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Comparative Evaluation of the Fracture Strength of Monolithic Crowns Fabricated from Different all-ceramic CAD/CAM Materials (an *in vitro* study)

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The objective of this *in vitro* study was to evaluate and compare the fracture strength of monolithic crowns fabricated from five different all-ceramic CAD/CAM materials (lithium disilicate, zirconia, reinforced composite, hybrid dental ceramic, and zirconia-reinforced lithium silicate) using single load to failure test. Forty sound human maxillary first premolar teeth extracted for orthodontic purposes were selected for use in this study. Teeth were prepared according to a standard protocol with 1 mm deep chamfer finishing line, 4 mm axial height with planer occlusal reduction and 6º total convergence angle. Teeth were then divided into five groups of eight teeth each according to the material used for the fabrication of the monolithic crowns as follow: Group A: Crowns fabricated from lithium disilicate (IPS e.max CAD, Ivoclar Vivadent), Group B: Crowns fabricated from zirconia (CEREC Zirconia, Dentsply Sirona), Group C: Crowns fabricated from reinforced composite (BRILLIANT Crios, COLTENE), Group D: Crowns fabricated from hybrid dental ceramic (VITA ENAMIC, VITA Zahnfabric), Group E: Crowns fabricated from zirconia-reinforced lithium silicate (CELTRA DUO, Dentsply Sirona). Teeth of all groups were then scanned with CEREC Omnicam digital intraoral scanner and the crowns were then designed using CEREC Premium software (version 4.4.4) and milled using CEREC MC XL milling unit. Post-milling, crowns of each group were subjected to either a firing procedure or to a polishing only according to the manufacturer's instructions of each material. The internal surfaces of the crowns of each group were then subjected to surface treatment according to the manufacturer's instructions of each material and the crowns were then cemented on their respective teeth using a universal dual-cured adhesive resin cement (Duo-Link Universal, Bisco Inc.). All teeth with the cemented crowns were then stored in deionized distilled water at room temperature for 24 hours before testing. All samples were then subjected to compressive axial loading until fracture in computer-controlled universal testing machine (Zwick Z010, Ulm, Germany) at a crosshead speed of 0.5 mm/min. The data were statistically analyzed using one-way ANOVA test and LSD test at a level of significance of 0.05. The results of this study showed that the highest mean value of fracture strength was recorded by Group B (2337.37), followed by Group C (1880.59), Group E (1404.49), Group A (1085.39) and Group D (767.06), respectively with statistically highly significant differences among the different groups ($p<0.01$). From the results of this study, it seems that the differences in the chemical composition and microstructure of the tested all-ceramic CAD/CAM materials may be responsible for the differences in the fracture strength of the fabricated crowns.

Keyword: All-ceramic crowns, monolithic crowns, CAD/CAM, zirconia, lithium disilicate, zirconia-reinforced lithium silicate, hybrid dental ceramic, reinforced composite, fracture strength.

Fracture has been reported as one of the main problems of all-ceramic restorations. However, with increasing popularity of CAD/CAM systems, a rising number of machinable esthetic materials with different compositions have been developed. These materials are fabricated under standardized and optimal conditions, producing highly homogenous materials with superior mechanical properties as compared to laboratory-processed restorations and can be used for the production of monolithic restorations. These materials can be generally categorized into three main categories based on the presence of specific components in their formulation including: glass-matrix ceramics, polycrystalline ceramics and resin-matrix ceramics [1-3].

Lithium disilicate ceramic is one of the all-ceramic systems that belongs to the category of synthetic glass-matrix ceramics that can be used for the fabrication of monolithic restorations. It has gained popularity for anterior and posterior single crowns and partial coverage restorations because of its good physical properties and superior esthetics [4]. However, this material may be less suitable for applications where stress concentration can be high [5].

In an attempt to provide a material suitable for applications requiring high strength, yttria-stabilized tetragonal zirconia, which is a kind of polycrystalline ceramics, has been introduced. The main feature of this material group is the fine grain crystalline structure which provides high strength and fracture toughness, but this is at the expense of limited translucency. However, the microstructure of zirconia for monolithic restorations has been tailored to improve their translucency as compared with conventional zirconia [6].

As an approach for optimizing CAD/CAM materials, glass ceramic materials reinforced with polycrystalline ceramic have been developed. These glass ceramics were designed to contain lithium silicate as the main crystalline phase enriched with zirconia (H"10% by weight) [7]. It has been claimed that this generation of glass ceramic materials combine the positive material characteristics of zirconia and glass ceramic. The zirconia particles are incorporated in order to reinforce the ceramic structure by crack interruption [8].

Another approach for optimizing CAD/CAM materials is by developing resin-matrix CAD/CAM blocks from composite or ceramic-composite mixture (hybrid ceramic). These materials belong to the category of resin-matrix ceramics, or the so called "ceramic-like materials". Composite blocks were developed using novel techniques to reach better degree of conversion and more favorable filler loading and distribution. On the other hand, hybrid ceramic material consists of a ceramic network of a fine structure feldspathic ceramic that has been infiltrated by a polymer [9]. The rationale behind developing such materials was to obtain a material that more closely simulates the modulus of elasticity of dentin, easy to mill, and can also be more easily repaired intra-orally [2].

Duo to the high number of products available and the speed at which new products are being introduced, the clinician may face a complex decision process when choosing a CAD/CAM ceramic restorative material for a particular indication. More often, the selection in the posterior area is based on strength of the material measured *in vitro* [2]. Therefore, this study was conducted to evaluate and compare the fracture strength of monolithic crowns fabricated from five different all-ceramic CAD/CAM materials (lithium disilicate, zirconia, reinforced composite, hybrid dental ceramic, and zirconia-reinforced lithium silicate).

MATERIALS AND METHODS

Sample selection

Forty sound human maxillary first premolar teeth with two roots extracted for orthodontic purposes were used in this study. Only sound teeth free from caries, enamel defects and cracks and with regular occlusal anatomy and approximately similar crown size were selected [10]. Each tooth was embedded along its long axis in self-cured acrylic resin to within 2 mm apical to the CEJ to simulate the alveolar bone support of natural teeth [11].

Sample grouping

Teeth were then divided into five groups of eight teeth each according to the type of all-ceramic CAD/CAM material used for the fabrication of the monolithic crowns as follows:

Group A: crowns fabricated from lithium disilicate (IPS e.max CAD) (Ivoclar Vivadent, Liechtenstein).

Group B: crowns fabricated from zirconia (CEREC Zirconia) (Dentsply Sirona, USA).

Group C: crowns fabricated from reinforced composite block (BRILLIANT Crios) (COLTENE, Switzerland).

Group D: crowns fabricated from hybrid ceramic (VITA ENAMIC) (VITA Zahnfabric, Germany).

Group E: crowns fabricated from zirconia-reinforced lithium silicate (CELTRA DUO) (Dentsply Sirona, USA).

Tooth preparation

A standarized tooth preparation was performed for all teeth that was fit with the preparation requirements of all CAD/CAM materials used in this study which included: axial reduction of about 1.5mm, planar occlusal reduction of about 1.5-2mm, circumferencial deep chamfer finishing line of 1.0 mm depth, and a total convergence angle of 6º. Tooth preparation was done with the aid of a modified dental surveyor to control the variables of tooth preparation including the degree of axial taper, design of the finishing line and path of insertion [12]. The preparation was divided into two steps: axial reduction and occlusal reduction.

Table 1. Descriptive statistics of fracture strength of the different groups measured in N

Groups	No.	Mean	S.D.±	Min.	Max.
Group A	8	1085.4	57.39	998	1166
Group B	8	2337.4	108.17	2223	2500
Group C	8	1880.6	288.58	1420	2266
Group D	8	767.06	94.57	638	911
Group E	8	1404.5	236.51	1136	1803

Digital workflow and crowns fabrication

After completion of tooth preparation, a three-dimensional image for each tooth was taken by using CEREC Omnicam digital intra-oral scanner (Sirona, Germany) with CEREC Premium software (version 4.4.4). The scanning procedure was done following the manufacturer's instructions.

In order to standardize the design of the crowns for all teeth, "Biogeneric Reference" design mode was selected, whereby unprepared maxillary first premolar dentoform tooth was used as a reference tooth for calculating the restoration suggestion. Scanning of the referance tooth was

Table 2. One-way ANOVA test for comparison of significance among the different groups

ANOVA	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1E+07	4	3E+06	95.111	0
Within Groups	1E+06	35	32766		(HS)
Total	1E+07	39			

Table 3. LSD test for comparison of fracture strength among the different groups

Groups	(J) factor	Mean Difference (I-J)	Standard Error	Sig.
Group A	Group B	-244.66604*	90.507	.000 (HS)
	Group C	-787.88097*	90.507	.000 (HS)
	Group D	325.64822*	90.507	.001 (HS)
	Group E	-311.79057*	90.507	.002 (HS)
Group B	Group C	456.78506*	90.507	.000 (HS)
	Group D	1570.31426*	90.507	.000 (HS)
	Group E	932.87547*	90.507	.000 (HS)
Group C	Group D	1570.31426*	90.507	.000 (HS)
	Group E	476.09041*	90.507	.000 (HS)
Group D	Group E	-637.43879*	90.507	.000 (HS)

* The mean difference is significant at the 0.05 level.

done in a way similar to that used for the prepared tooth.

The desining procedure was done using the restoration parameters preset by the manufacturer. The same parameters were used for the designing of crowns of all groups. The milling process was done using CEREC MC XL milling unit, a 4-axis milling unit. Dry milling was used for the fabrication of zirconia crowns (Group B), while wet milling was used for the fabrication of crowns of all other groups according to the manufacturer's instructions of each material. After completion of milling process, the crowns fabricated from lithium disilicate (Group A) and zirconia-reinforced lithium silicate (Group E) were subjected to crystallization/glaze and glaze/only firing at 840 ºC for 22 minutes, while crowns fabricated from zirconia (Group B) were subjected to a sintering at 1541 ºC for 15 minutes using CEREC Speed Fire Furnace. on the other hand, crowns fabricated from reinforced composite (Group C) and hybrid resin-ceramic (Group D) were subjected to polishing only according to the manufacturer instruction, using a two-step polishing set (Polishing Set clinical, VITA Zahnfabrik, Germany).

Cementation procedure

The fabricated crowns were then cemented on their respective teeth using a universal adhesive cementation system (Duo-Link Universal, Bisco Inc. Schaumburg, IL, USA). This cementation system consists of a universal dual-cure adhesive resin cement, ceramic primer, zirconia primer and a universal adhesive. The cementation procedure was done in three steps: (1) Surface treatment of the restoration (according to the type of CAD/CAM material used for crown fabrication), (2) Surface treatment of the tooth, (3) Cementation with the adhesive resin cement.

For Groups A, D and E, the intaglio surface of the restoration was etched with hydroflouric acid gel (9.5%) for 90 seconds according to the manufacturer instructions, then was rinsed with a copious amount of water and placed in an ultrasonic cleaner for 5 minutes to remove salts and debris produced from hydrofluoric acid etching of the porcelain. Two coats of ceramic primer (PORCELAIN PRIMER, Bisco Inc. Schaumburg, IL, USA) were then applied to the etched internal surface of the restoration with a brush applicatore and left for 30 seconds, then dried according to the manufacturer's instructions.

For crowns fabricated from zirconia two coats of Z-PRIME Plus were applied uniformly to the internal surface of the restoration, then air dried for 5 seconds according to the manfacturer's instructons.

On the other hand, the internal surfaces of crowns fabricated from BRILLIANT Crios reinforced composite were sandblasted, and then thoroughly cleaned in an ultrasonic cleaner for 5 minutes. One coat of ALL-BOND UNIVERSAL light-cured dental adhesive was then applied to the internal surface of restoration air dried and then light cured for 10 seconds according to the manufacturer's instructions.

Concerning the surface treatment of the tooth, total etching was done using phosphoric acid gel (35%) for 15 seconds, then washed thoroughly and the excess water was removed by suctioning without drying to leave the preparation visibly moist according to the manufacturer's instructions. Two separate coats of ALL-BOND UNIVERSAL adhesive were then applied to the prepared tooth surfaces by scrubbing the preparation with a microbrush for 15 seconds per coat, then the excess solvent was evaporated with an air syringe for 10 seconds, followed by light curing for 10 seconds according to the manufacturer's instructions.

After completion of the surface treatment of the restoration and the tooth, Duo-Link Universal dual-cure adhesive resin cement (universal shade) (Bisco Inc. Schaumburg, IL, USA) was used to cement each crown on its respective tooth. The cementation procedure was done using a modified dental surveyor under a constant load of 5 Kg. The load was applied vertically on the occlusal surface of the crown for 5 minutes. During this period, the excess cement was removed with a microbrush followed by spot curing of the margins for 2-3 seconds per surface (buccal, distal, lingual and mesial) using a light curing unit held in direct contact with each surface according to the manufacturer's instructions. Following the cementation procedure of the crowns of all groups, the cemented samples were kept undisturbed for one hour to bench set, then stored in distilled deionized water at room temperature for 24 hours prior to testing [13].

All samples were subjected to compressive axial loading in a computer-controlled universal testing machine (Zwick Z010, Ulm, Germany) at a crosshead speed of 0.5 mm/min using rod 4 mm in diameter. All samples were loaded until fracture and the maximum breaking load of each sample was recorded automatically in Newton (N) by a computer connected to the loading machine.

The data were statistically analyzed using one-way ANOVA test and LSD test at level of significance of 0.05.

RESULTS

The descriptive statistics including the mean, standard deviation, minimum and maximum values of the fracture strength in (N) of the five different groups are shown in Table 1.

From this table it can be seen that the highest mean value of fracture strength was recorded by zirconia crowns (Group B) (2337.37 N), followed by reinforced composite crowns (Group C)(1880.59 N), zirconia-reinforced lithium silicate crowns (Group E) (1404.49 N), lithium disilicate crowns (Group A) (1085.39 N), respectively. While the lowest fracture strength mean value was recorded by resin-hybrid ceramic (Group D) (767.06 N).

Comparison of significance among the different groups using one-way ANOVA test revealed a statistically highly significant difference among groups ($p<0.01$) as shown in Table 2.

Further comparisons between each two groups using LSD test showed statistically highly significant difference between each two groups ($p<0.01$) as shown in Table 3.

DISCUSSION

In this study, despite the statistically highly significant differences in the fracture strength among the different groups, it is worth to mention that the mean value of fracture strength of crowns of all groups exceeded the maximum biting force in the premolar region (450 N) [14].

This finding could be attributed, from one hand, to the adequate tooth preparation that fulfilled the preparation requirement of the different materials used in this study which provided enough bulk of the material to resist the applied load. On the other hand, this could be attributed to the use of adhesive cementation protocol with proper surface treatment of each material according to the manufacturers' instructions.

However, the statistically highly significant differences in the fracture strength among the different groups could be attributed, in general, to the differences in the mechanical properties, chemical composition and microstructure.

Zirconia

The highest mean value of fracture strength (2337 N) recorded for crowns fabricated from CEREC Zirconia (Group B) as compared with crowns fabricated from other materials could be attributed to the superior mechanical properties of zirconia including: high flexural strength (> 900 MPa), high fracture toughness (7 MPa $m^{1/2}$) as a result of the polycrystalline structure of zirconia in which all of the atoms are packed into regular crystalline arrays through which it is much more difficult to drive a crack than it is through atoms in the less dense and irregular network found in glasses. Hence, polycrystalline ceramics generally are much tougher and stronger than glass-based ceramics [15, 16].

The superior mechanical properties of zirconia also could be attributed to the stress-induced toughening mechanism in which a stress field at the head of an advancing crack triggers the transformation of the embedded tetragonal particles to the monoclinic form. This crystal phase shift results in a localized volumetric expansion that creates a compressive force on the developing crack, preventing it from propagating. it is considered as a significant contributor to the high strength of zirconia and its ability to resist chipping and fracture under function [17].

The above finding is in agreement with previous studies done by Preis *et al.* [9], Al-Joboury and Zakaria [18] , Aboushelib and Elsafi [19], Zhang *et al.* [20] and Gungor and Nemli [21] who all compared the fracture strength of all-ceramic crowns fabricated from zirconia and different other materials and found that the highest fracture strength mean value was recorded by crowns fabricated from zirconia.

Brilliant Crios reinforced composite

The most intersting finding of this study is that the highest fracture strength mean value next to zirconia was recorded by crowns fabricated from BRILLIANT Crios reinforced composite (Group

C), which despite its lower flexural strength (198 MPa) as compared with the two glass ceramic materials tested in this study (lithium disilicate and zirconia-reinforced lithium silicate) which have flexural strength values of 360 and 370 MPa, respectively, BRILLINAT Crios recorded higher fracture strength mean value (1880 N) than these two materials which recoreded lower fracture strength mean values (1085 N and 1404 N, respectively). This finding suggests that for brittle materials including ceramics, unlike metals, one should not rely on the flexural strength value of the material alone to predict its structural performance as the strength of a material is more of a "conditional" than an inherent property [22].

The high fracture strength of crowns fabricated from BRILLINAT Crios could be attributed to the following:

I. BRILLIANT Crios has a relatively low elastic modulus (10 GPa) which is close to that of dentin (11-19 GPa). This allowed the material to undergo plastic deformation at the same degree of the underlying dentin and, thus, will transmit the applied load to the underlying dentin rather than being accumulated in the restoration.

II. The monoblock created from the adhesive bonding of the reinforced composite and the tooth via the resin cement duo to the similarity in the chemical composition between the reinforced composite block, resin cement and the adhesive bonding agent, which created a high bond capacity among them. According to the manufacturer, the use of All-Bond universal provides higher bonding with composite (48.8MPa) than with other materials including glass ceramic (21.5MPa) and zirconia (26.9MPa) (Bisco,2016). This is due to the combined chemical and mechanical bonding between the restoration and the bonding agent, as monomers of bonding agent will penetrate into the polymerized resin matrix of the composite material. This leads to the formation of chains within the resin matrix of the composite which ideally leads to mechanical bonding "interlooping" [23]. This high bonding of the restoration to the tooth can increase the fracture strength of the indirect restoration [24].

III. BRILLIANT Crios has a relatively high fracture toughness as the organic content absorbs the chewing forces, which may suggest a toughening mechanism [2].

Glass ceramic materials

Crowns fabricated from the two glass ceramic materials (IPS e.max CAD and CELTRA DUO) recoreded lower mean values of fracture strength as compared with the crowns fabricated from CEREC Zirconia with statistically highly significant differences. This could be attributed to the lower mechanical properties of these two materials as compared with zirconia including lower flexural strength, lower elastic moduli and lower fracture toughness.

On the other hand, crowns fabricated from these two materials recorded lower mean values of fracture strength as compared with crowns fabricated from reinforced composite with statistically highly significant differences which could be attributed to the following:

I. Higher elastic moduli of these two materials (95 GPa for IPS e.max CAD and 70 GPa for CELTRA DUO) as compared with dentin (11-19 GPa). Thus, they are not capable of undergoing plastic deformation at the same degree of the underlying dentin; therefore, stresses will accumulate inside the restoration inducing crack.

II. Absence of the monoblock concept due to the dissimilarity in the chemical composition of the crown material, resin cement and the adhesive bonding agent.

Lithium disilicate versus zirconia-reinforced lithium silicate

Despite that these two materials belong to the same category of all-ceramic materials "glass-matrix ceramic", the mean value of fracture strength of crowns fabricated from CELTRA DUO was higher than that of crowns fabricated from IPS e.max CAD with statistically highly significant difference. This could be attributed to the following:

I. The incorporation of highly-dispersed and completely-dissolved submicron-sized zirconia grains in the glassy matrix of CELTRA DUO (10%), which is assumed to enhance both the flexural strength and fracture toughness of the material as compared with IPS e.max CAD. The incorporated zirconia grains act as nuclei for crystallization producing a greater number of smaller crystallites (0.5-1ìm) rather than the fewer large crystallites (1.5 ìm) that are present in the IPS e.max CAD, and that's why the glass phase of CELTRA DUO is present at a higher ratio when compared with conventional lithium disilicate ceramic despite that lithium disilicate has higher percentage of crystal phase (about 70%) as compared to CELTRA DUO (40-50%) [25]. Meanwhile, the incorporated zirconia will increase the fracture toughness via the stress-induced toughening mechanism that prevents crack propagation [26]. This is supported by the findings of a SEM study which showed very clear semicircular arrest lines close to the origin of failure were shown in crowns fabricated from CELTRA DUO, which leads to the assumption that microcracks may have a smaller influence on the fracture strength of CELTRA DUO as compared with lithium disilicate ceramic crowns which show dominant hackles from the origin of failure to the die [27].

II. The lower modulus of elastisity of CELTRA DUO (70 GPa) as compared with that of IPS e.max CAD (95 GPa), which suggests that stress accumulated in the crowns fabricated from IPS e.max CAD is more than that accumulated in the crowns fabricated from CELTRA DUO.

The above finding is in agreement with Preis *et al.* [28] and Schwindling *et al.* [29] who compared the fracture strength of crowns fabricated from zirconia-reinforced lithium silicate and lithium disilicate and found that crowns fabricated zirconia-reinforced lithium silicate showed higher mean value of fracture strength than those fabricated from lithium disilicate.

However, the above finding disagrees with.the findings of Sieper *et al.* [27] and Gungor and Nemli [21] who tested the fracture strength of crowns fabricated from lithium disilicate, zirconia-reinforced lithium silicate and other all-ceramic materials and found that the fracture strength of all-ceramic crowns fabricated from lithium disilicate was higher than that for zirconia-reinforced lithium silicate crowns. Such disagreement may be due to the difference in the type of zirconia-reinforced lithium silicate material used as they used VITA Suprinity.

Hybrid dental ceramic

In this study, the lowest fracture strength mean value was recorded by crowns fabricated from hybrid ceramic material VITA ENAMIC (767 N). This could be attributed to the relatively low mechanical properties of this material including low flexural strength (150-160 MPa) and low fracture toughness (1.5 MPa $m^{1/2}$).

Another possible factor may be the hybrid nature of this material as it is composed of interconnected networks of ceramic and polymer, which leads to different rates of ablation for ceramic and polymer during the grinding and polishing processes, that may result in microcracks in the network boundaries, and this is assumed to decrease the mechanical properties of the material [30, 31].

Moreover, in a hybrid material, failure could be initiated from any weak point of the microstructure, like the polymer in polymer infiltrated ceramic [32].

This result is in agreement with the findings of Bilkhair [33] who compared the fracture strength of monolithic crowns fabricated from hybrid dental ceramic with that fabricated from lithium disilicate and feldspathic ceramic and found that the fracture strength of crowns fabricated from hybrid dental ceramic was lower than that for lithium disilicate crowns.

This finding is also in agreement with Sieper *et al.* [27] who compared the fracture strength of all-ceramic crowns fabricated from hybrid dental ceramic, lithium disilicate and zirconia-reinforced lithium silicate and found that the lowest fracture strength of all-ceramic crowns was recorded by crowns fab from hybrid dental ceramic.

CONCLUSION

Within the limitations of this in vitro study, the following conclusions could be drawn:

1. The fracture strength of the crowns fabricated from the different materials used in this study exceeded the maximum biting force in the premolar region. This suggests that all these materials could be successfully used clinically as monolithic crown restorations in the premolar region taking into account that adequate tooth preparation is fullfilled and adhesive cementation protocol with proper surface treatment are used.
2. The highest fracture strength mean value was recorded by monolithic crowns fabricated from zirconia (CEREC Zirconia) followed by crowns fabricated from reinforced composite (BRILLIANT Crios), zirconia-reinforced lithium silicate (CELTRA DUO), and lithium disilicate (IPS e.max CAD), while the lowest fracture

strength mean value was recorded by crowns fabricated from hybrid dental ceramic (VITA ENAMIC).

3. The chemical composition and microstructure of the material used for fabrication of monolithic CAD/CAM crown had a significant effect on the fracture strength of the fabricated crowns.

4. For bonded restorations, one should not rely on the flexural strength value of the material to be used alone, but should consider other material properties including the fracture toughness and the modulus of elastisity. i.e., the inherent strength of the all-ceramic crown, as a stand-alone item, is of limited interest as the overall strength of restored tooth-crown complex that is clinically relevant.

From a clinical point of view and based on the above conclusions, it is recommended to use the reinforced composite block to fabricate monolithic crowns in the premolar area as it provided high fracture strength with the added advantage of easy intra-oral repair of the restoration when needed.

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