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Influence of Thermomechanical Fatigue Loading on the Fracture Resistance of All-ceramic Posterior Crowns

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Abstract - *This study evaluated the fracture resistance and the survival rate of different all-ceramic crowns in-vitro after thermomechanical fatigue loading in comparison to porcelain-fused-to-metal posterior crowns. Sixteen crowns for human mandibular first molars were made of each of the following: Cercon, IPS-Empress 2, In-Ceram Zirconia, Procera AllZircon and porcelain-fused-to-metal. Half of the specimens of each group was thermocycled and dynamically loaded using a chewing simulator. All samples were thereafter tested for the maximum fracture resistance. The survival rates after 1-2 million cycles in the artificial mouth were 100% in all the tested crown systems. The chewing simulation and thermocycling did not significantly decrease the fracture strength of the ceramic crowns (P> 0.005). The median fracture load of Cercon, Procera AllZircon, In-Ceram Zirconia and PFM was significantly higher than IPS-Empress 2 both for loaded and non loaded groups (P< 0.005) while the difference between Cercon, Procera AllZircon, In-Ceram Zirconia and PFM was not significant (P> 0.005). All-ceramic systems showed fracture load values similar to those of porcelain-fused-to-metal molar crowns and therefore may be considered for use in clinical studies.*

KEY WORDS: All-ceramics; dynamic loading; fracture resistance; thermomechanical fatigue.

INTRODUCTION

All-ceramic crowns are very popular for patients and dentists because of good aesthetics, excellent biocompatibility and physical properties compared to porcelain-fused-to-metal (PFM) crowns. Today, the use of all-ceramic systems has been extended to include posterior areas also [1-4]. Restorations in the posterior regions of the mouth must withstand masticatory forces greater than higher than 600 N [5]. Thus, the mechanical properties of the ceramics have to meet the requirements needed to withstand the forces that can arise in the molar regions. However, most dental ceramics are brittle and tensile stresses caused by occlusal loading can lead to crack propagation starting at cracks [1,2,6].

The mechanical properties of high strength alumina and zirconia ceramics make them possible to use for all-ceramic restorations in high stress-bearing areas [5,6]. These new ceramic materials can withstand high levels of forces without failure. Pallis et al. [4] found that the maximum load for IPS-Empress 2 molar crowns was between 771 and 1115 N and Procera AllCeram molar crowns was between 859 and 1086 N.

Zirconium-reinforced core materials have been developed in an attempt to achieve substantial improvements in strength and longevity of all-ceramic restorations [7,8]. In dentistry, zirconia ceramics have been used for orthodontic brackets, prefabricated post-and-core pins, implants, implant abutments and frameworks for crowns and bridges [9,10]. The clinical use of zirconium oxide as a core material has advantages, including favourable optical properties and a high fracture strength and flexural strength (over 1000 MPa) [11,12]. Polycrystalline zirconium oxide (ZrO_2) is typically used in a tetragonal crystalline phase, partially stabilized with yttria. A unique property is the so-called 'transformation toughening' where a partially stabilized zirconium oxide can actively resist crack propagation through a transformation from a tetragonal to a monoclinic phase at the tip of a crack, which is accompanied by a volume increase [12]. However, in vitro and randomized controlled in vivo trials are needed to evaluate the long-term performance of densely sintered zirconia.

The aim of this study was to compare the fracture resistances of different all-ceramic molar crown systems with conventional PFM restorations. In addition, the influence of thermomechanical fatigue loading in a dual axis chewing simulator was evaluated. The research hypothesis tested was that there is no difference in fracture resistance and survival rate between the different types of all-ceramic crown systems after thermomechanical fatigue loading.

MATERIALS AND METHODS

Eighty recently extracted caries free human mandibular first molars of comparable size were selected, and those that were found to be sound and free from hypoplastic defects and cracks were used. All teeth were cleaned by scaling and stored in distilled water throughout the study.

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In order to simulate physiological tooth mobility, all roots of the abutment teeth were covered with an artificial periodontal membrane made out of gum resin (Anti-Rutsch- Lack) [13]. Each tooth was coronally covered with wax 2 mm short of the cemento-enamel junction (CEJ) and then dipped once in the gum resin. After the gum resin had dried, the excess resin on the root tip was removed using a scalpel so that a uniform coating remained on the root surface. Thereafter, the teeth were embedded into polyester resin (Technovit 4000) until 2 mm below the CEJ to simulate the clinical bone level.

Each tooth was prepared for a complete-coverage restoration with a 6° convergence angle using a silicone index as a depth guide. An occlusal reduction of 2.0 mm was prepared, followed by a circular 90° and 1.2 mm wide shoulder with rounded inner angle using appropriate burs (No: 386023, No: 837 KR.0.12, No: 8837 KR.0.12). The 80 abutment teeth were arbitrarily assigned to each of the 5 test groups. Polyvinylsiloxane impressions of each tooth were made with Elite HD+ with custom-made impression trays. Dies were fabricated using Fuji Type 4 Dental Stone.

Four different types of all-ceramic and one group of metal-ceramic crowns were fabricated according to the manufacturers' directions (Table 1).

Cercon crowns

A conventional wax model of the framework to a target thickness of 0.6 mm was prepared. The Cercon Blank and the wax model were placed into Cercon Brain in order to fabricate the zirconia core with the CAD-CAM technique. The zirconia ceramic used in Cercon was hot isostatic pressed zirconia. The framework was then sintered in the Cercon Heat Furnace. Finally, the framework was veneered with low-fusing dental ceramics which was specially tailored to the coefficient of thermal expansion of zirconium oxide. Veneering porcelain thickness was 0.6 mm on the proximal and 1.4 mm on the occlusal surfaces. Then the crowns were glazed.

IPS-Empress 2 crowns

A wax model of the framework to a target thickness of 0.7 mm was made and a castable lithium-disilicate ceramic ingot (IPS-Empress 2) was heated and pressed into an investment mould after the burn out of the wax analogue [14]. Then, the framework was circularly veneered with feldspathic porcelain (Empress 2) to a target thickness of 0.5 mm on the proximal and 1.3 mm on the occlusal surfaces and then glazed.

Procera AllZircon crowns

The die model was scanned using the Procera® Scanner and the data were sent to the manufacturing site. The framework was designed by the manufacturer using the computer software to a coping thickness of 0.7 mm. The zirconia ceramic used in Procera was hot isostatic pressed zirconia. The framework was returned to the laboratory for the veneering procedure (Triceram) and final finishing. The target veneering porcelain thickness was 0.5 mm on the approximal and 1.3 mm on the occlusal surfaces. The crowns were then glazed.

In-Ceram Zirconia crowns

In-ceram zirconia copings to a target thickness of 0.7 mm were prepared using the slip casting technique [15]. The slip material was applied. Sintering firings were then made in the Vita Inceramat. After glass infiltration of the VITA In-Ceram coping, the frameworks were veneered with Vitadur Alpha to a target thickness of 0.5 mm on the proximal and 1.3 mm on the occlusal surfaces and the crowns were then glazed.

Porcelain-fused-to-metal crowns

The framework was cast with dental metal alloy to a target thickness of 0.5 mm (Ni-Cr, Kera N). Each specimen was completed by veneering with feldspathic porcelain (Vitadur Alpha) to a target thickness of 0.7 mm on the proximal and 1.5 mm on the occlusal surfaces on the framework.

The prepared surfaces of each abutment were etched with 37% phosphoric acid, Panavia Etching Agent V for 15 s and the abutments were treated with Panavia ED Primer. All samples with the final thickness of 1.2 mm on the proximal and 2 mm on the occlusal surfaces were bonded to the abutments using an autopolymerizing resin cement, Panavia F. Excess resin was removed with sponge pellets before curing and an air-blocking gel, Oxyguard II was applied during the setting time of the resin cement. Finally, the samples were washed with distilled water and stored in distilled water for at least 24 hours before testing.

Eight of the 16 specimens in each group were exposed to 1.2 million cycles of thermomechanical fatigue in a computer-controlled chewing simulator (Table2, Fig 1). In previous studies it has been stated that 1.2 milion cycyles in the dual axis chewing simulator demonstrates a 5 year clinial period [16,17]. A load of 49N was applied in the centre of the occlusal surface of the crowns using a 6 mm diameter ceramic antagonist ball (Steatite). Vertical movement of the antagonist was set at 6 mm, horizontal movement at 0.5mm and the cycle frequency at 1.6Hz. During testing, all samples were allowed to reach a thermal equilibrium between 5- 55C for 60s each with an intermediate pause of 12s, maintained by a thermostatically contolled liquid circulator for 10,000 cycles [18]. During the dynamic loading, all samples were examined twice a day.

In order to evaluate the fracture resistances of the crowns, all specimens were statically loaded in the Lloyd universal testing machine, until fracture of the veneering material, the copings or the tooth occurred. A perpendicular load was applied to the occlusal surface of the crowns at a crosshead speed of 0.5mm/min [19]. Maximum fracture resistances were recorded and analysed with Lloyd' s software.

STATISTICS

The Kruskall-Wallis test was used to analyse the static fracture resistances. Differences between the groups were evaluated with the multiple pairwise comparisons (Mann-Whitney U tests). A *P*-value of <0.05 was considered statistically significant.

Table 1. *Test and control group(s) used in this study.*

Test group	*Manufacturer*	*Core Material*	*Veneering Material*	*Processing*
Cercon	Degussa Dental, Hanau, Germany	Cercon Core	Cercon Smart Ceram S	CAD-CAM
In-Ceram Zirconia	Vivadent, Germany	Vita In-Ceram Zirconia Slip Casting	Vitadur Alpha Porcelain	Glass Infiltration
IPS-Empress 2	Ivoclar, Schaan, Liechtenstein	IPS-Empress 2 (Ingot)	IPS-Empress (IPS Eris)	Heat and Pressed
Metal Ceramic (Control)	Kera N, Einsenbacher Dentalwaren GmbH, Wörth/ M, Germany	Kera N, Ni-Cr Alloy	Vitadur Alpha Porcelain	Casting
Procera AllZircon	Nobel Biocare, Göteborg, Sweden	Procera AllZircon Core	Triceram	CAD-CAM

Table 2. Test parameters of chewing simulation

Cold/ hot bath temperature	*5 °C/ 55 °C*
Vertical movement	6 mm
Rising Speed	55 mm s^{-1}
Descending speed	30 mm s^{-1}
Load per sample	49 N
Kinetic energy	2250 X 10^{-6} J
Dwell time	60 s
Horizontal movement	0.3 mm
Forward speed	30 mm s^{-1}
Backward speed	55 mm s^{-1}
Cycle frequency	1.3 Hz

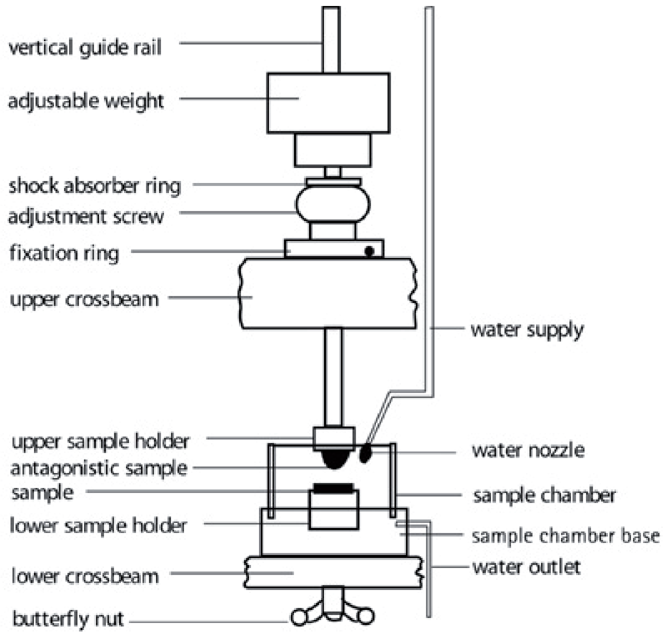

Figure 1. *Schematic drawing of one chewing chamber.*

RESULTS

All 40 specimens survived 1,200,000 cycles of dynamic loading and thermal cycling in the artificial oral environment. The median fracture resistances obtained with / without thermomechanical fatigue resistances were seen in Fig 2. No statistically significant differences between the loaded and non loaded groups were found.

Within all between-group comparisons with and without artificial aging, the failure resistances of IPS-Empress 2 crowns were significantly lower than those of Cercon, Procera AllZircon, In-Ceram Zirconia and PFM specimens ($P<0.05$). The difference between the fracture resistances of zirconium-based ceramic and PFM crowns was not significant.

DISCUSSION

The results from previous studies can not be compared directly to the present study due to the different test parameters and methods related to the abutment teeth, the die material, the core thickness of the crowns, the fatiguing regimes. Nevertheless, the median failure resistance values in this investigation ranged from 1213N to 2930N, reaching higher levels than the physiological load values in the posterior area reported in the literature [5, 20].

Cercon, a yttria-stabilized ZrO_2 ceramic revealed the highest median fracture resistance values. The highest fracture resistance value achieved with the Cercon crowns could be attributed to the mechanical properties of zirconia blank which is stabilized with 5% yittria for the Cercon system [21]. Moreover, the blank material for the CAD-CAM coping was manufactured under optimized industrial conditions. The minimized risk of voids and volume defects might have resulted in improved strength properties for the Cercon system.

The second highest fracture resistance values in this investigation were found for the non-resistanceed group of the In-Ceram zirconia-reinforced crowns. In-Ceram Zirconia, which was developed by adding a stabilizing oxide (33% ZrO_2 stabilized by 16% CeO_2) to In-Ceram Alumina, is an attempt to combine the toughening

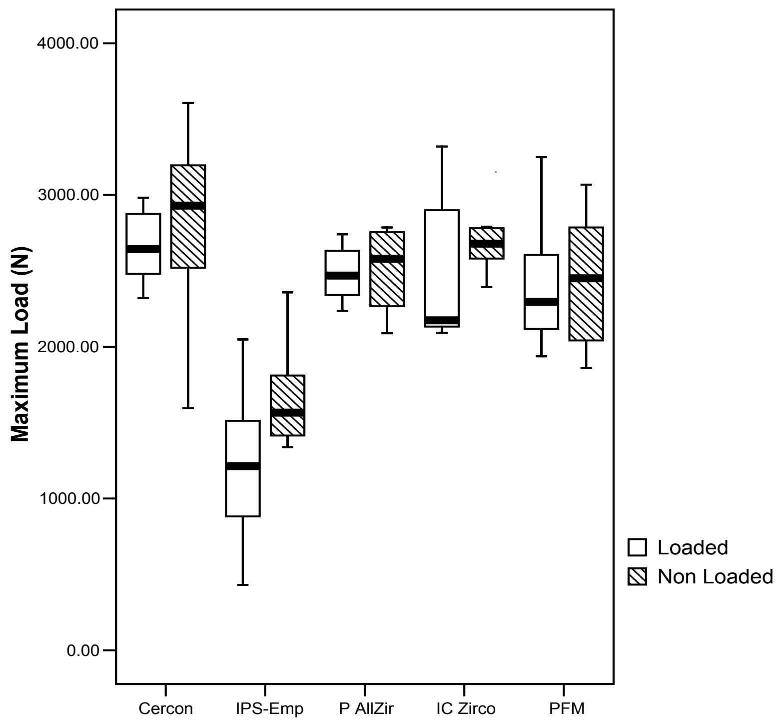

Figure 2. *Box-plot of load at fracture values of molar crowns. The horizontal bold line in each box represents the median value (IPS Emp= IPS Empress 2, P AllZir= Procera AllZircon, IC Zirco= In Ceram Zirconia, PFM= Porcelain-Fused-to-Metal) The upper and lower end of the vertical lines in the boxes denote the maximum and the minumum observations in each group.*

mechanism due to the phase transformation of zirconia to the versatility and ease of use of the partially-sintered glass-infiltrated alumina [22]. The transformation-toughening mechanism contributes to the improved fracture resistance of In-Ceram Zirconia [23,24].

In the present study, the resistance to fracture the In-Ceram Zirconia crowns was 2679N for the non-aged group. However, in a previous study, Pallis et al [4] found that the fracture strength of In-Ceram Zirconia posterior crowns was 998 to 1183N. The median resistance to fracture the In-Ceram Zirconia crowns were almost twice as high as those reported by Pallis et al. However, it has be considered that the coping thickness used in that study was 0.5 mm whilst the coping thickness was 0.7 mm in the current study.

Due to small sample sizes within groups all comparisons were done using non-parametric methods. Five different types of porcelain systems were compared by using Kruskall-Wallis analysis of variance and when the results yield a significant difference Mann-Whitney-U-test was used to detect the groups which are different from others. In-Ceram Zirconia is available as either slip or dry-pressed [22]. Guazzato et al, reported that the strength behaviours of In-Ceram Zirconia slip and dry-pressed were similar and the difference in strength and toughness between the two processes were insignificant [22]. However, there is a lack of studies comparing the slip to the dry-pressed, although the dry-pressed material is thought to have better mechanical properties as a result of more consistent processing. If the non-statisticly significant decrease seen with cycling with the slip specimens in the present study (data not shown) means anything, it may be attributed to the process-dependent brittle characteristics of this material as it has little capacity to deform and thereby decrease the concentration of stresses at the crack tip [11,25-28]. Cycling under wet conditions, results in the propagation of small cracks which may initiate from processing-related defects within the crowns. These cracks fuse to a growing fissure that weakens the slip crown [28].

Conversely to high strength zirconium-based ceramics, IPS Empress 2 exhibited the lowest failure resistances among the ceramics tested and revealed the median failure resistances of 1213 and 1566N in the loaded and non-loaded conditions, respectively. IPS Empress 2 is a lithia-disilicate glass ceramic ($Li_2O.SiO_2$), with an average fracture strength of 350 MPa [22]. Therefore, IPS Empress 2 crowns cannot achieve properties that are similar to zirconia. In this study, the fracture resistance value of IPS Empress 2 is in good agreement with previously reported values [4,7]. Additionally, in a previous study, Chitmongkolsuk et al [18] reported that after 1.2 million cycles, the fracture resistance of IPS Empress 2 bridges were lowered by 20% which correlates with the current study.

CONCLUSIONS

Clinical failure of all-ceramic restorations is a very complex process involving patient variables, dynamic loads, restoration geometry, material properties, fatigue phenomena, and multiple failure modes. In this study, the four-tested all-ceramic systems showed fracture load values similar to those of PFM molar crowns and therefore may be considered for use in clinical studies.

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MANUFACTURER'S DETAILS

- Anti-Rutsch- Lack, Wenko-Wenselaar, Hilden, Germany.
- Technovit 4000, Heraus Kulzer, Wehrheim, Germany.
- Burs (No: 386023, No: 837 KR.0.12, No: 8837 KR.0.12) Brasseler, Lemgo, Germany.
- Elite HD+ , Zhermack, Rovigo, Italy.
- Fuji Type 4 Dental Stone, GC Europe, Leuven, Belgium.
- The Cercon Blank, Degudent, Hanau, Germany.
- IPS-Empress 2, Ivoclar, Schaan, Liechtenstein.
- Procera® , Nobel Biocare, Göteborg, Sweden.
- Triceram, Dentaurum, Germany.
- Vita Inceramat, Vita, Bad Säckingen, Germany.
- Dental metal alloy , Ni-Cr, Kera N, Eisenbacher Dentalwaren, Germany.
- Panavia Etching Agent V, Kuraray, Osaka, Japan.
- Oxyguard II, Kuraray, Osaka, Japan.
- Chewing simulator , Willytech, Munich, Germany.
- Ceramic antagonist ball, Steatite, Ceramtec, Wunsiedel, Germany.
- Lloyd universal testing machine, Ametek, Hampshire, UK.

ADDRESS FOR CORRESPONDENCE

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