led to the determination that 1.2 mm of labial overall crown thickness was the minimum ideal dimension for predictable esthetics for normal colored substrates (1.5 mm for discolored substrates). The core can be thinned to 0.3 mm on the facial, leaving room for 0.9 mm of porcelain. All of the restorations were documented and measured for final crown dimensions before cementation, and a subjective analysis was made as to the esthetic success of

the cemented restorations. It was determined that a 1.2-mm facial crown dimension allowed predictable shade reproduction and subjective esthetic success (Figure 25). A minimum of 1 mm of crown thickness is required for the interproximal and lingual walls. Incisal edge thickness can be as little as 1.5 mm, but 2 mm is esthetically ideal. In posterior areas, it is necessary to have 2.5 mm of occlusal reduction for both esthetic all-ceramic and metal-ceramic restorations, especially if natural unworn occlusal anatomy is desired in the final restoration. The best aid the authors have found to accomplish this reduction is the 2-mm Reduction Guide from Belle De St Clair® if the 2-mm guide passes with only slight binding through the occluded opposing arches, then close to 2.5 mm of interocclusal space remains (Figure 26).

Cementation

The ability to acid etch and adhesively lute conventional ceramics has greatly increased their clinical predictability. Hydrofluoric acid dissolves the glassy matrix leaving microscopic undercuts around the leucite crystals. Low viscosity resins are used, which fill these retentive

*Kerr Labs, Orange, CA 92867; (800) 322-6666



Figure 21—Preoperative view of a patient requiring crowns on teeth Nos. 7 through 10.



Figure 23—Preoperative condition of a difficult case in which the patient required extraction of tooth No. 8 and periodontal crown lengthening.

areas creating a strong micromechanical bond. As a result of the minimal or no glassy phase in the materials, hydrofluoric acid etching and silane coating have proven ineffective to promote increased adhesion.²³ A recent study by Kern and Thompson²⁴ reported high bond strengths of alumina or zirconia to a new resin or to various surface treatments of the alumina or zirconia material that are designed to increase the silica content on the internal cementable surface of alumina materials. In a study by McLaren and Sorensen,²⁵ it was found that with specific surface treatment and/or resin combinations of aluminous oxide air abrasion at 50 psi for 10 seconds bonded with Panavia 21TC^h on either the alumina or spinell, both alumina and spinell had the same shear bond strength as conventionally etched porcelain. Clinically, it is necessary to use a dentin bonding agent on the tooth to minimize the potential for postcementation sensitivity. No other material is placed in the crown other than the mixed Panavia 21TC. Once the crown is placed, excess cement is removed and Oxyguard II^h is placed.

As a result of the high strength of these

^hJ. Morita USA, Irvine, CA 92618; (888) 566-7482



Figure 22—Postoperative view of four spinell crowns.



Figure 24—Postoperative view of teeth Nos. 6 through 11 restored with Procera[®] alumina frameworks. Teeth Nos. 7 through 9 are a three-unit Procera[®] FPD.

materials, some conventional cements can be used. Glass ionomer cements have been used with great clinical success.²⁶ The physical properties of glass ionomer cements are extremely sensitive to the powder/liquid ratios, in which even small alterations could affect the clinical performance. Glass ionomers are susceptible to early moisture attack, and therefore require exceptional saliva control until the cement is completely set. Pre-encapsulated versions are available (3M[™] ESPE[™] Aplicap^l) that eliminate the problems associated with the proper powder/liquid ratio, and are preferred over the hand-mixed versions. The authors have discontinued the use of zinc phosphate cement based on experience indicating a high incidence of microleakage and staining at the margins. The only correlation to cement type and fracture of the restoration in the authors' clinical samples was with zinc phosphate. One possible explanation for this is that ceramics are subjected to stress corrosion or chemically assisted crack growth in the presence of moisture. Thus, as a result of the microleakage and subsequent stress corrosion, the ceramic failed at a much smaller load. The physical properties of polycarboxylate cements may be inadequate for use with



Figure 25—Tooth No. 8 has a 1.2-mm facial crown thickness, which is adequate for teeth with close to normal colored substrates.



Figure 26—The 2-mm Reduction Guide being used to check occlusal reduction.

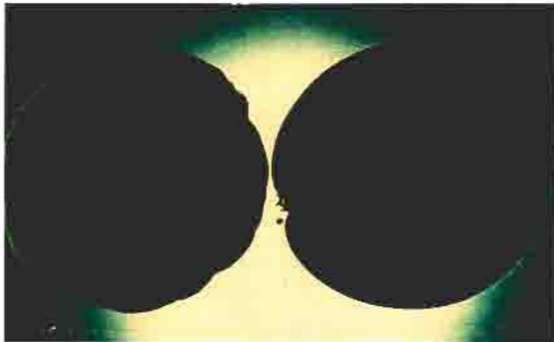


Figure 27—Transilluminated section of zinc phosphate and glass ionomer cements that are 100- μ m thick. Note the almost complete lack of light transmission.

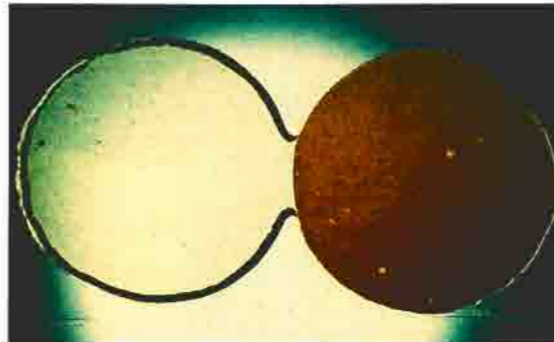


Figure 28—Transilluminated section of a clear translucent cement on the left and Panavia tooth colored on the right (both are only 100- μ m thick).

these materials, and there is no reported data supporting their use.

Resin-reinforced glass ionomers or compomer-type cements have been suggested for this class of material. There have been anecdotal reports concerning some of the compomers causing cracking of all-ceramic crowns shortly after cementation.²⁷ There are high amounts of hydroxyethyl methacrylate (HEMA) in these products, which expand significantly on exposure to moisture. It is theorized that the stresses developed because of the expansion of the HEMA is sufficient enough to cause the cracking. In a laboratory study,²⁷ all-ceramic crowns were fabricated and cemented with various compomer classes of cements and stored in water. Cement was also placed in capillary tubes and stored in water. Several of the crowns fractured after a few days stored in water; however, no exact percentages or sample size was given. Of the Advance^{™,i} samples fractured, 25% of the FUJI Plus^{™,j} samples fractured, and none of the Vitremer^{™,k} samples fractured. The authors have used Vitremer[™], which is now called Rely X[™] Luting^f for posterior restorations

for several years for this type of restoration with no failures to date using this cement. Therefore, the authors recommend Rely X[™] luting for use with single crowns.

Although certain conventional cements appear to be strong enough to use, problems associated with their optical properties have become apparent. As a result of the relatively opaque nature of these cements (Figure 27), they can negatively affect the final optical result of the cemented restoration. The main rationale for using these restorations is to match translucency and value to the natural dentition. In situations where maximum translucency is necessary (eg, anterior teeth) translucent resin cements are indicated (Figure 28). The optical properties of Panavia 21TC and Variolink[®] II^k have been found by the authors to be ideal for use with this system.

Conclusion

The ideal restorative material would be able to withstand the mechanical and chemi-

ⁱDentsply Caulk, Milford, DE 19963; (800) LD-CAULK

^jGC America, Alsip, IL 60803; (800) 423-2963

^kIvoclar Vivadent, Amherst, NY 14228; (800) 533-6825