Fracture Strength of Zirconia and Alumina Ceramic Crowns Supported by Implants

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Due to the brittleness and limited tensile strength of the veneering glass-ceramic materials, the methods that combine strong core material (as zirconia or alumina) are still under debate. The present study aims to evaluate the fracture strength and the mechanism of failure through fractographic analysis of single all-ceramic crowns supported by implants. Forty premolar cores were fabricated with CAD/CAM technology using alumina (n = 20) and zirconia (n = 20). The specimens were veneered with glass-ceramic, cemented on titanium abutments, and subjected to loading test until fracture. SEM fractographic analysis was also performed. The fracture load was 1165 (±509) N for alumina and 1638 (±662) N for zirconia with a statistically significant difference between the two groups (P = 0.026). Fractographic analysis of alumina-glass-ceramic crowns showed the presence of catastrophic cracks through the entire thickness of the alumina core; for the zirconia-glass-ceramic crowns, the cracks involved mainly the thickness of the ceramic veneering layer. The sandblast procedure of the zirconia core influenced crack path deflection. Few samples (n = 3) showed limited microcracks of the zirconia core. Zirconia showed a significantly higher fracture strength value in implant-supported restorations, indicating the role played by the high resistant cores for premolar crowns.

Key Words: fracture, strength, alumina, zirconia, implant-supported prostheses

INTRODUCTION

The increased demand for aesthetic dentistry by patients has led to a wide request for all-ceramic restorations in either posterior or anterior regions.1 As a consequence, metal-free crowns have also become popular for implant-supported restorations due to their excellent biocompatibility reported, especially for a single missing tooth.2 The long-term success of all-ceramic fixed partial dentures (FPDs) is well established in natural dentition; however, the risk of failure for the implant-supported prosthesis is less certain. Pjetursson et al3 reported a significantly lower risk after 5-year of ceramic fracture for tooth-supported versus implant supported FPDs (2.9% vs 8.8%). Kinsel and Lin4 reported a fivefold increase of failure in implant-supported as compared to tooth-supported ceramic restorations. The absence around osseointegrated implants of periodontal tissue and of neurological reflex mechanism—as protective mechanism against the masticatory force—offers possible explanations for differences in failure rate among restorations involving natural dentition and implants.5–11

In implant dentistry, the key factor for long-term success of the restorations is the stress distribution and the load transferring to the surrounding bone.12 With this in mind, the implant’s abutment plays an important role in transferring occlusal forces to the implant, and the mechanical properties of the material of the abutment may influence the stress of implant-supported restorations. The maximum tensile stress within the all-ceramic crown was higher when titanium abutment was used.13 Adell et al14 indicated that an all-ceramic crown placed on titanium abutment was more likely to fracture than when placed on a ceramic abutment. While the resistance to fracture of all-ceramic implant-supported restorations has been investigated mainly on anterior teeth,15,16 little is known about the performance of all-ceramic restorations prepared through computer-aided design/computer-aided manufacturing (CAD/CAM) technology for premolar teeth. That said, the premolar regions belong to highly aesthetic locations in the dental arch, especially for patients with a high lip line. The implant-supported single-tooth restorations of these regions are subject to higher stress than those in the anterior region. The occlusal force in adults is on average about 100 N higher in the premolar region than in the anterior.17 It has been shown that under loading conditions, ceramic restorations accumulate damage; which weakens the ceramic restoration and can cause clinical failures.18–20 The ceramics are brittle materials because of atomic bonds that do not allow the atomic planes to slide when subjected to loading; thus, the ceramics cannot withstand a deformation of >0.1% without fractures.21

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formation of microscopic flaws during the laboratory processing or the clinical function, such as voids or cracks, can lead to the failure of dental ceramics; moreover, the load failure of all-ceramic systems is influenced by prostheses’ geometry, size, and location of flaws.\textsuperscript{21} New ceramic materials cores and manufacturing processes (CAD/CAM) were developed to improve the resistance to crack propagation, essentially introducing crystalline structure materials.

Fifteen years ago, the introduction of CAD/CAM techniques allowed dentistry the use of high purity industrially manufactured alumina.\textsuperscript{22,23} CAD/CAM also makes it possible to store all production steps electronically and attain good reproducibility, accuracy, and precision. Subsequent to the CAM step, the alumina cores were densely sintered and veneered with glass-ceramic to create the appearance of a natural tooth.\textsuperscript{24} Clinical studies have indicated that such alumina crowns may be used for restorations in all locations of the oral cavity.\textsuperscript{25,26} However, the best mechanical properties of all the dental ceramics are attained with yttrium-stabilized zirconium dioxide (zirconia).\textsuperscript{27,28} Zirconia is an intermetallic compound with a high mechanical resistance due to its tetragonal crystalline structure, allowing the material to undergo a transformation under critical load, limiting the propagation of the microcracks.\textsuperscript{29,30} The transformation toughening leads to a high initial strength and resistance to cracks, resulting in an excellent durability for zirconia frameworks.\textsuperscript{31}

Zirconia or alumina used as cores for tooth restorations forms a "laminate system" with several layers: (1) abutment material, (2) the cement, and (3) the core and glass-ceramic veneering material. When a complex multilayered system is subjected to occlusal load, it undergoes a fatigue stress inside the material’s bulk and its interfaces. In response to such stress, the clinical performance differs as function of the material’s system is adopted. The aims of the present study were to compare the fracture strength of the premolar’s crowns of zirconia and alumina cemented over implant abutments and to evaluate the mechanism of failure through fractographic analysis. Therefore, we tested the hypothesis that there is no difference between the fracture strength of the premolar crowns with alumina or zirconia cores.

**MATERIALS AND METHODS**

**Specimens’ preparation**

Forty identical single premolar-crown copings were prepared through CAD/CAM technology on titanium standard ITI abutments (Institut Straumann AG, Zurigo, Svizzera) (Figure 1). Twenty crowns were made in pure alumina using Nobel Procera Alumina (Nobel Biocare AB, Göteborg, Sweden), whereas the other 20 crowns were made of three-mol \%YO3 doped zirconia, yielding a predominantly tetragonal fine-grained microstructure; Y-TZP, Lava, (3M ESPE, Seefeld, Germany). Prior to glass-ceramic firing, alumina and zirconia cores were sandblasted with 110 \textmu m of Al2O3 under two bars of pressure at 2.5 cm from the coping surface. All copings were veneered by an experienced master dental technician in a dental laboratory using Vita VM 7 (VITA Zahnfabrik H. Rauter GmbH & Co KG, Bad Säckingen, Germany) over alumina copings and Lava Ceram Overlay Porcelain (3M ESPE) over the zirconia copings.

All firing cycles were carried out according to the manufacturer’s recommendations in a calibrated porcelain furnace (Flagship VPF Jelenko, New York, NY). The furnace was automatically calibrated using the appropriate device recommended by the manufacturer. In the last step, the crowns were autoglazed.

**Cementation**

The crowns were cemented by means of dual-cure self-adhesive resin cement (RelyX Unicem, 3M ESPE, St Paul, Minn) according to the manufacturer’s instructions on the standard ITI abutments (Institut Straumann AG, Zurigo, Svizzera). A standardized load of 10 N for 7 min was used during the cement-setting reaction by means of a universal loading machine (Lloyd 30K, Lloyd Instruments Ltd). Excess cement was removed, and the crowns were stored in distilled water with a temperature of 37°C until subjected to mechanical testing.

**Compressive loading tests**

All the samples were put into the holding device of a universal loading machine (Lloyd 30K, Lloyd Instruments Ltd) to perform compressive loading tests under static conditions until the fracture of the specimens occurs, allowing assessment of maximum load resistance and fracture mechanisms. A controlled load at a crosshead speed of 1 mm/min was applied by means of a stainless steel rod with a spherical tip of 7 mm of diameter to simulate an occlusal load. The applied force was parallel to the longitudinal axis of the specimens and acted at level of the central fossa, 2 mm from the tip of the supporting cusp (Figure 2). All samples were loaded from 0 N until fracture. The load fracture was recorded in N by means of a computer connected to the loading machine, using a specific measurement software (Nexigen ver. 4.0 issue 23 Lloyd Instruments Ltd). Both maximum load and work at maximum load were evaluated.

**Scanning electron fractographic analysis**

To highlight the influence of the sandblasting procedure on the fracture strength at the interface between glass-ceramic and zirconia, some additional zirconia copings (n = 3) were prepared. The copings were sandblasted as reported in specimen’s preparation section except for the following: only one side of the vestibular cusp (occlusal wall) was sandblasted, while the buccal wall of the vestibular cusp was left as delivered by the milling center. The additional specimens were veneered with glass-ceramic as reported in the specimen preparation section. The fracture test was carried out, applying the load on the tip of vestibular cusps.

All the experimentally fractured specimens were coated with a very thin layer of gold by vacuum evaporation using a Technics Hummer II-Au-sputtering (Anatech Technologies, Alexandria, Va) and were observed with a scanning electron microscope (SEM) (Cambridge Stereoscan 200, Cambridge Instrument Company Ltd, Cambridge, UK) equipped with tetra solid-state detector for back-scattered electrons. The fracture surfaces were analyzed starting from the starting point of the fracture once well identified, until the arrest point of the cleavage plane. Type and location of initiating flaws—such as
porosity and surface defects—were also evaluated if present. The fractographic patterns commonly observed in brittle fractures were evaluated as follows: mirror area that appears as a flat shiny area; the mist area that appears to be slightly rougher; the hackle area, that appears as ridges and grooves radiating from the starting point, as well as layers resulting from branching of the fracture path. Different magnifications were used to analyze the fractures because some patterns were easily recognized at higher magnifications and others were more apparent at lower magnifications. To assess the accuracy of the method, the same operator performed the analyses twice.

**Statistical analysis**

All the data were analyzed by means of the computerized statistical package (Sigma Stat 3.5, SPSS Inc, Ekrath, Germany). The mean fracture loads of alumina and zirconia crowns were compared using the Student t-test with a confidence interval of 95%. Statistical differences were considered significant for a $P$ value of $<0.05$.

**Results**

**Fracture strength**

The fracture strength value (mean ± SD) was 1165 ± 509 N for alumina and 1638 ± 662 N for zirconia; the difference of the means was 473 N. The statistical analysis showed a significant difference between the two groups ($P = 0.026$) (Table).

**Scanning electron fractographic analysis**

Most of the specimens noted cohesive fractures of the glass-ceramic (Figure 3). The alumina and zirconia glass-ceramic bond was always stronger than the cohesive forces of the glass-ceramic itself (Figure 4); in fact, the main fracture path propagated through the glass-ceramic body. In both the experimental groups, the core-glass-ceramics interface transferred most of the energy accumulated by the system under load to the bulk of the glass-ceramic, annihilating it by fracture.

For alumina glass-ceramic restorations, mostly microcracks were generated on the occlusal surface at the level of the supporting cusp, where the arbitrary load was applied; they

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<td><strong>Unpaired t-test: fracture load (Newtons), SD = standard deviation</strong></td>
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*95% confidence interval for difference: -95.22 to 847.2; $t = 1.615$ with 38 degrees of freedom; $P = 0.026$
FIGURE 3. SEM images of copings after fracture. (a) and (a1) Alumina-ceramic specimen. (b) and (b1) Zirconia-ceramic specimen. White arrows indicate the core microcracks.
easily propagated into the bulk of the veneering material and reached the prosthetic copings (the cores), causing a cata-
strophic fracture of the core (Figure 3a and a1). On the contrary, in the zirconia glass-ceramic restorations, the fractures were concentrated at the level of the supporting cusp with a limited extent of the fracture path. The cleavage fracture appeared to be stopped by the prosthetic copings (the core) surface with only small partial microcracks that involved the zirconia core (Figure 3 b and b1).

Analyzing the fracture's pattern from the energy point of view, the alumina specimens emerged when the cleavage plane (plane of fracture) reached the surface of the core (extended mirror area); it conserved a high energy level sufficient for the core's fracture, without any deflection (hackle area) of the fracture path (Figure 4 a and a1). To the contrary, the zirconia core seemed to be able to best dissipate the occlusal load (energy) since a catastrophic fracture of the core was not present, and few microcracks on the occlusal area of the copings were noted. The energy of the cleavage plane, in this case, appears to be mostly annihilated by the sequence of mirror, mist, and hackle areas of fractures inside the glass-ceramic layer; thus when it reached the zirconia core surface, the residual energy was able to produce just microcracks in the core (Figure 4b and b1). Only limited areas of zirconia framework appeared uncovered by glass-ceramic (Figure 4b and b1). The vitreous phase of the ceramics satisfactorily imbibed the zirconia structure, confirming the effectiveness of the core-glass-ceramics bond under high load condition.

Moreover, the microtexture (sandblasting) of the zirconia core appeared to influence the behavior of the cleavage plane on zirconia specimens (Figure 5). The evaluation of additional specimens with double surface treatments (rectangle 1 sandblasted and rectangle 2 as received by milling center; see Figure 5a) showed different fractographic patterns after fracture. The sandblasted surface (Figure 5b) appeared to be able to influence the cleavage plane development with arrest lines to 10 μm from the core surface, while outside, this frontier wake hackle area was evident. Any detachment line was noted at the zirconia/glass-ceramic interface. The zirconia core surface as received by milling center (Figure 5c) showed arrest lines at the zirconia/glass-ceramic interface with wake hackle area in proximity to the interface. A detachment line was seen at the interface.
As for the microstructure of alumina, high magnification SEM images showed a polycrystalline structure made of aluminum oxide sintered grains; very few post-sinterization voids were evident, whose dimension reached a maximum of about 330 nm. The dimension of the grains (mean ± SD) was of $1.77 \pm 0.54 \mu m$ with a polygonal appearance (Figure 6a and a1). The microstructure of 3 mol %Y-TZP zirconia, sintered at 1450°C for 2 h, showed a mean (± SD) grain sizes of $0.45 \pm 0.15 \mu m$ with round appearance (Figure 6b and b1).

**DISCUSSION**

The results of the present study sustain a rejection of the null hypothesis because the fracture strength between the two groups showed a statistically significant difference of 473 N ($P = 0.026$). The results also revealed that the breaking strength was higher for glass-ceramic/zirconia.

A possible explanation was supported by the fractographic analysis. In implant-supported prosthetic restorations, the most stressful regions are the interfaces, such as the contact area between core and porcelain. The effectiveness of the alumina/and zirconia/glass-ceramics bond is influenced by the different physical characteristics of both veneering glass-matrix and crystalline core ceramics. As reported in the scientific literature, a good mechanical resistance to compression characterizes porcelain, but it is negatively affected by shear-flexural stresses. Such stresses might arise in the occlusal third and at the level of the cervical margin of the crown, possibly causing local failure of the core/glass-ceramic bond and the detachment of porcelain.

The present findings of fractographic analysis are in accordance with previously reported observation in which the cleavage planes always pass through areas with low fracture strength, presenting different fracture patterns in the veneering ceramics, alumina, and zirconia.

The deflection of the crack growth path was evident in both groups since the crack lines changed their direction following the profile of the copings, annihilating the energy as much as possible (Figure 3a and b). Moreover, it was associated with the change of the force direction vector from the compressive stress in the occlusal area to the shearing stress of the axial regions.

The explanation for these results involves the local stress level that exceeded the cohesive resistance of the glass-ceramics in all the specimens, breaking the atomic bonds. Yet, due to surface tension, ceramic structures tend to fail catastrophically, with cracks propagating by slow growth from a point where the applied load exceeds the material resistance. If a die made of a high modulus material supports a crown, the fracture strength will increase dramatically compared with that of crowns supported by a low modulus material. In fracture mode, however, the zirconia cores seemed to be more resistant compared with alumina cores, as significantly more of the fractured alumina crowns were totally fractured. This could imply that the zirconia core resists higher loads than alumina, but that the veneer porcelain fractures at a lower load. A ceramic laminate will always form a constant strain system because of a mismatch of the modulus of elasticity across the core-veneer interface. The interface is an important source of structural flaws because of wettability factors, such as microstructural roughness (or sandblasting treatment), which can influence the coupling degree of glass-ceramic both during the ceramic buildup and the subsequent ceramic firing procedures. In this study, different surface properties of the two core materials caused difficulties in building up a dense, homogenous layer of green porcelain, without trapping air bubbles, over the core surface prior to firing.

Veneer fractures often occur during interfacial stresses or because microstructural regions in the porcelain are mechanically defective. Such microstructural flaws include porosities, agglomerates, inclusions, and large grained zones.

**CONCLUSIONS**

Within the limits of this study, based on the rejection of the null hypothesis, it was possible to state that the glass-ceramic/
Zirconia had a fracture strength value significantly higher than that of the glass-ceramic/alumina. In addition, both systems of restoration when supported by implants achieved higher values of breaking strength than the functional load of the premolar region. Finally, the sandblasting procedure of zirconia core was shown to be effective for improving adhesion at the interface between zirconia and ceramic.

**ABBREVIATIONS**

CAD/CAM: computer-aided design/computer-aided manufacturing  
FPD: fixed partial denture  
SEM: scanning electron microscope

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