Zirconia Ceramic in Dental CAD/CAM: How CAD/CAM Technology Enables Zirconia To Replace Metal In Restorative Dentistry

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Dental ceramic is, in combination with metal (Figure 1) or completely self-supporting (Figure 2), applied in different forms in restorative dentistry for replacement of lost tooth structure. In addition to esthetics, biological and physical arguments play an increasingly important role in the choice for ceramics. Cosmetic aspects play a role especially in the visible part of the restoration where translucency and color are of decisive importance. Its complete inertness toward oral fluids and its isolating character with regard to electric current and heat, make ceramic the most stable and similar to natural tooth material of all restorative materials.

Considerations with respect to strength, or rather the brittleness, of ceramic have for decades undermined the trust in the clinical durability of all-ceramic restorations. This doubt is fed by clinically high failure rates, partly caused by handling mistakes to which ceramic is sensitive, but in some cases caused by a too low intrinsic long-term strength. Metal-free, full-ceramic restorations, particularly in higher stressed structures, have experienced many ups and downs. However, computerized dentistry has paved the way for a new generation dental ceramic with an unprecedented high strength and durability derived from developments in nano-ceramic technologies in the last decades. This so-called yttrium-stabilized zirconia gets its strength from a transformation-toughening phenomenon (also known from the process of hardening of steel) and opens the way towards a completely metal-free restorative and prosthetic dentistry.

During the last decade, the research group for Computerized Dentistry of the Academic Centre for Dentistry Amsterdam has been working in cooperation with the industry on the interaction of CAD/CAM technology with new materials applications. Ceramic Types

Ceramic materials have reached a high quality standard and restorative and prosthetic dentistry cannot be imagined without them. The esthetic possibilities of ceramic, in combination with an excellent biocompatibility, are great. Recent clinical experience has shown that for different types of ceramic a differentiation in application is unavoidable in view of a successful long-term success.
With an appropriate choice of indication and application, ceramics can in more than one aspect represent an improvement over old techniques.

The demands made on esthetic teeth are increasing. Presently, most veneered crown and bridge restorations consist of metal and ceramic. The demand for full-ceramic solutions is increasing. Therefore, pressure is exerted on industry and science to develop full-ceramic systems.

In introducing full-ceramic restorations, especially for base structures, computerized dentistry plays a key role. The present ceramic systems (Figure 3) for metal-free restorations can be ranked by a decreasing glass-content with a corresponding increase in strength, as follows: veneering ceramic, press ceramic, glass-infiltration ceramic and sinter ceramic.

- Veneering or silicate ceramic has a bending strength between 50 and 200MPa and a fracture toughness of less than 2.5 MPa.m⁰. This ceramic type contains in general less than 20 percent high-expansion leucite crystals to adjust the expansion to the base material to be veneered or to obtain a strengthening effect. Silicate ceramic is the material of choice for adhesively bonded restorations, thus for bonded inlays, partial crowns and veneers and for veneering of ceramic or metal substructures.
- Restorations, whereby the ceramic is not supported by metal or sinter ceramic, should be cemented adhesively. Restorations can be veneered (Carrara) or pressed-over a substructure (Sakura Volumia), pressed as a whole (Empress) or milled from a block (Cerec). The adhesively placed restorations have an excellent prognosis.
- Press ceramic has a bending strength between 100-350MPa and a fracture toughness of less than 3.5MPa.m⁰. This material contains up to 60 percent crystals (for example with Empress 2: lithiumsilicate). The crystallisation must be conducted under precisely defined conditions to prevent the formation of coarse crystals that can lead to early fracture in the mouth. Industrially crystallized ceramic blocks (e.MAX) are therefore more reliable. For the molar region is the chance of fracture too big.
- Glass-infiltration ceramics has a bending strength of 400-500MPa. With a fracture toughness of 4-4.5MPa.m⁰. Although crowns supported with glass-infiltration ceramic have shown excellent clinical results (5 percent breakage per year) their indication in the molar region is still at risk. Anterior small-span bridges in the front (esthetic) can be applied in certain cases.
- Sinter ceramic has a strength of 500-1200MPa with a fracture toughness of 5-12MPa.m⁰. Base structures of zirconia, that in the meantime have almost entirely replaced alumina, can only be produced by CAD/CAM technology. Because of its high strength and toughness zirconia can, within geometric boundaries as we know them for metal, be used for all indications. With bridges exposed to loading by chewing essentially bending moments occur that cause tensile forces. Structure ceramic must possess a high fracture toughness to withstand fracture during cyclic loading in the mouth. This means that zirconia will be suitable for these indications.

**Indication Decision**

The availability of silicate, press, glass-infiltration and sinter ceramics orientates onto different indications that give exposure to different chewing loads. The loading of front teeth will amount to about 25kg that increases to 35kg for premolars and to 100kg for molars. Therefore, in the front region silicate ceramic with its opalescent, translucent esthetics is indicated. From premolar up to molars the high-strength zirconia ceramic is indicated. For more extensive restorations silicate ceramic is a contra-indication.

**Y-TZP Zirconia Ceramic**

On the basis of the specific material properties of zirconia, known under the
abbreviation Y–TZP (Yttrium-stabilized Tetragonal Zirconia Polycrystal), it has been applied since 1969 in orthopaedics in hip joint implants. Earlier attempts to extend the application to dentistry failed because this material could not be processed by traditional methods known in dental technology. With the emergence of computerized dentistry, zirconia can be processed in an economical manner into substructures for veneered copings and bridges and implant abutments. The introduction of this material in restorative and prosthetic dentistry will probably be the decisive step toward full-ceramics without limitations. Under the existing ceramic systems, outside zirconia, there did not exist a reliable possibility for the indication of bridges without limitations in size. This trend seems to have been broken when by the high-strength and fracture toughness of zirconia. The three-point bending strength of over 900MPa makes the material suitable for practically all full-ceramic restorative and prosthetic solutions: such as bridges, implant abutments and root pins. The fact that industrially produced zirconia root pins have been in use since 1990, confirms the strength of zirconia.

This strength and toughness are caused by a material specific crystal transformation (from tetragonal to monoclinic crystal structure) that smoothes crack initiation. By adding three Mol-percent (five weight percent) yttrium-oxide to zirconia, a fine nano-crystalline structure (Figure 4) is obtained that accelerates the re-crystallisation process. The fast occurring volume expansion that accompanies this transformation retards the crack formation and eventually increases the strength with an order of two.

The key to transformation toughening in ceramics that contains tetragonal zirconia, is that the tetragonal-monoclinic transformation, that takes place in bulk ZrO₂ at around 1100°C is suppressed except in the stress area around crack formation. Tetragonal zirconia transforms to monoclinic zirconia with a 3.5 percent volume increase, whereby the area around the crack comes under compression. The compression pressure leads to a decrease in tensile stress at the point of the crack, whereby an increase of the fracture toughness is realized. Transformation strengthening of yttrium-stabilized zirconia was first reported in an article Ceramic Steel? by Garvie, Hannink and Pascoe. This title was chosen with the aim to emphasize the properties that zirconia-based materials have in common with alloys of iron. Garvie et al. compared zirconia with hardened steel. The similarities in the material properties are surely remarkable. Both materials have comparable values for bending strength, elasticity module, thermal expansion efficient and density. What makes the comparison even more striking is the fact that both materials owe their strength to the same martensitic crystal transformation with approximately the same volume expansion.

**CAD/CAM System Requirements**

About 15 CAD/CAM systems for the manufacturing of individualized restorations are presently available in dentistry. Differences exist in the technical as well as the logistic strategy. At the end of the day, the costs and clinical suitability of the dental devices must be in line with present restorations. The new CAD/CAM technology must fulfill some basic principles when it wants to deliver a lasting contribution in the future.

The simplest variant, the generation of a base structure is the best matured part of most systems. In the Cyrrina CAD/CAM system (Oratio B.V., The Netherlands) many design rules and clinical decision support based on recent evidence-based dentistry is built into the software. The minimal requirement that CAD software must
fulfil is the automated detection of the preparation line, preferably without operator interaction (Figure 5). This should however not prevent a possibility to choose for a longer or shorter extraction, with or without overlap. An important improvement consists of the automatic generation of the coping and bridge-structures using the occlusal space available. The pontics and copings must preferably show a reduced tooth shape to obtain an equal porcelain thickness. For this design step a scanned registration bite is indispensable (Figure 6). Another design rule guarantees sufficient strength of a bridge-construction by automatically calculating the minimal cross-sectional area of the connectors depending on the location in the mouth and the span-length of the bridge. The choice for a tight or loose fit, by modifying the thickness of the virtual cement-layer, is based on the individual judgement of the clinician in relation with the type of cement.

Extra-oral, optical scanners are available that scan the preparation and its surroundings in different views which are automatically combined. The necessary accuracy of 10-15 μm is with some of the laser scanners (Figure 7) available. Restorations must be produced with a clinically acceptable fit of at least 50-80 μm and this kind of fit starts with an accurate scan. Another scanner property is the ability to scan over the edge. This is important for the exact determination of the preparation line and the equator of the crown.

Figure 6. The occlusal space must be included in the design of copings and pontics. Photo Credit: Oratio B.V.

Accurate scanning combined with the exact calculation of a cement layer of constant thickness gives CAD/CAM restorations, especially bridges, a more easy fit than restorations manually modelled in wax. The calculation of the path of insertion of a bridge demands an integrated extraction of the scanned dies in order to realize a good fitting bridge on multiple abutment teeth (Figure 8).

In designing the occlusal and approximal dimensions, the quality of the antagonistic and neighboring surfaces play an important role. To obtain an interference-free articulation, a low-risk disclusion-variant can be chosen. For virtual articulation a registration bite of the antagonists in special scan-silicone must be made and digitally scanned. Then the teeth of the upper and lower jaw can be brought into a spatial correct functional relation.

Only when a combination of all factors lead to a reasonably priced restoration and decisive advantages compared to conventional methods are realized, can dental CAD/CAM thrive. Up to now it is difficult for chairside or laboratory CAD/CAM solutions to satisfy the requirements of economic viability. That is why at the present state of technology centralized production is economically the most interesting. The obligation to earn back stand-alone solutions cuts the user off from the innovations taking place in technology-driven, centralized manufacturing facilities. By investing in a relatively low-cost, non-central, scan system with scan-design software, it is possible to generate a virtual design of the restoration, which is subsequently sent by Internet to an efficiently operating service provider that sends back the restoration to the laboratory within days. This way the dental laboratory can
outsource more and more base work and focus on a better service for dentists and patients.

**Esthetics**

Because of its white base color, which can shine through where there is less space for porcelain, most CAD/CAM systems provide zirconia in different base shades for different porcelain color groups (Figure 9). For esthetics it is important that the light transmission simulates natural teeth. Incident light in modern dental ceramics passes through causing an opalescent effect, while a fluorescent liner returns the UV-constituent as a natural white light (Figure 10).

If there is one reason for the euphoria about zirconia among dental technicians it concerns the edge area of the crown. Edges can be trimmed knife-sharp, which is not possible with metal because this would cause chipping of the porcelain. Furthermore, the edge is homogeneous, stable, biocompatible and stays in its place even after firing. Zirconia shows a high translucency, so that discolored elements need to be masked by an opaque cement (Figure 11).

More and more restorations are made in full-ceramic. According to market surveys it is estimated that full-ceramic restorations are replacing metal-ceramic restorations at a rate of 10-20 percent per year. This seems to end a long period of stagnation. The drivers behind the increase in demand for full-ceramic are the higher consciousness of the patients for esthetics and the wish for increased safety with regard to biocompatibility. An often-heard opinion is that ceramics belong in the body and metal can, at most, be a replacement. The high biocompatibility of ceramics is based on the fact that its components are already in their highest oxidation state. A further oxidation (corrosion) in the moist oral environment, as known with metals, is not likely to be expected. Interaction with surrounding tissue does not take place. Patients who are sensitive to metals can, in many cases, be treated with the full-ceramic alternative. Apart from this, the very low accumulation of microbacterial plaque on ceramic materials is positive also.

**Preparation Requirements**

If possible, sharp corners on incisal and occlusal preparation surfaces should be avoided. In some CAD software packages provisions for an internal round-off of the inside are present. Chamfer and shoulder preparations should have a strongly rounded inside and 4-5 degree angulations. Frontal elements should not be prepared too sharp but rather be rounded off. Also, some
software packages will take care of the rounding. Sufficient axial preparation of total 0.8mm-1.2mm, depending on the local situations and an occlusal space of 1.2mm-1.5mm are required. Only with zirconia is the so-called metal-prep allowed.

Root Pins and Implant Abutments

The requirements of high corrosion resistance, tissue-friendliness and esthetics are better served with ceramic root pins than those made out of metal. However, the high strength that is required was missing in dental ceramics, until zirconia became available.

With the introduction of standard root pins (for example Cerapost or Cosmopost) metal-free root pin build-ups are available that are promising in respect to esthetics and physical characteristics. With recently developed overpress ceramic for zirconia (Sakura Volumia) an individual tooth build-up can be pressed over the zirconia root pin. An increase in root pin retention in the root channel and an improvement of the stress dissemination in the root pin is obtained by cementing with Panavia 21 or F.

Also, implant abutments are increasingly produced in zirconia (Figure 12). This is done for esthetic reasons, but also because zirconia in comparison with titanium demonstrates a much lower accumulation of bacterial plaque. This is important because of the positive relation that exists between plaque and bone loss. Scarano et al. compared the accumulation of cocci and filamentous bacteria on titanium and zirconia. Their conclusion was that microbiological pathogens greatly influence the occurrence of periimplantitis and implant loss. Zirconia gave a significant decrease of bacterial growth that appeared not to be dependent on surface roughness (Figure 13).

In-Vitro Tests

To get an idea of the possible differences in quality between zirconia copings produced by some commercially available systems, a quantity of five incisal copings were produced with each system and veneered with Sakura Interaction ceramic. The crowns were cemented on a chrome-cobalt die and cemented with standard phosphate cement. Then they were placed under pressure in a jig in a tensile test machine until the first crack appeared (Figure 14). The results are presented in Table 1. Although Cyrtina crowns without liner proved to be the strongest, the high variation that is inherent to manually veneered crowns, showed no significant difference between the other systems.

Table 1 is a comparison of commercially produced incisal copings (N=5) veneered with Sakura Interaction porcelain.

Investigation of the crowns shows that much of the porcelain was separated from the coping but that a thin layer of porcelain remains attached to the zirconia surface (Figure 15). This can also be seen in a section made through a crown after testing, whereby the fracture is cohesive in the porcelain and not adhesive through the zirconia-porcelain interface (Figure 16).

A follow-up investigation on crowns, whereby the zirconia coping was kept .5mm-1mm short from the edge to allow for a full porcelain shoulder, appeared to be only 20 percent weaker when compared with crowns that had zirconia support up to the crown edge.

A long-term prognosis, in order to compare it with the proven prognosis for metal-ceramic bridges, can only be ob-

Table 1

<table>
<thead>
<tr>
<th>CAD/CAM system</th>
<th>Surface before veneering with porcelain</th>
<th>Average breakload in N</th>
<th>Standard-deviation in N</th>
<th>Minimum value in N</th>
<th>Maximum value in N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava Liner</td>
<td>4,837</td>
<td>1,765</td>
<td>3,450</td>
<td>7,565</td>
<td></td>
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<tr>
<td>Cercon Liner</td>
<td>5,598</td>
<td>1,534</td>
<td>3,589</td>
<td>7,727</td>
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<tr>
<td></td>
<td>Without liner</td>
<td>5,913</td>
<td>908</td>
<td>4,530</td>
<td>6,912</td>
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<tr>
<td></td>
<td>15 min 1000°C, liner</td>
<td>4,550</td>
<td>2,567</td>
<td>2,347</td>
<td>8,853</td>
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<tr>
<td></td>
<td>Spray liner</td>
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<td>1,058</td>
<td>4,000</td>
<td>6,816</td>
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<td>DCS Liner</td>
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<td>4,118</td>
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<td>Cyrtina Liner</td>
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<tr>
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<td>6,519</td>
<td>8,500</td>
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</table>
tained with chewing simulators with 1.2 million chewing cycles simulating five years of chewing. To investigate the fatigue behavior of three-unit bridges with a zirconia base, they were loaded in a fatigue machine. After five-year simulation thermo-cycling and mechanical loading (TCML), the residual break load of the bridges after fatigue was measured. The parameters of the thermal and physical loading procedure were the same as the tested proposition from literature. A test load of 50N is by Eichner and Krejci described as representative for the average chewing load. The hypothesis of Krejci that states that 240 mechanical cycles correspond with an oral loading period of one year (1.2 million equal five years) is supported by recent research that showed the agreement between clinical test and artificial mouth results. The thermo-cycle varied from 5°C -55°C. The average residual break load after 1.2 million mechanical chewing simulation cycles was still at 1,512 ± 344 N (N = 8). This means that the bridge is hardly weakened by fatigue in comparison with the control bridge that broke at an average load of approximately 1,600 N. These results are comparable with metal-supported bridges. During the chewing simulation no damage of the porcelain was observed. After the fracturing of the bridge (Figure 17) the good adhesion of porcelain to the zirconia can clearly be observed. Resuming it can be concluded that the zirconia substructure adequately protects the porcelain against fatigue.

Clinical Experience

Research into the application of leucite-strengthened press-ceramic (Empress) and glass-infiltrated ceramic (In-Ceram) in small three-unit bridges in the frontal and premolar region show good clinical results. For crowns of leucite-strengthened press-ceramic (Empress) after an observation period of approximately four years, a survival rate of 98 percent could be calculated. Crowns from glass-infiltrated ceramic (In-Ceram) showed hardly any fracture after six years, even after being cemented with conventional cement. Comparably positive results were obtained with full-ceramic crowns of alumina (Procera-AllCeram), with a cumulative survival rate of 93.5 percent after 10 years.

Clinical results are only available over a limited amount of time about CAD/CAM-produced zirconia bridges (Cercon, Cyntina, DCS, Lava, Procera, e.o.). The longest clinical experiences are from 1998, whereby up to now no fracture has occurred. The first clinical results with veneered zirconia bridge structures, also those with more than three units, show no fracture up to now. Adhesively placed silicate-ceramic restorations have been instrumental in
the present status of cosmetic dentistry thanks to their excellent long-term prognosis. Up to now, esthetics was the main driver for choosing ceramics. Now tissue friendliness of metal-free ceramics has become increasingly important. Vox populi has spoken out for biocompatibility.

By the emergence of CAD/CAM technology, the advantages of the new high-tech zirconia ceramic can now be utilized in restorative dentistry. Because the material can be applied posterior and shows a high biocompatibility, it opens a new horizon in the application of metal-free, full-ceramic restorations. The paradigm that for ceramic restorations preparation requirements have to be adjusted (compared to metal-ceramic restorations) has disappeared with the arrival of zirconia. The introduction of zirconia ceramic in dentistry is probably the decisive step towards metal-free, full-ceramic restorations without limitations in indication. Computerized dentistry has caused a revolution in implantology and clinical decision support, but also plays a key role in the introduction of new materials by interaction with dental CAD/CAM.  

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Van der Zel is professor of computerized dentistry at the faculty of dentistry (ACTA) of the University of Amsterdam. He is a pioneer in the area of computer assisted implantology and prosthodontics and since 1987 has worked on the development of dental CAD/CAM systems (Cyrtina). He is founder and chair of the Special Interest Group Dental CAD/CAM of the International Association of Dental Research. You can view his Web site at www.dentalxs.com.

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