

Material selection for single-tooth crown restorations

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14.1 Introduction

With the introduction of the lost wax technique by W.H. Taggart [1] in 1907 for producing precise cast metal forms, there was a persistent quest to develop newer and better extra-coronal restorative materials that could maintain aesthetics, restore a tooth's strength, provide durability, and at the same time remain biocompatible and cost-effective. This has offered dentists of the 21st century multiple options when it comes to crown restorations of a single tooth.

Single-tooth crown restorations may be required to cover and support a heavily restored tooth, to hold together parts of a cracked tooth, to restore the original shape and contour of a severely attrited/fractured tooth, or to restore the aesthetics of a severely discolored tooth. The choice of material for single-tooth crown restoration seems rather case-specific, and is driven by several factors, such as aesthetic demands, demands for high strength, cost-benefit analysis, as well as a patient's related factors, such as hypersensitivity to certain metals, preference, economic concerns, and so forth. So, a thorough knowledge of the different materials available for this purpose, and their applications as well as limitations, will enable the dentist to select the best option available for the needs of each patient, thereby enhancing the quality of the treatment delivered.

Permanent crown restorative materials can be classified into three broad categories: (1) all-metal restorations, (2) all-ceramic restorations, and (3) metal-ceramic restorations.

14.2 All-metal restorations

All-metal crown restorations are fabricated from predominantly four categories of alloys: high noble metal alloys, noble metal alloys, base metal alloys, and titanium alloys. High noble metal alloys must contain greater than or equal to 40% gold, and greater than or equal to 60% by weight of noble metal elements. Gold has an excellent track record in the oral cavity in terms of biocompatibility, and is the least reactive among all metals. However, pure gold is too soft and ductile to be used as a crown restorative material. So, it is alloyed with other metals to improve its properties. Platinum added to gold-based high noble metal alloys increases hardness, elasticity

of gold, and the melting temperature of the alloy. Palladium also serves the same purpose as platinum, but is costlier than platinum. Copper is the principal hardener, and it renders the alloy heat-treatable, enabling it to undergo the phenomenon of “age hardening” when heated at a temperature between 200 and 450 degrees Celsius for 15–30 min, followed by quenching it in water. By this process, the proportional limit, hardness, and yield strength of the alloy are increased, while the ductility is reduced [1a]. The addition of silver helps in offsetting the reddish color of the copper. Zinc act as an oxygen scavenger during the melting and casting of the alloys. Iridium or ruthenium is added in small quantities as a grain refiner, improving the yield strength of the alloys. Examples of such high noble metal alloys used for all-metal prosthetic restorations include Au-Ag-Pd alloys and Au-Pd-Cu-Ag alloys. The benefits high noble metal alloys offer when used for crown restorations are:

- (I) Owing to the low Knoop hardness value (KHN) of pure gold (KHN-75) compared with enamel (KHN-340), such gold-based high noble metal alloys turn out to be extremely gentle on the opposing teeth, and are well suited for persons with para-functional habits such as bruxism.
- (II) The low hardness value of these alloys also permits easy finishing and polishing of crown restorations made from them.
- (III) Crown restorations made from such alloys are very durable and long lasting, even in thin sections, due to their high fatigue resistance; this property of the alloy makes allowances for more conservative tooth preparation.
- (IV) The reasonable amount of malleability and ductility of such alloys permits easy bur-nishability of the crowns at the preparation margin of the tooth, facilitating precise adaptation of the crown over the prepared tooth structure. Nevertheless, from the cosmetic point of view, they are preferably not used to restore a front tooth, where cosmetic concerns are higher, as the yellow color of such restorations would be aesthetically objectionable.

Noble metal alloys must contain greater than or equal to 25% by weight of noble metals. The hike in the gold price in the seventh decade of the 19th century resulted in an introduction of less expensive palladium-based alloys. These alloys are white in color, and predominantly contain silver; but they must contain at least 25% palladium to provide nobility and resistance to tarnish and corrosion. They may also contain copper and a small amount of gold. Examples of such alloys used for all metal crown restoration include Ag-Pd and Ag-Pd-Au-Cu. These alloys, however, have been associated with certain drawbacks. First, both palladium and silver have the propensity to dissolve oxygen in the molten state, resulting in porous castings. Second, low gold content lowers the density of such alloys, resulting in a decrease in kinetic energy of the molten metal during casting, ultimately resulting in the poor castability of such alloys [2]. Also, these alloys have been associated with greater potential for tarnish and corrosion resistance compared with gold alloys. Nevertheless, precise control of casting and mold temperatures can help limit these drawbacks and produce acceptable castings [3].

The high price of noble metal alloys rendered such crown restorations a costly treatment modality. This turned out to be a limiting factor restricting the popularity of such restorations, as they cannot be afforded by a major section of society. So to overcome this limitation, base-metal alloys were researched. Base metal alloys contain less

than 25%, by weight, of noble metals, and in these alloys, the resistance to corrosion is imparted by adding chromium, which forms a thin layer of chromium oxide on the surface and prevents the diffusion of oxygen into the underlying metal surface. The two most commonly used base metal alloys for extra-coronal single-tooth crown restoration are nickel-chromium and nickel-chromium-beryllium. Beryllium acts as a grain refiner and improves the physical properties of the alloys: it increases strength and lowers the melting point of the alloy, which improves castability. Base metal alloys have the advantage of being lightweight, and having a high modulus of elasticity, which provides rigidity, even in thin sections, and can be sandblasted to obtain high bond strengths with the selected resin adhesives. However, the extreme hardness of such base metals renders them difficult to cut, grind, and polish. Casting conditions need to be very well controlled to obtain precise fitting restorations, and these alloys are hard to adjust and difficult to finish. Also, the constituents of these base metal alloys are liable to cause health hazards. Nickel has been well documented to cause contact dermatitis in sensitized individuals [4], and approximately 4.5% of the general population demonstrate a sensitivity to nickel, with a reaction being 10 times more likely to occur in women than in men [5]. Beryllium grindings and casting fumes are also found to be extremely hazardous, and can cause acute problems such as conjunctivitis, dermatitis, and bronchitis. Chronic beryllium disease manifests itself several years after exposure [6]. Thus, an effective exhaust and filtration system is a must while handling these alloys. Despite these challenges, base metal alloys became a material of choice for fixed restorations, and continue to be popular even today; if the treatment cost is the patient's major concern.

Titanium and its alloys have been used for dental application since the 1970s. Titanium-based crown restoration is now considered to be a viable alternative to more traditional noble and base metal alloys; but careful selection of the processing methods and laboratory skill are necessary to ensure success. Titanium is a highly reactive metal, and readily reacts with the surrounding oxygen to form a thin passivating oxide film on the surface (approximately 10 nm thick), which accounts for its high corrosion resistance. Despite the fact that it is abundantly available in the earth's crust as oxide rutile, and that it is considered to be the most biocompatible metal used for dental restorations, with strength, rigidity, and ductility comparable with those of noble metal alloys used in dentistry, the casting of titanium poses several challenges. It has a high melting point of 1668°C, and is highly reactive to oxygen above 900°C. Incorporation of even low concentrations of atmospheric oxygen in the castings can lead to significant loss of ductility, leading to the embrittlement of the cast metal [7]. So casting of titanium demands a special casting machine with arc melting capability and an inert gas (Argon) atmosphere, with casting investments consisting of oxides, such as MgO, ZrO₂, or Y₂O₃, which are more stable than titanium oxide. Castability indices for commercially pure titanium (CP Ti), when cast with centrifugal force, have been found to be comparable with those of traditionally cast high noble metal and Ni-Cr alloys, while the final fit of such titanium castings has been found to be intermediate between those made from a high noble alloy and Ni-Cr alloy. Over the past few decades, developments in processing methods such as computer aided milling (CAM) and electroforming have improved the quality of titanium castings. Electroforming is

a novel approach, introduced in 1989, which involves the milling of the titanium blank by spark erosion in order to erode the metal, giving it the final shape [8]. Nevertheless, the technologies necessary for producing titanium crown restorations are quite expensive compared with those used for conventional dental casting alloys. Hence, the fabrication of titanium-based crown restorations has been reserved for certain special situations, and has not become a prevalent laboratory and clinical practice [9].

14.3 All ceramic restorations

The pursuit for aesthetically pleasing, tooth-colored restorative material led to the introduction of ceramics in dentistry, and the person accredited with the fabrication of the first ceramic crown is Charles Land (1903) [10, 11]. Dental ceramics are non-metallic, inorganic materials, primarily containing compounds of oxygen with one or more metallic or semimetallic elements. They are generally composed of a glass phase that imparts translucency, refractiveness, and gloss to the crown, giving it a life-like appearance, within which is dispersed a crystal phase that provides strength to the material. These materials also have excellent biocompatibility, good color stability, chemical durability, wear resistance, and the ability to be formed into precise shapes. Nevertheless, along with these advantages come the two greatest disadvantages of dental ceramics as a restorative material—its high susceptibility to tensile fracture, and its low fracture toughness. Dental ceramics are brittle materials, which accounts for their low tensile strength, and the fact that they cannot suppress crack growth by deforming plastically in areas adjacent to crack tips that are subjected to tensile stress, leading to crack propagation, which explains their low fracture toughness. Even microcracks, or surface flaws incorporated in the framework during processing or grinding of the restorative framework, are liable to propagate, resulting in a breakdown of the restoration [12]. Also, masticatory loading can cause tensile fracture of the framework, and hence failure of the restoration. Despite these challenges, the dental ceramic technologies have evolved rapidly over the past three decades, resulting in significant improvements in the fracture toughness and tensile strength of these materials, and hence have widened their applications as crown restorative materials. Earlier dental ceramics were used for veneering or masking the metallic color of the underlying metal substructures. But with the evolution of material and advancements in technologies, dental ceramics are now also used as substructures of crown restorations. These types of restorations are termed as “all-ceramic restorations,” while “metal ceramic restorations” is the name given to the former one.

Today, all-ceramic restorations are the most aesthetically pleasing restorations available in dentistry, giving the tooth almost a life-like appearance, and a high degree of aesthetic satisfaction to the patient.

Dental ceramics can be broadly classified into four categories: (i) predominantly glass ceramics, (ii) particle-filled glass ceramics, (iii) glass-infiltrated ceramics, and (iv) polycrystalline ceramics. Predominantly glass ceramics are those in which the amorphous glass phase predominates over the dispersed crystal phase. These are aesthetically pleasing ceramics that mimic the optical properties of enamel and dentin due

to the presence of high glass content in them. Manufacturers can alter the percentages of filler/crystalline particles in them to control optical effects, such as opalescence, color, and opacity. Chemically, these are mostly feldspathic porcelains ($K_2O \cdot Al_2O_3 \cdot 6SiO_2$), and they were the very first material used for all ceramic crown restorations. These crowns exhibited excellent aesthetics, but exhibited high incidences of fracture due to poor strength and low fracture toughness. Now their use is limited, as veneering materials over high-strength core substructures or copings.

Further development included increasing the proportion of crystalline particles/fillers with an intent to improve its mechanical behavior, which led to the evolution of a second category of dental ceramics—particle filled glass ceramics, which include aluminous porcelain and glass ceramics. Particle-filled ceramics are those in which the glass matrix is heavily filled with crystalline particles, which are added mechanically during manufacturing as powder (aluminous porcelain), or precipitated within the glass by a special heat treatment to induce nucleation and crystal growth (glass ceramics). McLean and Hughes (1965) [13] developed an alumina-reinforced porcelain core material (aluminous porcelain), consisting of a glass matrix filled with 40%–50% crystalline alumina by weight, and reported significant improvement in fracture resistance of the crown. However, the decreased glass phase and increased crystalline phase in the ceramic core material resulted in diminished aesthetics, and a chalky white opaque appearance of the restoration. This demanded feldspathic porcelain veneering of the aluminous porcelain core material to achieve acceptable aesthetics. Aluminous porcelain has been found to be suitable for single-tooth crown restoration in the anterior region, but its strength is still not sufficient, and hence is contraindicated for posterior tooth crown restorations. HI ceram is an aluminous porcelain that is directly baked upon the refractory die through a sintering procedure.

Glass ceramics are those that are formed into the desired shape as glass, and then subjected to a special heat treatment to induce partial devitrification. The most popular of these systems are leucite-based glass ceramics, and lithium disilicate-based glass ceramics. Leucite-reinforced glass ceramics, as well as lithium disilicate glass ceramic restorations, can be manufactured either by a hot pressing technique, or less commonly, by a sintering process. The most popular leucite-based products that employ a hot press technique include IPS Empress, the SL Pressable Ceramic System, and the Finesse All-Ceramic System, while the one that makes use of the sintering procedure is OPTEC HSP. IPS Empress 2 and Optec OPC 3G are lithium disilicate-based glass ceramics that employ a hot press technique to fabricate the prosthesis. Hot-pressed, leucite-based glass ceramics contain approximately 35%, by volume, of leucite crystals, while hot-pressed lithium disilicate-based glass ceramics contain 65%–70%, by volume, of lithia disilicate crystals. The fracture toughness of leucite-based glass ceramics is $0.9\text{--}1.3\text{ MPa m}^{1/2}$, which is insufficient for molar crowns. So their primary application is mainly confined to anterior, single-unit crowns, and anterior laminate veneers. They are very successful as aesthetic veneering material because their index of refraction is very close to that of feldspathic glasses, and also they create an effective micromechanical bond with resin cements by virtue of their “selective etching” property, in which the leucite etches at a much faster rate than the base glass, creating numerous micropores for resin cements to enter [14]. Lithium disilicate-based glass

ceramics have a fracture toughness of $3.3 \text{ MPa m}^{1/2}$, which is fairly high, compared with leucite-based glass ceramics, enabling their usage for most anterior and posterior crowns. Although they are translucent, they are still somewhat more opaque, and comparatively less aesthetic, than leucite-based glass ceramics.

The third category, glass-infiltrated ceramics, include three ceramic systems—in ceram alumina (alumina based), in ceram zirconia (zirconium oxide and alumina based), and in ceram spinell (spinell based). All three are processed by a slip-casting technique. This ceramic evolved to overcome the limitations associated with the particle-filled glass ceramics in terms of the amount of core crystalline materials that can be added to feldspathic glass during the prefitting process. The slip-casting technique employs an alternative approach to achieve high core crystalline content in the final ceramic prosthesis. It involves condensation of an aqueous porcelain slip on a refractory die. The porosity of the refractory die helps in condensation by absorption of water from the slip by capillary action. The refractory die is fired at a high temperature, during which the refractory die shrinks more than the condensed slip, which helps in easy removal. The partially sintered core is then glass infiltrated. Glass infiltration is the process by which molten glass is drawn into the pores by capillary action at high temperatures. The resulting ceramic restoration has a high volume fraction of crystalline phase, which accounts for its greater strength. In ceram alumina has a high strength of around 500 MPa, while in ceram zirconia has even higher strength of around 700 MPa, making these materials suitable for anterior, as well as posterior, crowns. However, due to large differences in the refractive index of the crystalline phase and glass in such materials, an intense refraction of light occurs at the aluminum oxide crystals, which accounts for their opacity. This necessitates veneering when such restorations are planned in the aesthetic zone of human dentition. In ceram spinell has a moderate strength of about 350 MPa, limiting its usage as anterior crown material, and it is contraindicated for posterior crown restorations. The refractive index of the crystalline phase used in this ceramic system is close to that of glass, giving it good translucency, and making it a material of choice when high translucency is needed in the anterior regions of human dentition.

Polycrystalline ceramics are those in which there is no glassy component, and the entire structure is made up of densely packed atoms arranged into regular crystalline arrays. They are much tougher and stronger than glass-based ceramics, and are suitable for anterior, as well as posterior, crowns. They are usually made from alumina or zirconia oxides. These are generally used as core materials for all ceramic crown restoration, which can be layered with more aesthetic veneering ceramic, or in cases where aesthetic demand is not too high, these can also be used as monolithic crown material. Such polycrystalline ceramics are formed from powders that can be packed only to 70% of their theoretical density, and shrink around 30% by volume when made fully dense during firing [15]. Hence, a well-fitting prosthesis made from polycrystalline ceramics is not practical unless the amount of shrinkage is accurately predicted and compensated for. Two major developments in the dental ceramic technology that made it possible were the availability of well-characterized starting powders that can be uniformly packed to achieve predictable shrinkage, and the application of the CAD/CAM technique for ceramic processing.

Procera All Ceram is an alumina-based polycrystalline ceramic. To produce a Procera All Ceram crown, an oversized die is manufactured first, based on measurements taken during the mechanical scanning of the laboratory die. Alumina is dry pressed on the oversized die to create an oversized greenware (unfired alumina), which is then predictably shrunk during sintering to become a well-fitting single crown substructure. Cercon, Lava, IPS e.maxZirCAD, and Vita In Ceram YZ cubes are some of the zirconia-based polycrystalline ceramics. The remarkably high fracture toughness ($8\text{--}10.3\text{ MPa m}^{1/2}$) of the zirconia crowns is attributed to the phenomenon of transformation toughening that involves a transformation from the tetragonal phase of zirconia crystals to the monoclinic phase at the tip of the cracks that are in the region of tensile stress. The monoclinic phase occupies 4.4% more volume than the tetragonal crystal phase, and this increase in volume squeezes the crack closed, thereby inhibiting crack propagation [16–19]. To produce zirconia-based polycrystalline crown restorations, blocks of green/compacted state/unfired zirconia are machined first into an oversized greenware (unfired part), based on measurements taken during the mechanical scanning of the laboratory die. The oversized greenware is then sintered, and the resulting shrinkage yields the desired crown shape and size.

There are certain cases that preclude the use of all-ceramic crown restorations. All ceramic crown restorations are contraindicated in patients with bruxism, reduced interocclusal distance, insufficient overjet and overbite, opposing supra-erupted teeth; and young patients with a large pulp chamber. Because the tooth preparation for all ceramic crowns is the least conservative of all preparations used for full crown restorations, all ceramic crowns are also contraindicated in teeth with insufficient tooth structure, or badly attrited teeth. An additional drawback of ceramic crown restoration is the increased wear of the opposing tooth, especially when the surface of the restoration becomes rough [20].

14.4 Metal ceramic restorations

The high propensity to tensile fracture of the porcelain jacket crown (PJC) in the early 1900s led to rigorous research and development in the field of ceramic crown restorations. Researchers were looking for ways in which such restorations could be reinforced to enhance their physical properties, and hence, durability. Such endeavors led to two parallel streams of developments in this field. One of them is the all-ceramic restorations, which we discussed earlier, while the other one is the metal-ceramic restoration. While all-ceramic crowns relied upon the use of high-strength ceramic core copings, such as alumina core ceramics or yttria-stabilized zirconia to serve as the foundation upon which the feldspathic glass porcelain is veneered to attain the desired aesthetics, the metal-ceramic crowns use a metal substructure, upon which a porcelain veneer is bonded to resemble a natural tooth in appearance. Nevertheless, both these technologies are, to some extent, identical in capitalizing on the basic concept that a strong, rigid substructure beneath the low-strength porcelain veneer could resist flexure, and hence development, of tensile strength within the porcelain veneer, thereby preventing its fracture.

Two major breakthroughs helped in developing insights into the metal-ceramic restorations. One among them was Brecker's published "Porcelain bakes to gold-A new medium in prosthodontics" in 1956, in which he reported a method of chemically bonding low-fusing feldspathic porcelain to a metal substructure using a gold-based alloy [21]. Another breakthrough came in the form of two U.S patents by Weinstein and Weinstein (1962) [22] and Weinstein et al. (1962) [23], in which they described the formulation of feldspathic porcelain that could provide control over its sintering temperature and coefficient of thermal expansion (CTE) to make it compatible with the metal substructure. In their patent, they also described the alloy composition that could enable chemical bonding with the feldspathic porcelain veneer, and at the same time, remain compatible with it for stability of the bond. Soon after, many newer products emerged, and metal-ceramic restorations became the most popular crown restorative material in dentistry. A laboratory survey published in 2003 found that 65% of the restorations made in a 6 month period were porcelain-fused-to-metal restorations, and only 23% of were all-ceramic restorations [24]. The areas in which metal-ceramic restorations score over all-ceramic restorations are fracture resistance, amount of tooth reduction required, simplicity in fabrication techniques, and cost effectiveness.

Structurally, a metal ceramic crown is a composite entity consisting of two distinct components: (1) a metal substructure, and (2) a porcelain veneer. A surface oxide on the metal substructure helps to form a chemical bond with the porcelain veneer, and the bond between the metal substructure and porcelain veneer is both chemical, as well as mechanical, in nature. The thickness of the metal substructure for a single crown restoration can vary from 0.2 to 0.5 mm, depending upon the type of casting alloy used, and the amount of tooth structure removed by the dentist. Besides, the alloy used for fabrication of the metal substructure needs to possess certain specific criteria to form a stable bond with the porcelain veneer:

- (i) They must have the ability to form a thin film of surface oxide that does not fall off the metal, and hence produce chemical bonding with porcelain.
- (ii) They should be formulated so that their coefficient of thermal contraction should be slightly greater (average contraction coefficient difference of $0.5 \times 10^{-6}/\text{K}$ or less between 600°C and room temperature) than that of the porcelain veneer.
- (iii) Their melting range should be considerably higher than the sintering temperature of the porcelain that veneers it.
- (iv) They must have a high sag resistance and should not distort as a result of repetitive firing of the porcelain veneer overlying it.

The first alloys used for fabrication of metal ceramic copings were all high-noble metal alloys (Au-Pt-Pd, Au-Pd-Ag, Au-Pd) with iron, indium, and tin used for hardening, and to create a superficial oxide layer to which ceramic could be bonded [2]. The high gold content of these alloys made such restorations quite expensive, and so to deal with it, high-palladium, low-gold alloys were introduced as an affordable alternative. Besides, these high-palladium alloys (Pd-Ag, Pd-Cu-Ga) have the advantage of a high modulus of elasticity, and are therefore more rigid, allowing thinner copings. These alloys contain either gallium, or indium, or both, to promote chemical bonding with porcelain [2]. A common problem encountered with the Pd-Ag alloys is their tendency to discolor porcelain veneers due to a diffusion of silver compounds into

porcelain, appearing as a greenish hue. The base metal alloys (Ni-Cr, Ni-Cr-Be) used for all metal crowns can also be used for fabricating metal copings of metal-ceramic crowns. Among the two, Ni-Cr-Be alloys are generally regarded as possessing superior qualities, and have been more popular [25, 26]. Beryllium-containing Ni-Cr alloys have more fluidity, which improves castability. Control of oxide layer thickness on the metal substructure is important to avoid problems of porcelain debonding. An oxide layer that is too thick can result in ceramic de-bonding [2]. The addition of beryllium to Ni-Cr alloys lessens the tendency of these alloys to form a thick oxide layer on the surface at high temperatures, and thus aids in the formation of a stable bond with porcelain [27].

Titanium oxidizes quite readily, and a thick nonadherent oxide layer can form under repetitive porcelain firing, compromising the bond strength. A 6-year follow-up showed a higher risk of metal ceramic failures with titanium alloys, as compared with other alloys [28].

The porcelain veneer of the metal-ceramic crowns consists of several discreet layers-opaque porcelain, dentin body, enamel veneer, and a surface glaze; each having some specific function, but fused together as a single mass. The opaque porcelain has a uniform thickness of 0.2–0.3 mm, and serves to mask the color of the metal substructure. Besides, they serve to establish the porcelain-metal bond, and also initiate the development of the selected porcelain shade. The dentin body porcelain contains pigmented metal oxides, and imparts color to the porcelain veneer. Enamel porcelain is placed in areas where translucency is desired, especially in the incisal and interproximal areas. For more accurate shade duplication, the combined thickness of the dentin body and the enamel porcelain range from a minimum of 0.5–1.0 mm (in the gingival third), to a maximum of 1.5–2.0 mm (incisal and occlusal third), depending upon the level of characterization in the natural tooth to be produced [29]. However, the thickness should never exceed 2.0 mm, to minimize the potential for fracture. This can be explained by the theory that the porcelain veneer is under compression for the first 2.0 mm of thickness from the metal porcelain interface to the region about 2 mm external to it, beyond which it comes under tension. And because porcelain is strongest under compression and weakest under tension, 2 mm becomes the limiting thickness of the porcelain veneer [30]. Glazes are colorless, low-fusing porcelain, and they serve to fill the small surface porosities and irregularities when fired, and impart a glossy surface to the natural tooth.

Nevertheless, even with all its advantages, in our aesthetically driven modern society, metal ceramic restorations fall just short of all-ceramic restorations when it comes to restoration of aesthetics of the prepared tooth, especially in the anterior regions of the arch. An all-ceramic crown offers a greater potential for success in matching the appearance of the adjacent natural tooth, especially when a relatively high degree of translucency is desired [1a]. Besides, the dark line visible at the facial margin of the metal ceramic crown is a significant aesthetic concern in cases where a high smile line is present, or when gingival recession has occurred. Another area in which all-ceramic crowns score over metal ceramic crowns is biocompatibility. Metal ceramic crowns have the potential for metal allergy, especially when nickel-containing alloys are used. All-ceramic crown restorations are free of such problems.

Moreover, with the introduction of zirconia- and alumina-based high strength core ceramics that could be veneered with feldspathic porcelain to give the desired aesthetic outcome, coupled with the recent advancements in ceramic processing techniques such as CAD-CAM, the all-ceramic crown restorations have come in their own way to challenge the metal-ceramic crown restorations, especially in demanding clinical situations, and this trend is expected to continue.

References

- [1] W.H. Taggart, A new and accurate method of making gold inlays, *Dent. Cosmos* 49 (1907) 1117–1121.
- [1a] J. Anusavice Kenneth, S. Chiayi, R.H. Ralph, *Phillip's Science of Dental Materials*, First South Asian ed., Reed Elsevier India Private Limited, New Delhi, India, 2014.
- [2] R.W. Wassell, W.G. Walls, J.G. Steele, Crowns and extra-coronal restorations: material selection, *Br. Dent. J.* 192 (2002) 199–211.
- [3] S. Cohen, A. Kakar, T. Vaidyanathan, T. Viswanadhan, Castability optimization of palladium based alloys, *J. Prosthet. Dent.* 76 (2) (1996) 125–131.
- [4] A.A. Fisher, *Contact Dermatitis*, third ed., Lea and Febiger, Philadelphia, PA, 1986.
- [5] L. Peltonen, Nickel sensitivity in the general population, *Contact Dermatitis* 5 (1) (1979) 27–32.
- [6] L. Pierce, R. Goodkind, A status report of the possible risks of base metal alloys and their components, *J. Prosthet. Dent.* 62 (2) (1989) 234–238.
- [7] D. Brown, All you wanted to know about titanium but were afraid to ask, *Braz. Dent. J.* 182 (10) (1997) 393–394.
- [8] M. Andersson, B. Bergman, C. Bessing, G. Ericson, P. Landquist, H. Nilson, Clinical results with titanium crowns fabricated with machine duplication and spark erosion, *Acta Odontol. Scand.* 47 (5) (1989) 279–286.
- [9] F.C. Eichmiller, Titanium applications in dentistry, *J. Am. Dent. Assoc.* 134 (3) (2003) 347–349.
- [10] C.H. Land, Porcelain dental art, *Dental Cosmos* 45 (6) (1903) 437–444.
- [11] C.H. Land, Porcelain dental art: no II, *Dental Cosmos* 45 (6) (1903) 615–620.
- [12] P. Bergmann Carlos, S. Aisha, *Dental Ceramics: Microstructure, Properties and Degradation*, Springer, Berlin, 2013.
- [13] J.W. McLean, T.H. Hughes, The reinforcement of dental porcelain with ceramic oxides, *Br. Dent. J.* 119 (6) (1965) 251–267.
- [14] J.R. Kelly, P. Benett, Ceramic materials in dentistry: historical evaluation and current practice, *Aust. Dent J.* 56 (Suppl. 1) (2011) 84–96.
- [15] A. Shenoy, N. Shenoy, Dental ceramics: an update, *J. Conserv. Dent.* 13 (4) (2010) 195–203.
- [16] H.H.J. Richard, M. Kelly Patrick, C. Muddle Bary, Transformation toughening in zirconia containing ceramics, *J. Am. Ceram. Soc.* 83 (2000) 461–487.
- [17] C. Picano, G. Maccauro, Zirconia as a ceramic biomaterial, *Biomaterials* 20 (1) (1999) 1–25.
- [18] M. Guazzato, M. Albakry, S.P. Ringer, M.V. Swain, Strength, fracture toughness and microstructure of a selection of all-ceramic materials, part II. Zirconia based dental ceramics, *Dent. Mater.* 20 (2004) 449–456.

- [19] I. Denry, J.R. Kelly, State of the art of zirconia for dental applications, *Dent. Mater.* 24 (2008) 299–307.
- [20] A. Elmaria, G. Goldstein, T. Vijayaraghavan, R.Z. Lageros, E.L. Hittelman, An evaluation of wear when enamel is opposed by various ceramic materials and gold, *J. Prosthet. Dent.* 96 (5) (2006) 345–353.
- [21] S.C. Brecker, Porcelain bakes to gold—a new medium in prosthodontics, *J. Prosthet. Dent.* 6 (1956) 801–810.
- [22] M. Weinstein, A.B. Weinstein (inventors), Porcelain covered with metal-reinforced teeth, US patent 3,052,983, September 1962.
- [23] M. Weinstein, S. Katz, A.B. Weinstein (inventors), Fused porcelain-to-metal teeth, US patent 3,052,982, August 1962.
- [24] G.J. Christensen, The confusing array of tooth colored crowns, *J. Am. Dent. Assoc.* 134 (2003) 1253–1255.
- [25] J.J. Tuccillo, P.J. Cascone, in: J.W. Mc Lean (Ed.), *The evolution of porcelain-fused-to-metal(PFM) alloy systems*, Dental Ceramics: Proceedings of the First International Symposium on Ceramics, Quintessence, Chicago, 1983, pp. 347–370.
- [26] G.J. Christensen, The use of porcelain-fused-to metal restorations in the current dental practice: a survey, *J. Prosthet. Dent.* 56 (1986) 1–3.
- [27] R.H. Scholle, L.R. Maloney, Report on base metal alloys for crown and bridge applications, benefits and risks. Council on dental materials, instruments, and equipment, *J. Am. Dent. Assoc.* 111 (1985) 479–483.
- [28] M. Walter, P.D. Reppel, K. Boning, W.B. Freesmeyer, Six year follow up of titanium and high-gold porcelain fused to metal fixed partial dentures, *J. Oral Rehabil.* 26 (1999) 91–96.
- [29] W.P. Naylor, *Introduction to Metal Ceramic Technology*, second ed., Quintessence Publishing Co Inc, 2009.
- [30] M. Yamamoto, *Metal Ceramics Principles and Methods of Makoto Yamamoto*, Quintessence Publishing Co Inc., Chicago, 1985.