Review Article

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Dental Ceramics: A Review

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ABSTRACT

Background: Dental ceramics are presented within a simplifying framework allowing for facile understanding of their development, composition and indications. Over the past forty years, the technological evolution of ceramics for dental applications has been remarkable, as new materials and processing techniques are steadily being introduced. By understanding the classifications, composition, and characteristics of the latest all-ceramic materials, which are presented in this article in order of most to least conservative, dentists and laboratory technicians can best determine the ideal material for a given treatment. This review presents the art of ceramic for dental applications.

Keywords: Ceramics, dentistry, prosthodontics.

INTRODUCTION

It is quite useful reviewing how and why ceramics came to be used in dentistry. This account serves three purposes: (1) to alert practitioners to the fact that the use of ceramics, since the very beginning, always represented the adoption of 'high technology' versus 'craft art'; (2) to reinforce the concept that ceramics and improved ceramics were introduced in order to solve

specific problems or to increase restorative versatility; and (3) to provide a gentle background into the nature and science of ceramics.[1] Applications for ceramics in dentistry became increasingly popular in the 18th century, largely due to the esthetic characteristics of the material compared to other tooth substitutes.[2] Alexis Duchateau, a Parisian apothecary, integrated ceramics into dentistry when he created a complete set of dentures using porcelain ceramic material.[3] Later, in 1903, Charles Land further advanced dental ceramics by developing all-ceramic inlays, onlays, and crown restorations using fired porcelains,[4,5] innovations that led to the creation of porcelain jacket crowns.[6] Since then, dental ceramics have evolved with modifications to their chemical composition, esthetic properties, manufacturing processes, packaging, and indications. Highly esthetic and biocompatible results were achieved with early versions of dental ceramics, but the material's weakness in tensile and shear stresses necessitated development of ceramic materials with greater strength and durability,[7,8,9] especially when thicker restorations are necessary and/or cementing mainly to dentin is required. With the development of adhesive dentistry and improvement of the resins, the use of metal-free restorations has increased. In the recent past decades, the development of ceramic materials has increased significantly and their use has been more and more frequent. This material presents features, such as translucence, fluorescence, thermal-linear expansion coefficient close to dental structure, biological compatibility, chemical stability and compression and abrasion resistance. These properties enable it for being used as a substitute of natural tooth .[10] This review covers the history of dental ceramics, different classification methods and a description of the different types of material and processing technologies. Emphasis is placed on

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how these new materials and fabrication methods are overcoming the aforementioned problems, and clinical aspects are also discussed.[11]

HISTORICAL EVOLUTION

In the early 1700s many European rulers were spending enormous sums importing porcelain from China and Japan. Europeans strived at 'porcelain discovery' without much success for about 200 years and this activity is credited with being largely responsible for the growth of modern analytical chemistry from its roots in alchemy.[1] An historical timeline of porcelain discovery appears as Fig 1.

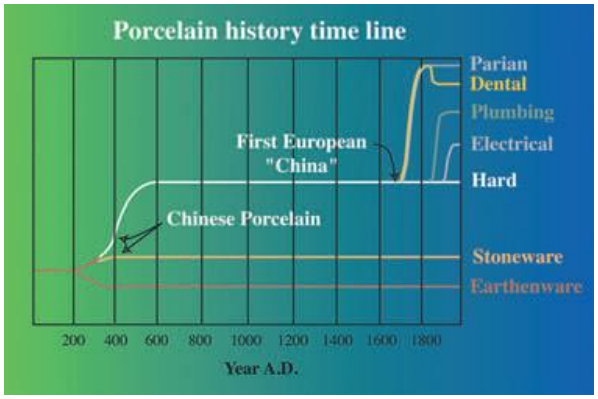

Fig 1. Timeline of porcelain development from ancient China to modern formulations.

By 1776, porcelain making was the topic of a review paper given at the Academy of Sciences in Paris. In 1770 another apothecary, Alexis Duchateau, tired of his stained and malodorous dentures, sought assistance from Parisian dentist Nicholas Dubois de Che´mant. Working with porcelain formulations and (then) high technology kilns of the Guehard Porcelain Factory, they succeeded by 1774 in fabricating a complete denture for Duchateau. Porcelain dentures represented a huge step forward in personal hygiene, leading public honours for de Che´-mant from the likes of Edward Jenner (smallpox vaccine), the Academy of Sciences and the Academy of Medicine of Paris University.[12] Since porcelain was a new invention in Europe and only available in collaboration with a high technology company – from the very beginning its use in dentistry was certainly not craft art. In 1808 another Parisian dentist, Giuseppangelo Fonzi, significantly improved the versatility of ceramics by firing individual denture teeth, each containing a platinum pin. This invention allowed teeth to be fixed to metal frameworks enabling: (1) partial denture fabrication; (2) repairability; and (3) increased aesthetics. Platinum had only been known to Europeans since around 1741 and given its extremely high melting point (1769 C) was generally only worked into small wires and crucibles by hammering individual red-hot nuggets. Platinum was not used in jewellery until 1915.[12] In 1808 platinum was used by alchemists in early chemistry experimentation, so it is likely that Fonzi obtained platinum wire from a local university or an early 'scientific supply house'. It was also the only metal that would not crack the denture tooth on cooling given its closely matched coefficient of thermal contraction. Again, this next major improvement in our ability to use ceramics in dentistry clearly stands as 'high technology'.[12] One major advance in porcelain itself came in 1962 with the development of a formulation that could be fired on common dental casting alloys. This invention built on a paper published in the Journal of the American Ceramics Society (JACS) demonstrating an oddity in the thermal expansion of a certain feldspar rock (with a potassium content over 11%) when melted and cooled quickly, forming a glass.[13] Leucite was later used for dispersion strengthening at 35 to 50 mass%in both powdered ceramics and later in the first pressed ceramics. Leucite was a good choice as a strengthening filler since its index of refraction is close to that of the feldspathic glass, so moderate strengthening could be achieved without severely increasing opacity. Allceramic systems based on leucite-filled feldspathic glasses remain some of the most aesthetic and popular dental ceramics, and have been extensively studied clinically and found to be highly reliable.[14] The use of a feldspathic glass dates back to Bottger in 1710. It became the major component of dental formulations with the work of de Che´mant in England in the early 1800s and a special property of high potassium feldspars was taken advantage of in 1962, leading to the vast majority of aesthetic dental ceramics in use today, either metal-ceramic or all-ceramic.[14] Except for pressing ingots, by the mid 1980s all dental Seven different approaches were developed beginning in the mid 1980s through to the late 1990s to deal with or avoid shrinkage to provide prostheses that were, what an engineer would call, being made to a 'net shape': (1) a pressed ceramic powder / polymeric binder that expanded and crystallized during firing to fill a lost-

wax mould (Cerestore; Johnson & Johnson, New Brunswick, NJ, USA);[15,16] (2) casting of a special glass into a lost-wax mould, embedding the clear-glass casting in an investment and heat-treating to form crystals within the glass (termed a 'glass ceramic', trade named DICOR; Dentsply International, York, PA, USA); (3) lightly sintering aluminum oxide (and later magnesium aluminate spinel and zirconia / alumina) to form necks between touching particles and then infiltrating this porous ceramic with glass (In-Ceram; Vita Zahnfabrik, Bad Sa¨ckingen, Germany);[17] (4) pressing solid ingots of filled-glass (leucite or lithium disilicate) into a lost-wax mould (Empress; Ivoclar Vivadent, Schaan, Liechtenstein);[18] (5) computer-aided machining of 'net-shape' parts from solid, full-dense blocks (CEREC; Sirona, Bensheim, Germany);[19] (6) computeraided fabrication of an oversized die, pressing of alumina powder onto the die creating an oversized part and sintering to final size (Procera; Nobel Biocare, Zurich, Switzerland);[20] and (7) computer-aided machining of oversized parts from lightly sintered blocks of zirconia and alumina which are then sintered to final size (Cercon, Lava, Vita YZ, Ivoclar e.max zirCAD).[21] ceramic 'parts' started as powders or mixtures of clay and power particles. Approach number (1) provided the first introduction of advanced ceramics processing equipment into the dental laboratory and approach (2) introduced 'glass ceramics' into dentistry; where strengthening filler particles are grown inside of the glass from the chemistry of the glass (during a special heat treatment called 'ceramming') as opposed to being added as separate powder particles. While all seven approaches stand clearly as being high technology, numbers (5) and (7) can be viewed as being revolutionary. In 1987, Mormann and Brandestini introduced a prototype machine that would capture a 3-D image of a prepared tooth. They used 3-D design software to iteratively develop a proposed restoration and then directed the computer-aided milling of inlays and onlays from solid blocks of aesthetic, filled-glass ceramics (CEREC I, then Siemens Dental now Sirona, Bensheim, Germany). Machining of aesthetic glass-based ceramics is relatively straightforward and special formulations were quickly developed that were much higher quality than what was available from dental laboratory processing based on either strengthened and fine grained feldspathic ceramics(Mark II, Vita) or the first glass- ceramic introduced for dental use (containing interlocking tetrasilisic fluoromica flakes, DICOR-MGC, Dentsply International).[19]

Further advances in the manipulation of 3-D data sets along with the fruits of a decade of research into ceramics processing provided the underpinning for an innovative solution proposed by Filser and Gauckler at the University of Zurich. This involved machining of an oversized part from a ceramic block only lightly sintered to what is termed the 'initial sintering' stage.[22, 23, 24] The green machining technique allowed the individually customized and high tolerance parts dentistry requires to be manufactured from polycrystalline ceramics such as alumina and zirconia. As of today, the last major advance in dental ceramics comes with the introduction of transformation toughened zirconia.[24, 25, 26] First, there are only three main classes of dental ceramics: (1) predominantly glassy materials; (2) particle-filled glasses; and (3) polycrystalline ceramics.[27, 28, 29] Defining characteristics will be provided for each of these ceramic types as they are represented in Fig 2. Second, virtually any ceramic within this spectrum can be considered as being a 'composite', meaning a composition of two or more distinct entities.

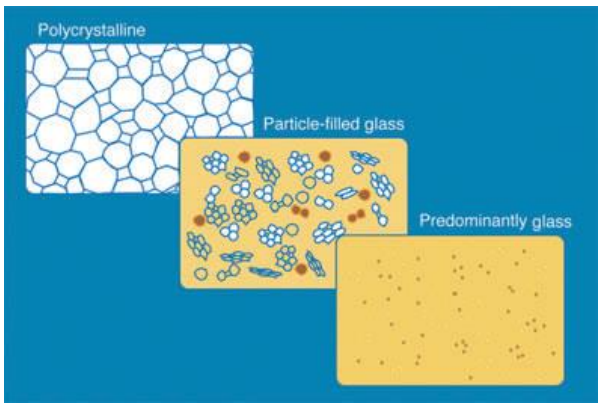

Fig 2: Based on their microstructure, dental ceramics fall within three basic classes: (1) predominantly glass; (2) particle-filled glass; and (3) fully polycrystalline.

COMPOSITION, CHARACTERISTICS, CLASSIFICATION AND ITS DENTAL APPLICATION

Ceramics are inorganic, nonmetallic solids produced by the heating at high temperatures and subsequent cooling of raw compounds such as nitrides, carbides, metal oxides, and borides, as well as

mixtures of these materials. Therefore, a material labeled as ceramic is in fact *not* ceramic by definition if it is created by another processing technique or has organic components. Ceramic materials may contain a crystalline or partly crystalline structure, or they may be amorphous (eg, a glass). Since most dental ceramics have at least some crystalline component, some authors limit the definition of ceramics to inorganic crystalline-containing materials, rather than including non-crystalline glasses, even though glasses are ceramics.[30, 31] Understandably, dental ceramics are generally categorized by their microstructure,[32] which facilitates scientific understanding of the structural and chemical nature of dental ceramics but does little to aid dentists or ceramists in selecting the appropriate material for a given clinical situation. The manner in which a ceramic is processed greatly influences its mechanical behavior and, therefore, its clinical behavior. Therefore, classifying dental ceramics based on their composition and how they are processed can better provide clear clinical parameters for evaluating and appropriately choosing the most conservative ceramic for each clinical situation.16 The categories below are presented from most conservative to least conservative in terms of healthy tooth structure preservation. The following is an update to a previously published classification system that takes into account increased clinical documentation of the success of newer glass ceramics, and introduces some new materials.[33]

CL-I(Powder/Liquid)

Class I (CL-I) powder and liquid porcelains are created from materials primarily containing silicon dioxide and possess a glassy matrix and varying amounts of a crystalline phase within the glassy matrix (eg, Creation Porcelain, Jensen Dental, www.jensendental.com; Ceramco 3, DENTSPLY International, www.dentsply.com; EX-3, Kuraray Noritake Dental, Inc, www.kuraraynoritake.com). The CL-1 group includes feldspathic porcelains, referred to as such because they were originally—and some continue to be—made from naturally occurring feldspars (ie, aluminosilicates composed of assorted quantities of potassium, sodium, barium, or calcium).[32, 34] Several feldspathic material options are available on the market today (eg, VITA VM 13, VITA Zahnfabrik, www.vita-zahnfabrik.com; Vintage Halo, Shofu, www.shofu.com). CL-I materials are fabricated by hand; they are the most conservative and generally the most translucent ceramic materials, but they are also the weakest.[32, 35, 36] The material's high translucency and esthetics create the illusion of natural teeth.[32] Powder/ liquid porcelain materials are ideal for cases in which significant enamel remains and/or there is healthy tooth structure on the teeth (ie, 50% or more remaining enamel on the tooth, 50% or more of the bonded substrate is enamel, and 70% or more of the margin is in the enamel). Feldspathic porcelain restorations that are bonded to primarily enamel substrates have proven to be highly successful long term.[37] Powder/liquid porcelains demonstrate high esthetics and workability, and because they can be layered very thinly and placed directly on the enamel, they are considered the most conservative of the metal-free ceramic classes.10 CL-I porcelains require a thickness of 0.2 mm to 0.3 mm for each shade change.[38, 39] This class of materials is generally indicated for anterior restorations, but can also be used for the occasional bicuspid and rare molar, providing all parameters are at a very low risk level.

CL-II(Glass Ceramics)

The composition of CL-II ceramics is similar to CL-I porcelain in that both possess a glassy matrix, but the two classes vary in their glasscrystalline ratios and crystal types. In CL-II materials, crystal types can either be added to the glass or grown into the glassy matrix. CL-II ceramics also differ from CL-I porcelains in manufacturing, as they are formed into dense industrial blocks for pressing and machining. Based on their crystal type and documented clinical behavior, CL-II pressed and machined glass ceramics can be further subdivided into two distinct groups.

CL-IIa

Materials in this subdivision contain low-tomoderate (<50%) leucite-containing feldspathic glass. Such materials (eg, IPS Empress® CAD, Ivoclar Vivadent, www.ivoclarvivadent.com; Authentic® Jenson Dental; VITABLOCS® Mark II, VITA Zahnfabrik) contain less than 50% crystalline and perform more like a glass, which requires bonding. Like all CL-II materials, which have come

to be known as glass ceramics, CL-II a materials can be used for the same indications as CL-I materials—including anterior teeth, bicuspids, and rarely molars. Additionally, they have documented long-term clinical success in higher stress situations or when more dentin is exposed. They may be highly translucent, but traditionally they have required slightly thicker dimensions for workability and esthetics/ shade matching (ie, minimum working thickness of 0.8 mm if layered with a veneering porcelain).[38, 39] Materials in this subcategory demonstrate increased material strength, primarily due to the processing technique of using a dense, industrial-made block, and possibly due to the leucite and its ability to alter the coefficient of thermal expansion, inhibiting crack propagation. These dense glass- and leucitecontaining materials are indicated for thicker veneers, anterior crowns, and posterior inlays and onlays, but only when a long-term bond and seal can be maintained.

CL-IIb

This is a new subcategory that includes moderate-to-high (ie, >50%) crystalline-containing glass or glass ceramics. The material's microstructure consists of a glass matrix surrounding a second phase of individual crystals. It originates as homogeneous glass, after which a secondary treatment nucleates and grows crystals, a process that imparts improved mechanical and physical properties by maximizing the presence of crystals and the generation of compression stress around the crystals. An example of this material subcategory is lithium disilicate (eg, IPS e.max®, Ivoclar Vivadent), a glass ceramic material composed of silica, lithium dioxide, alumina, potassium oxide, and phosphorous pentoxide. After the crystalline component has reached optimal growth through the manufacturing process, it is pulverized into powder and processed through a variety of different techniques.[40] Lithium disilicate is indicated for the same clinical situations as other glass ceramics; however, when fabricated to a full-contour, monolithic restoration and seated with resin cement, it is also appropriate for higher stress situations, such as those requiring full crowns, even on molars. New additions to the category are zirconia- reinforced lithium silicates (ZLSs) (eg, VITA Suprinity®, Figure 12; CELTRA™ Duo, DENTSPLY). ZLS materials comprise a lithium silicate glass ceramic that is strengthened with approximately 10% zirconia crystals. Although these materials are new to the market as of press time, initial in vitro testing shows they have excellent optics and physical properties similar to lithium disilicates. Only lithium disilicates have long-term clinical data to support their use as single restorations anywhere in the mouth, however. Restorations fabricated from this material subcategory demonstrate high strength, fracture resistance, and natural-looking esthetics,[41] yielding a versatile and strong alternative for a wider variety of indications. They are indicated when higher risks are involved (eg, less than 50% enamel remains on the tooth, less than 50% of the bonded substrate is enamel, and/or when 30% or more of the margin is in dentin). Due to the material's glass properties, adhesive bonding is recommended. However, bonding to dentin results in less predictable restorations due to dentin's flexibility; restorations bonded to enamel are much more predictable, given enamel's significant stiffness compared to dentin.[37]

CL-III (High-Strength Crystalline)

CL-III materials are high-strength crystalline ceramics with minimal or no crystalline phase, and are also produced through industrial processes. They differ from glass or glass ceramics based on the manner in which a sintered crystalline matrix of high-modulus material (85% to 100% of the volume) creates a junction with the particles in the crystalline phase.

Table 1: Inc., www.captek.com)* From manufacturer's data: http://vident.com/products/cadcam/, accessed 12/31/2009

Crystalline Phase	Crystalline phase	Crystallinity (%)	Strength (MPa)	Brand	Manufacturer
Sintered on metal substructure	Leucite	15–25	61 ± 5 [16]	Ceramco ®3	Dentsply
Heat-pressed	Leucite	≈ 35	106 ± 17 [27]	IPS Empress	Ivoclar
Heat-pressed	Lithium disilicate	65	306 ± 29 [27]	IPS Empress ®	Ivoclar
	Alumina	Highly Crystalline		Eris	Nobel Biocare
Dry-pressed and sintered	Alumina		607 ± 73 [40]	Procera®	Vident
Slip-cast & glass-infiltrated or soft machined and glass-infiltrated	Spinel	67–68			Vident
Slip-cast & glass-infiltrated or soft machined and glass-infiltrated	12 Ce-TZPalumina	65–68	594 ± 52 [27]	In-Ceram® Alumina	Vident
Slip-cast & glass-infiltrated or soft machined and glass-infiltrated	3Y-TZP Alumina	67		In-Ceram® Spinell	Dentsply
Soft-machined & sintered	Sanidine Leucite	Highly crystalline	378 ± 65 [26]	In-Ceram®	Vident
Soft-machined & sintered	Lithium disilicate	Highly crystalline	630 ± 58 [47]	Zirconia Cercon	
Hard-machined			1087 ± 173	In-Ceram®	Vident

Hard-machined		≈ 30	[94]	AL	
			700*	Vitablocs ®	Ivoclar
		≈ 35		Mark II	Ivoclar
Hard-machined & crystallized		65	122 ± 13 [26]	IPS Empress ® CAD	
			106 ± 17 [27]	IPS e.max CAD	
			262 ± 88 [55]		

CL-IIIa

CL-IIIa materials are manufactured by creating a porous matrix that is formed into a block, and then final processed to shape using CAD/CAM technology, after which a second-phase material melts and fills the pores within the material. Lanthanum aluminosilicate glass is drawn in either a liquid or molten glass form into all of the pores via capillary action, creating a dense and interpenetrating material from the internal to external surfaces. The final material is an 85% crystalline mesh infused with a small amount of glass. This material is disappearing from the marketplace and being replaced entirely by 100% polycrystalline ceramics.

CL-IIIb

CL-IIIb high-strength 100% crystalline ceramics initially were alumina-based materials (Procera®, Nobel Biocare, www.nobelbiocare.com), and more recently zirconia-based materials (eg. LAVA™, 3M ESPE, www.3mespe.com; Prettau®, Zirkonzahn, www.zirkonzahn.com). Alumina systems have proven successful for single units, but are being replaced by zirconia and lithium disilicate due to the increased risk of failure in the molar region.[42, 43] Zirconia can also be used when significant tooth structure is missing, when high risk for flexure and stress is present, for posterior full-crown and fixed partial denture situations , and when adhesive bonding is problematic, such as with subgingival margins. In cases where the bond and seal cannot be maintained (ie, high-risk bonding situations, including moisture control problems, high shear and tensile stresses on bonded interfaces, and variable bonding interfaces), high-strength CL-III

ceramics or metal ceramics (CL-IV, see below) are appropriate, because they can be placed using conventional cementation techniques. A concern with full-contour zirconia, however, is wear on opposing dentition.[44] Whether alumina or zirconia, these materials demonstrate greater strength than CL-I and CL-II materials and can be used to fabricate a core substructure to replace metal.

However, they are more opaque due to their greater crystalline content, which detracts from overall esthetics. They are therefore layered with porcelain,[45] allowing these materials to offer both superior strength and improved esthetic results.[46] CL-III high-strength ceramics require a thickness of 1.2 mm to 1.5 mm, depending on the substrate color.[38, 43] More translucent versions are now used in the posterior region as full-contour or monolithic all-zirconia restorations. Marketed first in this category was BruxZir® (Glidewell Laboratories, www.bruxzir.com), with many other manufacturers entering the market.

CL-IV (Metal Ceramics)

CL-IV represents metal ceramics, which are essentially CL-1 materials fused to a highly supportive substrate metal, allowing their use in high-stress clinical situations where conventional crowns and esthetics may be required. They are ideal when minimal-to-no tooth structure remains. Like CL-III materials, CL-IV metal ceramics demonstrate greater strength but limited esthetic characteristics. CL-IV metal ceramics require a thickness of at least 1.5 mm to create life-like esthetics.[46] These metal ceramics demonstrate similar qualities to CLIII zirconia-based restorations, but the metal substructures do not have the same thermal firing sensitivity as zirconia.[47] CL-IV metal ceramics can be improved in esthetic qualities with a much higher gold framework material (eg, Captek™, Argen USA.

CONCLUSION

The technological evolution of dental ceramics has been remarkable over the past four decades. From feldspathic porcelains to zirconia-based all-ceramics, tremendous progress has been made in terms of mechanical performance, with a ten-fold increase in flexural strength and fracture toughness. Indications for and composition of today's dental ceramic materials provide a foundation for determining the appropriate class of ceramics to use for a given case. Other factors that influence material selection include preservation of tooth structure, bond maintenance requirements, esthetics, smile design, and shading. Both CL-I and CL-II ceramic materials provide high esthetics but limited strength. Although all types of ceramics are weak in tensile and shear stresses compared to compressive stresses, if the stresses can be controlled, weaker materials can be used successfully. CL-III and CL-IV ceramic materials offer strength but low esthetic qualities. When functional stresses cannot be controlled and stronger materials (eg, zirconia, alumina, metal) are used, porcelain can be veneered to the substructure for esthetics. An ideal case would require only one of these ceramic classifications. However, with today's available material options, delivering restorations that satisfy all requirements is possible.

CONFLICT OF INTEREST

No potential academic conflict of interest relevant to the above article was reported.

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