Research Article

High-Strength Porcelain Veneering of Zirconia Prosthetic Mimetic Restorations (PRIMERO) by Cognitive Design and Manufacturing

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Abstract

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. Concern about the high incidence of chipping with some of the porcelains for zirconia substructures has led to a massive shift from veneered zirconia to the use of monolithic zirconia for crowns and bridges. Because zirconia has four times the hardness of metal, initial concern about antagonist abrasion could with numerous studies be negated. Clinical long-term effects of lack of abrasion of full zirconia crowns, in comparison with 30-75 µm/year for surrounding and opposing dentition is still poorly documented. Massive crack formation in enamel probes has been reported in specimens after in-vitro fatigue testing with opposing monolithic zirconia. In-vitro and clinical studies have shown that only reinforcement of the structure of veneering material can prevent chipping.

This article compares the fatigue behavior of three-unit bridges with a substructure of Primero zirconia veneered with Primero Enamel (PR) with bridges with Cercon Base zirconia inner-structure veneered with Ceramco PFZ and Cercon Ceram S (CR1 and CR2) and assess the possibilities and increase their scope to cognitive design and manufacturing of porcelain veneered zirconia crowns and bridges. Fatigue testing of four times eight 3-unit bridges were produced for each of the three porcelains and a reference. The results show that efficient crack-stopping prevented chipping with the PR bridges, while the bridges with conventional porcelains CR1 and CR2, showed failures. We conclude that chipping is mainly porcelain related. Cognitive design and fabrication of the dentin zirconia core will lead to Prosthetic Mimetic Restorations (PRIMERO) with natural esthetics.

Introduction

In particular, the correct individual layering-or, in other words, the correct three-dimensional structure-of the crown is crucial for a perfect reproduction of a natural tooth. The internal structure of the crown-especially the anatomy of the dentin core-will determine the esthetics of a restoration to a considerable extent. Experienced dental technicians are able to mimic the dentin in its three-dimensional manifestation but will generally not be able to provide any precise spatial definitions. The design of the dentin core is therefore based mainly on the training and the experience of the dental technician and often follows a "traditional" approach. Thus, almost all dental technicians leave a clearly discernible "signature" as they prepare their restorations, a restorative artefact that does not, strictly speaking, have any connection with the case at hand.

With the introduction of zirconia around 2000 as a substructure of veneered prosthetic restorations, it has taken a central place as the material of choice in present day dentistry [1]. Veneering of zirconia with conventional porcelain led, especially in the first years of introduction of zirconia, to chipping, delamination and cracks in the porcelain within the first two years [2]. These problems have been the main driver for dental laboratories to produce mainly

monolithic zirconia crowns and bridges from colour-and structure-graded zirconia blocks with CAD/CAM. Monolithic zirconia crowns and bridges lack the natural reflection, color from within and color gradients of natural teeth, although they are milled out of pre-sintered blocks which four to seven layers of different shades and structures, to alleviate these deficiencies.

This study is an investigation of the effect of fatigue loading on the chipping behavior of different veneering materials for zirconia and proposes a new fabrication method of veneered Prosthetic Mimetic Restorations (PRIMERO) with CAD/CAM.

Cognitive Design of Dentin Zirconia Core

In the production of dental restorations specifically made for one patient, dental technicians with their problem-solving skills, dexterity and cognitive skills are until recently the only way to provide the required flexibility, adaptability and reliability [3]. The reason is that people have brains, computational mechanisms that are capable of acting competently under uncertainty, reliably dealing with unforeseen events and situations and adapt quickly to changing tasks, capabilities and environments. The realization of comparable cognitive skills in technical systems therefore has enormous potential for creating CAD/CAM systems that can overcome today's boundaries [4,5]. Prosthetic Mimetic Restorations (PRIMERO) that mimic the histo-anatomic structure of natural teeth by cognitive design of the dentin core present a new production paradigm to create natural restorations of veneered zirconia using a high strength porcelain. These restorations are produced with a core of dentin-colored zirconia, on which a high strength translucent porcelain layer has been applied by a CAD/CAM method. Once the external tooth geometry has been digitally linked to the internal tooth geometry, a correlation is formed between the two records, a correlation that is dynamic. In a dynamic correlation, however, the internal tooth structure is modified in response to any modifications of the external tooth surface [6].

The internal structure of the restoration is produced based on a record from the database, where the external surface corresponds exactly to the internal tooth structure of a record selected from the database. In this regard, the most important factor for the optical integration and esthetic appearance of dental restorations is a thorough understanding of the histo-anatomical structures and dynamic light interaction of natural dentition. In particular, the three-dimensional shape of the dentine core, as defined by the Dentin-Enamel Boundary (DEB), and the special three-dimensional surface of the dentine core with its S-shaped curvature, turns out to be decisive for the optical appearance of a crown [7]. The DEB and the enamel outer contour are essential three-dimensional structures of the tooth that significantly affect its visual appearance (Figure 1).
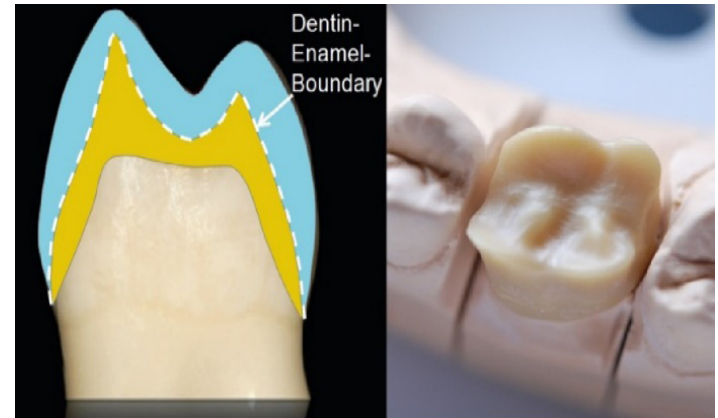

Figure 1: Cognitive design of Dentin-Enamel Boundary (DEB) and dentin zirconia core before veneering.

Therefore, it is a prerequisite for the production of layered dental restorations copying the histo-anatomic tooth structure with three-dimensional information of the outer and also the inner structure of natural teeth. This information forms the basis for the production of Prosthetic Mimetic Restorations (PRIMERO). Korenhof [8] cognitive histo-anatomic design discovered that the Dentin-Enamel Transition (DEB) exhibits a greater degree of "primitiveness", compared to the enamel surface: the DEB has rudimentary cuspules, ridges and cingula that are not clear at the EOS. On the basis of the lack of a topographical correspondence between the DEB and outer contour, Korenhof suggested that the DEB may be more useful than the outer contour for the determination of the dynamic relationship between the two.

The DEB includes significant information about the outer surface of the tooth. Conversely, this can also allow for the determination of the inside architecture (DEB) from the outer surface. The outer and inner geometry are dynamically linked to each other. This implies that a virtual alteration of the enamel-outer surface in the CAD software automatically leads to a change of the corresponding inner structure [9]. In the production of dental restorations specifically made for one patient, dental technicians with their problem-solving skills, dexterity and cognitive skills are until recently the only way to provide the required flexibility, adaptability and reliability (Figure 2). The realization of cognitive skills in the design of Prosthetic Mimetic Restorations (PRIMERO) therefore, has enormous potential for creating industrial automation systems that can overcome today's boundaries.

Figure 2: Cognitive design of the biomimetic dentin core for four frontal elements.

Porcelain Application with the PRIMERO Lab System

First the dentin core is milled out of a cervical-colored zirconia block, that has been iso-statically pressed at a pressure of 3000 bar. This pressure is necessary in order to achieve a 100% density with a minimal shrinkage during sintering The system uses a transfer block in which the lower contour and the dies are milled out. The Primero zirconia substructure is placed on the die in the transfer block (Figure 3). The transfer block is filled with superfluid PRIMERO Enamel Paste Porcelain on a vibratory table. The porcelain is then dried by microwave, because heating is from within. This means that the shrinkage begins at the zirconia and progresses to the surface. With microwave drying, the product being dried is hot and dry on the inside and cooler and wetter on the outside. Thus, a surface crust, which is formed by conventional drying, does not develop. Because of the more homogeneous drying, the green strength and the quality of the dried porcelain is improved. After drying the outer contour of the porcelain is milled taking account of 15% linear shrinkage during firing. In the PRIMERO Lab System, the porcelain is directly applied on the zirconia, without an intermediate connection layer, in order to simulate natural light transmission through the dentin-enamel interface and the color "from the inside out. "
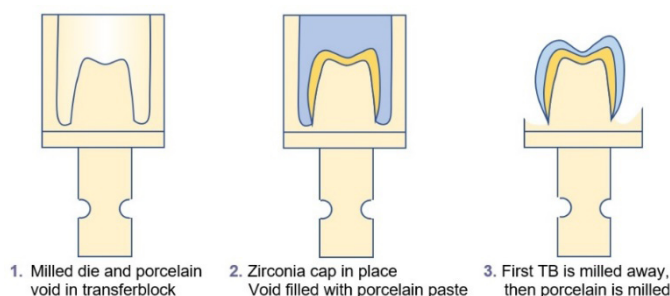

1. Milled die and porcelain void in transferblock
2. Zirconia cap in place Void filled with porcelain paste
3. First TB is milled away, then porcelain is milled

Figure 3: PRIMERO Lab System (DENTALXS.COM, Hoorn, The Netherlands).

Esthetics

The ceramic veneer was made of Primero Enamel, a three component glass ceramic, which shows similar mechanical and optical properties as natural enamel. The mono-color glass ceramic achieves a good result when using the incisal single layer technique, because, just like in natural teeth, the color gradients are a result of variations in thickness of the enamel layer. The result is a two-layer restoration in which both the inner dentin core and the outer enamel surface were obtained in a digital procedure. In an end control and finalizing step the crown is checked for the correct contact points on a printed replica of the dentition of the patient (Figure 4a-c). In the subtle cooperation between the dentin-colored zirconia and the veneering porcelain, the zirconia color shines through the translucent porcelain layer, all the more as the porcelain layer is thinner. This creates the same color dynamics with "color from within" as found in natural elements [10].
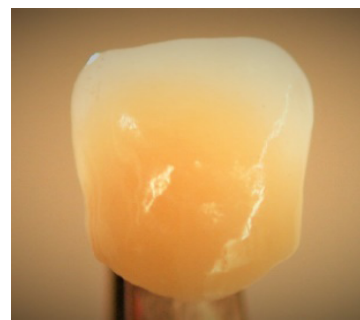

Figure 4: Primero front crown, premolar, and molar.

Method and Materials

Fatigue Loading Tests

Thirty-two three-unit bridge zirconia cores (Cercon Base, DeguDent GmbH, Hanau, Germany and Primero zirconia, DENTALXS.COM, Netherlands) were fabricated according to the manufacturer's instruction. The cross-section of the connectors was 12 mm² (height: 4 mm). The yttria-stabilized zirconia Cercon Base was pre-sintered, the Primero zirconia was milled in a "pressed" condition and both sintered to final dimensions. Frameworks were veneered with various ceramic materials using a conventional layering technique (CR1 and CR2) and with a new fabrication method (PR). (Table 1). The thickness of all veneering was in a clinically relevant range of 0.5 to 1.5 mm. For CR1 and CR2 the porcelain was applied by a dental technician manually, while PR used the Primero Lab System to apply the porcelain by a CAD/CAM method. For the Primero bridges a cognitive histo-anatomic design of the inner-structure was used (Figure 1).

To investigate the influence of fatigue, one zirconia group with the recommended veneering was investigated without aging. All bridges were adhesively cemented to the abutment teeth using the dual curing composite cement Variolink II (high viscosity) and the dentin adhesive system Syntac classic (both IvoclarVivadent, Schaan, Liechtenstein) after total etching. Artificial aging was used to simulate a 5-year period of oral service. The settings were [11]: 1,200,000 mechanical loadings with 50 N and a simultaneous thermal cycling with distilled water between 5°C and 55°C (3,000 times with 2 min each cycle).

Influence of Ceramic Veneering on the Fracture of Zirconia Bridges

Zirconia cores promise high-strength restorations, but veneering with "weaker" conventional glass-ceramics (with crystalline phases), which are used for esthetic appearance, function and protection, may influence the resistance to fracture of the restoration in service. Sailer et al. reported about 15% chipping in 44 bridges after 42 months [2]. The clinical studies coincidently showed no fractures of the high-strength core materials over the whole observation time. Zirconia cores may be veneered with various porcelain ceramics, but an inappropriate combination of core and veneer may show unpredictable failure of the veneering. This may be a reason for the clinically reported chipping of up to 15% in zirconia bridges [2].

#	Reference	CR1	CR2	PR
Comments	No fatigue	After fatigue	After fatigue	After fatigue
Veneering material	Cercon Ceram S	Ceramco PFZ	Cercon Ceram S	Primero Enamel
Veneering material structure	Homogenous	Homogenous	Homogenous	3 components
Core material	Cercon Base	Cercon Base	Cercon Base	Primero Zirconia
Core material state	Pre-sintered	Pre-sintered	Pre-sintered	Pressed
Manufacturer	DENTSPLY, USA	Ceramco, USA	DENTSPLY, USA	DENTALXS, NL
Thermal expansion, μm/mK	9.5	10.5	9.5	9.9
Firing temperature FT [°C]	830	900	830	865
Fracture force median [N]	1735	1380	1227	1440
25%	1305	940	1115	1294
75%	1891	1710	1467	1550
Bridges that survived fatigue	8	8	8	8
Number chipped out of 8	4	4	3	0

Table 1: Materials, manufacturing, thermal expansion, firing temperature and results [12].

Significant decisions for evaluating the usability of dental materials or restorations have been made using evidence-based information, but clinical studies are cost- and time- expensive. Artificial oral environments, which combine thermal cycling with mechanical loading, are used for the prompt and cost-effective estimation of the usability of dental reconstructions. The fatigue tests were performed in accordance with the procedures described in previous work [11].

The (Table 1) shows the median fracture results and the number of bridges which survived fatigue. No correlation was found between chip failures and fracture force. Fatigue loading reduced the median fracture force from 1735 N (control without fatigue to 1227 N (#CR2), but the difference was not statistically significant (p = 0.195). Different commercially available ceramic layer materials had no significant influence on the fracture force of the bridges.

Discussion

It has been shown that the loading capacity of ceramic specimens suffers from moisture and dynamical loading [12]. Zirconia-based ceramics lose about 50% of their flexural strength with increasing number of loading cycles and show low-temperature degradation. Similar behavior is observed for zirconia bridges: aged with fatigue loading tests, their fracture resistance is reduced about 30% from 1735 N to 1227 N (#CR2). The mechanical degradation over time may be caused either by spontaneous transformation of the tetragonal into monoclinic phase [12] or interactions between core and veneering, but it may also be influenced by processing reactions on the zirconia surface. A further explanation would be a limitation of the partial stabilization. In spite of the fatigue-induced degradation, only three out of 42 tested bridges failed below the assumed chewing force of about 500 N in posterior areas. Most bridges fractured at a maximum load above 1000 N and thus provided fracture results comparable to PFM bridges.

A bridge construction achieves most of its strength by the core, but a strong influence of the veneer on the fracture potential of the entire construction is shown in finite element analysis [13]. The same authors reported an improvement of the bridge fracture resistance after veneering the core material. The influence of the veneer on the strength of the bridge is underlined by a finite element analysis which showed that constant veneer thickness is requested to achieve optimal, even distribution of the occlusal forces. Bi-layered ceramic systems may be susceptible to chipping due to the combination of a "weak" veneering ceramic with a stronger zirconia core [14]. It has been shown that bi-layered glass-ceramics deteriorate due to loading in the contact areas. Esquivel et al. [15] concluded in their clinical study, that there is no difference in the in vivo maximum wear of enamel opposing monolithic zirconia crowns, enamel opposing porcelain fused to metal crowns and enamel opposing enamel [16].

Patients were recalled at six-months and one-year for re-impression. There were no statistical differences in mean wear of crown types, enamel antagonists and enamel controls after one year. However, the research did not cover a long enough period to find out the effect of concentration of chewing forces as a result of the wear-free behavior of monolithic zirconia crowns. Natural dentition will wear about 30-75 µm in vertical height each year. High hardness monolithic zirconia restorations will stand above the rest of the dentition after 5 or 10 years. New generation porcelains, such as Primero Enamel, have a low melting component that will in contact with saliva exchange sodium for water molecules which creates a hydrolyzed surface with a 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. [2] 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. Most conventional porcelains used for veneering zirconia were single component glass-ceramics, without any crack-stopping mechanisms. Primero Enamel (DENTALXS.COM, Hoorn, The Netherlands) consists of three glass components, with different melting points, crystal content and expansion coefficient, resulting in an overall melting point of 865°C. The small multi-directional internal micro-stresses caused by the three different components results in an effective crack-stopping mechanism.

The current procedure describes the production of durable layered restorations with an innovative, simple method on the basis of the copy of the histo-anatomic natural tooth structure. This makes the manufacture quick and predictably. The costs of the production process can be valued as large cost-saving compared the manual application of porcelain by a dental technician. The products exceed in their optical behavior even their natural model. Moreover, the production effort is considerably simplified in comparison with other known methods for layered restorations, such as manually firing, press-on technique and digital veneering by sintering a tooth colored glass cap onto a zirconia cap [17]. The latter technique makes it, when undercuts are present in the dentin core, impossible to fit the outer part on the zirconia cap. In the Primero method, the porcelain paste follows the dentin zirconia core surface completely and reaches all the undercut areas correctly.

Conclusion

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. A new porcelain that has three components, differing in melting point and thermal expansion, has internal micro-stresses that create a non-linear crack growth and effectively act as crack-stopper. A new CAD/CAM method, to produce veneered Prosthetic Mimetic Restorations (PRIMERO) with a chip-resistant porcelain and an histo-anatomic build-up, is presented. Cognitive design follows a histo-anatomic structure of the dentin-enamel junction, to mimic the build-up of the teeth of the patient. 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.

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