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Fifty Years Full Ceramic in Dentistry (1973-2023)

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Summary

A summary of the development of full ceramic dental restorations over the last 50 years is challenging, especially because of the variety of the fabrication processes, that were as essential for on their quality and function as the constitution of the ceramics themselves. The contribution of the developments and innovations in full-ceramics in the advancement of biocompatibility and aesthetics cannot be underestimated. The development from the first full-ceramic restorations in feldspathic porcelain in 1973 to the veneered or monolithic zirconia restorations of today, would not have been possible without the development of dental CAD/CAM and laboratory and intraoral scanning. Some major innovations, of which some did not survive and others survived until this day, have been the trigger for amazing achievements in the field of full ceramic dental restorations.

Keywords: CAD/CAM, dental porcelain, zirconia, lithium disilicate, digital veneering, artificial intelligence, histo-anatomic structure, biomimetic veneering, porcelain chipping, fuzzy logic.

Introduction

The technology for creating full ceramic restorations in dentistry has significantly advanced since 1973. In the past, full ceramic restorations were limited to materials like feldspathic porcelain, which had limited strength and durability. However, with the development of new materials and manufacturing techniques, full ceramic restorations have become a popular choice for dental restorations due to their excellent aesthetics and biocompatibility.

One of the most significant advances in full ceramic restoration technology was the development of computer-aided design and computer-aided manufacturing (CAD/CAM) around the 90s. These systems allow for precise processing of a range of new ceramic dental materials for the production of full-ceramic restorations. Additionally, CAD/CAM systems have reduced the time required to create a restoration, making the process more efficient. The introduction of lithiumdisilicate and zirconia were two main steps in the further development of full-ceramic restorations. Chipping problems of porcelain veneered on zirconia was a problem with most porcelains on the market except some porcelains with an adequate crack stopping mechanism. However, the chipping problem has slowed down some developments such as digital veneering. However, now that present zirconia porcelains have less sensitivity to chipping digital veneering can again become a new opportunity.

Feldspathic Porcelain

The first all-ceramic crowns were introduced in 1973 by John W McLean, and since then, there have been many advancements in ceramic materials used for dental restorations. These advancements have led to improved strength and durability of ceramic crowns, making them a popular choice for dental restorations [1].

In 1985 the technique of producing porcelain veneers, onlays and inlays became popular and has proven to give good esthetic and functional results [2]. The technique for producing inlays, onlays and veneers consist of casting a refractory model of the impression of the preparation, burnout of the model and condensing the porcelain against the refractory model, building-up the contour of the restoration, firing the porcelain and removing the refractory. [3]. Bonding to tooth structure was achieved using an adhesive composite cement technique. At first, metal-ceramic was still the number one veneering material. In the 1990s, low-fusing hydrothermal porcelains in combination with a rich yellow gold alloy came onto the market (Carrara® System) [4,5].

Press ceramic, lithiumdisilicate

The increase of leucite crystal phases in feldspathic porcelains raises the coefficient of thermal expansion and strength, but also increased the resistance to slow crack propagation. High leucite-containing ceramics Empress®1 by Ivoclar, optimal pressable glass (OPC) by Jeneric and Volumia®Press by Elephant were introduced in the late 1980s and were the first pressable ceramic materials. Although the initial steps for fabrication for Empress, Volumia and OPC were similar to Dicor® and Cerestore® in which the restoration was formed in wax, a heated leucite-reinforced ceramic ingot was pressed into the refractory mold using a specially designed pressing furnace, whereas the Dicor® crown was created using centrifugal casting. This process of pressing ceramic ingots became very popular due to the esthetics and ease of use in the laboratory. Despite the increase in strength of leucite-reinforced pressed glass-ceramics, fracture was still possible when used in the posterior region. In 1998 Ivoclar introduced IPS Empress II, which was a lithiumdisilicate ceramic material used as a single- and multiple-unit framework indicated for the anterior region. The framework was layered with a veneering ceramic specially designed for the lithium disilicate. In 1991 the first pressed ceramic came onto the market and the success story of press technology began. This heralded the age of “metal-free” restorations. A lot happened in material development in 1998. The all-ceramic system IPS e.max is considered a pioneering innovation in the field of dental ceramics after the innovations in the 1990s [6]. It came onto the market in 2005 and has set new standards in terms of optical and mechanical properties.

A modular, comprehensive all-ceramic system was now available for the first time, which combines high-strength and highly aesthetic materials for press and CAD/CAM technology and thus makes all indications available, from single teeth to long-span bridges. The selection of the translucency level depended on the clinical requirements of the respective patient case and the desired processing technique. Restorations with IPS e.max have been clinically proven a million times over [7,8]. No wonder then that the IPS e.max system and with it the lithiumdisilicate glass-ceramic have been extremely successful to this day. Incidentally, after almost 25 years of pressable ceramics, it is now possible for the first time to press multicolored press blanks into highly aesthetic monolithic restorations. The first generation of lithium disilicate enabled new indications and expanded applications for pressed ceramics.

At the same time, an innovative crystal was developed. Due to its structure, the fluorapatite crystal enabled a perfect reproduction of natural tooth substance, coupled with a brightness that had not been achieved before. The fluorapatite glass ceramics still deliver aesthetics almost like nature. Parallel to the metal ceramics, the first pressed ceramics established themselves - initially for single-tooth restorations.

Lithium disilicate re-emerged in 2006 as a pressable ingot and partially crystalized milling block (Cerec® for chairside and inLab® milling units for laboratories). The flexural strength of the material was found to be more than 170% higher than any of the currently used leucite-reinforced ceramics. The ceramic material can be milled or waxed, and then pressed to full contour and subsequently stained. Another option allows for cutting the crown back, followed with layering with different specially designed apatite ceramic glass. The layering ceramic has the same basic components as natural tooth enamel. CAD/CAM milling of a ceramic framework (zirconiumoxide), a full-contoured crown (lithium disilicate at chairside or in the laboratory), or an implant abutment has opened the market for digitized restorative dentistry.

CAD/CAM

The first commercially available CAD/CAM system was Cerec® processing of dental ceramics chairside had already begun in the mid-1980s enabling the delivery of inlays and onlays in one visit [9]. Early forms of digital imaging included both an intraoral imaging system integrated with the Cerec® system. In the mid1990s Nobel Biocare introduced the Procera® AllCeram core, which was the first full-ceramic CAD/CAM substructure. On this white core of 99.9% alumina a low expansion feldspathic ceramic was layered for aesthetics. Basically, the gypsum die was copied by a touch probe and reproduction-milled with an enlargement factor in presintered alumina to the inner surface with a coping of uniform 0,6 mm thick, then sintered to final density. The most important step that changed laboratory work dramatically in the direction of digital was the development of the first laser line laboratory scanner for full gypsum models in 2000 [11,12].

The first system that made use of contact-less scanning was CICERO® (Figure 1), whereby an shaded alumina based substructure was digitally veneered with a dentin and incisal porcelain layer by CAD/CAM, introduced, together with the laser line laboratory scanner (Figure 2) and the first laboratory CAD software with static and dynamic occlusal correction [13-15]. This pioneering CAD/CAM method of complete single crown fabrication consists of optically digitizing a gypsum die, designing the crown layer buildup, and subsequently pressing, sintering, and milling consecutive layers. The coping was applied as a fine grained alumina-glass composite which was applied on a milled refractory die by a robot operated slip-casting process, and sintered to full density. Slip-casting alumina on a gypsum model and after pre-sintering infused by a low melting glass was some years later introduced by Vita with the introduction of the In-Ceram® system. Both systems achieved a 85% alumina by volume. These pioneering CAD/CAM systems have accelerated the development of new materials [15], laboratory triangulation scanning, as well as advancements in digital radiography [16] in the fabrication of full ceramic restorations.

Figure 1: CICERO®: Digitally Veneered Alumina Coping [11].

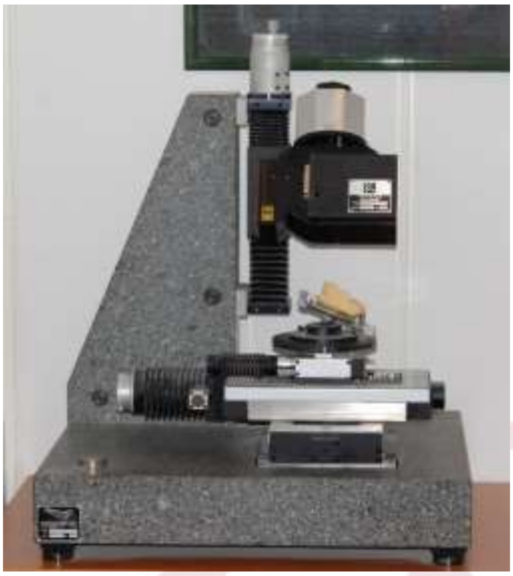

Figure 2: CICERO®: First laser-line laboratory scanner [12].

Zirconia

One of the achievements of computer-aided dentistry is that it has enabled the introduction of high-strength zirconia ceramics in dental prosthetics in 2000, which will most likely be the decisive step towards metal-free all-ceramic restorations without restrictions [17,18]. The development of new CAD software like Cyrtina®CAD, 3Shape, Exocadspurred a whole new generation of ceramic substructures consisting of zirconia. Several manufacturers (Lava, 3M ESPE; Procera Forte, Nobel Biocare; and Cercon, DENTSLY) introduced crown-and-bridge frameworks milled from blocks of presintered yttrium-stabilized zirconium dioxide blocks. The oversized milled frame-works were then sintered for 11 hours at 1500°C providing excellent fit with 900 MPa to 1300 MPa of flexural strength. Other manufacturers (Everest, KaVo, DC-Zirkon, Precident DCS) milled fully sintered zirconium dioxide blocks (because it removed the shrinkage factor), which one study found to have a superior marginal fit. Both fabrication methods provide a framework with sufficient flexural strength, allowing them to be used for multi-unit posterior bridges.

The recent evolution in CAD/CAM technologies is breathtaking, enabling clinicians and dental technicians to fabricate indirect restorations in the laboratory or at the chair in the dental office from a variety of ceramic materials, from resin matrix ceramics to silica-based and highly strong ceramics such as lithiumdisilicate and zirconia. Extensive world-wide research provided long-term scientific support and are used extensively with an increased understanding of optical, physical and biological material properties. This pertains not only to material properties and fabrication parameters, but also more clinical applications such as cementation and resin bonding protocols, which are critical to the success and survival of ceramic restorations.

Until recently, aesthetics were one of the most important motives for choosing ceramics, but now the fabric-friendliness of the metal-free ceramics has also been added. The patient has spoken out for biocompatibility. The paradigm that ceramic must always be prepared and modeled differently from metal ceramics has been eliminated with the advent of zirconia. Until recently, aesthetics were the main reason for choosing ceramics. The tissue-friendliness of metal-free ceramics has become an additional criterion. The public has expressed their preference for biocompatibility. With the introduction of zirconia, the paradigm that ceramics required a different approach to preparation and modeling than metal-ceramics was a thing of the past. One of the advantages of CAD/CAM is that it made the use of zirconia possible. With the exception of zirconia, the existing ceramic systems lack reliable potential for the different indications for bridges without size limitations. Ever greater demands are being placed on the aesthetics of the teeth.

CAD/CAM plays a key role in the introduction of all-ceramic restorations, such as base structures made of sintered ceramics. For aesthetics the focus is not only on computer-aided milled inlays, onlays and veneers made of natural-colored porcelain, but also on the application of different layers of enamel porcelain on base structures to improve the aesthetics of zirconia. Research is mainly focused on the strength of the bond between zirconia and enamel porcelain and the strength and stresses of the whole structure in terms of the difference in thermal expansion coefficient. The first dental multi-layered zirconia appeared on the market around 2010. Multi-layered zirconia is a popular material used in dental restorations due to its high strength and esthetic properties. Esthetic properties that mimic the natural look of teeth, allowing for a more seamless and natural-looking restoration. It has a high resistance to wear and chipping, ensuring a long-lasting restoration and has become a popular choice for dental restorations due to its combination of strength, esthetics, and biocompatibility. The multi-layer KATANA™ Zirconia Block is made up of four layers of zirconium in varying color nuances, so that restorations with natural tooth colors can be fabricated in practice. This excludes a time-consuming and complicated process of staining the restoration (Figure 3).

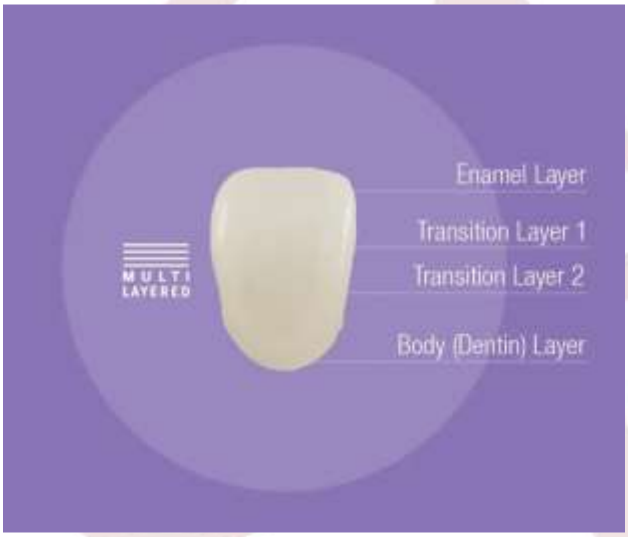

Figure 3: KATANATM multi-layered zirconia block.

Porcelain chipping on zirconia

In a literature review by Sailer et al. [19], for bridges on implants, conventionally veneered zirconia should not be considered a material selection of the first priority, due to the pronounced risk of breakage in bridges and porcelain chipping. Thanks to developments in veneering ceramics for zirconia and the use of strength control in the CAD-design of zirconia substructures, these problems no longer occur [20]. Ceramic veneering materials have differences in their thermal expansion, firing temperature and structure, which effect their longer term chipping behavior when fired on zirconia. Because chipping is a fatigue phenomenon, the presence of an effective crack-stopping mechanism is crucial for its prevention. Conventional porcelains are homogenous and show a linear crack growth behavior, which makes them sensitive to chipping. Most conventional porcelains used for veneering zirconia were single component glass-ceramics, without any crack-stopping mechanisms. In 1990 the first low melting CARRARA® porcelain was developed to veneer an alloy with a rich gold color (Figure 4).

Figure 4: CARRARA® low melting veneering porcelain.

A similar low melting Sakura® porcelain was developed for zirconia that has three components, differing in melting point creating internal micro-stresses and a non-linear crack growth that effectively act as crack-stopper. The three glass phases, crystal content and expansion behavior, result in a low overall melting point of 865oC, compared to 960oC of previous porcelains. The lowest melting component improves wetting of the zirconia surface during firing, resulting in an high bond strength [21]. The small multi-directional internal micro-stresses caused by the three different components results in an effective mechanism that prevents chipping of the porcelain on zirconia [22].

This new generation porcelains, have a low melting hydrolyzing component that will in contact with saliva exchange sodium for water molecules which creates a surface with an hardness equal to natural enamel. These hydrothermal porcelains will wear at the same rate and mode as natural teeth and will not cause chewing force concentrations after a period of time. De Kler et al. [23] found by finite element analysis that the highest stress at three different thermal expansion differences of zirconia and porcelain that the highest stress after cooling down is not at the interface, but about 0.1-0.2 mm from the interface in the porcelain.

Chipping is therefore mainly a matter of how sensitive the porcelain material itself is for crack propagation under fatigue loading. Extensive fatigue testing by Rosentritt et al. [24] revealed the chip resistance of these new porcelains. A number of 199 restorations were followed in a controlled clinical study over six years and the occurrence of chipping compared with studies on restorations where conventional porcelain and design of the zirconia sub-structure was used. The conclusion was that with the new porcelain and cognitive design and manufacturing, esthetic restorations are produced, that do not show any chipping.

Digital veneering of zirconia

Delamination and chipping have been major complications of veneering of zirconia-based all-ceramic restorations [19]. The absence of crack stopping in most porcelains was the cause for the blocking further developments such as digital veneering. Some digital veneering techniques were tested on zirconia frameworks and the veneering ceramic shapes were fabricated by CAD/CAM.

Digital veneering can also be motivated by the expectation of negative effects due to the high hardness of monolithic zirconia as opposed to that of glass ceramics. Three different digital veneering techniques were tested: the Lava DVS Digital Veneering System (3M ESPE), the Rapid Layer Technology (Vita Zahnfabrik), and the CAD-on technique (Ivoclar Vivadent) [25,26]. Anatomical framework design and digital veneering using lithium disilicate and fusion porcelain might decrease the risk of chipping and delamination of veneering ceramic on zirconia-supported all-ceramic restorations. However, this result is mainly supported by in vitro studies.

Biomimetic veneering of zirconia

Esthetic prosthetic restorations, with natural reflection, color from within and color gradients influenced by the internal dentinal core anatomy can best be accomplished by veneered zirconia, rather than with crowns of color and structure graded monolithic zirconia.

In order to mimic the optical and esthetic appearance of the restoration it is important to copy the histo-anatomic build-up of the teeth of the patient [28-30]. This means that the three-dimensional shape of the dentine core, as defined by the dentin-enamel boundary (DEB), and the particular surface of the dentine core, are important parameters to reach this objective. The DEB and the outer surface of the restoration determine most of how the restoration will look like. In order to make naturally looking layered restorations, the copying of the histo-anatomical structure of the inner teeth is a prerequisite. This information forms the basis for the production of prosthetic mimetic restorations. The PRIMERO® system (Figure 5) consists of placement of a zirconia substructure in a standard Vita dentine shade on a die milled in a refractory transferblock in which the die and crown contour below the equatorial line is milled. A transparent incisal porcelain in paste form was pressed onto the zirconia substructure and, after drying, milled in calculated oversize and sintered. The color gradients in the resulting restoration are created by the variation of in thickness of the incisal porcelain, that follows the biomimetic design of the dentin contour in the Cyrtina®CAD software (Figure 6).

Figure 5: PRIMERO® biomimetic veneering of zirconia with incisal porcelain.

Figure 6. Design of zirconia substructure with resulting biomimetic veneered front teeth.

Korenhof [27] discovered that the dentin-enamel boundary (DEB) shows a certain amount of “primitiveness”, more than the enamel surface. The outer and inner surface boundaries are connected by a relation. Therefore changing the enamel-outer surface in the CAD software automatically leads to a change of the dentin-enamel boundary. This data mining system of dentin geometries was used to produce a set of interpretable fuzzy rules that led to the 2HueTM color system for the production of the color resulting from a certain incisal build-up.

The fuzzy system obtained has the special characteristic whereby the rule antecedents correspond to thickness of the enamel layer to the colors of the well-known Vita commercial shade guide. Additionally, the rule consequents directly correspond with the expected CIELAB values for each Vita shade, thanks to a modification of the system's inference structure. Finally, the values of the CIELAB coordinates have been associated with Vita shades by evaluating their respective membership functions, thereby approximating which Vita shades are to be expected for each final shade [31]. A thorough understanding of the histo-anatomic structures and dynamic light interaction of the natural dentition provides dental practitioners with the ultimate strategic advantage with regard to optical integration of the final restoration [29].

Future Developments

The first application of artificial intelligence in CAD software was the integration of functional occlusion using virtual articulation in complete dental prosthetic rehabilitation [29]. It is likely that artificial intelligence in CAD software will play a greater part in the future. A first example is the mimicking of the color and shade distribution from intra-oral scanning as demonstrated by the 2HueTM software model for digital veneering in the CyrtinaCAD® software, whereby the enamel thickness is derived by the geometry of the dentin zirconia core by the subtracting the enamel porcelain thickness from the outer element contour.

In these times of scarcity and durable use of materials, the recycling of zirconia blocks after milling might start to play a role. In the 2HueTM build-up pressed and not presintered blocks in 16 dentin colors are used, that can be sorted and ground to be re-used again. When tested no deterioration of properties was detected, except that the homogeneity by back-mixing improved.

The production of zirconia substructures by additive manufacturing technology [32] by 3D printing is a durable alternative to address durability and the drawbacks of subtractive manufacturing in the CAM step of the dental digital workflow. Even though additive manufacturing has yet to be developed, it enables the production of ceramic parts with complex geometries, high precision, and low cost.

Conclusion

Full ceramic restorations have become increasingly popular in dentistry due to their superior aesthetics and biocompatibility. In terms of durability and longevity, studies have shown that full ceramic restorations can be just as durable as traditional metal-based restorations, if not more so. In summary, the technology for creating full ceramic restorations in dentistry has advanced significantly over time, with the development of CAD/CAM systems and new materials. These advancements have improved the accuracy, efficiency, and durability of full ceramic restorations, making them an excellent option for dental patients.

With biomimetic digital veneering restorations with a zirconia substructure with dentin shape and a milled layer of chip-resistant translucent enamel porcelain can be produced. For the computer-generated layer build-up, special dentin contour shape libraries – especially the anatomy of the dentin core - are designed with precise spatial definitions and determine the natural aesthetics of the restoration. The exemplary 2HueTM tooth shade model for these restorations is based on research into the effect of the thickness of the transparent enamel on the degree of transfer of the color of the internal dentine zirconia core. These advanced cognitive designed CAD/CAM restorations could give a new impulse to new innovations.

Pioneering efforts in the production of full ceramic systems could only fabricate inlays and onlays or copings or single crowns. Now there seems to be no more limitation in the types of full-ceramic restorations that can be produced, ranging from simple inlays to digitally designed and manufactured complete rehabilitations in full ceramic on implants. This means that the patient can be provided with ceramic restorations quickly and comfortably, and sometimes in one appointment. The latter can easily compete with the handmade equivalents with the latest production technology in aesthetics.

With the advent of restorations milled out of multi horizontally layered zirconia that mimic the color gradient in the restoration in a monolithic restoration rather than a veneered restoration, is now standard in CAD/CAM restorations [33]. The preliminary lab studies present different additive manufacturing technologies for processing zirconia for different clinical applications mainly in restorative and implant dentistry.

It is pretentious to say that with layered zirconia we have come to the end of developments in the area of full-ceramics and is also against human nature. Now that the porcelain chipping problem has been solved, possibilities for digital veneering or aesthetics by CAD can be explored. Cognitive design can follow a histo-anatomic structure of the dentin-enamel junction, to mimic the build-up of the teeth of the patient. New applications of artificial intelligence in dental CAD software could for example lead to new innovations in digital veneering.

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