Comparison of fracture resistance and fracture characterization of bilayered zirconia/fluorapatite and monolithic lithium disilicate all ceramic crowns

Abdulaziz M. Altamimi, BDS, Msc, FACP
Prosthodontist and Faculty member, Prince Abdulrahman Advanced Dental Institute,
Riyadh, Saudi Arabia

Aris Petros D. Tripodakis, DDS, MSc, Dr Dent
Associate Professor, Department of Prosthodontics, School of Dentistry,
National & Kapodistrian University of Athens, Greece,
Visiting Associate Professor, Tufts University School of Dental Medicine, Boston, USA

George Eliades, DDS, Dr Dent, FADM
Professor and Director, Department of Biomaterials, School of Dentistry,
National & Kapodistrian University of Athens, Greece

Hiroshi Hirayama, DDS, DMD, MSc, FACP
Professor and Division Head of Graduate and Postgraduate Prosthodontics,
Advanced Education in Esthetics Dentistry, Advanced Dental Technology & Research
Program, Tufts University School of Dental Medicine, Boston, USA

Corresponding author: Abdulaziz M. Altamimi
Prince Abdulrahman Advanced Dental Institute, Riyadh 11159, P.O.BOX 7897, Riyadh, Saudi Arabia.
Tel: +966 11 4983015; Fax: +966 11 4995789; E-mail: aziz77z@gmail.com

Abstract

Purpose: To compare the fracture resistance between bilayered zirconia/fluorapatite and monolithic lithium disilicate heat-pressed crowns and characterize the mode of fracture failure.
Materials and methods: Thirty crown samples were sequentially fitted on a mandibular right first molar metal replica of an ivory prepared molar tooth. The crown specimens were divided in three groups (A, B, and C; n = 10 for each group). Group A consisted of bilayered zirconia/fluorhapatite pressed-over crowns with standard design crown copings (0.7 mm uniform thickness), Group B of bilayered zirconia/fluorhapatite with anatomical design crown copings, and Group C of lithium disilicate monolithic crowns. The samples were then dynamically loaded under water for 100,000 cycles with a profile of 250 N maximum load at 1,000 N/s rate and 2.0 Hz frequency. Loading was performed with a steel ball (5 mm in diameter) coming into contact with the test crown, loading to maximum, holding for 0.2 s, unloading and lifting off 0.5 mm. The samples were then fractured under static loading, in order to determine the ultimate crown strength. Analysis of the recorded fracture load values was carried out with one-way analysis of variance (ANOVA) followed by Tukey tests. Fractured specimens were examined by stereomicroscopy and scanning electron microscopy.
Results: The fracture loads measured were (N, means and standard deviations): Group A: 561.87 (72.63), Group B: 1,014.16 (70.18) and Group C: 1,360.63 (77.95). All mean differences were statistically significant ($P < 0.001$). Catastrophic fractures occurred in Group C, whereas mainly veneer fractures were observed in Groups A and B.
Conclusion: In the present study, the heat-pressed monolithic lithium-disilicate crowns showed more fracture resistance than zirconia/fluorapatite pressed-over crowns. Within the bilayered groups, the anatomical zirconia coping design presented increased ceramic fracture resistance.

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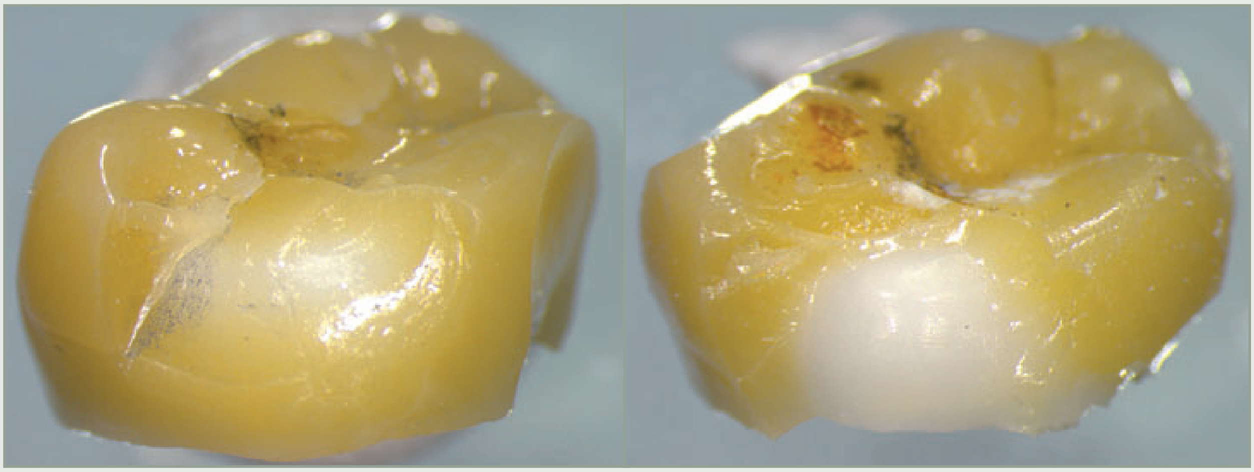

Introduction

All-ceramic crowns have been extensively used in prosthodontics in recent years for their superior esthetic quality, excellent biologic response and marginal accuracy comparable to traditional metal-based restorations.[1] Ever since all-ceramic technology was clinically applied, the bilayered approach was introduced in order to provide the crowns with a strong, yet rather opaque substructure, supporting a weaker and more translucent veneered ceramic material.

Toughened ceramics such as yttria-stabilized tetragonal zirconia (Y-TZP) offer the possibility of fabricating fracture-resistant ceramic cores for all-ceramic crowns with acceptable optical qualities.[2] The use of computer aided design/computer aided manufacturing (CAD/CAM) technology, which offers the advantage of a timesaving production procedure combined with precision, is necessary in order to process these reinforced substructures.

In general, the zirconia/ceramic relationship is one of the weakest aspects of these restorations, so that ceramic chipping or cracking of the veneer frequently occurs.[3-6] Factors that may influence veneer fracture include differences in thermal expansion coefficients between core and ceramic, firing shrinkage of ceramic, flaws on veneering, and poor wetting by veneering on core.[7,8]

Another important factor that can affect the clinical success of the bilayered restorations is the restoration design. It has been suggested that at all times, the veneer ceramic should attain an even thickness within the restoration contour by being accordingly supported by the ceramic substructure.[9,10] The positive influence of such a modification of core design over the clinical performance of the restorations has been documented and confirmed recently.[11]

The use of glass-ceramics has also been introduced for the production of all-ceramic restorations. These restorations produced with lithium disilicate have acceptable mechanical properties and improved optical behavior, providing the restorations with depth of translucency and light diffusion similar to the natural tooth substances.[12]

Lithium disilicate glass-ceramic material, whether CAD/CAM processed or heat-pressed, can be applied either as a full-contour monolithic restoration or as core for subsequent ceramic veneer. Because of its favorable translucency and shade variety, fully anatomical restorations can be fabricated with high clinical acceptance. The high strength that this material offers extends its indication for the fabrication of single crowns in the anterior and posterior regions.[13]

A recent clinical report about full-contour lithium disilicate crowns shows no mechanical failures in terms of fracture or chipping.[12] The behavior of the lithium disilicate ceramic based on both *in vitro* and short term *in vivo* evaluations also makes it a promising restorative material for high load areas in the posterior region.[14] Fluorapatite glass-ceramic material, heat-pressed over zirconia cores results in restorations that combine the high strength of the substructure with the superior optical behavior of the glass-ceramic veneer. The quality of the attained interface and the obtained esthetics are claimed to be superior to the bilayered restorations by using layering ceramics.[15] Yet, the fracture resistance of these restorations in comparison with lithium disilicate monolithic crowns has not been documented in the literature.

The present study aimed to compare the fracture resistance and mode of failure of the bilayered zirconia/fluorapatite pressed-over crowns to the full-contoured monolithic lithium disilicate heat-pressed crowns, and also to evaluate the effect of the modification of the zirconia coping to an anatomical design supporting the pressed-on fluorapatite ceramic veneer. The hypothesis was that the monolithic lithium disilicate ceramic crowns are more fracture resistant than the bilayered zirconia-based crowns, with the two zirconia crown groups (standard or anatomical coping designs) demonstrating a statistically significant difference in favor of the latter.

Materials and methods

The experimental modality implicated specimens of all-ceramic crowns fitted sequentially on a master die.

Master die fabrication

An ivory mandibular right first molar tooth was used to produce a metal master die replica. The tooth was mounted in an acrylic block using an autopolymerizing resin and was prepared for full coverage (Fig 1). It was then duplicated using an addition-type silicone and a base metal alloy (Wironium Plus, Bego). The produced metal replica was embedded in acrylic block up to 3 mm from the preparation margin and was used as a master die for all the groups in this study.

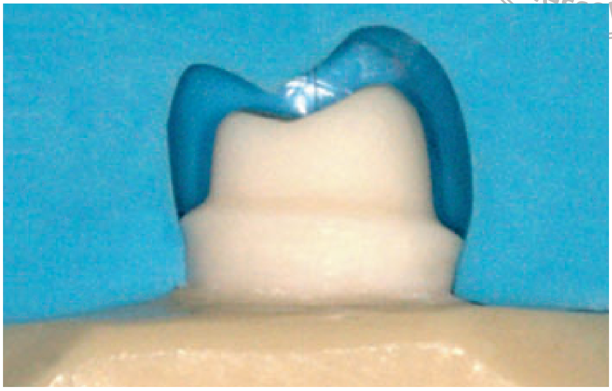

Fig 1 The preparation of the ivory tooth mounted on the acrylic block checked for proper reduction using the silicon keys taken preoperatively representing the full contour.

Test crowns fabrication

The fabricated crowns were divided in three groups of 10 specimens each. The number derived from a pilot study involving three specimens in each group which indicated that a sample size of 10 per group would produce 92% power, to detect a statistical significant difference among the 3 groups by assuming a common standard deviation of 400 and a = 0.05 (nQuery Advisor 7.0).

Group A consisted of bilayered zirconia/fluorapatite – standard design coping crowns. The master die was mounted on the scanning table and scanned using a contact type scanner (Procera Forte Scanner, Nobel Biocare). The default setting for the posterior region of the computer software (Procera CadDesign Software, Procera System Software, Version 2.2, Nobel Biocare) was used to design the coping, which attained an even thickness of 0.7 mm all around and contained a cervical margin that finished at the end of the axial wall, short of

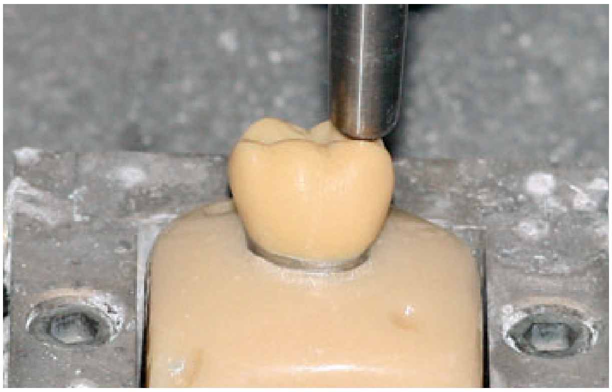

Fig 2 Loading points verified in the testing machine.

the tooth preparation margin. The information was then sent to the production facility to mill the copings. A thin layer of approximate thickness of 0.1 mm of a clear liner (ZirLiner, IPS e.max Ceram ZirLiner, Ivoclar Vivadent) was applied on the copings. A full contour wax-up was accomplished by injecting melted wax through a perforated silicone key, representing the outer form of the ivory tooth before preparation, which was precisely fitted on the acrylic base of the master die. The wax-up was checked in the dynamic loading machine to verify that the contact between the crown and the load application indenter was on the cuspal inclination of the mesiobuccal, the mesiolingual cusp and the mesial marginal ridge of the crown (Fig 2). The design of the contact would allow lateral direction of the forces on the test crown, which appears to be directly related to the fractures of ceramic crowns.[16] The test crown final shape was thus verified and its form was preserved on a new silicon key index. This silicon index was perforated occlusally in order to allow the injection of melted wax and used to fabricate the outer surface of all other test crowns in the study. The waxed crowns were then invested with ceramic investing material (IPS Press VEST Speed, Ivoclar Vivadent). Once the burn out cycle was completed, two fluorapatite ingots were inserted along with the plunger (ZirPress, Ivoclar Vivadent). The reaction layer formed during the press procedure was removed by immersing the test crowns in HF solution (IPS e.max Press Invex Liguid, Ivoclar Vivadent) in an ultrasonic cleaner for 5 min. The crowns were then glazed by evenly applying a thin glaze (IPS e.max Ceram Glaze paste/Glaze and Stain Liquid, Ivoclar Vivadent).

Group B consisted of bilayered zirconia/fluorapatite – anatomical design coping crowns. The anatomical modification of the core in this group was produced by a double scanning procedure. A thin layer of an autopolymerizing resin was applied on the master die to provide support and allow the safe removal of the wax-up used for the scanning procedure. A full contour wax-up was accomplished and a uniform cutback of approximately 1.0 mm followed. The master die was scanned without the wax-up, and then rescanned with the wax for the double scan procedure. The milled anatomical copings received the same press-on fluorapatite veneering procedures as Group A.

Group C consisted of lithium disilicate monolithic crowns. A full contour wax-up was accomplished directly on the master die as previously described. The monolithic crowns were produced by lithium disilicate (E-max Press, Ivoclar Vivadent) following the same pressing procedure used above.

Fatigue and catastrophic loading procedures

The test crowns were cemented sequentially on the master die using a resin modified glass-ionomer cement (FujiCem, GC Corporation). The cementation pressure was performed under 25 N static load applied with a Texture Analyzer Machine (TA.XTPlus, Stable Micro Systems). Samples of all groups were then loaded dynamically, simulating mouth motion under wet conditions using the same instrument 24 h after cementation. Each sample was loaded for 100,000 cycles with a profile of 250 N maximum load at 1,000 N/s rate and 2.0 Hz frequency. Loading was performed with a steel ball (5 mm in diameter) coming into contact with the test crown, loading to maximum, holding for 0.2 s, unloading and lifting off 0.5 mm. After the dynamic loading was completed, the crowns were inspected visually and with a low-power stereomicroscope, to identify the presence of cracks or fractures and they were then mounted on a universal testing machine (Model 5566A, Instron Corp) and loaded in compression up to catastrophic failure at a 1.0 mm/min loading rate. The fracture load in N was recorded for each specimen.

Statistical analysis

Analysis of the recorded fracture load values was carried out with one-way analysis of variance (ANOVA) followed by Tukey tests (a = 0.05).

Fracture characterization

Fractured specimens were studied under a stereomicroscope (M80, Leica Microsystems). Representative specimens from each group were coated with gold in a sputter-coating device (SCD 004, BalTec) and examined under a scanning electron microscope (Quanta 200, FEI) under the following conditions: high-vacuum mode, 25 kV accelerating voltage, 90 μA beam current, secondary electron detector. The type of failure was characterized as cohesive within the ceramic, as adhesive at the veneering ceramic/zirconia interface and as cohesive within the zirconia core.

Results

Fracture resistance

None of the samples failed during the cyclic loading. Certain specimens from Groups A and B demonstrated surface cracks or other defects. The results of the fracture load for all the groups tested are presented in Table 1. All mean values were statistically significant

Table 1 The results of fracture strength

Test groups	Mean (N)*	Standard deviation
Group A Bilayered (zirconia/fluorapatite) standard coping	561.87	72.63
Group B Bilayered (zirconia/fluorapatite) anatomical coping	1,014.16	70.18
Group C Monolithic lithium disilicate	1,360.63	77.95

*All mean values demonstrated statistically significant differences ($P < 0.001$)

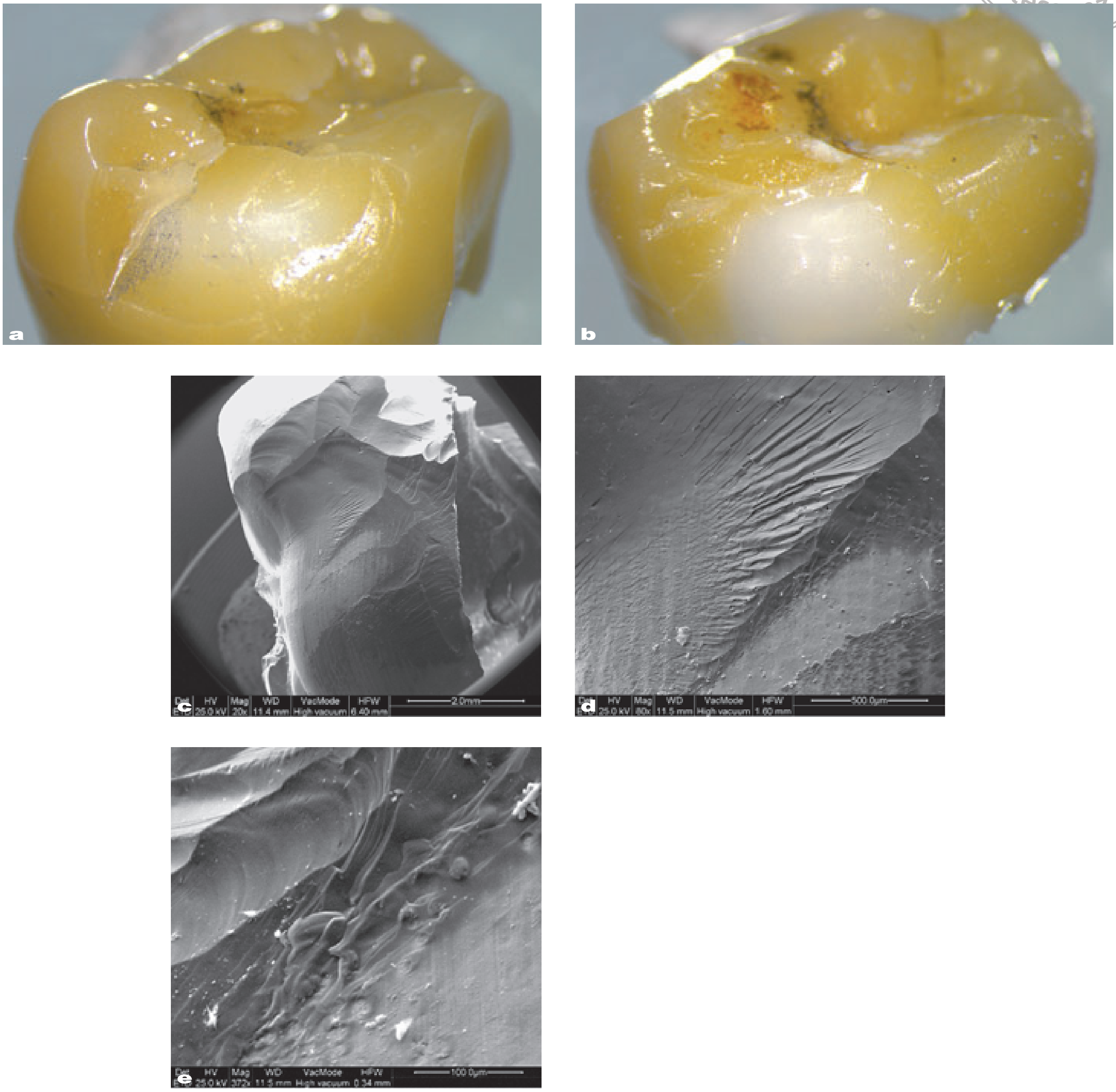

Fig 3 Fractured specimens from Group A demonstrating cracking and cohesive fracture of veneer. **a** Fracture of fluorapatite veneer with no zirconia core exposure (reflected light, 10X, bar: 2 mm). **b** Fracture of fluorapatite veneer with zirconia core exposure. The core appears intact. Note the difference in thickness between the occlusal and the axial veneer regions (reflected light, 10X, bar: 2 mm). **c** Secondary electron image of the same above veneer fracture with zirconia core exposure. The machining tracks are easily identified on zirconia core surface. Veneer delamination is more pronounced at the occlusomesial angle, than the mesial margin (20X, bar: 2 mm). **d** Detail of the same above cohesive fluorapatite veneer fracture. Note crack propagation and porosity (secondary electron image, 80X, bar:500 μm). **e** Secondary electron image of the zirconia/fluorapatite interface after veneer fracture, demonstrating a continuous transitional zone (372X, bar:100 μm).

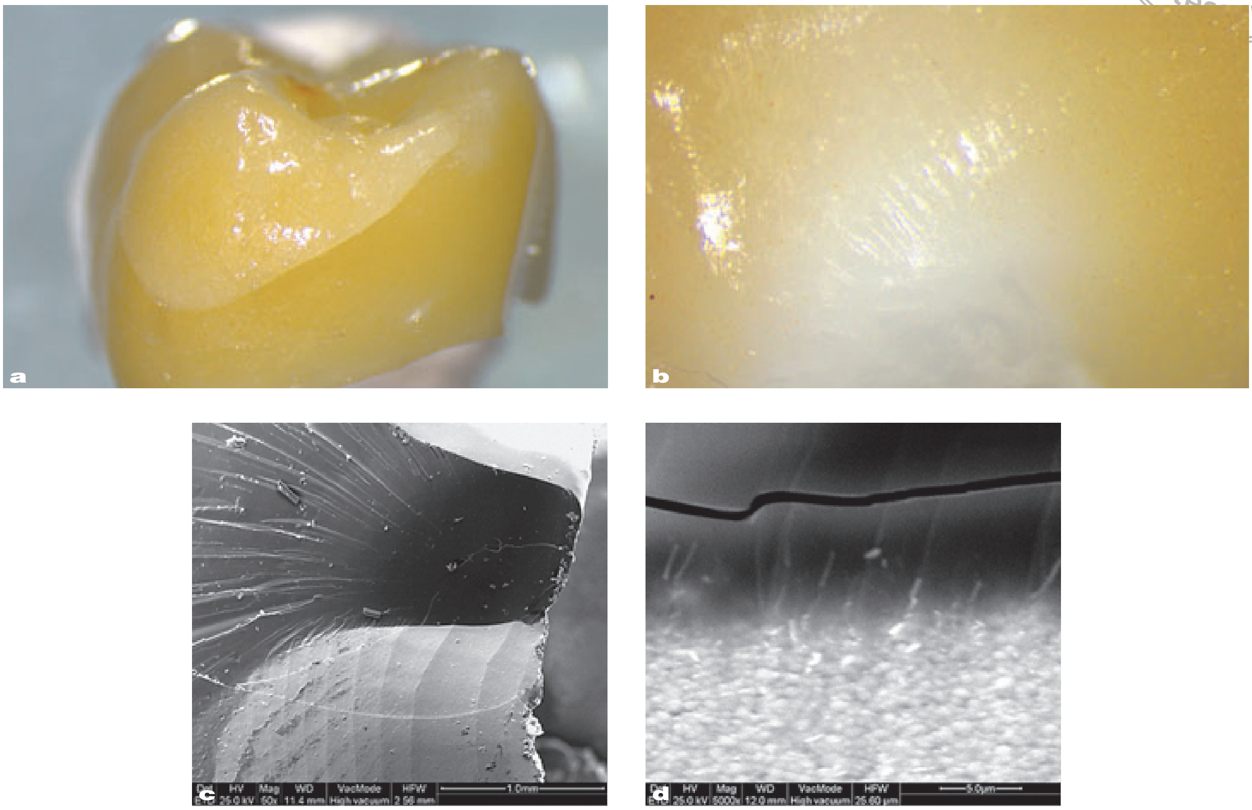

Fig 4 Fractured specimens from Group B. **a** Veneer cracking at the mesial area, without delamination (reflected light, 10X, bar: 2 mm). **b** Veneer delamination at the margin, with zirconia core exposure (reflected light, 10X, bar: 2 mm). **c** Secondary electron image of the marginal area revealing zirconia core delamination. Note the core crack extending into the veneering material and the radial cohesive fracture plane of the latter (50X, bar: 1 mm). **d** Secondary electron image of the zirconia/fluorapatite interface, with a cohesive crack into the veneering material, demonstrating an interfacial toughening effect of the fluorapatite ceramic from the zirconia core material (5,000X, bar: 5 μm).

($P < 0.001$). The highest strength was found in the monolithic lithium disilicate group (Group C), followed by the anatomical design of the bilayered zirconia/fluorapatite coping (Group B), whereas the lowest values were recorded in the standard zirconia/fluorapatite coping design group (Group A).

Fracture characterization

Specimens of Groups A and B presented cracking and cohesive fractures of the fluorapatite veneer. In most cases, the core zirconia structure was found intact, covered by a thin veneer layer (Figs 3 and 4). In some cases, core cracks extending into the veneer structure were identified. The major difference between Groups A and B was that core delamination was mostly limited at the margins of Group B, in contrast with Group A where occlusal areas were mainly involved. In both these groups, however, a strong and continuous zirconia core/flurapatite interface was established.

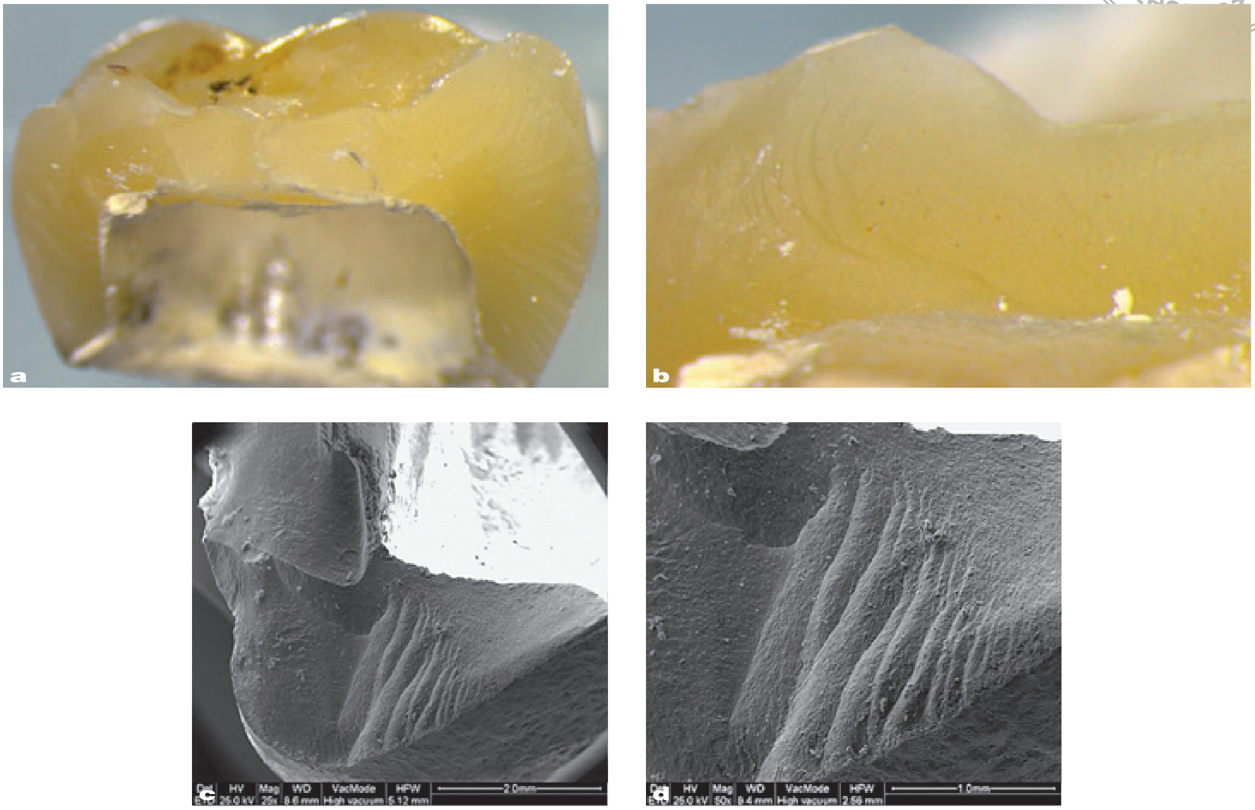

Fig 5 Fractured specimens from Group C. **a** Fracture mostly within a plane, with major cracks located at the occlusal area and many minor crack lines with radial distribution from the internal margin to the outer surface. Note the concentration of the minor crack lines around the internal angles (reflected light, 10X, bar: 2 mm). **b** Detail of the occlusal part of the previous image, with a characteristic deviation of the crack lines radial to the occlusal fissure (loading point) up to the internal margin (reflected light, 26X). **c** Secondary electron image of a monolithic lithium disilicate fractured specimen (25X, bar: 2 mm). **d** Detail of a previous image at higher magnification (50X, bar: 1 mm).

In Group C, all fractures were catastrophic in nature (Fig 5). They were mostly found to be within a plane, with major cracks located at the occlusal area, below the loading point. Many minor crack lines were observed with radial distribution from the internal margin to the outer surface. Concentration of these cracks was observed around internal angles. It appeared that the greater strength of the internal margins (due to the presence of the abutment) transformed the radial direction to an almost parallel one.

Discussion

The results of the present study confirmed the testing hypothesis: the monolithic lithium disilicate crown group was the strongest one, followed by the group of bilayered zirconia/fluorapatite anatomical coping design, with the lowest values recorded in the standard coping design group.

In the course of the ongoing developments in dental material science and technology, ceramic materials applied in the fabrication of all-ceramic restorations have attained a continuous series of improvements related to their flexural strength and their optical behavior. Various methods and techniques have been recommended to strengthen dental ceramic, including ion exchange, controlled crystallization, microstructure tailoring, the use of resin luting agents, and the use of supporting substructure.[17]

Failures of all-ceramic crowns clinically usually occur through slow crack propagation initiating from fatigue caused by repeated occlusal contact.[18] The samples in this study were fatigued under wet conditions in order to simulate the clinical application. The test crowns were fabricated with an occlusal morphology that represented natural anatomy in order to produce comparable effects on the stress distribution and fracture patterns to those that clinically appear.[19]

The general outcome in the development process of all-ceramic technology has shown that the stronger the material, the less translucent it is. Thus the superior physical properties of zirconia are followed by a rather opacious optical quality. The industrially produced material, customized via CAD/CAM milling procedures, provides a good foundation for bilayered prosthetic dental restorations, bearing a more translucent and esthetically acceptable ceramic veneer.[20] However, the overall longevity of these restorations is affected by the weaker mechanical properties of the veneer and its reduced physical compatibility with the supporting substructure. Ceramic chipping or cracking of the veneer is an incidence that frequently occurs in the course of long-term clinical application.[5,21]

Adequate support of the veneer ceramic in order to attain an even overall thickness has been suggested as a positive mechanical factor.[9] In the present study, the anatomical modification was introduced by a full contour wax-up, followed by a uniform cutback and a double scanning procedure, so that the milled copings provided the required support to the heat-pressed fluorapatite glass-ceramic veneer. The group with anatomical design copings demonstrated increased fracture strength over the standard design coping group. Moreover, the failures that occurred in specimens with the standard design coping were mainly cohesive in nature and were found within the bulk of the veneered fluorapatite material. They initiated occlusally and mainly involved the thicker unsupported veneer material. The work of several authors also supports this finding.[9,22] Silva et al[11] recently showed that the modified anatomical design of the zirconia cores improved the reliability of the bilayered all-ceramic crowns.

The precise nature of the generated interface between yttria-stabilized zirconia milled copings and the pressed-over fluorapatite veneer remains unknown. However, the fracture characterization findings of the present study suggest the presence of a strong and continuous interface. Moreover, the fact that the compressive stresses applied on the better supported porcelain on the occlusal surface generated veneer fracture only when the axial unsupported part received strong tensile stresses, clearly demonstrates the importance of the support provided by the core.

The use of heat-pressed glass-ceramics has also been introduced for the production of all-ceramic restorations. The optical behavior and the high mechanical strength of lithium disilicate allow the fabrication of fully anatomical monolithic restorations with high clinical acceptance in both the anterior and the posterior regions of the dental arch.[13] Inasmuch as the flexural strength of this glass-ceramic material is inferior to zirconia, a higher fracture resistance of the monolithic lithium disilicate crowns has been reported, compared to the zirconia/ceramic bilayered crowns.[13,23]

The results of the present study, where the veneer bilayered crown groups involved heat-pressed glass-ceramic fluorapatite veneers, also confirm the above findings. A significant difference was achieved between the monolithic lithium disilicate group and both bilayered groups. The lower strength of fluorapatite glass-ceramic material in comparison to lithium disilicate most likely has an effect on this finding.[13,24]

While the fracture failures in bilayered groups solely involved the fluorapatite veneer – which appeared to be the weak link of the crowns – no fractures occurred in the zirconia cores, apart from a few cases of detectable cracking. On the other hand, the fractures in the monolithic lithium disilicate group were entirely catastrophic. Nevertheless, in view that chipping and cracking of the veneer in a bilayered crown is in reality a clinically irreparable incident, the different fracture failure modes in all groups can be considered equally as detrimental for the restoration.

The fracture characteristics of the monolithic lithium disilicate group revealed that the fractures were generated by major cracks mostly found to be within a plane, located at the occlusal area. Lithium disilicate glass-ceramic material as a result of a controlled crystallization procedure attains a rather uniform internal structure with homogenous crystal distribution within the glass matrix. The radial distribution of the minor crack lines initiating from the internal margin to the outer surface can thus be explained and even expected. Their concentration around the internal angles and the transformation of the radial direction to an almost parallel one reveals the importance of the presence of the abutment in enhancing the strength of the monolithic crown. Nevertheless, the positive effect of this parameter requires more documentation that needs to be related to the overall thickness of the monolithic lithium disilicate crown, combined with the factor of adhesion, which was not taken into account in the present investigation.

The use of a metal die in the present study provided a reproducible abutment support. The metal die did not match the mechanical properties (elastic modulus and fracture toughness) of natural tooth structures. Moreover the metal die did not provide a similar substrate for adhesion of the cement as the natural tooth structure would and therefore it could be considered as being comparable to a custom metal implant transmucosal abutment. Adhesion being a major reinforcing factor, especially for glass-ceramic restorations, was not a main concern in the present investigation. The selected cement that was applied in all groups was conventional and not chemically active as recommended for glass-ceramics.[13] Thus, the parameter of adhesion that would only favor the glass-ceramic group was excluded.

Conclusions

Within the limitations of the present in-vitro investigation the following conclusions can be drawn:

- The failure of the zirconia/fluorapatite bilayered restorations mostly involved the heat-pressed glass-ceramic veneer, which appeared to be a weak link within the crown complex.
- When the zirconia coping provided adequate support to the veneer, the strength of the restoration was improved.
- The mode of the failure of the lithium disilicate crowns was entirely catastrophic at all times, while their strength was found to be higher than all bilayered crowns.

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