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Evaluation of Zirconia and Zirconia-reinforced Glass Ceramic Systems Fabricated for Minimal Invasive Preparations Using a Novel Standardization Method

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The authors do not have any financial interest in the companies whose materials are included in this article.

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Abstract

Objective: Currently, minimal invasive approach combining less invasive finish line preparations and reduced ceramic thickness are required. The aim of this study was to evaluate the fracture resistance of two ceramic systems fabricated with two preparation designs using CAD/CAM standardization technology.

Materials and methods: Forty intact human maxillary premolars were divided into 2 main groups according to the preparation technique. **Group H (Horizontal):** teeth with shoulder finish line and **Group V (Vertical):** teeth with feather-edge. Each main group was subdivided randomly into 2 subgroups according to the materials used. **Group CD (Celtra Duo)** zirconia reinforced glass ceramics and **Group K (KATANA)** monolithic zirconia. CAD/CAM was used for standardization of natural teeth preparation. After cementation using self-adhesive resin cement, all specimens were subjected to 5000 thermal cycles then were loaded until fracture. Failure types were evaluated using Stereomicroscope and Scanning Electron Microscope.

Results: Non-significant; the higher mean value was recorded with VCD Group (482.5±103.8N) and VK Group (1347.6±177.4N) versus HCD Group (471±107.6N) and HK Group (1255.6±121.3N). SEM findings showed that fractures occurred mainly at the occlusal side of the crowns.

Conclusions: Vertical preparation showed a promising alternative to horizontal preparation. Moreover, both Celtra Duo and KATANA crowns can be used in premolar area with 0.5 mm margin thickness.

Clinical Significance: Zirconia reinforced glass ceramic and monolithic zirconia crowns may not necessitate the preparation of invasive finish lines as the type of finish line did not impair the strength after aging conditions.

Key words: Verti prep, In-vitro, CAD/CAM, Standardization, Celtra Duo

Introduction

The growing demands for highly esthetic restorations and concerns about the deleterious effects of metals have been reported by many professions to consider the use of all-ceramic restorations. Polycrystalline zirconium dioxide ceramics and lithium disilicate glass ceramics are now mainly used in restorative indirect restorations for their optimal mechanical and esthetic characteristics.[1,2]

Zirconia possesses excellent biocompatibility, mechanical properties with a flexural strength of 900-1200 MPa and adequate optical properties which expand the potential application of all-ceramic restorations in premolar and molar regions where greater fracture resistance is required.[3] While excellent strengths have been reported for zirconia core material, several studies[4,5,6] regarding the veneering ceramic reported fractures. To avoid fracture and facilitate the manufacturing processes zirconia restorations are currently used in a monolithic design without being veneered. Different studies[7,8] reported that monolithic zirconia crowns have a higher fracture resistance than conventional veneered versions.

The group of glass ceramics still provides the best translucency and esthetic qualities. Although, new generation lithium disilicate based ceramics have improved mechanical properties with a flexural strength of 300-400 MPa, they are only recommended for single unit restorations and short span bridges in anterior regions.[9] This group of ceramic allow better adhesive link to the tooth structure using adhesive resin cement enabling clinicians to perform more conservative preparation designs.[10]

Among others, a new group of machinable ceramics has recently been introduced; zirconia reinforced lithium silicate ceramics.[11] These materials offer mechanical properties ranging from 370 to 420 MPa. Thus, they are comparable with the clinically well-proven lithium disilicate glass ceramics. The improved strength and reliability are reached by the addition of 8–10 % by weight zirconium oxide. Moreover, it has improved esthetic and bond strength compared to zirconia.[12]

For successful restorations, the concept of minimally invasive preparation is essential.[13] The ultimate goal of reconstructive dentistry is to obtain excellent esthetic results while simultaneously respecting the biological structures. Currently, both clinicians and technicians have an access for different materials and procedures that enable esthetics and function to be created in a predictable and simpler ways. All-ceramic restorations and new adhesive systems enable greater preservation of remaining hard tooth structures particularly regarding single restorations.[14,15]

Commonly, there are two types of preparation; preparation with finish lines called horizontal and preparation without finish lines which is described as vertical or feather-edge preparation.[16,17] Vertical preparation is usually indicated for periodontally involved abutments for fixed prostheses as this approach may be more conservative than horizontal preparation under different clinical situations.[18]

In horizontal preparations, the dentist places a well-defined finish line which is registered during impression making and replicated in the working model. For vertical preparation, the laboratory technician locates the margins based on data obtained from gingival tissue.[19] The vertical preparation can preserve a maximum of sound tooth structure as it provides the most acute marginal restoration.[20] Although, tapered and thin margins have some drawbacks like difficult accurate processing and liability to chipping fracture, minimally invasive approaches are indicated to prevent residual dental tissue weakening or pulp insult. As a consequence, reducing coping thickness of restorations and minimal invasive finish lines including feather-edge are mandatory.[21]

The absence of homogeneity in methodology is one of the main issues faced by in-vitro dental researches which do not allow the ideas of evidence-based dentistry to be applied. It also avoids accurate comparisons among distinct study works even when using the same materials and methods and avoids the extrapolation of the outcomes acquired.[22] There are distinct methods to manufacture samples manually to be comparable in the continuing study. Inability to standardize prevents the estimation of outcomes by other facilities or authors that may wish to replicate or improve the study. This does not promote another team to repeat a survey aimed at verifying and contrasting the information acquired. Another issue is that the materials used to create hand-made stump specimens such as noble metals, epoxy resins and polymethylmethacrylate (PMMA) do not usually act in the same manner as natural teeth and some do not allow recent bonding techniques.[23]

CAD/CAM innovation allows the preparation of extracted natural teeth to be standardized for in-vitro testing and offers a reproducible technique that can be applied to various researches. This can allow comparisons among researches and decreasing bias arising from sample manufacturing. The use of digitally standardized dental specimens would make it much easier to compare the data obtained between the studies and to extrapolate the results to other research situations.[24]

One of the major problems that face clinicians is the liability of all-ceramic restorations to fracture under occlusal and lateral forces due to the high biting forces applied to premolar and molar teeth and the fragility of the ceramic materials.[25] Ceramics are sensitive to tension and their resistance to fracture is affected by internal voids and superficial flaws. Many factors are blamed to be responsible for this phenomenon like margin design, thickness of restoration, processing stresses, direction and magnitude of the load applied and oral environmental conditions.[26]

In premolar and molar regions, higher fracture resistance of materials used as crowns is required. There is 20 years evidence for feldspar ceramic restorations working perfectly fine in this region. Feldspar ceramic require a minimum thickness of 1 mm. Since in this technique the ceramic thickness should be minimal, the ceramic used in this study at the marginal area have a thickness of 0.5 mm only requiring materials that have higher fracture resistance.[27]

This in-vitro study aimed to compare the fracture resistance applied to monolithic zirconia and zirconia reinforced glass ceramic with horizontal and vertical preparation under static compressive load (not cyclic). Moreover, modes of fracture were evaluated qualitatively using Stereomicroscope and Scanning Electron Microscope.

Materials and methods

Forty intact human maxillary premolars freshly extracted for orthodontic and periodontal reasons with homogenous dimensions and morphology were selected for this in-vitro study. The selected teeth were divided into 2 main groups; H and V (n=20) according to the preparation technique.

Group H (Horizontal): 20 teeth with conventional preparation for all-ceramic crowns (shoulder finish line).

Group V (Vertical): 20 teeth with minimally invasive preparation (feather-edge).

Each main group were further subdivided randomly into 2 equal subgroups (n=10) according to ceramic system used.

Subgroup CD: 10 crowns fabricated with zirconia reinforced lithium silicate glass ceramic (Celtra Duo LT/ B1/ C14).

Subgroup K: 10 crowns fabricated with monolithic zirconia (KATANA A light/ B2/T18).

The roots of each tooth were vertically embedded in a transparent epoxy block to facilitate handling of the teeth during preparation, scanning and cementation procedures. During the manufacturing of epoxy block a specially designed and locally manufactured centralizing machine was used to allow accurate centralization of the tooth inside the mold.

CAD/CAM technology has been used to standardize the preparation of the natural extracted teeth. Standardization began with the development of hand-made prepared teeth creating a plan and profile of particular sizes. Two teeth were prepared with horizontal and vertical preparation by operator's hand using dental surveyor with the following dimensions; height (6 mm), bucco-palatal diameter (9 mm) cervically and (7mm) occlusally, and mesio-distal dimension (5 mm). Then, the teeth were scanned by optical scanner (Ceramill Map400, Amann Girrbach, Germany).

Software tool (Rhinoceros business 3D) was used to alter and optimize the design allowing trimming and smoothing after specimen has been scanned and appeared on the computer screen. Using (3-shape 3D viewer) **(Figure 1)**, the scanned teeth were then transformed to 3D models. In this way, the virtual stump's design and specifications were completed before its reproduction.

The molded milling packaging of e.max block was used to manufacture a specially designed acrylic holder **(Figure 2)** that acts as a holder for the epoxy blocks holding the teeth and has the same size of e.max block. The attachment portion of the ceramic block was then fixed to the (Ceramill motion II, Amann Girrbach, Germany) milling machine's attachment platform that could be recognized by the milling system's calibration function. After checking the virtual stump design, the tool paths were selected, the milling axis was adjusted in (Hyperdent Company) and the command (mill) was selected. Selecting the correct length of the e.max CAD temp block size was done to visualize the tooth position within the total block.

Afterwards, the acrylic holder holding the epoxy block of natural tooth was fixed in the milling machine and the milling started. The device defines and calibrates the size of the block when ongoing recording the width and the height to determine whether this is a block that has already been operated or a fresh one. In this situation, the current sizes were acknowledged as if this was a block already in use and milled accordingly. It took about 27 minutes for each specimen to mill. The teeth were wet-milled using diamond stones and the final prepared teeth were absolutely standardized as shown in **(Figure 3).**

A total of forty ceramic crowns were CAD/CAM constructed using (Ceramill motion II) milling machine, half from Celtra Duo (Denstply Sirona, Germany) and half from KATANA zirconia (Noritaka, Japan). The marginal thickness was adjusted at 0.5 mm for crowns in vertical preparation groups and 1 mm for horizontal groups.

For intaglio surface of Celtra Duo crowns (Group CD) were treated with 9.5% hydrofluoric acid for 20 sec according to manufacturer’s instructions. Crowns were then rinsed and dried with air syringe. The intaglio surface of all the crowns were coated with one coat of porcelain primer then air dried for 3-5 seconds following the manufacturer's instructions. For KATANA crowns (Group K), sandblasting of their intaglio surfaces was performed using 50 µm alumina oxide particles at 4 bar (0.4 MPa) air pressure for 14 seconds. The tip of sandblaster was fixed and adjusted 10 mm away from the crowns.[28] The intaglio surface of all the crowns were coated with one coat of zirconia primer then the primer was air dried for 3-5 seconds following the manufacturer's instructions. Dual-cure self-adhesive resin cement (G-CEM capsule, GC Co., Japan) was used for cementation of both groups.

The specimens were subjected to 5000 cycles of thermal cycle using (Thermo-cycler SD Mechatronic, Germany) at temperature between 5°C and 55°C for 20 seconds at 10 seconds intervals.

In total, all specimens were loaded in a Universal Testing Machine (Instron Universal Testing Machine model 3345, England) until fracture occurred. The load cell (5000 newton) was applied vertically with a 5 mm diameter stainless steel ball placed at the center of the occlusal surfaces of the crowns and a crosshead speed of 1 mm/min. Fracture was identified when there is a visible cracks accompanied by drops of the load as demonstrated by stress strain curve fracture load was recorded using a computer software (BlueHill Instron).

The data were tabulated and statistically analyzed using Student t–test, One way ANOVA and Two way ANOVA tests. Mode of failure was categorized according to Burke's classification[29]. Type I: minimal fracture or crack in the crown. Type II: less than half of the crown lost. Type III: crown fracture through midline or half of the crown displaced or lost. Type IV: more than half of the crown lost. Type V: severe fracture of the crown and/or tooth. In addition, cracks, chipping, delamination and catastrophic total failures were noted.

Fractured specimens were further evaluated using Stereomicroscope (Stereomicroscope SZ2-ILST, Olympus co., Japan) at 10× to 80× and Scanning Electron Microscope (SEM) (JSM-6510V; JEOL Ltd., Akishima, Tokyo, Japan) at 20× to 150× magnifications.

Results

(A) Quantitative results:

1. Descriptive data:

The fracture resistance of Groups HCD and HK were 471±107.6 N and 1255.6±121.3 N, respectively. The fracture resistance of Groups VCD and VK were 482.5±103.8 N and 1347.6±177.4 N, respectively. Means and standard deviations (±SD) of the fracture resistance of the groups of this study were shown in (**Table 1)**.

2. Student t-test: (Figure 4)

- Using student t-test for the values of the fracture resistance of the crowns milled with Celtra Duo; there was no significant difference between horizontal and vertical preparations as a total value (P=0.87).
- Applying student t-test for the values of the fracture resistance of the crowns milled with KATANA; there was no significant difference between horizontal and vertical preparation as a total value (P=0.37).
- Applying student t-test for the values of the fracture resistance of the crowns fabricated with vertical preparation; there was high significant difference between Celtra Duo and KATANA as a total value ($P<0.001$).
- Applying student t-test for the values of the fracture resistance of the crowns fabricated with horizontal preparation; there was high significant difference between Celtra Duo and KATANA as a total value ($P<0.001$).

(B) Qualitative results:

These results were obtained using Stereomicroscope and Scanning Electron Microscope. Cracks and chipping were not observed in our specimens. Type III and IV failures fracture of the crown were more common in Group VCD and Group HCD. Type V failures (severe fracture of the crown and/or tooth) were more common in Group VK and Group HK **(Table 2).** Stereomicroscopy **(Figure 5)** and SEM findings **(Figure 6)** showed that fractures occurred mainly at the occlusal side (the area where the indenter was placed) and propagated toward the cervical line.

Discussion

Conservative dentistry has a challenge of achieving suburb esthetic results while simultaneously respecting the biological structures involved as much as possible.[30]

The idea of minimally invasive dental restorations is essential for successful restorations. Thus, minimum thickness all-ceramic restorations have been increasingly indicated.[13]

In this study, results showed that there was a non-significant difference between the resistances to fracture under loading applied to the vertical and horizontal preparation using the same material. However, there was a high significant difference between the Celtra Duo and KATANA crowns in the same preparation. Since after long term of thermal cycling and loading till fracture, the type of finishing line did not significantly impair the fracture strength of zirconia reinforced lithium silicate and monolithic zirconia crowns.

Cortellini D et al. [31] **(2015)** evaluated the durability of lithium disilicate crowns bonded on prepared teeth with Knife edge and large chamfer finish lines after cyclic loading. The results showed that the finishing line type has no significant effect on the mean fracture strength of glass ceramic crowns (KE: 1655±353 N, LC: 1618 ±263 N) (p =0.7898). SEM findings showed that fractures occurred mainly from the cement/ceramic interface at the occlusal side of the crowns. They stated that lithium disilicate ceramic crowns bonded to abutment teeth with Knife edge preparation showed similar fracture strength to those bonded on abutments with large chamfer finish line. These results are agreed with our results.

In a similar study the fracture resistance of casted glass ceramic (Dicor) crowns was tested and the results showed that no significant finish line preparation effect. However, no conditions of fatigue were simulated in that study and ceramic crowns were bonded to natural teeth.[32]

Reich S et al.[33] **(2008)** studied the effect of finish line preparation and layer thickness on the failure load and fractography of zirconia copings. The results showed higher mean failure load was measured for vertical preparation (0.5 mm, 1110 ±175 N and 0.3 mm, 730±160 N) versus chamfer preparation (0.5 mm, 697 ±126 N and 0.3 mm, 455 ±79 N). They stated that vertical preparation can be a promising alternative to chamfer finish line as the fracture load required for vertical preparation was greater than that required for chamfer preparations by 38%.

A clinical crown's fracture strength is affected by multiple factors such as cementation protocol, loading force, and supporting elastic modulus. Increasing the elastic modulus of the supporting material resulted in an increase in the fracture resistance.[34] The fracture strength of the crowns could give more accurate results if natural teeth were used as supporting model. For all of the specimens in this study, the other factors of loading condition and cementation techniques were the same.[35]

The lack of literature on reproducible specimen manufacturing and the inability to standardize stump manufacturing protocols prevent the ability to compare the reciprocal results of laboratory testing.[22] However, the manufacturing and reproduction techniques are technique-sensitive and subjected to various errors.[36]

Rego M et al.[32] **(2004)** standardized natural teeth using high-speed turbine to prepare teeth using a surveyor with mounted rod to achieve a standard taper of 6^{o} and standard height of 4 mm but it was impossible to standardize the area/volume of obtained specimens. **Cortellini D et al.** [31] **(2015)** used abutments fabricated from epoxy resin instead of natural teeth as it is harder to standardize the natural teeth dimensions.

CAD/CAM technique allows the manufacture of standardized samples using methods that possesses many advantages as compared to manually fabricated models. First of all, they can be exactly duplicated. The method is economical because noble metal alloys or other expensive materials are not required. When using natural teeth, the researcher can perform various bonding techniques that have a significant influence on the behavior of the materials being investigated.[37,38]

In in-vitro studies, the dentin wetness, thickness and the pressure of the tooth pulp are influential variables that try to imitate in-vivo conditions. The modulus of elasticity of natural teeth is essential factor when applying fracture tests as the other materials do not behave as natural teeth. Finally, if the specimens are natural, thermal cycling aging will be closer to clinical conditions rather than artificial ones.[39]

The vertical preparation was chosen to evaluate whether zirconia and zirconia reinforced lithium silicate ceramics could be an effective esthetic crowns alternatives while holding stress in very minimal thickness. However, due to the total 10^{0} occlusal convergence of the axial walls and the geometry of the vertical margins, the amount of exposed cement was very limited and consequently, the possible plaque accumulation and dissolution of the cement could be very limited.[1]

Vertical preparation concept allowed the use of periodontally affected teeth as abutments for ceramic fixed restorations. In addition, it allows conservation of a sound tooth structure during the preparation of the tooth for fixed abutments so it offers a less invasive alternative to horizontal finish line. This extend the indications to include other clinical situations such as endodontically treated teeth, young individuals' vital teeth and teeth defects at the gingival third of the teeth.[40,41]

Within the limitation of this study, the use of a vertical preparation as an alternative to horizontal preparation offered an effective and durable alternative to traditional preparation techniques and could be recommended for minimally invasive restorations. Although, before any clinical recommendations, clinical confirmatory studies are still required.

Conclusions

Under the conditions of current study the following conclusions were drawn;

1) Vertical preparation offered a durable alternative to horizontal finish lines. The fracture load required for vertical preparation was higher than that required for horizontal preparation.
2) Both zirconia groups (KATANA) has greater fracture resistance than the same groups of zirconia reinforced glass ceramics (Celtra Duo). They can be used in premolar area with 0.5 mm margin thickness in the vertical preparation.
3) Celtra Duo mainly undergoes delamination (favorable fracture) during fracture test so it can be easily repaired. However, KATANA undergo catastrophic failure to the tooth (unfavorable fracture).

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Table (1) Shows the means and standard deviations (±SD) among the four groups

Preparation Design	Ceramic Material		n=10
Vertical preparation	Celtra Duo	Mean	**482.5**
		Std. Deviation	**103.8**
	KATANA	Mean	**1347.6**
		Std. Deviation	**177.4**
Horizontal preparation	Celtra Duo	Mean	**471**
		Std. Deviation	**107.6**
	KATANA	Mean	**1255.6**
		Std. Deviation	**121.3**

Table (2) Distribution of failure modes (in percentage) according to Burke's classification for each experimental group

<table>
<tr><th colspan="2">Failure modes</th><th colspan="4">Groups</th></tr>
<tr><th colspan="2">Burke's classification</th><th>HCD</th><th>HK</th><th>VCD</th><th>VK</th></tr>
<tr><td>Cracking and chipping</td><td>I</td><td>0 %</td><td>0%</td><td>0%</td><td>0%</td></tr>
<tr><td rowspan="3">Delamination</td><td>II</td><td>20 %</td><td>0 %</td><td>10 %</td><td>0 %</td></tr>
<tr><td>III</td><td>40 %</td><td>0 %</td><td>40 %</td><td>10 %</td></tr>
<tr><td>IV</td><td>20 %</td><td>20 %</td><td>20 %</td><td>10 %</td></tr>
<tr><td>Catastrophic failure</td><td>V</td><td>20 %</td><td>80 %</td><td>30 %</td><td>80 %</td></tr>
<tr><td colspan="6">Cracking: veneer ceramic cracked at the interface.
Chipping: fracture in the veneer ceramic without exposure of the tooth.
Delamination: veneer ceramic was damaged and the tooth exposed.
Catastrophic failure: fracture in both the veneer ceramic and the framework.</td></tr>
</table>

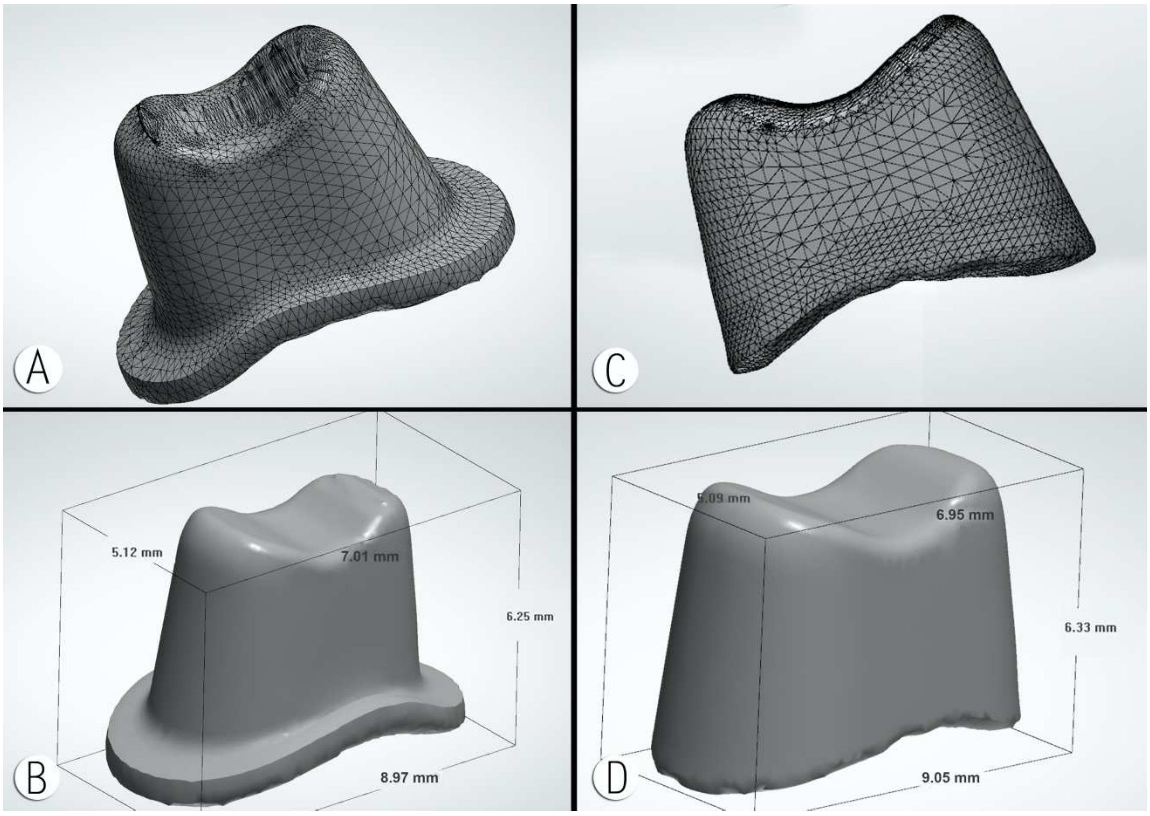

Figure 1. 3D designs of prepared teeth using (3shape 3D viewer);
(A and B) Horizontal preparation (C and D) Vertical preparation

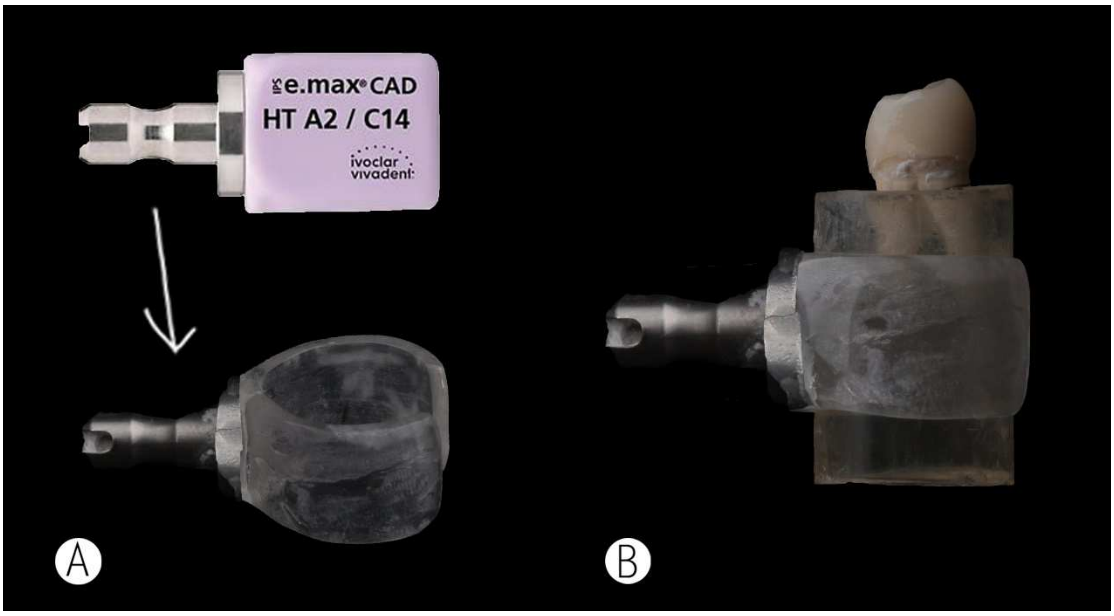

Figure 2. (A) Acrylic holder from the molded packaging of e.max block
(B) Tooth in epoxy block attached to acrylic holder

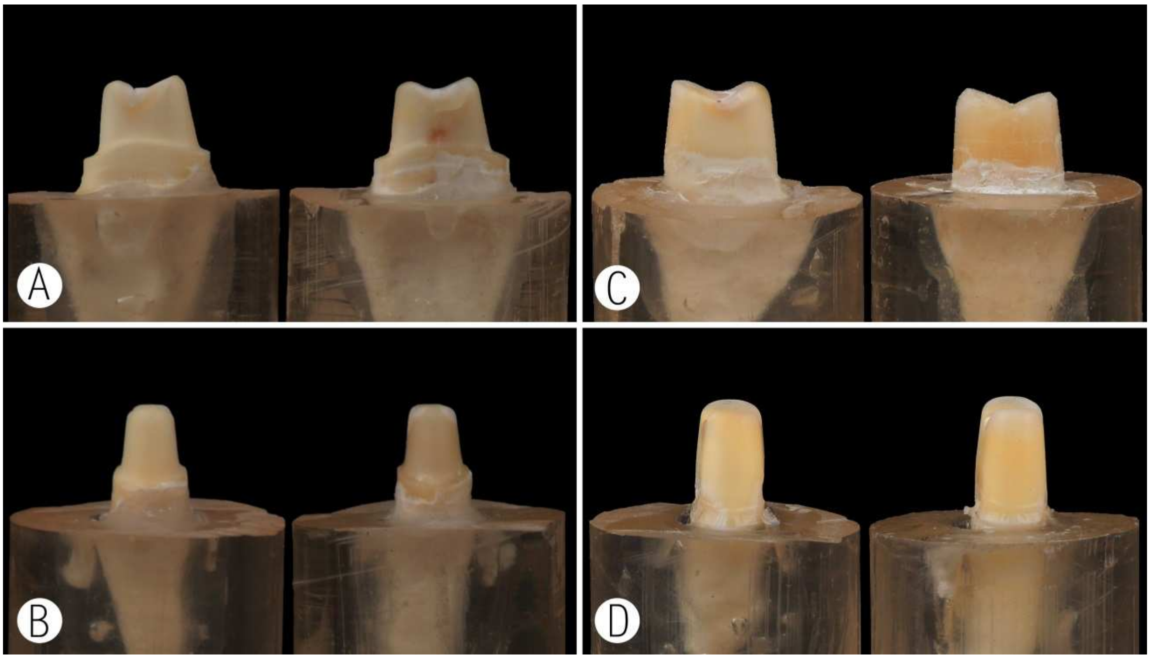

Figure 3. Final preparation with absolute standardization;
Buccopalatal (A) and mesiodistal (B) views of horizontal preparation
Buccopalatal (C) and mesiodistal (D) views of vertical preparation

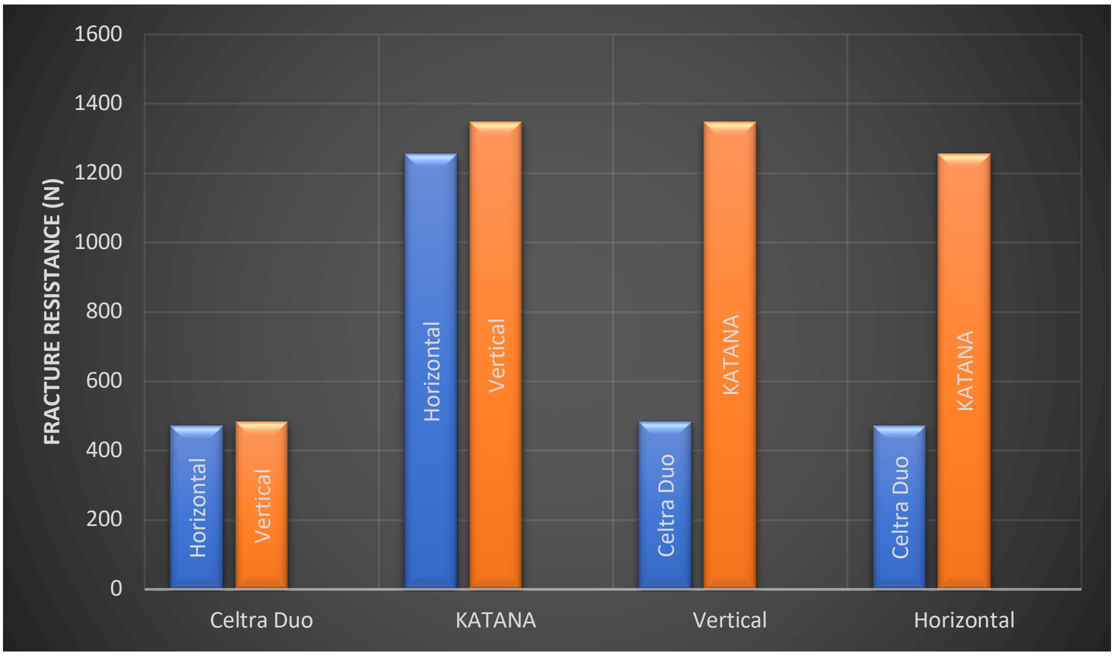

Figure 4. Bar chart of Student t-test

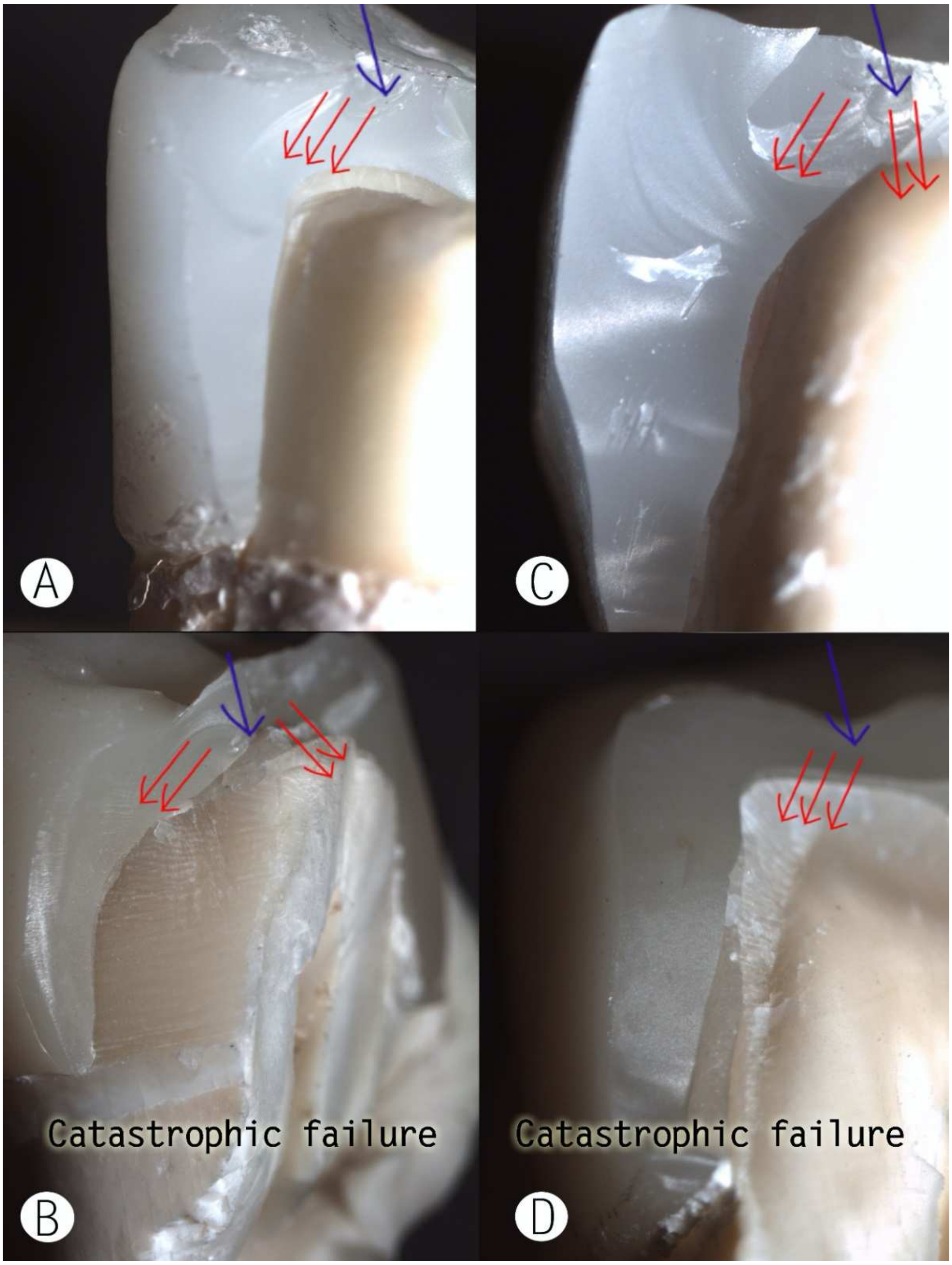

Figure 5. Stereomicroscopy images (12×) corresponding to the area of crack origin;

(A) Representative crown from Group HCD

(B) Representative crown from Group HK with catastrophic failure

(C) Representative crown from Group VCD

(D) Representative crown from Group VK with catastrophic failure

The blue arrows indicate the load area (origin) and the red arrows refer to the direction of the crack propagation.

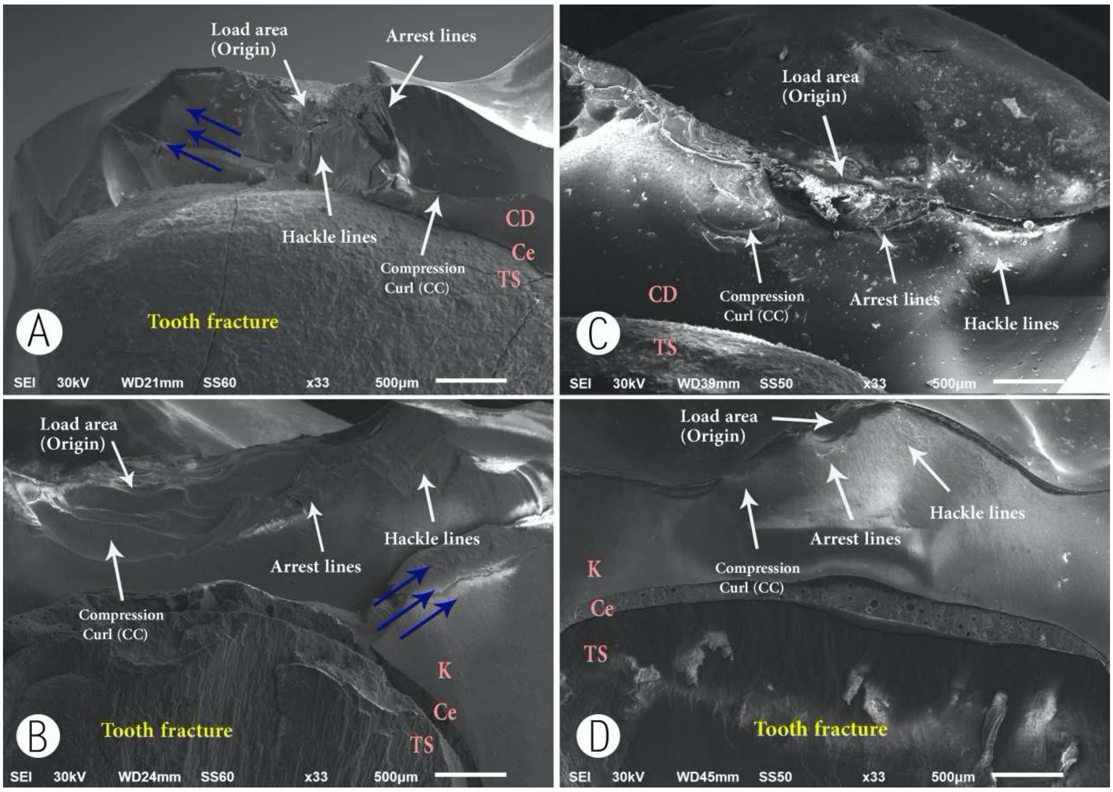

Figure 6. SEM images of the crowns after fracture at (33X) showing the load area;

(A) Representative crown from Group HCD

(B) Representative crown from Group HK

(C) Representative crown from Group VCD

(D) Representative crown from Group VK

The blue arrows indicate the direction of the crack propagation

CD: Celtra Duo, **K**: KATANA, **Ce**: Cement, **TS**: Tooth structure