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Dental ceramics: current thinking and trends

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Background concepts in ceramics science and fracture

There are two useful concepts that help demystify dental ceramics by providing a structure within which to organize thinking. First, there are only three main divisions to the spectrum of dental ceramics: (1) predominantly glassy materials, (2) particle-filled glasses, and (3) polycrystalline ceramics [1–3]. Defining characteristics are provided for each of these ceramic types. Second, virtually any ceramic within this spectrum can be considered as being a "composite," meaning a composition of two or more distinct entities. Many seemingly different dental ceramics can be shown to be similar or closely related to each other when reviewed within the framework of these two simplifying concepts. Additionally, the rationale behind the development of ceramics of historic and recent interest can be more easily understood. Two examples of the utility of these concepts include these statements: (1) Highly esthetic dental ceramics are predominantly glassy, and higher strength substructure ceramics are generally crystalline; and (2) the history of development of substructure ceramics involves an increase in crystalline content to fully polycrystalline. Tables 1 and 2 provide basic composition details and commercial examples of many esthetic and substructure dental ceramics organized by these three main divisions.

Predominantly glassy ceramics

Dental ceramics that best mimic the optical properties of enamel and dentin are predominantly glassy materials. Glasses are three-dimensional (3-D) networks of atoms having no regular pattern to the spacing (distance and angle) between nearest or next nearest neighbors; thus, their structure is amorphous, or without form. Glasses in dental ceramics derive principally from a group of mined minerals called feldspar and are based on silica (silicon oxide) and alumina (aluminum oxide); hence, feldspathic porcelains

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Table 1
Esthetic ceramics: basic composition, uses, and commercial examples

Base	Fillers	Uses	Commercial examples
Predominantly glassy ceramics			
Feldspathic glass	Colorants Opacifiers High-melting glass particles	Veneer for ceramic substructures, inlays, onlays, veneers	Alpha, VM7 (Vita) Mark II (Vita) Allceram (Degudent)
Moderately filled glassy ceramics			
Feldspathic glass	Leucite (~17–25 mass%) Colorants Opacifiers High-melting glass particles	Veneer for metal substructures, inlays, onlays, veneers	VMK-95 (Vita) Omega 900 (Vita) Vita Response (Vita) Ceramco II (Dentsply) Ceramco 3 (Dentsply) IPS d.SIGN (Ivoclar-Vivadent) Avante (Pentron) Reflex (Wieland Dental)
Highly filled glassy ceramics			
Feldspathic glass	Leucite (~40–55 mass%) Colorants Opacifiers	Single-unit crowns, inlays, onlays, veneers	Empress (Ivoclar) OPC (Pentron) Finesse All-Ceramic (Dentsply)

belong to a family called aluminosilicate glasses [2]. Glasses based on feldspar are resistant to crystallization (devitrification) during firing, have long firing ranges (resist slumping if temperatures rise above optimal), and are biocompatible. In feldspathic glasses, the 3-D network of bridges formed by silicon-oxygen-silicon bonds is broken up occasionally by modifying cations such as sodium and potassium that provide charge balance to non-bridging oxygen atoms. Modifying cations alter important properties of the glass, for example, by lowering firing temperatures or increasing thermal expansion/contraction behavior.

Particle-filled glasses

Filler particles are added to the base glass composition to improve mechanical properties and to control optical effects such as opalescence, color, and opacity. These fillers are usually crystalline but can also be particles of a higher melting glass. Such compositions based on two or more distinct entities (phases) are formally known as ‘‘composites,’’ a term often reserved in dentistry to mean resin-based composites. Thinking about dental ceramics as being composites is a helpful and valid simplifying concept. Much confusion is cleared up in organizing ceramics by the filler particles they contain (and how much), why the particles were added, and how they got into the glass.

Table 2
Substructure ceramics: basic composition, uses, and commercial examples

Glass	Fillers	Uses	Commercial examples
Highly filled glassy ceramics			
Feldspathic glass	Leucite (~40–55 mass%)	Inlays, onlays, veneers, single-unit crowns	Empress (Ivoclar) OPC (Pentron) Finesse All-ceramic (Dentsply)
Feldspathic glass	Aluminum oxide (~55 mass%)	Single-unit crowns	Vitadur-N (Vita)
Lanthanum	Aluminum oxide (~70 vol%)	Single-Unit crowns, anterior three-unit bridges	In-Ceram Alumina (Vita)
LABS	Aluminum oxide (~50 vol% Zirconium oxide (~20 vol%)	Single-unit crowns, three-unit bridges	In-Ceram Zirconia (Vita)
Modified feldspathic glass	Lithium disilicate (~70 vol%)	Single-unit crowns, anterior three-unit bridges	Empress 2 (Ivoclar) 3G (Pentron)
Polycrystalline ceramics			
Aluminum oxide	<0.5 mass%[a]	Single-unit crowns	Procera (Nobel Biocare)
Zirconium oxide	Yttrium oxide (3–5 mass%)[a]	Single-unit crowns	Procera (Nobel Biocare)
Zirconium oxide	Yttrium oxide (3–5 mass%)[a]	Single-unit crowns, Three-unit bridges, Four-unit bridges (?)	Cercon (Dentsply) Lava (3M-ESPE) Y- (Vita)

Abbreviation: LABS, aluminoborosilicate.
[a] Dopants.

The first fillers to be used in dental ceramics contained particles of a crystalline mineral called leucite [1,2]. This filler was added to create porcelains that could be successfully fired onto metal substructures [4,5]. Leucite has a high thermal expansion/contraction coefficient (~20 × 10^{-6}/°C) compared with feldspathic glasses (~8 × 10^{-6}/°C). Dental alloys have expansion/contraction coefficients around 12 to 14 (×10^{-6}/°C). Adding about 17 to 25 mass% leucite filler to the base dental glass creates porcelains that are thermally compatible during firing with dental alloys. Metal-ceramic systems, first developed in 1962, are used to fabricate 70% to 80% of fixed prostheses.

Moderate strength increases can also be achieved with appropriate fillers added and uniformly dispersed throughout the glass, a technique termed "dispersion strengthening." The first successful strengthened substructure ceramic was made of feldspathic glass filled with particles of aluminum oxide (~55 mass%) [6]. Leucite also is used for dispersion strengthening at concentrations of ~40 to 55 mass%, which is much higher than needed for metal-ceramics. Commercial ceramics incorporating leucite fillers for strengthening include a group that are pressed into molds at high temperature (OPC, Pentron [Wallingford, Connecticut]; Empress, Ivoclar-Vivadent [Schaan, Liechtenstein]; and Finesse All-Ceramic, Dentsply Prosthetics [York, Pennsylvania]) and a group provided as a powder for traditional porcelain build-up (OPC Plus, Pentron; Fortress; Mirage Dental Systems [Kansas City, Kansas]).

Beyond thermal expansion/contraction behavior, there are two major benefits to leucite as a filler choice for dental ceramics—the first intended and the second probably serendipitous. First, leucite was chosen because its index of refraction is close to that of feldspathic glasses, an important match for maintaining some translucency. Second, leucite etches at a much faster rate than the base glass, and it is this "selective etching" that creates a myriad of tiny features for resin cements to enter, creating a good micromechanical bond.

Glass-ceramics (special subset of particle-filled glasses)

Crystalline filler particles can be added mechanically to the glass, for example by mixing together crystalline and glass powders before firing. In a more recent approach, the filler particles are grown inside the glass object (prosthesis or pellet for pressing into a mold) after the object has been formed. After forming, the glass object is given a special heat treatment causing the precipitation and growth of crystallites within the glass. Because these fillers are derived chemically from atoms of the glass itself, it stands to reason that the composition of the remaining glass is altered as well during this process termed "ceraming." Such particle-filled composites are called glass-ceramics. The material Dicor (Dentsply), the first commercial glass-ceramic available for fixed prostheses, contained filler particles of a type of crystalline mica (at ~55 vol%) [7]. More recently, a glass-ceramic containing 70 vol% crystalline lithium disilicate filler has been commercialized for dental use (Empress 2; Ivoclar-Vivadent).

Polycrystalline ceramics

Polycrystalline ceramics have no glassy components; all of the atoms are densely packed into regular arrays that are much more difficult to drive a crack through than atoms in the less dense and irregular network found in glasses. Hence, polycrystalline ceramics are generally much tougher and stronger than glassy ceramics. Polycrystalline ceramics are more difficult to process into complex shapes (eg, a prosthesis) than are glassy ceramics. Well-fitting prostheses made from polycrystalline ceramics were not practical before the availability of computer-aided manufacturing. In general, these computer-aided systems use a 3-D data set representing the prepared tooth or a wax model of the desired substructure. This 3-D data set is used to create an enlarged die upon which ceramic powder is packed (Procera; Nobel Biocare, Göteborg, Sweden) or to machine an oversized part for firing by machining blocks of partially fired ceramic powder (Cercon, Dentsply

Prosthetics; Lava, 3M-ESPE [Seefeld, Germany]; Y-Z, Vita Zahnfabrik [Bad Säckingen, Germany]). These approaches rely upon well-characterized ceramic powders for which firing shrinkages can be predicted accurately [8,9].

Polycrystalline ceramics tend to be relatively opaque compared with glassy ceramics; thus, these stronger materials cannot be used for the whole-wall thickness in esthetic areas of prostheses. These higher-strength ceramics serve as substructure materials upon which glassy ceramics are veneered to achieve pleasing esthetics. Laboratory measures of the relative translucency of commercial substructure ceramics are available for a single-layer of materials and for those that are veneered [10,11]. Although laboratory measures of opacity have equated some polycrystalline ceramics to cast alloys, all ceramic substructures transmit some light, whereas metals do not.

Substructure ceramics

The development of higher-strength ceramics for veneered all-ceramic prostheses can be represented as a transition toward increases in the volume percentage of crystalline material with decreasingly less glass and finally no glass. In 1965, McLean [6] reported on the strengthening of a feldspathic glass via addition of aluminum oxide particles, the same year that General Electric first applied that new technology (dispersion strengthening of glasses) to high-tension power line insulators. In the late 1980s, a method was developed to significantly increase the aluminum oxide content (from ~55 mass% to 70 vol%) by first lightly firing packed alumina powder and then infiltrating the still porous alumina compact with glass [12]. During the first light firing, adjacent alumina particles become bonded where they touch, forming a 3-D network of linked particles. Infiltration involves a low-viscosity glass drawn into the porous alumina network by capillary pressure, forming an interpenetrating 3-D composite (the alumina and glass being continuous throughout the ceramic and neither representing an isolated "filler"). Although, with only 70 vol% aluminum oxide, this ceramic (In-Ceram Alumina; Vita) has strength and fracture toughness identical to many 100% polycrystalline alumina ceramics.

Two key developments allowed fully polycrystalline ceramics to become practical for fixed prostheses: (1) the availability of highly controlled starting powders and (2) the application of computers to ceramics processing. Unlike glassy ceramics, polycrystalline ceramics cannot be pressed as a fully dense material into slightly oversized molds (molds that have expanded just enough to compensate for cooling shrinkage as is done in the casting of metals). Polycrystalline ceramics are formed from powders that can be packed only to ~70% of their theoretical density. Hence, polycrystalline ceramics shrink around 30% by volume (10% linear) when made fully dense during firing. For the final prostheses to fit well, the amount of shrinkage needs to be accurately predicted and compensated for. Well-characterized starting powders that can be uniformly packed are a prerequisite for achieving predictable and reproducible shrinkage. Research in ceramics-processing science from the late 1980s through the 1990s led to the commercial availability of powders suitable for dental use. Almost simultaneously with high technology, powder refinement came the development of computer-aided machining and the ability to capture and manipulate 3-D data sets.

Two approaches are offered commercially for fabrication of prostheses from polycrystalline ceramics, both of which create oversized greenware (unfired part) using 3-D data sets and the specific shrinkage characteristics of well-behaved starting powders. In the first approach, an oversized die is manufactured based on ~20,000 measurements taken during the mechanical scanning of a laboratory die. Aluminum oxide or zirconium oxide is pressed onto the oversized die and predictably shrunk during firing to become well-fitting, single-crown substructures (Procera, Nobel Biocare) [8]. In the second approach, blocks of partially fired (~10% complete) zirconium oxide are machined into oversized greenware for firing as single- and multiple-unit prostheses substructures (Cercon, Dentsply Prosthetics; Lava, 3M-ESPE; Y-Z, Vita). In these systems, individual blocks are bar coded with the actual density of each block (for the fine-tuning of shrinkage calculations), and the milling machines can keep track of the number of blocks milled and automatically change milling tools to assure accuracy of fit [9].

Transformation-toughened zirconium oxide

Transformation-toughened zirconia, a polycrystalline ceramic now available for dentistry, needs further explanation because its fracture toughness (and hence strength) involves an additional mechanism not found in other polycrystalline ceramics. Fracture toughness and strength are discussed in more detail below, but it is sufficient here to understand toughness as meaning the difficulty in driving a crack through a material.

Unlike alumina, zirconium oxide is transformed from one crystalline state to another during firing. At firing temperature zirconia is tetragonal, and at room temperature it is monoclinic, with a unit cell of monoclinic occupying about 4.4% more volume than when tetragonal. Unchecked, this transformation was unfortunate because it led to crumbling of the material on cooling. In the late 1980s, ceramic engineers learned to stabilize the tetragonal form at room temperature by adding small amounts (~3–8 mass%) of calcium and later yttrium or cerium. Although stabilized at room temperature, the tetragonal form is "metastable," meaning that trapped energy exists within the material to drive it back to the monoclinic state. The highly localized stress ahead of a propagating crack is sufficient to trigger grains of ceramic to transform in the vicinity of that crack tip. In this case, the 4.4% volume increase becomes beneficial, essentially squeezing the crack closed (ie, transformation decreases the local stress intensity).

With fracture toughness twice or more that of alumina ceramics, transformation-toughened zirconia represents a potential substructure material. Possible problems with these zirconia ceramics may involve long-term instability in the presence of water, porcelain compatibility issues, and some limitations in case selection due to their opacity. However, as of this writing, 3-year clinical data involving many posterior single-unit and three-unit prostheses (plus one five-unit) have revealed no major problems (discussed more fully below).

Strength and fracture toughness

There are three inter-related properties that often are quoted regarding ceramics intended for structural purposes: (1) strength, (2) fracture toughness, and (3) susceptibility toward chemically assisted crack growth. Because strength is the most frequently encountered property in professional and advertising literature, some discussion regarding the meaning and application of strength is warranted. The main point to understand about strength is that it is not an inherent material property, meaning that strength values depend on the condition of the material and how the test was conducted [13]. Fracture toughness (discussed below) is more an inherent property of ceramics and is increasingly seen as being more useful when comparing commercial materials.

Strength

Strength is a global measure of three things: (1) the type and size of failure-starting flaws and their distribution, (2) the fracture toughness, and (3) the influence of water. If all three things are well controlled to faithfully represent clinical prostheses, then comparisons based on strength have some meaning. Flaws are most often the result of processing steps (dental laboratory and dentist) used to fabricate prostheses, but flaws can also be inherent to the material. Hence, the best measure of strength comes from testing parts that have received all dental laboratory and dentist processing steps. Because it often is not practical to fabricate standardized test specimens (eg, bend bars) using all dental laboratory and dentist steps, the condition of the test specimen may not reflect the condition of finished prostheses, and reported strengths may not be meaningful. On the other hand, although actual prostheses adequately reflect the processing condition of the ceramic, stresses in prostheses at the point of failure (ie, strength) are difficult to calculate. In addition, most attempts to duplicate clinical loading of prostheses, especially single-unit crowns (“crunch the crown” tests), create failure from artificial damage produced during testing that is never seen clinically [14].

It has been known since 1958 that water decreases the strength of most glasses and ceramics. Water, acting chemically at crack tips, allows the slow growth of cracks under conditions where growth would not occur otherwise. Ceramics differ in sensitivity to water, a fact not well controlled for or taken into account in strength testing of dental ceramics or in published comparisons of strength data. Water is available to any surfaces exposed to saliva, but it also is available to cementation surfaces from dentinal tubules. All dental cements allow water (from saliva and dentin) to reach internal ceramic surfaces by diffusion.

Strength also is generally reported only for single materials. Prostheses often are made of multiple materials having different properties. The performance of such prostheses may depend as much on variables related to the use of multiple materials, such as bond strengths, residual stresses at material interfaces due to thermal contraction mismatches, and interfacial stresses during loading arising from mismatches in material stiffness (elastic moduli). For example, one type of all-ceramic three-unit prosthesis was found to fail clinically primarily from stresses and flaws within connectors at the core-veneer interface [15]. Similarly, single-unit crowns have been reported to fail from their internal (cementation or intaglio) surface due to chewing loads, not from damage or stresses on their occlusal surface [16–18]. With the cementation surface being at risk, survival probabilities can be influenced by the type of cement used or the surface treatment given.

Thus, strength is more of a "conditional" measure than an inherent material property and must be used cautiously (if at all) in judging the likely clinical performance of a new ceramic system. One better measure for comparing the structural performance of ceramics is fracture toughness, but this is limited in describing single material behavior. Overall, the case for clinical trial data becomes compelling given the factors discussed here that may influence clinical success and yet remain absent from laboratory testing protocols.

Fracture toughness

Because ceramics fail via crack growth from existing flaws, it is useful to have some measure of the ease with which this happens. Tensile loads (pulling) create stresses (load per area) at crack tips. As loads increase, the intensity of crack tip stresses rises rapidly. Purely straight opening, without the crack sliding or shearing, is termed "mode I" opening (mode one), and the stress intensity caused by this is designated by the letter "K"; thus, the stress intensity at a crack tip in simple mode I opening is written as K_I. At some "critical" stress intensity, conditions are right for the crack to become unstable and separate the ceramic part into two pieces.

Critical stress intensities for mode I opening, written as K_{IC} (with units of MPa $\times$ $\sqrt{m}$) are generally not dependent on the condition of the material (ie, they are flaw size insensitive) and can be used to compare different materials. K_{IC} values for metal-ceramic porcelains are ~0.9 to 1.2; for leucite-reinforced dental ceramics K_{IC} values are ~1.5 to 1.7 (eg, Empress, Ivoclar); and for alumina K_{IC} values are ~4.5 (eg, In-Ceram, Vita; Procera, Nobel Biocare), with transformation toughened zirconia ranging from 8 to 12 and metal alloys starting around 20.

Role of metal in "strengthening"

The role that the metallic substructure provides toward clinical durability is not well understood. Therefore, it is difficult to assess which characteristics of a metal casting need to be retained in substructures formed by alternative metal-forming technologies such as foils, electroforming, or melt-infiltrated capillary networks. It often is stated that porcelain needs to be "supported" by the metal framework. It is not defined what "supported" means.

There are a number of conceivable mechanisms by which metal castings might contribute to the longevity of veneering porcelain. First, porcelain needs to be protected from developing tensile stress in the vicinity of flaws located in critical areas. This implies that the metal might influence stress distributions within the porcelain, particularly at surfaces and interfaces. Second, where such stresses develop, porcelain benefits if the growth of flaws into cracks is suppressed. This implies that metal, well bonded to porcelain, might "bridge" the base of cracks (resisting further opening). Third, flaws that may eventually cause failure grow more slowly if kept dry. This implies that another role the cast metal substructure may play involves keeping water from entering the crack (eliminating chemically assisted crack growth).

Clinical concepts and performance issues

Advantages of all-ceramic versus metal-ceramic systems

All-ceramic systems

Esthetic advantages are real when the completely light-blocking metal is replaced, even by an opaque ceramic. All-ceramic systems can provide a better esthetic result for a wider range of patients than can metal-ceramics because a wide range of translucency-opacity (or "value" in the Munsell color system) can be achieved with commercially available ceramic systems. Other advantages relate as much to soft tissue health as to esthetics. Lesser amounts of plaque and adherence molecules are recovered from ceramic surfaces than from gold alloys or amalgam, and intra-oral plaque of a qualitatively healthier composition can form on ceramic surfaces [19–21]. It often is acceptable to leave the margin of all-ceramic prostheses supra-gingival or at the gingival margin, with the added benefit of more predictable and less traumatic impression making. Emergence profiles are less likely to be over-contoured, as is often the result with metal-ceramic prostheses due to efforts to provide a thicker layer of porcelain to mask the opaque-metal surface.

Metal-ceramic systems

Advantages of metal-ceramic systems lie in their predictable structural performance, their versatility, and that fact that less knowledge is required for choosing an appropriate system. The structural performance of metal-ceramic systems remains far better than for any all-ceramic system. As is discussed in more detail below, bulk failure and porcelain cracking affect approximately 5% to 10% of single-unit prostheses by around 6 years. Success rates are generally higher for anterior than for posterior single-unit prostheses. Less clinical data are available for three-unit prostheses, and not all systems have been well studied. Conversely, structural problems related to the porcelain can be as low as ~3% to 4% at 10 years for metal-ceramic prostheses (nontitanium), and ~74% can still be in service at 15 years with the majority of problems being biologic (secondary caries, periodontal disease, and endodontic failures) [22–24]. Porcelain survival on titanium substructures has not been nearly as good, even at 6 years, due to inherent problems at the titanium–porcelain interface [25,26].

Metal-ceramic systems are well enough developed that little special knowledge is required for their routine use. Most practitioners are likely unaware of which metal-ceramic systems their laboratory provides, and any system is generally suitable for anterior single-unit and posterior multi-unit prostheses. Successful use of all-ceramic systems requires a higher level of knowledge to maximize the esthetic result and to choose appropriately for structural longevity. All-ceramic systems are more commonly prescribed by specialty-level practices serving patients placing a premium on esthetics.

Decisions based on simple failure statistics

Initial survival data (1–2 years) is commonly presented regarding new all-ceramic systems, often first as a research meeting presentation and then repeated in advertising. Along with the limited observation times, two other aspects can render such studies difficult to interpret and to use for making comparisons. Many of these studies use simple survival rates based on the number of units surviving divided by the total number of units delivered. For example, in Figs. 1 and 2, results from two hypothetical studies are presented with the number of units cemented each month represented by light bars and the number that failed in any month represented by an overlaid dark bar. Studies A and B have both cemented 60 units, both have had five failures, and both have been active for 2 years. Given these last facts, investigators in both cases could be temped to claim 92% success at 2 years (55/60).

Looking more critically at the studies in Figs. 1 and 2 reveals two striking problems. First, crowns in both studies have been under examination for different periods of time. For example, the investigators in Study B did not have as much early success at recruiting patients, with the bulk of crowns not having been cemented until early in the second year. Second, neither study has crowns that have been under observation for the full 2 years. Simple survival data can be distorted, especially in early data.

Results from both studies are presented in Figs. 3 and 4 as probability of survival plots using Kaplan-Meier statistics, where the crowns are represented only for the period of time under observation. Additional methods exist to account for crowns (patients) lost to the study. This analysis (Figs. 3 and 4) demonstrates that neither investigation should report 92% success and that

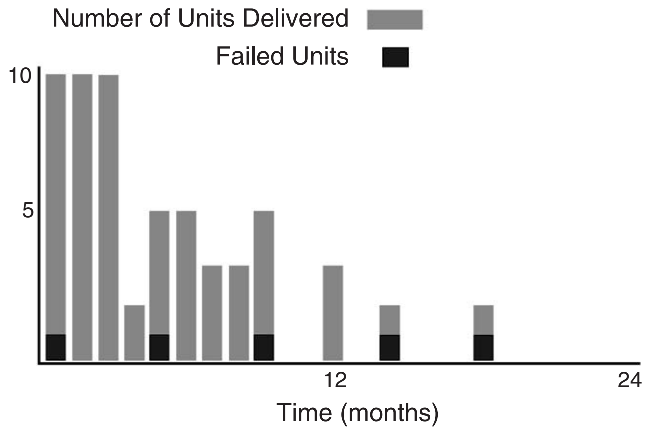

Fig. 1. Frequency of crowns cemented per month in Study A. Grey bars represent the number of cemented crowns. Overlaid dark bars represent the number of failed crowns in any given month.

the crowns of Study B are failing miserably. Such life table analysis allows clinicians to make valid comparisons among clinical trial data.

Survival literature for all-ceramic restorations

Veneers

Ceramics are particularly well suited for veneer restorations. With limited exceptions [27,28], porcelain veneers fabricated from a wide variety of ceramics have failure rates (loss of retention or fracture) of <5% as reported

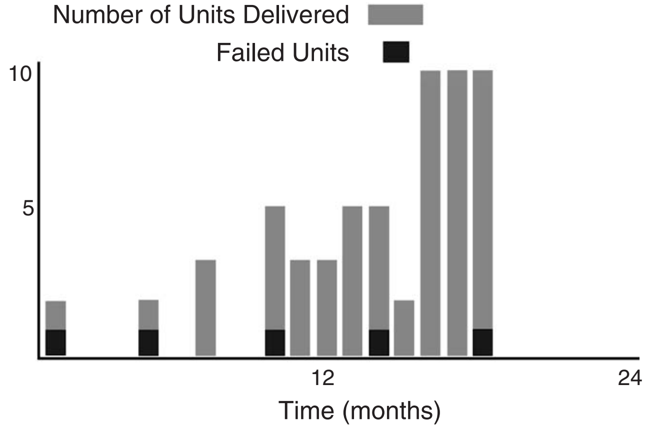

Fig. 2. Frequency of crowns cemented per month in Study B. Grey bars represent the number of cemented crowns. Overlaid dark bars represent the number of failed crowns in any given month.

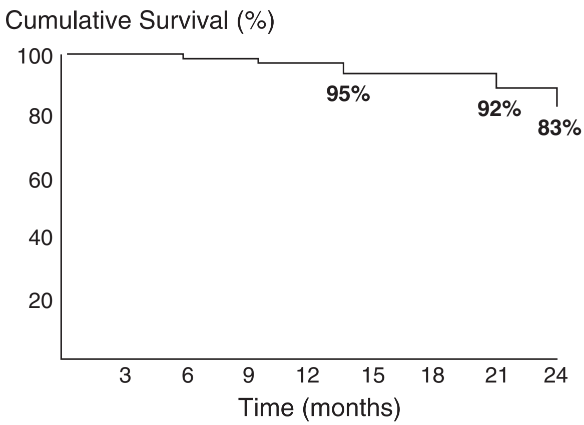

Fig. 3. Life table analysis (Kaplan Meier) of crowns in Study A calculating actual survival per month.

from eleven studies of generally 3 years to 5 years duration [29]. Materials and clinical and performance issues related to the use of ceramic veneers are well covered in two relatively recent review articles [29,30].

Inlays and onlays

The most extensively studied ceramic inlay/onlay restorations are those fabricated via the Cerec computer-aided design/computer-aided machining system (Sirona; A.G., Bensheim, Germany). Two ceramics were available when most published studies were initiated: a felspathic porcelain (Mark I; Vita) and a mica-filled glass (Dicor; Dentsply). Systematic analysis of 15

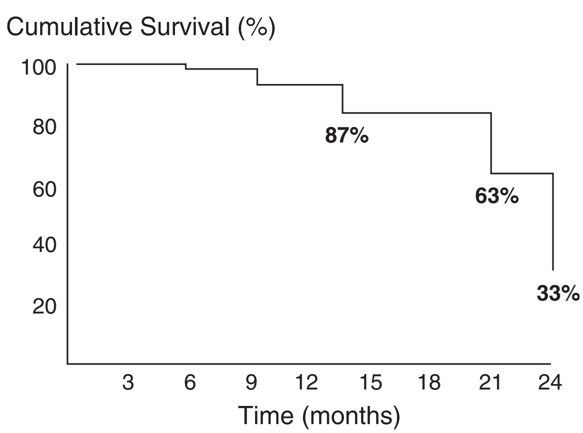

Fig. 4. Life table analysis (Kaplan Meier) of crowns in Study B calculating actual survival per month.

clinical trials found a mean survival rate of 97.4% over 4.2 years with excellent color stability and wear [31]. An 8-year follow-up of 16 patients, each receiving two inlays, reported that 3 of the 32 restorations fractured [32]. Cerec inlays and onlays (200 restorations) provided in a private practice were reported to have a survival rate (Kaplan-Meier) of 90.4% over 10 years with failures being due to ceramic fracture (53%), tooth fracture (20%), and endodontic problems (7%) [33]. One of the leucite-reinforced pressed ceramics has also been relatively well studied as an inlay/onlay material (Empress, Ivoclar). A literature review of six clinical trials reported that survival rates ranged from 96% at 4.5 years to 91% at 7 years [34].

Single-unit crowns

Four ceramic systems have received notable attention in peer-reviewed literature: (1) a leucite-reinforced glass (Empress, Ivoclar), (2) a glass-infiltrated alumina (In-Ceram Alumina, Vita), (3) a glass-infiltrated magnesium aluminate spinell (In-Ceram Spinell, Vita), and (4) a polycrystalline alumina (Procera, Nobel Biocare). In most cases, fracture rates seem to be lower for anterior crowns than for molar crowns, with the lowest failure rates for posterior restorations being reported for the high fracture toughness/high strength alumina-like and alumina materials (In-Ceram Alumina and Procera).

The glass-infiltrated material based on magnesium aluminate spinell (a more translucent, but lower strength cousin of the glass-infiltrated alumina) seems to be indicated for anterior restorations. One 5-year study of 40 anterior crowns reported a 97.5% survival rate (Kaplan-Meier) [35]. Data for anterior versus posterior leucite-reinforced crowns seem to trend toward higher survival for anterior teeth [36], but this can be nonsignificant statistically [37], and one contrary study exists [38]. This confusion is likely due to in part to the inclusion of premolar crowns in the "posterior" category and the relatively low number of failing crowns and studied restorations (ie, low statistical power). In a review of six clinical trials, the survival rate for leucite-reinforced crowns (Empress, Ivoclar) ranged from 92% to 99% at 3 to 3.5 years [39].

Studies of crowns having substructures of the higher toughness/strength alumina-based ceramics (In-Ceram Alumina, Vita; Procera, Nobel Biocare) report generally similar results for both materials. No bulk fracture was reported for 28 anterior and 68 posterior In-Ceram crowns at 4 years [40]. In a private practice setting, 223 In-Ceram crowns had a survival rate of 96% after 3 years, with anterior crowns trending toward higher survival (98%) than premolars or molars (94%) [41]. In a 4-year university trial of 80 In-Ceram crowns (73% anterior, 27% posterior), one molar crown fractured and the marginal ridge of one premolar crown chipped [42]. Of 97 Procera alumina crowns followed for 5 years, three crowns experienced bulk fracture, and two had some loss of veneering porcelain [43]. The 5- and

10-year survival rates reported in another study of Procera crowns were 98% and 92%, respectively [44].

Multi-unit prostheses

Two all-ceramic systems have been recommended by their manufacturer for anterior three-unit prostheses: a glass-infiltrated alumina (In-Ceram Alumina, Vita) and lithium disilicate glass-ceramics (Empress 2, Ivoclar; G3, Pentron). In a study of 18 In-Ceram Alumina prostheses (64% cantilevered two-unit and 36% three-unit) with 62% involving a posterior tooth, the survival rate (Kaplan-Meier) was 93% at 5 years and 83% after 10 years [45]. There do not yet seem to be peer-reviewed publications regarding the clinical performance of multi-unit prostheses fabricated with lithium disilicate glass-ceramics.

Two other all-ceramic systems are being recommended for posterior three-unit prostheses by their manufacturers: a glass-infiltrated alumina/zirconia (In-Ceram Zirconia, Vita) and transformation toughened polycrystalline zirconia (Cercon, Dentsply Prosthetics; Lava, 3M-ESPE; Y-Z, Vita). Ongoing trials of zirconia prostheses are heavily focused on posterior multi-unit prostheses, including studies at the University of Zurich (58 posterior prostheses; three-unit, four-unit, and one five-unit), Saarland University (38 posterior multi-unit prostheses), University of Gottingen (62 posterior prostheses; three-unit and four-unit), and the Louisiana State University (20 posterior three-unit prostheses). Although results from these trials have yet to be fully published, updates have been presented at international research meetings with no instances of bulk fracture reported. The longest trial, at the University of Zurich, recently completed the 3-year recall for all active patients.

Practical aspects

Choosing a system by translucency (value)

Many leaders in the use of all-ceramic and metal-ceramic systems recommend choosing a system based on the value (Munsell lightness-darkness scale) of the dentition being restored. Opaque teeth (often whitish) are best matched using an opaque substructure; this includes many of the highly crystalline ceramics and metal-ceramic systems. Highly translucent teeth (often grayish) are difficult to match unless the substructure allows more light transmission than is characteristic of metals and opaque ceramics. Most systems allow the incorporation of internal coloration, variations in incisal translucency, and the addition of opalescence. If an all-ceramic system is to be chosen, consideration should be given to the structural indications developed from clinical data and manufacturer recommendations.

Etching and bonding

One classic piece of research demonstrated that the first commercial glass-ceramic crowns (Dicor, Dentsply) had a much higher survival rate (Kaplan-Meier) over 16 years if they had been etched and cemented with a resin cement rather than being non-etched and cemented with a zinc phosphate cement [46]. The improved clinical survival of later feldspathic ceramics having roughly similar strengths and toughness to Dicor (eg, Empress, Ivoclar; Mark II, Vita) is widely thought to be at least partially due to their ability to be etched and form strong bonds with resin cements. For ceramics other than Dicor, a possible relationship between bonding and clinical success remains conjecture, but this concept has led to the technique being almost universally applied.

The first requirement for forming a micromechanical bond is the presence of small components within the ceramic that can be selectively attacked by acids (etched) at a higher rate than surrounding ceramic. The selective etching of crystalline leucite, leaving behind microscopic glassy crypts, is the most common dental example. A second requirement for good bond formation relates to the size of the structure(s) formed by etching and how well they are still attached to the remaining bulk ceramic. For example, some selective etching of In-Ceram Alumina is possible, but the scale of roughness that develops is insufficient for good bond formation. Polycrystalline ceramics can be etched, revealing the boundary between crystalline grains, but these etched grain boundaries provide little micromechanical retention.

Chemical bonding is possible with virtually all dental ceramics but only with the use of resin cements containing special adhesive molecules. The durability of chemical bonding between resin cements and substructure ceramics has not been definitively addressed.

Glazing versus polishing

Auto glazing (firing in air) and polishing are two options for finishing the surface of esthetic porcelains. These techniques received recent attention in a review of a number of studies comparing prepared surfaces using visual, microscopic, and profilometry measures [47]. All studies agree that glazing can produce a smooth porcelain surface. However, polishing can produce as smooth a surface that can be more esthetically similar to natural enamel. Many authorities favor polishing given that a higher level of control is possible over final surface finish and that an added firing can add problems and time to the delivery appointment.

Repair

Approaches to the repair of porcelains have recently been reviewed [48]. Repair often offers a cost-effective alternative to replacement. Repair involves the bonding of resin-based products to remaining porcelain. The porcelain-resin bond is formed by etching the surface to create micromechanical attachment features and by the application of silane coupling agents to provide some chemical interaction between the silicon-based ceramic and carbon-based resins. It is reported that porcelain repair systems form durable bonds to fractured porcelain and exposed metal surfaces [48].

Summary

Ceramics are widely used in dentistry due to their ability to mimic the optical characteristics of enamel and dentin and their biocompatibility and chemical durability. Most highly esthetic ceramics are filled glass composites based on aluminosilicate glasses derived from mined feldspathic minerals. One common crystalline filler is the mineral leucite, used in relatively low concentrations in porcelains for metal-ceramic systems and in higher concentrations as a strengthening filler in numerous all-ceramic systems. In general, the higher the fraction of polycrystalline components, the higher is the strength and toughness of a ceramic. The development of substructure ceramics for fixed prosthodontics represents a transition toward fully polycrystalline materials. Although the strength of a dental ceramic can be a meaningful number, it is not an "inherent" property and varies due to testing parameters that are often not well controlled to optimize clinical relevance. Fracture toughness is a far more "inherent" measure of the structural potential of a ceramic and represents a more easily compared value. Clinical data for all-ceramic systems are becoming available, and results exist for many commercial materials, providing guidance regarding clinical indications.

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