Ceramics in dentistry: Historical roots and current perspectives

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This article presents a brief history of dental ceramics and offers perspectives on recent research aimed at the further development of ceramics for clinical use, at their evaluation and selection, and very importantly, their clinical performance. Innovative ceramic materials and ceramics processing strategies that were introduced to restorative dentistry since the early 1980s are discussed. Notable research is highlighted regarding (1) wear of ceramics and opposing enamel, (2) polishability of porcelains, (3) influence of firing history on the thermal expansion of porcelains for metal ceramics, (4) machining and CAD/CAM as fabrication methods for clinical restorations, (5) fit of ceramic restorations, (6) clinical failure mechanisms of all-ceramic prostheses, (7) chemical and thermal strengthening of dental ceramics, (8) intraoral porcelain repair, and (9) criteria for selection of the various ceramics available. It is found that strong scientific and collaborative foundations exist for the continued understanding and improvement of dental ceramic systems. (J Prosthet Dent 1996;75:18-32.)

The American Academy of Fixed Prosthodontics recently established the Ad Hoc Committee on Research in Fixed Prosthodontics. This Committee was assigned the responsibility of helping to sustain academic excellence and interest in fixed prosthodontics, which includes the related sciences, ethics, and social issues. The objective of the Committee was to disseminate knowledge and prepare perceptively for the future by making influential contributions to current literature that will have a significant bearing on the practice of fixed prosthodontics. Specifically, this involves defining an area of scientific investigation or clinical practice for review with an emphasis on vision and perspective. The Committee has selected ceramics as the focus of its first contribution.

OVERVIEW

Dental ceramics are known for their natural appearance and their durable chemical and optical properties. However, dentists have remained suspicious of the structural longevity, potential abrasivity, and fit of ceramic restorations. It was predictable that recent dental research in ceramics addressed issues of clinical survival, response during wear, and fit. These concerns have directly influenced the development of recently introduced ceramic materials and laboratory processing systems. After a brief historical perspective, this review focuses on recent improvements concerning the appropriate use of dental ceramics and, more importantly, how they perform clinically. Studies of clinical failure and damage mechanisms are crucial, because they provide data for substantial engineering improvements. This article concludes with a discussion of the esthetic versatility provided by current ceramic systems for fixed prosthodontics.

HISTORIC PERSPECTIVES

Ceramics as a restorative material

Although routine use of ceramics in restorative dentistry is a recent phenomenon, the desire for a durable and esthetic material is ancient. Most cultures through the centuries have acknowledged teeth as an integral facial structure for health, youth, beauty, and dignity. Teeth have routinely been designated with an equally powerful, if occasionally perverse, role in cultures where dentitions were purposely mutilated as inspired by vanity, fashion, and mystical and religious beliefs.[1, 2] Therefore, it has been almost universal that unexpected loss of tooth structure and, particularly, missing anterior teeth create physical and functional problems and often psychologic and social disturbances as well.

Although dental technology existed in Etruria as early as 700 BC and during the Roman first century BC, it remained virtually undeveloped until the eighteenth century. Candidate materials for artificial teeth during the 18th century were (1) human teeth, (2) animal teeth carved to the size and shape of human teeth, (3) ivory, and finally

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(4) "mineral" or porcelain teeth. Other than for costly human teeth that were scarce, the selection of artificial tooth materials was based on their mechanical versatility and biologic stability. Animal teeth were unstable toward the "corrosive agents" in saliva, and elephant ivory and bone contained pores that easily stained. Hippopotamus ivory appears to have been more desirable than other esthetic dental substitutes.[2, 3] John Greenwood carved teeth from hippopotamus ivory for at least one of the four sets of complete dentures he fabricated for George Washington.[4]

Mineral teeth or porcelain dentures greatly accelerated an end to the practice of transplanting freshly extracted human teeth and supplanted the use of animal products.[4] Feldspathic dental porcelains were adapted from European triaxial Whiteware formulations (clay-quartz-feldspar), nearly coincident with their development. After decades of effort, Europeans mastered the manufacture of fine translucent porcelains, comparable to porcelains of the Chinese, by the 1720s.[5] The use of feldspar, to replace lime (calcium oxide) as a flux, and high firing temperatures were both critical developments in fine European porcelain.[5] Approximately 1774, a Parisian apothecary Alexis Duchateau, with assistance of a Parisian dentist Nicholas Dubois de Chemant, made the first successful porcelain dentures at the Guerhard porcelain factory, replacing the stained and malodorous ivory prostheses of Duchateau.[4, 6] Dubois de Chemant continually improved porcelain formulations, was awarded both French and British patents, and fabricated porcelain dentures as part of his practice.[2, 4, 6] While in England, Dubois de Chemant procured supplies from collaborations with Josiah Wedgwood during the formative years of the famous porcelain manufacturing concern that currently bears his name.[4, 6] In 1808, individually formed porcelain teeth that contained embedded platinum pins were introduced in Paris by Giuseppangelo Fonzi.[4] Fonzi called these teeth "terro-metallic incorruptibles" and their esthetic and mechanical versatility provided a major advance in prosthetic dentistry. Although probably not involving feldspathic porcelains, the enameling of metal denture bases was described in 1723 by Pierre Fauchard in the pivotal text "Le Chirurgien Dentiste".[4, 7] Fauchard was credited with recognizing the potential of porcelain enamels and initiating research with porcelains to imitate color of teeth and gingival tissues.[6]

Mechanical versatility and esthetics

Improvements in translucency and color of dental porcelains were realized through developments that ranged from the formulations of Elias Wildman in 1838 to vacuum firing in 1949.[8] Glass inlays (not porcelain) were introduced by Herbst in 1882 with crushed glass frit fired in molds made of plaster and asbestos.[6] In 1885 Logan resolved the retention problem encountered between porcelain crowns and posts that were commonly made of wood by fusing the porcelain to a platinum post (termed a Richmond crown). These platinum post crowns represented the first innovative use of a metal-ceramic system since platinum pin denture teeth fabricated by Fonzi 79 years earlier.[6] By combining burnished platinum foil as a substructure with the high, controlled heat of a gas furnace, Land was capable of introducing the first fused feldspathic porcelain inlays and crowns in 1886.[9, 6] The all-porcelain crown system, despite its esthetic advantages, failed to gain widespread popularity until the introduction of alumina as a reinforcing phase in dental porcelain.[10, 11] A noteworthy development occurred in the 1950s with the addition of leucite to porcelain formulations that elevated the coefficient of thermal expansion to allow their fusion to certain gold alloys to form complete crowns and fixed partial dentures (FPDs).[12-14] Refinements in metal-ceramic systems dominated dental ceramics research during the past 35 years that resulted in improved alloys, porcelain-metal bonding, and porcelains. The introduction of a "shrink-free" all-ceramic crown system[15] (Cerestore, Coors Biomedical, Lakewood, Colo.) and a castable glass-ceramic crown system[16] (Dicor, Dentsply/York Division, York, Penn.) in the 1980s provided additional flexibility for achieving esthetics results, introduced advanced ceramics with innovative processing methods, and stimulated a renewed interest in all-ceramic prostheses.

Articles in *The Journal of Prosthetic Dentistry*

Fig. 1 demonstrates a steady increase in numbers of articles about ceramics published in *The Journal of Prosthetic Dentistry* between 1981 and 1993. Most research focused primarily on mechanical and materials science considerations, such as marginal integrity, fracture, bond strength, and repair techniques, instead of esthetics. Although the total number of dental ceramic articles published per year nearly tripled from 1983 to 1993, there was no concomitant increase in number of articles concerning esthetics. This relative dearth of research about esthetics may merely indicate that the esthetics of ceramics are taken for granted or may reflect the complexities inherent to quantifying color analyses and esthetics. Fig. 1 clearly emphasizes that traditional concerns about the fit and strength of ceramic restorations remain.

WEAR OF CERAMICS AND OPPOSING ENAMEL

The dental professional is usually inclined to accept the hardness of a ceramic as a predictor of its potential to abrade opposing teeth. The phenomenon of increasing hardness being related to increasing wear has generally been true for abrasion of most metals and certain ceramics tested against abrasive papers (SiC, Al_2O_3) or with loose abrasive particles.[17] However, neither of these conditions may fully model intraoral conditions where breakdown of

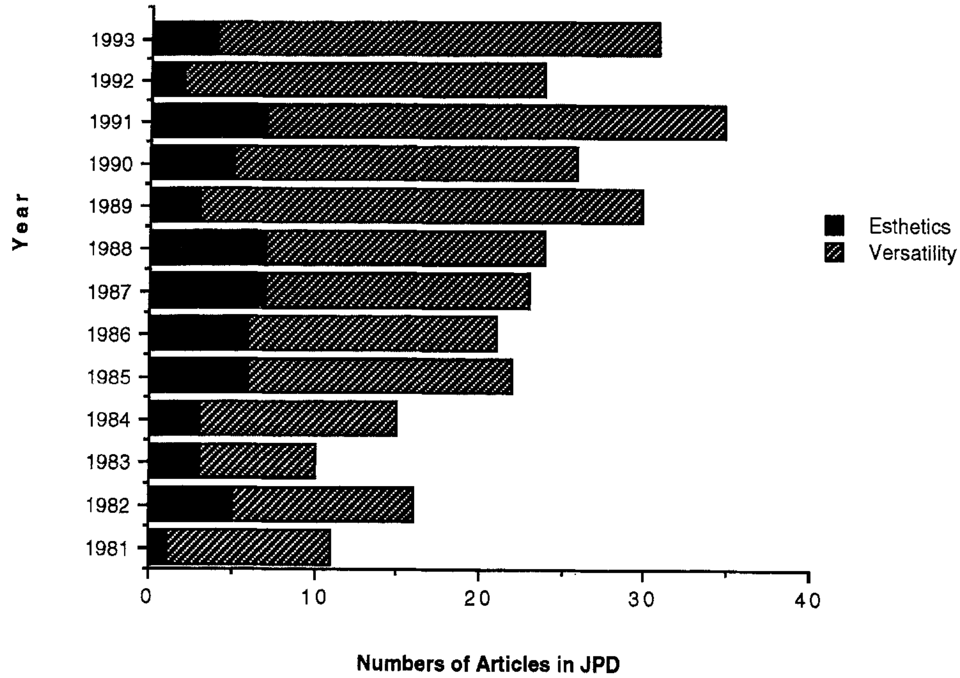

Fig. 1. Number of articles on ceramics and porcelain published in *The Journal of Prosthetic Dentistry* from 1981 through 1993.

ceramic surface creates abrasive surface features that can wear opposing dentition. The character, size, and shape of these abrasive surface features (factors known to influence wear) also depend on the microstructural elements of the ceramic and its fracture toughness as well as its hardness.[17] In a revealing wear study of five dental ceramics with Knoop hardnesses (KNH) that ranged from 379 to 443, no correlation was found between hardness and wear rates of enamel with an enamel pin on a rotating ceramic disk.[18] Criticism of this study was directed to the narrow range of hardness examined. However, similar tests of two other high-hardness ceramics In-Ceram [(KNH ≈ 1040), Vita Zahnfabrik, Bad Sackingen, Germany] and a beta-quartz glass-ceramic [(KNH ≈ 709), Beta Quartz Glass Ceramic Insert, Lee Pharmaceuticals, S. El Monte, Calif.] revealed extremely low enamel wear compared with traditional dental porcelain, which validated the implication of the mentioned[18] hardness versus wear study.[19, 20] Hardness is only one critical contributing factor that determines wear.

The size and shape of abrasive features that developed on a dental ceramic surface during contact appeared critical for determining enamel wear.[19, 20] The character of abrasive surface features is known to be a function of the fracture toughness of the ceramic, the size of its microstructure (grains, filler particles, pores), and local property variations in its microstructure.[17] Two recent research articles have validated the influence of microstructural features and their size on the wear of enamel for two different dental ceramics. First, Dicor glass-ceramic was discovered to be substantially more abrasive when opposing enamel than feldspathic porcelains if the outer "skin layer" of Dicor ceramic remained intact, which is normal for clinical practice.[21] This outer "skin layer" on Dicor ceramic contains needlelike crystals of the mineral enstatite ($MgSiO_3$) oriented perpendicularly to the surface and is the site of considerable residual porosity.[22, 23] Second, for feldspathic compositions, the fine-microstructure porcelain for CAD/CAM fabricated restorations (Mark II, Vita) caused appreciably less enamel wear than a traditionally sized feldspathic porcelain in a "chewing machine" that tested machined inlays cemented in extracted teeth against unrestored teeth.[24]

There has been no universal consensus with respect to interpreting laboratory wear tests or to their clinical meaning, and many reports appear contradictory. However, in the opinion of the authors there are indications that much greater wear kindness can be achieved in dental ceramics for both glass-ceramics and feldspathic porcelains than traditionally believed. In addition, investigators are increasingly monitoring material loss of both enamel and ceramic instead of simply reporting enamel wear, yielding better information for the dentist.[20, 21, 24, 25]

POLISHING OF PORCELAIN VERSUS GLAZING

There has been repeated confirmation that an appropriate polishing regimen can create smoother surfaces than achieved by a glaze firing. Scanning electron microscope (SEM) and visual observations of two porcelain systems revealed that each could be suitably polished but responded differently to various commercial polishing systems.[26] It has also been reported that better surfaces were created with a generic polishing regimen of pumice and water slurry followed by whiting (calcium carbonate) than with a commercial diamond paste system.[27] Because various porcelains respond differently—and with many diverse polishing systems to chose from—one of the most practical findings was that simple visual examination proved as effective as SEM photomicrographs in judging the quality of polished porcelain.[26]

Highly polished metal-ceramic and aluminous porcelains can also be stronger than glazed or as-fired equivalents.[28, 29] The improved strengths may result from elimination of surface flaws and/or development of residual compressive stresses in the porcelain surface. This phenomenon may provide still greater incentive, beyond possible improvements in wear and plaque retention, to include a disciplined polishing procedure in the delivery of porcelain restorations. Regimented polishing also allows better control over development of esthetic surface texture and luster.

CERAMIC MATERIALS AND SYSTEMS

This section briefly reviews the nature of currently available ceramics and how they are processed. Introductory background material is provided to establish a common base from which to gain insight into current research. Ceramics receiving attention include Dicor (Dentsply), In-Ceram (Vita), IPS-Empress (Ivoclar AG, Schaan, Liechtenstein), Optec (Jeneric Pentron, Wallingford, Conn.), and opalescent and metal-ceramic porcelains from various manufacturers.

Metal-ceramics

Metal-ceramic restorations have been available for approximately 35 years. During this period, substantial improvement in alloy substrates and veneering porcelains have resulted in widespread acceptance of metal-ceramic restorations. Continued research efforts have led to a more detailed, practical understanding of metal-ceramic systems.

Leucite concentration alterations (thermal behavior). The crystalline mineral leucite is included in porcelains for metal-ceramic restorations to elevate their thermal expansion coefficient to match that of casting alloys, to minimize residual thermal stresses. Therefore, thermal expansion behavior of dental porcelains is quite sensitive to changes in leucite concentration. Quantitative x-ray diffraction analysis of multiple-fired dental porcelains has revealed that leucite concentrations are definitely altered during repeated firings, with the leucite content of certain commercial porcelains increasing and others decreasing.[30, 31] Slow cooling accomplished in a furnace muffle without power has caused 11% to 56% increases in leucite content of many porcelains.[32] Under an isothermal hold at 750° C for 4 to 16 minutes, conditions that simulated post-soldering, the leucite content of six commercial body porcelains increased 6% to 21%.[33] These percentage increases in leucite content are sufficient to cause substantial alterations in the coefficients of thermal expansion.[34]

Leucite concentration alterations (mechanical behavior). Slow cooling and multiple firing of FPDs can promote immediate and delayed porcelain cracking.[35] This cracking has been attributed to differences in thermal stresses that develop because of differences in heat transfer rates and overall thermal history. However, it appeares conceivable that alterations in the coefficient of thermal expansion previously discussed may also influence porcelain cracking during normal dental laboratory procedures. Because leucite is considered an unstable phase in current porcelains for metal-ceramic restoration, repeated firings, slow cooling, or extended heat soaks can definitely alter the leucite content. Once-fired porcelains can also be stronger than multiple-fired porcelains, providing another independent indicator of an essential compositional or microstructural change with repeated firing.[29]

Esthetics. Compositional changes in metal-ceramic porcelains have not been linked to change in the esthetics of these restorations. There seems to have been no laboratory confirmation to support the traditional concept that color and/or translucency of metal-ceramic porcelain is altered during multiple firings. Numerous studies based on either standardized visual measurements or spectrophotometric analysis examined the effects of repeated firing on color stability.[36-40] None of these investigations documented variations in measured color variables or appearance of porcelain as the result of repeated firing. It appears that either common experience or the research has been misleading; or perhaps translucency has not been adequately addressed during color measurements. Other manipulative variables, such as modeling liquid, firing temperature, and extent of powder condensation also did not appear to have an influence on the color of metal-ceramic restorations.[41]

Metal substructure design and fit. Facial porcelain margins are one substructure modification developed to enhance esthetics by eliminating the display of metal and allowing more natural transmission of light.[42-45] A more aggressive modification of substructures for abutments was advocated to improve esthetics of metal-ceramic restorations, by preparing castings 1 to 3 millimeters short of the shoulder preparation of the tooth.[46-48] These shortened metal copings can provide a more natural optical effect in the gingival third of the restoration than traditional "porcelain butt" margins. Shortened coping restorations have been described as promoting an "internal luminance" or "fiber optic" effect in conjunction with the root and overlying soft tissues, improving esthetics of the restoration and reducing "graying" of the gingiva.[48, 49] Restorations fabricated with shortened metal copings have been reported to be as strong during compressive loading as full-length copings based on laboratory testing but are technically more demanding to fabricate and probably more vulnerable before and during cementation.[50]

The fit of metal-ceramic restorations improved substantially (fourfold) with completion of an initial thermal cycling of the alloy substructure before finishing of the surface and adjustment of the fit of the casting.[51] Distortion of metal-ceramic castings during oxidation bakes and porcelain firing was apparently caused by relaxation of casting-induced stresses coupled with effects of cold working the alloy surface during metal finishing. Residual stresses that resulted from both cold working and casting appeared to act synergistically during distortion of metal copings.[51-56]

Opalescent porcelains

Opalescence in dental porcelains is a light-scattering effect achieved with the addition of minute concentrations of high index of refraction oxides in a size range near the wavelengths of visible light. Teeth display some opalescence, and incorporation of this effect in dental ceramic restorations can provide an additional subtle vitality in concert with natural translucency, hue, value, chroma, and surface texture. Opalescent formulations have been introduced in a number of incisal porcelains for both metal-ceramic and all-ceramic restorations, which include Vintage Opal (3M Dental Products, St. Paul, Minn.), Vita Alpha and Omega porcelains (Vita), and Creation porcelain (Jensen Industries, North Haven, Conn.). Because opalescent compositions do not differ markedly from traditional feldspathic porcelains, their physical properties are similar. The flexural strength of opalescent porcelains was reported equal to or greater than conventional metal-ceramic porcelains.[57] The polishability of opalescent and conventional porcelains is also similar, and smoother surfaces can be created with polishing than with self-glaze firing.[58]

Dicor ceramic

Dicor ceramic, introduced in the early 1980s, is a micaceous glass-ceramic (45% volume glass and 55% crystalline tetrasilicic mica) processed by a combination of conventional lost-wax investment techniques and glass casting.[59] This ceramic was originally intended to be shaded with a thin surface layer (50 to 100 µm) of colorant glass. Because of the esthetic limitations of surface shading, practicioners began veneering cutback Dicor copings with feldspathic porcelains used for other all-ceramic systems.[60, 61] The technique of fabricating crowns of veneered Dicor ceramic (often referred to as "Willi's glass" crowns) was developed outside the time frame of this review, but it was included to provide perspective to the recent introduction of Dicor Plus ceramic (Dentsply Int.). Dicor Plus ceramic is a compatible veneering porcelain for fabricating "Willi's glass" crowns, offered by the distributor of Dicor. Marginal openings of 30 to 60 µm have been reported for Dicor restorations, which are comparable to those of metal-ceramic crowns.[62-65]

In-Ceram ceramic

In-Ceram ceramic consists of two three-dimensionally interpenetrating phases; alumina (aluminum oxide) and a glass. A dispersion of alumina particles in water, called a slip, is painted on a gypsum die. Water, flowing under capillary pressure into the gypsum die, compacts the alumina particles against the die. This is an ancient process termed slip casting and is used to make common objects such as beer steins, where a much more watery slip is poured into a porous split mold. In the In-Ceram ceramic process, the compacted alumina particles are partially sintered together to form necks between touching particles. This porous, partially sintered alumina, mistakenly referred to as the slip in some dental literature, is then infiltrated with a low-viscosity glass to yield a ceramic coping of high density and strength. Independent compositional analysis confirmed that the particles were alumina (99.56 wt%)[66] and the infiltration glass was a lanthanum aluminosilicate with small amounts of sodium and calcium.[67] Lanthanum decreases the viscosity of the glass to assist infiltration and increases its index of refraction to improve translucency of In-Ceram ceramic. Substitution of magnesium aluminate spinel for the aluminum oxide also improved translucency, partly because of the crystalline habit of the spinel, which provides isotropic optical properties, and partly because of its lower index of refraction compared with alumina. However, the spinel-based core ceramic (In-Ceram Spinel, Vita) was not as strong as the alumina-based material.[68]

The laboratory techniques and clinical use of In-Ceram ceramic have been described.[69, 70] Marginal fits of In-Ceram ceramic crowns and FPDs have been reported indistinguishable from metal-ceramic units, with marginal openings of 24 µm for crowns and 58 µm for FPDs.[71-73] Tensile strengths reported for the In-Ceram ceramic core material were three to four times greater than for other dental ceramics.[68, 69, 74, 75] No failures were recorded for 21 anterior and 40 posterior In-Ceram crowns over service lives of 4 to 35 months (mean 20.8 months).[76] If a thin layer of infiltration glass is inadvertently left on the surface of the core material during laboratory processing, it may not create structural problems. A thin layer of infiltration glass increased the loads sustained by central incisor In-Ceram ceramic crowns during load-to-failure testing[77] and elevated the shear bond strengths of the core-veneer interface.[78]

Clinical failure of In-Ceram ceramic FPDs originated from their connectors, often internally at the interface between the core ceramic and veneering porcelain.[79] Observations of fractured FPDs, along with computer stress and failure analysis of the failed In-Ceram ceramic connectors, suggested that the veneering porcelain overwhelmingly determined failure and that strengthening the core material may not improve the load-bearing ability of the connector.[79]

Although not recommended by the manufacturer, In-Ceram ceramic has been investigated for resin-bonded FPDs.[80, 81] A chemical bond to In-Ceram ceramic can apparently be created with Panavia resin cement (Kurary, Japan), in lieu of micromechanical retention developed by etching, which is considered routine for other ceramics.[82] One experimental approach has been reported for creating mechanically retentive surfaces, but awaits further development.[83] High failure rates by fracture have been reported after the first year of clinical trials with resin-bonded In-Ceram ceramic FPDs.[84, 85]

IPS-Empress ceramic

The problem of fit with traditional feldspathic porcelains is related to the density change (powder to solid) and resultant shrinkage during firing. IPS-Empress ceramic simplifies the problem of creating restorations having close tolerances by transfer molding or pressing the ceramic into a mold at high temperatures under viscous flow.[86] In this manner the only dimensional change occurs during cooling and can be controlled with an investment having the appropriate expansion. The ceramic is primarily a glass (as most dental ceramics) (filled [23.6 wt% colored ceramic;[87] 41.3 wt% opaque ceramic[88]] with crystalline leucite) that can strengthen the ceramic without significantly diminishing its translucency.

The strength of IPS-Empress ceramic has been reported to improve as a result of the pressing step,[86, 89] which is interesting from a materials science point of view. The strength of IPS-Empress ceramic may also increase during subsequent heat treatments such as veneer firing.[86] Strength increases as a result of multiple firings may be related to increases in leucite.[88] One clinical trial that involved a limited number of class II IPS-Empress ceramic inlays reported no problems over a 1.5-year evaluation period.[90] Initial reports from a clinical trial involving 75 IPS-Empress crowns revealed no failures over a length of service ranging from 1 to 30 months.[91]

Optec ceramic

Optec ceramic is also a feldspathic composition glass filled with crystalline leucite. The leucite concentration in Optec was reported as 50.6 wt% and appreciably greater than IPS-Empress ceramic (23.6 wt% or 41.3 wt%) or the traditional metal-ceramic porcelains Vita VMK (19.3 wt%) and Ceramco II (21.5 wt%).[87, 88] Optec ceramic restorations are fabricated from powders of the leucite-containing glass by the same type of sintering process used for traditional dental ceramics. A clinical study of 205 ceramic inlays, followed up for an average period of 8.1 months, reported no specific problems other than a slightly roughened surface for 86% of the ceramic inlays, and marginal integrity was rated as excellent for 67% of the Optec ceramic inlays.[92]

MACHINING AND CAD/CAM CERAMICS

Machining has become a viable option as a forming method in fabrication of ceramic restorations. Both a CAD/CAM system (Cerec, Siemens, Bensheim, Germany) and a precision copy-milling machine (Celay, Mikrona Technologies AG, Spreitenbach, Switzerland) are commercially available. Two classes of ceramics are available for machining fabrication of individual ceramic restorations and veneers: (1) two fine-scale feldspathic porcelains (Vita Mark II and Celay; Vita) and (2) two glass ceramics (Dicor-MGC light and Dicor-MGC dark; Dentsply). While both types of machinable ceramic evolved from existing dental ceramics, both are superior in specific properties to their dental laboratory–produced predecessors and are available to dentists only via a machining route. Although machining does lower the strength of ceramics, reported "as-machined" strengths of both types of ceramic are equal or superior to the strengths normally reported for equivalent dental laboratory–fabricated ceramics.[93-97] More important, Cerec inlays of either type of ceramic were judged clinically successful and equivalent with respect to fracture resistance, wear, appearance, and marginal integrity in university-based clinical trials that ranged from 3 to 5 years.[98, 99] One non-university study was equally impressive, where 1011 Cerec inlays inserted under private practice conditions had a calculated 95% survival rate at 5 years, based on lifetime statistical analysis of inlay performance examined over a period of 3.3 to 6.6 years.[100]

Exposed bands of resin cement are commonly reported 60 to 150 µm wide at the margins of Cerec ceramic and dental laboratory fabricated porcelain inlays.[101, 102] Wide bands of resin cement may not jeopardize the success of adhesively bonded ceramic inlays as much as was initially feared. Clinically, the wear of luting composite resin at inlay margins is reported to stabilize at a depth just slightly less than the width of the gap for marginal gaps up to approximately 150 µm.[103] The clinical data on Cerec ceramic inlays cited in this article[98-100] appear to support this type of restoration, even though the fit was not within traditional guidelines.

The marginal fit of the Celay ceramic inlays fabricated with a copy-milling system can be better than that of Cerec ceramic inlays.[101] Celay ceramic inlays were considered clinically acceptable by traditional criteria.[104] Marginal fits were reported to differ slightly depending on whether the inlay pattern was fabricated directly on the prepared tooth or on a laboratory die.[105] An In-Ceram-like ceramic block, optimized for the Celay machine, has recently become available (Vita). Under factory conditions, a porous preform of alumina is manufactured that is as strong (before glass infiltration) as many dental porcelains.[106] Copings for single-unit crowns and frameworks for simple FPDs are machined from these blocks with the Celay machine and then infiltrated. The time for infiltration is only a few minutes compared with 4 hours for dental laboratory In-Ceram ceramic.

Two exciting opportunities are provided by the availability of CAD/CAM or other machining routes to ceramic prostheses and restorations. First, these systems remove ceramics processing, and hence microstructural control, from the dental laboratory and place it within jurisdiction of the manufacturer. Many important physical and optical properties are directly dependent on how the ceramic is made, and a ceramics manufacturer can generally provide a superior material compared with a dental laboratory. The In-Ceram ceramic blocks optimized for the Celay milling machine are an excellent example of this contention. Second, the manufacturer merely provides a few sizes of simple blocks; complex shaping is controlled by the machining process. Both of these factors could allow a broader spectrum of materials to become available for restorative and prosthodontic practice.

CLINICAL FAILURE OF ALL-CERAMIC CROWNS

Previous investigation of the fracture surfaces of a limited number of all-ceramic crowns (mainly Dicor ceramic) revealed that most clinical failures had initiated from the cementation or internal surface.[107, 108] A recent independent study of clinically failed glass-ceramic crowns confirmed those earlier findings of cementation surface-failure origin.[109] Finite element modeling of a single-unit glass-ceramic crown demonstrated the effect of internal surface flaws and cement voids in raising internal stresses, and the results were in agreement with the mode of clinical failure observed for glass-ceramic crowns.[110]

Dicor ceramic crowns luted with zinc phosphate cement were reported to have poorer success rates than crowns cemented and bonded with composite resin cements. For example, 3-year failure rates for molar, premolar, and anterior Dicor ceramic crowns when zinc phosphate cement was used were 35.3%, 11.8%, and 3.5%, respectively.[111] An overall failure rate of 1.3% at 2 years was reported for 143 anterior and 254 posterior Dicor ceramic crowns luted with a light-activated cement.[112] At 4 years the failure rate of bonded Dicor ceramic crowns was recorded as only 2.9%.[113] This clinical result is consistent with the discussed fracture-surface observations based on two factors. First, failures originated from cementation surfaces that identified the internal surfaces as the location of highest tensile stresses and/or critical flaws and is therefore the surface that needs to be strengthened. Second, etching and polymer coating of tensile surfaces has been shown to substantially improve the strength of ceramic structures.[114, 115] This strengthening effect may be caused by the elimination, blunting, or "bridging" of cracks, or coatings may act to reduce the ability of water to be transported to the crack tip, which lessens the stress-corrosion. Hydrophobic silane treatments have been shown to significantly increase the strength of feldspathic dental porcelains.[116]

Etching the cementation surface and bonding with a low viscosity composite resin can minimize the influence of flaws at cementation surfaces. Perhaps a similar regimen of etching the internal surface and bonding a thin layer of low-viscosity composite resin can reduce the fracture susceptibility of other all-ceramic crowns, possibly those subsequently cemented with zinc phosphate or glass ionomer cements.

CHEMICAL AND THERMAL SURFACE TREATMENTS (STRENGTHENING)

Chemical strengthening

Ion exchange strengthening (or ion "stuffing") is a process that creates a thin surface layer of high-compressive stress by the exchange of smaller glass modifying-ions with larger ones, for example replacing sodium with potassium ions.[117] The larger ions enter the glass or porcelain by diffusional exchange at elevated temperatures, usually from a molten salt bath. During cooling the larger ions are trapped in the porcelain surface and occupy more space because of higher molar volume, which diminishes the potential of this layer to shrink and leaves it in compression. Deeper layers of untreated material, constrained from shrinking by the "stuffed" outer layer, are left in equivalent residual tension. Because many glass and ceramic structures (but not all) fail from surface flaws and because surface compressive stresses must be exceeded before cracks can propagate, this scheme allows treated structures to support greater loads before they fail.

Because molten salt baths are not pleasant to maintain or work with routinely, practical application of ion stuffing to dental ceramics languished until the introduction of a paste system designed to facilitate treatment in standard dental laboratory ovens (Tuf-Coat, G-C Dental Industrial Corp., Tokyo, Japan). The chemistry of traditional dental porcelains (feldspathic) allows the development of a surface layer of high compressive stress by ion exchange.[118, 119] Ion exchange strengthening has been effective in increasing the strength of IPS-Empress ceramic.[120] However, the chemistry of the glass phase in Dicor ceramic did not appear amenable to ion exchange with potassium.[121]

Chemical strengthening affects a very thin layer of material, and removal of only 16 to 18 µm of ceramic by air abrasion eliminated the strengthening affect, after ion exchange by use of the commercially available system.[122] However, an experimental dual ion chemical strengthening treatment was developed for feldspathic porcelains that surpassed the strengthening of a single ion treatment and survived air abrasion.[119, 122, 123]

In addition to the effect of air abrasion, other practical aspects of chemical strengthening should be recognized regarding the procedure. There is no visible alteration in the treated porcelain. This is a definite advantage esthetically, but there is no indication of whether a specific ceramic unit has been treated. Residual stresses would be annealed out during any subsequent firing of a unit (for example, colorant bake), so that the strengthening treatment should be performed only after the unit is ready for delivery.[124] Adjusting the ceramic unit with rotary instruments would likely remove the strengthening effect and the results of etching, either before or after chemical strengthening. Further study of the adjustment of ceramic units with rotary instruments need investigation.

Thermal strengthening

Thermal tempering has also been studied for strengthening dental porcelains. Advantages of thermal treatment include stress profiles that generally extend much deeper into the material than noted with chemical treatment, and tempering can be performed with compressed air.[117] Thermal tempering with compressed air or immersion in a silicone oil has been successfully applied to simple shapes such as disks of metal-ceramic porcelain.[125, 126] This strengthening of dental porcelains appeared to occur by inhibiting crack initiation instead of propagation.[127] Forced-air tempering was better than ion exchange strengthening alone (commercial system) or a combination of tempering and ion exchange strengthening.[128] The thermal tempering effect for one porcelain survived grinding to a depth of 150 μm,[129] which illustrates the greater depth profile of compressive stresses commonly associated with thermal compared with chemical treatments.

Compared with chemical strengthening, the disadvantages of the thermal method include difficulty in controlling cooling rates (and hence the effect) that may be exacerbated for objects having complex shape, such as an artificial crown. However, a three-dimensional finite element analysis study of a metal-ceramic crown indicated that this tempering effect should apply irrespective of its complex shape and cooling behaviors, although seriously high tensile stresses may form within the opaque porcelain.[130] The same caveats regarding subsequent thermal treatments, discussed for chemically treated crowns, are applicable for thermally tempered crowns, although the thermal strengthening effect may be less sensitive to air abrasives, grinding, or etching.

INTRAORAL PORCELAIN REPAIR

The successful use of composite resin systems to repair dental porcelain depends not only on creating a high quality bond but also on resistance of the composite resin and bonding resins to fatigue damage during cyclic loading. The importance of cyclic fatigue damage in the deterioration of composite resins has been well-established.[131, 132] In one noteworthy study, eight porcelain repair systems, each having its own porcelain treatment and bonding agent, were tested with one or more of six composite resins (creating 11 separate test conditions).[133] These 11 different system couples were tested under realistic loads in the presence of water. Three systems had a fatigue life equal to or greater than 2 million cycles (namely, there was no failure at 2 million cycles), and a fatigue life greater than or equal to 1.5 million cycles was recorded for one system. The remaining seven were classified into a completely different group with fatigue levels that did not exceed approximately 0.5 million cycles.

One crucial point indicated by this fatigue study was that changing either the bonding agent or the composite resin in the highly successful systems seriously compromised their performance.[133] There appeared a considerable lack of compatibility between systems and composite resins, and the hybrid composite resins were more fracture resistant than the microfilled composite resins. The two system couples found to have fatigue lifetimes that exceeded 2 million cycles were All-Bond with Bisfil (Bisco, Downers Grove, Ill.) and Clearfil porcelain bond (J. Morita, Tustin, Calif.) with Herculite XR (Kerr, Romulus, Mich.).

Water is well known to decrease the strength and toughness of composite resins, both by plasticizing the resin and degrading silane bonds.[134-138] The effects of water may be exacerbated by thermal stresses. A recent study examined the bond strength of four commercial bonding systems with one composite resin (Herculite XR) before and after thermal cycling in water.[139] All systems displayed a substantial reduction in bond strength after thermal cycling. In certain systems failure was predominantly in the composite resin and for others primarily in the porcelain-resin bond. Both Clearfil porcelain bond and Scotchprime (3M Dental Products, St. Paul, Minn.) bonding agent performed well.

HEALTH RISKS ASSOCIATED WITH DENTAL PORCELAINS

There are no recognized health risks to patients from the use of ceramics in prosthodontic and restorative dentistry, other than possible abrasive damage to opposing dentition and the potential for fracture.[140, 141] Excessive exposure to acidulated fluoride can enhance chemical degradation of porcelain surfaces, but the products of such degradation are usually not ingested. The toxicity of leachable elements in dental ceramics are all extremely low.[140] Surface attack may conceivably result in greater plaque accumulation that affects soft tissue, but this appears more an exercise in speculation than a real health concern. All mined minerals, from which dental porcelains derive, emit extremely low levels of radiation.[140, 141] Under voluntary regulatory guidelines established in 1981, radiation levels in dental porcelains should not have been increased by the manufacturer beyond their natural background levels[142] and new International Standards Organization (ISO) specifications call for complete monitoring of radiation levels in ceramics for all-ceramic prostheses.[143] Patients might be

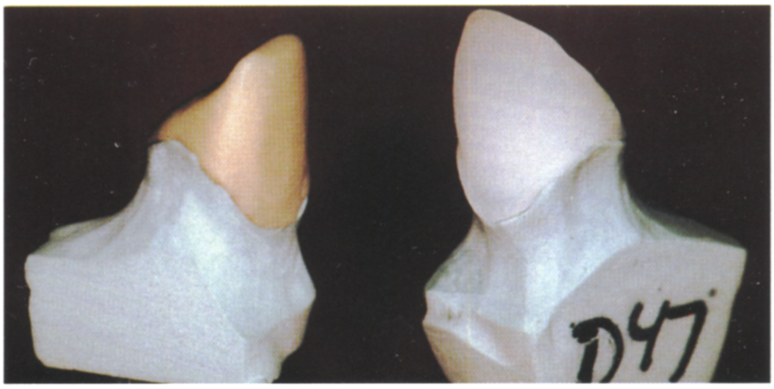

Fig. 2. Coping substructures of Dicor *(right)* and In-Ceram *(left)* ceramics demonstrate fundamental difference in translucency and color content.

Table I. Flexural strength values of all ceramic materials (MPa) from inclusive studies

	Seghi and Sorensen[68] (three-point)	Giordano et al[75] (four-point)	Lehner and Scharer[145] (three-point)	Rizkalla et al[147] (three-point)
Vita VMK (feldspar glass)	66 (5)	67 (3)	71 (6)	
Vitadur aluminous core		91 (7)		151 (20)
Hi-Ceram	142 (19)		182 (17)	128 (17)
Optec	105 (11)		167 (10)	
Dicor	125 (19)	71 (7)	114 (24)	
In-Ceram	446 (64)	236 (22)	419 (62)	484 (63)
In-Ceram Spinel	378 (65)			
IPS-Empress	127 (18)	65 (10	182 (26)	

exposed to siliceous dust by inhalation or tissue embedment during grinding procedures. However, the extent of any risk from silica exposure remains undocumented even for high risk groups having continual daily exposure, such as dental technicians.[141]

CLINICAL APPLICATIONS AND SELECTION CRITERIA

Three fundamental criteria are traditionally considered in the selection of materials for partial and full coverage restorations: fit, strength, and esthetics. Clinical longevity is a critical outcomes measurement hopefully related to these selection criteria. The fit of all-ceramic restorations currently available for fixed prostheses have been reported as comparable to metal-ceramic restorations and clinically acceptable.[61-64, 70-72]

Comparative strength

Strengths of ceramics are typically determined by use of bend bars with three- or four-point loading and/or disks tested in biaxial flexure. Numerous studies have examined the strength of commercially available ceramics.* Measured strengths vary as a function of the specimen preparation and testing methodology including, for example, surface condition, three-point versus four-point bending, and different stressing rates. Because reported strengths may be greatly influenced by the specimen fabrication process and testing method, it may be more enlightening to focus on the relative strengths reported within inclusive studies instead of "absolute" values (Table I).

Extrapolation of strength data alone to clinical performance must be considered cautiously, if it is done at all.[148] Proper use of strength data for predicting the lifetime of structures requires knowledge that (1) the critical flaw in test specimens is the same as that involved with clinical failure; (2) environmental influences have been replicated in the laboratory; (3) failure parameters describing the flaw size, distribution, and crack growth rates are known; and (4) stress distributions in the clinical structure are well characterized.[149, 150] These four criteria are sufficient for monolithic structures (made of one material) for which test specimens can be fabricated in the same manner as the manufactured counterpart.

Three practical examples can be used to illustrate points basic to these four criteria. First, simple test specimens such as multilayered disks or bend bars cannot always predict the load-bearing ability of multilayered structures such as prostheses because of substantial differences in stress distributions and failure probability profiles.[148, 151] Second, processing steps invariably introduce strength-

*References 22, 28, 73, 74, 67, 120, 122, 144-7.

controlling flaws in ceramic structures, and preparation of test specimens and prostheses often differ with respect to decisive processing steps. Third, clinical failure modes or critical flaws have not been well-characterized. Strength testing that does not simulate a clinical mode of failure is of questionable relevance. For example, if chemically assisted crack growth in the presence of water is a critical feature in clinical failure, then relevant testing must be conducted under wet conditions.

Esthetics

The potential for achieving esthetics when all-ceramic restorations are used compared with metal-ceramic restorations probably remains the fundamental rationale for their selection. Many restorative systems either use or have available a veneering porcelain, so the primary difference between systems lies in the color and translucency of the substructure or core material. The substructure material has an appreciable effect on the shade of the artificial crown.[152] Therefore, selection criteria can be based largely on various esthetic characteristics of the substrate materials.

Unfortunately, despite quite serious effort, no spectrophotometric or standardized visual assessments have become widely accepted to augment the practice of fixed prosthodontics.[153-162] This lack of quantitative esthetic analysis makes the prescription of selection criteria more arduous, and the dentist is commonly dependent on intuitive and subjective observations. Adding to the confusion, veneer porcelains do not appear to match their shade guides accurately,[163] and observable color differences exist between opaque and body porcelains of the same shade from the same manufacturer.[164] However, guidelines can be tentatively established and a subjective rank of translucency and color control can be extrapolated for substructure or core ceramics.

An ideal dental material for fabrication of artificial crowns would allow control of substrate color (hue, chroma, and value) and translucency, but none of the systems are presently that flexible. Current systems vary in their capabilities to control the color of the substrate (Table II). They range from Dicor ceramic, which is provided only as a single milky white translucent material, to Optec and IPS-Empress ceramics, which grant broader use of colors to form a basic restoration. Some color control of the substrate, of course, can be achieved through the use of surface color modifiers and veneering porcelains. Although not as desirable as inherent core shades, surface modifiers can be used to enhance the shading of substructures. Thus, adequate control of hue and chroma is often achievable within most ceramic systems.

Substrate translucency therefore becomes one of the primary factors in controlling esthetics and is a critical consideration in selection of materials. Transmission of light by the substructure directly influences the appearance of veneer porcelains. Translucency or opacity varies

Table II. Subjective rank order of translucency and color control for the various ceramic substrate materials

Translucency (Least to most)	Color control (Least to most)
Alloy (metal ceramic)	Dicor
Hi-Ceram	Metal ceramic
In-Ceram	Hi-Ceram
Optec	IPS-Empress
IPS-Empress	In-Ceram
Dicor	Optec

Bars indicate materials with similar optical characteristics.

tremendously among available materials (Table II and Fig. 2). Material systems can be classified in two fundamental groups: (1) those that use opaque high-strength cores (for example, Hi-Ceram and In-Ceram ceramics, Vita), and (2) those with sufficient translucency to allow construction of the entire restoration from the "core" material (for example, IPS-Empress, Dicor, and Optec ceramics). Translucency can also vary within these two categories. For example, In-Ceram ceramic is more translucent than previous alumina-containing core materials such as Hi-Ceram ceramic. The recently introduced In-Ceram Spinel core ceramic (Vita) offers extended esthetic capabilities because it is more translucent than the original alumina-based ceramic.

The visual impact engendered by coping translucency is more noticeable in the body and gingival third of restorations, as judged by the brightness or value in these regions.[165] For example, translucent materials can result in restorations of lower value and a more grayish appearance.[49, 60] This is particularly true of ceramic core materials with limited color content such as Dicor ceramic. Opaqueness of the substrate will also affect the ability to mask underlying structural differences such as post and cores and tooth structure deficiencies. It is important to select a substrate material that closely resembles the natural translucency and grayness of the teeth to be matched, to achieve the maximal esthetics available with ceramic restorations.

In recording the shade of natural teeth, it is critical to examine the relative value and opacity/translucency within the body of the tooth, because this will directly influence selection of the most appropriate substrate material. Teeth that exhibit translucency and low value are best matched with a minimally colored, translucent core material such as Dicor ceramic (Fig. 3). This is especially true when there is a gray or blue appearance to the tooth (Fig. 3). Teeth that exhibit translucency with average value are best matched with colored, translucent materials such as Empress or Optec ceramics. Opaceous, high-value teeth with less color content as demonstrated by Vita shades A-1 to A-2 are most appropriately matched with more opaque substructures such as Hi-Ceram, In-Ceram, or metal-ceramics res-

Fig. 3. Natural dentition with translucent, low-value, gray-toned teeth matched with veneered Dicor crown on maxillary canine and lateral incisor.

Fig. 4. Natural dentition with less translucency, higher value, average color content matched with an In-Ceram crown on maxillary canine.

torations. However, problems with shading in the gingival third of restorations may develop because of the high reflectivity of core materials and thin veneer. In these instances, framework modification should be considered to allow a more natural light transmittance, including potential contributions from an "internal luminance" optical effect. Teeth that are higher in value with more color content, as in Vita shades A-3 to A-4, are most suitably matched with opaque cores that offer color control such as with In-Ceram ceramic (Fig. 4).

Internal modifications of veneering porcelains and substrate surfaces can extend the useful range of all these materials. This results in considerable overlap in ability of various ceramic materials to match the esthetics and "light handling" characteristics of natural teeth. However, intelligent selection criteria would preclude certain materials/

natural tooth combinations. For example, attempting to restore a low value, translucent natural tooth with gray tones by using an opaque high-value substrate (for example, Hi-Ceram, metal-ceramics) unnecessarily complicates the esthetic challenge. Teeth with appreciable color content (for example, Vita shades A-3.5 to A-4), whether translucent or opaque, can be matched with most systems because the increasing color content and opacity of the veneering porcelain tends to mask underlying substrate materials. Optical effects in the gingival third often determine the overall esthetics, with more translucent materials normally providing better gingival esthetics because of their lower reflectivity and possible internal luminance contributions.

SUMMARY

Exciting ceramic materials and innovative ceramics processing strategies have been introduced in restorative dentistry since the early 1980s. Some of these ceramics still share roots with research that originated in Europe in the 18th century. Today, as in the era of Nicholas Dubois de Chemant, most advances are derived from collaborations with the ceramics engineering community. Notable recent progress includes (1) the advent of predictable ceramic materials and techniques for esthetic complete crowns, partial coverage, and laminate veneer restorations; (2) improved metal-ceramic esthetics with the advent of opalescent porcelains and framework modifications; (3) introduction of CAD/CAM and machining as a route to fabrication of restorations; and (4) improved understanding of the clinical response of all-ceramic prostheses and of the materials factors that influence clinical longevity. Strong scientific and collaborative foundations presently exist for continued development and improvement of ceramic systems by increasingly well-informed teams of researchers and dentists.

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