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Fracture Resistance of Different Monolithic Zirconia Crowns with Horizontal and Vertical Finishing Lines: A Comparative in Vitro Study

Mohammed Qasim Nasir [1] *
Alaa Jawad kadhim[2]
[1,2] Department of Restorative and Aesthetic Dentistry, College of Dentistry, University of Baghdad, Iraq

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***Corresponding Author:**
Email:
mohammed.Qasem1204a@codental.uobaghdad.edu.iq

(1) Department of Restorative and Aesthetic Dentistry, College of Dentistry, University of Baghdad, Iraq

Abstract
Objective: The primary objective was to examine how different preparation techniques and zirconia materials affected fracture strength. Materials and methods: 48 sound human maxillary first premolars of similar shape and size were used, categorized into two main groups of 24 teeth, as per the preparation technique:
Group A: chamfer preparation design. Group B: vertical preparation design. Then, based on the type of material, each main group was subcategorized into three subgroups of eight teeth: IPS emax Zircad LT, IPS emax MT and IPS emax Prime (IvoclarVivadent). All the samples, prepared by the same operator, with the assistance of a dental surveyor. Intra-oral scanning was performed on the prepared teeth. The SironaInLab CAD 20.0 software was used to design crowns and were subsequently generated using a 5-axis milling machine. Self-adhesive resin cement was used to bond crowns to their respective teeth. To assess the crown's fracture strength, a computer-controlled universal testing system was used, which records the fracture strength automatically in each sample in Newton (N) during a single load-to-failure test. Burke's classification was employed to assess the fracture mode by analyzing each sample under a 40x digital microscope. The collected data were evaluated using statistical analysis using the independent t-test and ANOVA, with a 0.05 significance level. Results: Vertical preparation technique had higher fracture strength than the chamfer preparation technique with a statistically significant difference ($p < 0.05$). While comparable fracture resistance was identified across various monolithic zirconia crowns. All samples demonstrated a severe fracture of the crown and/or tooth (Code V). Conclusion: The vertical preparation design illustrated significantly better fracture strength than the chamfer preparation design, Materials comparisons showed comparable fracture resistance.

Introduction:

All-ceramic restorations have gained popularity in dentistry because of their enhanced biocompatibility and esthetics (1). However, early ceramic materials raised concerns regarding their mechanical strength (2). Zirconia's prominence can be traced to the advancement of CAD/CAM technology and quick advancements in the mechanical attributes associated with ceramic materials (3). Zirconia's superior mechanical properties, achieved through the transformation toughening process, have influenced the utilization of full-contour zirconia restorations without the need for veneering porcelain, which is susceptible to chipping (4). The preparation technique plays a vital role in the fracture strength of the restoration, requiring careful consideration to minimize stress and maximize durability (5). Because zirconia is opaque, it is frequently coated with porcelain when utilized in clinical situations (6). However, veneering layer chipping has been recorded (7). Monolithic zirconia restorations have been introduced as an alternative to mitigate veneering porcelain chipping (4). The development of translucent zirconia materials, known as monolithic translucent zirconia, has overcome the poor optical characteristics of traditional zirconia (6) while retaining comparable mechanical properties (8).

Traditional horizontal preparation with shoulder finish lines and chamfer has been the norm or standard for all-ceramic restorations. On the other hand, these preparations are invasive and require the removal of intact tooth structure, which is unfavorable for biological and aesthetic reasons (9). With the emergence of high-strength polycrystalline materials, vertical preparation has been proposed as alternatives that are less invasive to horizontal preparation (10). Therefore, this research study aims to examine the fracture resistance of different monolithic zirconia materials in both horizontal and vertical preparation techniques. The null hypothesis posits that the type of zirconia and preparation technique would not significantly affect the fracture resistance.

Materials and Methods

Forty-eight human maxillary first premolars, chosen for this study, were extracted from orthodontic patients aged between 18 and 22. To minimize variables, the teeth were evaluated for crown size using a digital caliper and a digital microscope (Dino-Lite capture 2.0, version 1.3.6., Taiwan) at 40x magnification to exclude any teeth with caries, restorations, or cracks. To prevent fungal and bacterial infection, thymol solution is used at room temperature for one week, followed by immersion in distilled water to prevent the teeth from dehydrating.

The individual teeth were placed in a custom-made square rubber mold measuring 2.0 cm in height, 1.5 cm in length, and 1.5 cm in width) filled with freshly mixed cold cure acrylic. Next, a dental surveyor was involved in ensuring that each tooth was vertically aligned with the mold's horizontal plane. To mimic the support of healthy alveolar bone, the teeth were embedded 2 mm apical to the cementoenamel junction. The teeth were then categorized into two groups of 24, based on one of the preparation techniques (horizontal or vertical).

Group A: contains horizontally prepared teeth (chamfer finish line);

Group B: contains vertically prepared teeth. Then, based on the type of material, each main group is subcategorized into three subgroups of eight teeth.

Subgroup 1: Monolithic zirconia (IPS e.maxZirCAD LT) (IvoclarVivadent: Schaan, Liechtenstein);

Subgroup 2: Monolithic zirconia (IPS e.maxZirCAD MT) (IvoclarVivadent: Schaan, Liechtenstein);

Subgroup 3: Monolithic zirconia (IPS e.maxZirCAD Prime) IvoclarVivadent: Schaan, Liechtenstein).

For standardization, a dental surveyor was used to prepare all samples. The surveyor's vertical arm was adjusted to hold a high-speed turbine (Shengling, China) to assure parallelism between the bur's long axis and the tooth's long axis, which was verified with a protractor (11).

All teeth were prepared with an axial height of 4 mm measured from the mesial surface to the finish line situated 1 mm above the CEJ. The chamfer margin design (0.8 mm depth) for group A teeth was created with a round-end tapered fissure diamond bur (6856 314 016, Komet, Germany) with a total convergence angle of 6 degrees. (Fig. 1)
For group B teeth, the vertical margin technique was prepared using a round safe end tapered diamond bur (851-012C-FG, NTI, Germany) with 4 degrees total convergence angle (Fig. 2). The barrel-shaped trapezoid diamond bur (811LG.314.037, VERDANT, Poland) was used to perform a planar occlusal reduction of approximately 1.5–2 mm for both groups. A digital caliper was used to check all measurements.
CEREC Omnicam intraoral scanner (Sirona, Germany) was used to take a digital impression for every tooth. The crowns were then machined out of zirconia blanks (IPS e.maxZirCAD LT, MT, and Prime; Ivoclar Digital, Germany) with a 5-axis milling unit (In-Laboratory MC 5 milling machine, Sirona, Germany) using SironaInLab CAD 20.0 software. To keep their original color, strength, and size, the milled crowns were sintered at 1500°C in an InFire HTC Speed sintered Furnace (Sirona, Germany).
Glaze paste (FLUO Ivocolor glaze paste; IvoclarVivadent, Liechtenstein) was the used to brush the crowns. The glaze firing/ crystallization was carried out in the Programat P500 furnace (Ivoclar, Germany) at 710°C for 18 minutes. The interior surfaces of all crown restorations were sandblasted for 15 seconds with 1 bar at a distance of 10 mm and aluminum oxide particles ≤ 50 µm to Create a rough and retentive surface with a sandblasting machine (Renfert, Germany) to promote mechanical interlocking between the luting and zirconia (12).
The crowns were subsequently attached to their respective teeth with a self-adhesive resin cement (TheraCem BISCO, USA). Finger pressure was used to seat the crown before a 5kg vertical load was applied for 6 minutes with a cementation apparatus, customly made). Following that, all samples were immersed and kept in distilled water at a temperature of 37°C for one day (24 hrs) (13). The crowns' fracture loads were assessed by means of a single load to failure test on a universal testing equipment that was controlled electronically (Laryee, China). To apply a vertical force to each zirconia crown, a stainless-steel indenter with a round-end with a crosshead speed of 0.5 mm/min was employed. To prevent distortion induced by the crown and indenter being in direct contact with each other, a piece of 1 mm thick rubber was put between the indenter and crown. The crowns were loaded until they failed, and the load of the fracture was automatically recorded in Newton (N). (Fig. 3)

Burke's classification was employed to assess the fracture mode by analyzing each sample under a 40x digital microscope (14). Statistical evaluation was performed utilizing the SPSS Software version 27. The Shapiro-Wilk test was utilized to evaluate the variables' normal distribution. ANOVA was utilized to determine the significance of the mean difference in fracture strength within groups. An independent t-test was utilized to determine the significance of the fracture strength mean difference between groups.

Results

The results of the Shapiro-Wilk test demonstrated that the data were distributed normally with a p-value greater than 0.05. Table 1 displays descriptive information such as mean, and maximum and minimum fracture strength values in Newton (N), including standard deviation. Subgroup B1 (vertical preparation technique-Zircad LT material) had the fracture strength's highest mean value of 4641.125 N, while subgroup A3 (chamfer preparation technique-Zircad Prime material) had the lowest mean value, 3862.625 N. The fracture strength between groups was compared by performing an independent t-test at a significance of 0.05, as shown in Table 2. The outcomes of the current study demonstrate that there was a statistically significant difference in fracture strength between groups of all types of materials used ($p<0.05$). ANOVA with a level of significance of 0.05 was carried out to compare fracture strength within a group, as shown in Table 3. Within both main groups, no statistically significant differences were identified.

Regarding the fracture modes in this study, all samples exhibited a severe fracture of the crown and/or tooth (Code V). (Fig. 4).

Discussion

The demand for minimally invasive dentistry has led to the introduction of vertical preparation as a less intrusive approach to tooth structure treatment (9). Zirconia possesses high flexural strength due to its polycrystalline structure, which prevents crack propagation by organizing atoms into regular crystalline arrays (15). To ensure standardization in production, all crowns were fabricated using the same designing software (InLab CAD 20.0), restoration parameters, and a 5-axis milling machine (In-Lab MC X5), which offers better marginal accuracy compared to a 4-axis milling machine (16). The present study discovered that vertically prepared monolithic zirconia crowns exhibited significantly higher fracture loads compared to those with a chamfer design across all three materials. These findings are consistent with other in vitro studies, Jasim et al. (17) highlighting the influence of margin technique on crown restoration fracture loads. Several studies, including those by Kasem et al. (18) and Emam at al. (19) have shown that zirconia crowns with vertical and chamfer margins have comparable fracture strengths. However, it has been found that vertical and knife-edge designs exhibit higher fracture resistance compared to horizontal techniques. In fact, Emam at al. (19) demonstrated that the knife-edge preparations displayed the greatest mean fracture resistance when compared to the deep chamfer technique, likely due to a greater amount of remaining supporting structure at the knife-edge design.

The research findings are consistent with the conclusions drawn by Reich at al. (20), who showed that potential of knife-edge preparations being an ideal substitute to chamfer finish lines. In their research, the mean failure load of knife-edge preparations was significantly greater compared to chamfer preparations, with a 38% increase in the fracture load needed for knife-edge preparations.

Same findings have been tabled by (4,17,21), with shoulderless preparation achieving significantly greater fracture strength compared to chamfer preparation. According to Beuer at al. (21), the positive outcomes of the shoulderless preparation could be related to the distribution pattern of stress during loading. As the load rose, it could slide down the die's axial wall without being constrained by the margin, resulting in occlusal surface being concentrated with stress. Furthermore, they discovered that increasing the material thickness had no significant effect on loading capacity, indicating that a less intrusive preparation process should be the preferred and ideal option.

According to Mitov at al. (4), the study found that increased material thickness did not significantly affect the capacity of loading among the chamfer preparation groups. As a result, a minimally invasive preparation technique ought to be taken into consideration as the optimal option. The current study, for both preparation techniques, also found no significant difference within groups in terms of material type. The mean values associated with the highest fracture resistance were found in the non-gradient 3Y-TZP (ZirCAD LT), followed by the non-gradient 4Y-TZP (ZirCAD MT), and then the gradient 3Y-TZP and 5Y-TZP (ZirCAD Prime). These findings are consistent with those of Elsayed et al. (22), who found no statistically significant variations in fracture strength across the three groups (5Y-TZP, 4Y-TZP, and 3Y-TZP) without artificial aging.

In a study conducted by Badr (23), significant differences in fracture resistance were found between zirconia groups based on yttria concentration using Zircad LT, MT, and Prime. However, it is important to consider other variables, such as the use of fiber-reinforced resin dies instead of natural teeth as abutments, which may affect the accuracy of the results regarding fracture resistance (24). Additionally, thermocycling has been shown to reduce zirconia's flexural strength in several studies (25). Different luting agents and horizontal finishing lines may also influence the results. Nevertheless, the zirconia crowns' fracture resistance ranked as follows (from highest to lowest): ZirCAD LT, ZirCAD MT, and ZirCAD Prime.

When translucent zirconia was compared to traditional zirconia, study results by Vichi et al. revealed a similarity in flexural strength (8). Existing literature by Beuer et al. has shown that the overall strength of monolithic translucent zirconia crown restorations exceeds veneered zirconia crown restorations (1).

The current investigation found that the chamfer and vertical margin techniques with monolithic zirconia (Zircad LT, 3Y-TZP) had a higher fracture load than the chamfer and vertical margin techniques with monolithic zirconia (Zircad Mt, 4Y-TZP). It is related to the presence of a 25% cubic phase in monolithic zirconia, which corresponds to 4Y-TZP, the transformation toughening mechanism (transformation to monoclinic from tetragonal phase) is limited. This differs from monolithic traditional zirconia, which contains 3Y-TZP (26). The traditional monolithic, 3Y-TZP (ZirCAD LT), with 100% tetragonal phase and no cubic phase, was projected to have a high survival rate. The primary reason is attributed to the phenomenon of transformation toughening, this phenomenon occurs when the molecular structure of zirconia surrounding a fracture transition to a larger monoclinic phase from a tetragonal phase. This transition acts as a barrier, effectively stopping the crack from propagating further. This may also provide valuable insights into why there was high success rate of 4Y-TZP (ZirCAD MT), which contains a large proportion of the tetragonal phase (75%) (27).

According to Badr (23), the yttria concentration at the occlusal surface was discovered to be the most essential component in predicting zirconia fracture resistance, irrespective of the concentration of yttria at the middle and cervical thirds of the crown. This observation could explain the lower fracture resistance reported in the Zircad prime material, which has the most yttria in the occlusal surface.

The present study found that all crowns' fractures occurred at a higher level than the maximal mastication forces (900N) (28). The severe fractures observed in both preparation techniques (Code V) in this study may be attributed to the fracture test design, where the cusp slope and loaded applicator position in the course of loading play a significant role in establishing the fracture's behavior. The acute inclination of the palatal and buccal cusps under occlusal force makes upper premolars more susceptible to mesiodistal split vertical fractures (29). Previous study by Jassim and Majeed also found that a static load to failure test could result in a mesiodistal split fracture through the central fossa below the cementoenamel junction (30). This study used zirconias that were characterized with high strength, and this may provide another explanation for the observed catastrophic failures (ZirCADLabside Instructions for Use, Ivoclar, 2021).

The chamfer preparation technique in this study exhibited more damage compared to the vertical technique, which could have been caused by the increased depth of reduction of tooth preparation with the chamfer margin, leading to decreased fracture resistance of the tooth (13). It is critical to note that this in vitro study had a limitation in that the crowns were not subjected to artificial aging procedures, including thermocycling and cyclic loading. These processes could offer further insights into the clinical potential of the restorations. Nevertheless, a single load to failure test is in most cases assumed essential as an initial step and forms the basis for material testing.

Conclusion

In summary, based on the drawbacks associated with this vitro study, three main conclusions are made.

1. The fracture resistance of monolithic zirconia crowns, regardless of the preparation design, exceeds the

maximum biting forces.
2. The vertical preparation technique exhibits significantly greater fracture strength compared to the chamfer preparation technique.
3. When comparing materials within both preparation techniques, similar fracture resistance was observed.

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Authors' contributions: The study was carried out with Mohammed Qasim Nasir (B.D.S., M.Sc student) leading all aspects of the research, including conception, design, data collection, analysis, and manuscript preparation, while Alaa Jawad Kadhim (B.D.S., M.Sc.) provided supervision and guidance throughout the process.

Ethical approval: The use of extracted human teeth was ethically approved by the Research Ethics Committee of the College of Dentistry, University of Baghdad (Project No. 503522, Ref. No.503)

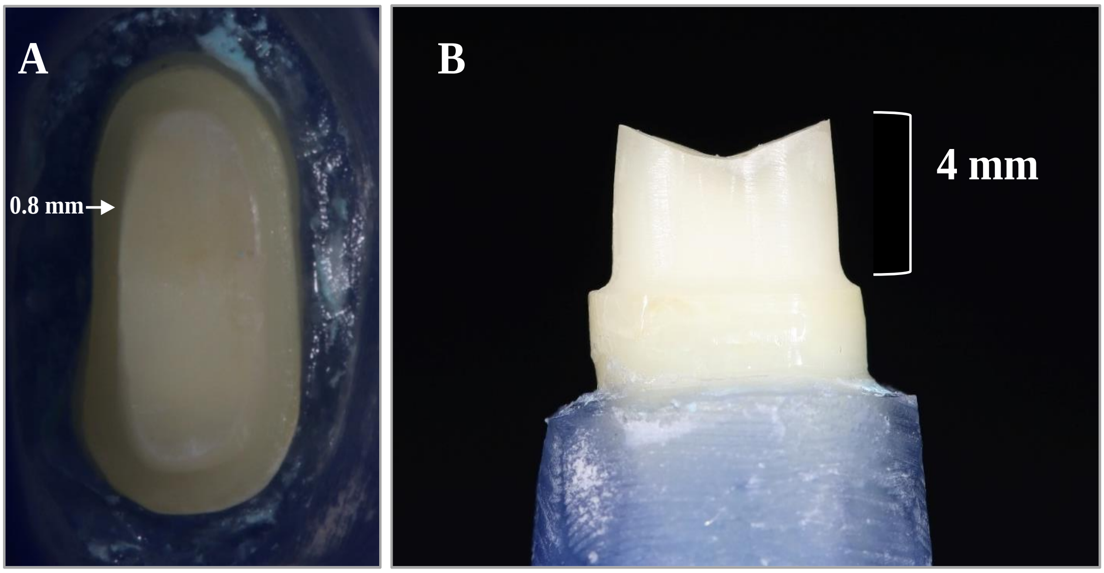

Figure 1: prepared tooth sample from group A. (A): Occlusal view. (B): Proximal view

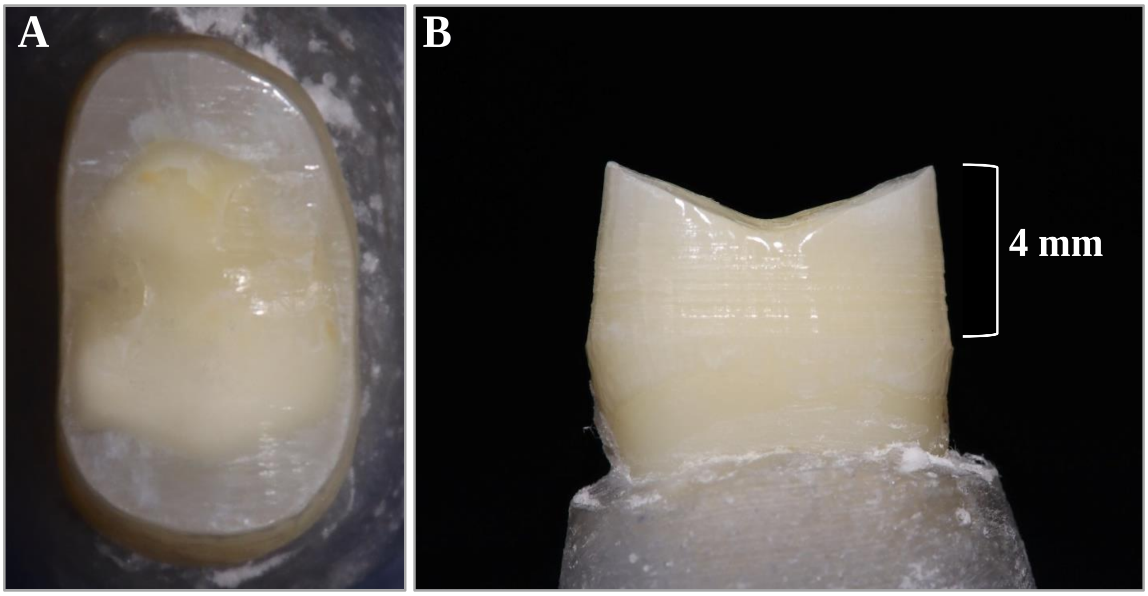

Figure 2: A prepared tooth sample from Group B. (A) Occlusal view. (B): Proximal view.

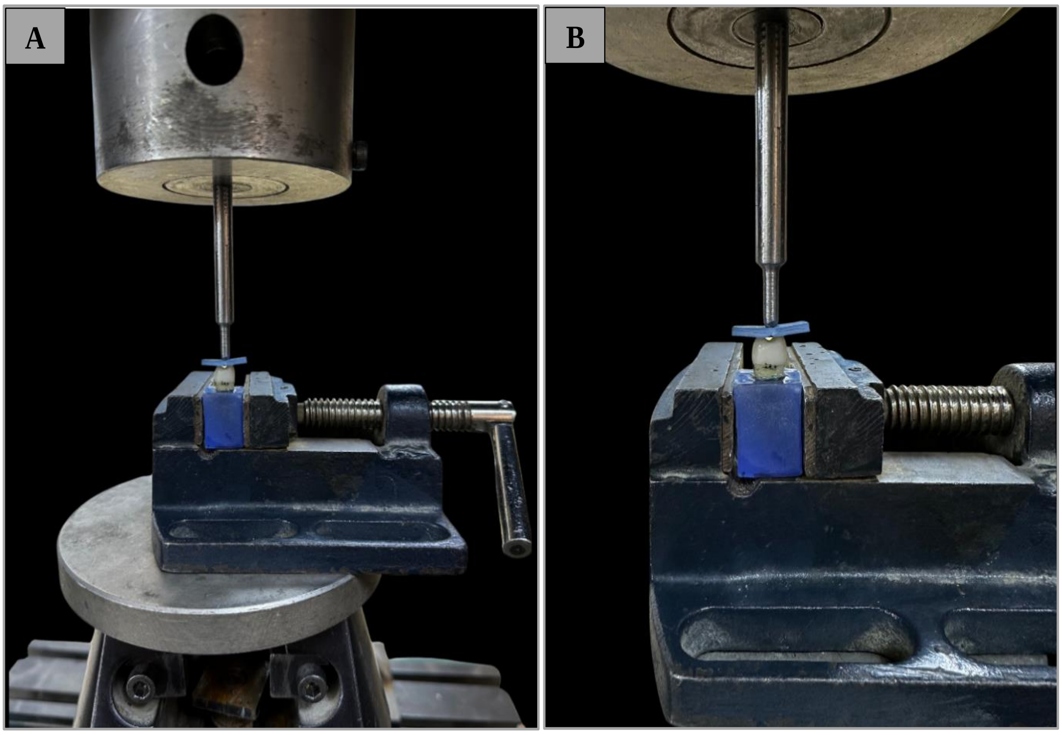

Figure 3: The computer-controlled universal testing machine. (A): Axial compression testing with a rod application. (B): The sample is secured to the testing device's base.

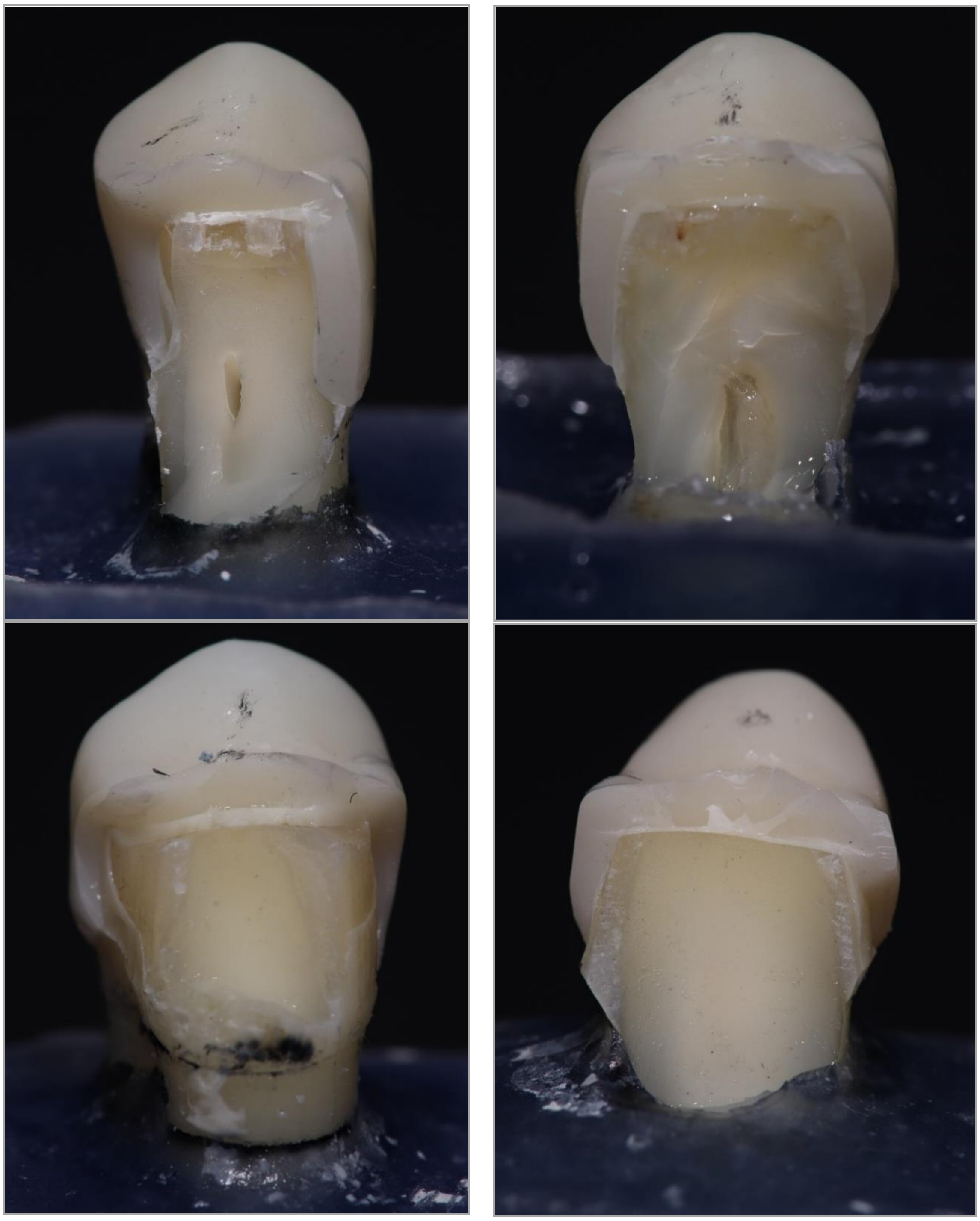

Figure 4: specimens showing Code V fracture mode

Table 1: Data for the fracture strength (mean and standard deviation) in Newton

main group	(A) Chamfer F.L			(B) Vertical F.L		
subgroup	(A1) LT	(A2) MT	(A3) Prime	(B1) LT	(B2) MT	(B3) Prime
Mean	4098.375	4008.375	3862.625	4641.125	4404.875	4246.75
SD	488.6845	364.1169	386.0951	378.8552	359.1559	291.4156

Table 2: Independent t-test for comparisons between groups

Subgroups		Mean Diff.	*t*	Df	*P*
A1	B1	-542.750	-2.483	14	0.026
A2	B2	-396.500	-2.193	14	0.046
A3	B3	-384.125	-2.246	14	0.041

Tables 3: ANOVA test for comparing fracture strength within groups

Groups		Sum of Squares	df	Mean Square	F	**Sig**.
A	Between Groups	226456.333	2	113228.167	0.653	**0.531**
	Within Groups	3643241.625	21	173487.696		
	Total	3869697.958	23			
Groups		Sum of Squares	df	Mean Square	F	**Sig.**
B	Between Groups	630264.583	2	315132.292	2.645	**0.095**
	Within Groups	2502131.250	21	119149.107		
	Total	3132395.833	23			

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