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TESTING THE STRENGTH OF THIN FEATHER-EDGE MONOLITHIC MULTILAYERED ZIRCONIA CROWNS: A PILOT STUDY WITH A NOVEL ACOUSTIC TEST

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Intoduction: Limited research has explored the mechanical characteristics of recently introduced multilayered monolithic zirconia (MZC) crowns with feather-edge margins design. Moreover, most of the conventional techniques for evaluating the mechanical behavior of brittle dental ceramics rely on destructive tests, making it impossible to precisely evaluate real strength values due to premature crack initiation detection failure.

Objectives: The main objective of the study was to assess the load capacity of translucent multilayered monolithic zirconia crowns with feather-edge margin thicknesses of 0.4 mm and 0.5 mm. Additionally, the research introduced a novel non-destructive acoustic emission testing (AET) technique in the laboratory to identify early cracks in dental ceramics.

Methods: Forty multilayered zirconia crowns produced using computer-aided design and computer-aided manufacturing (CAD/CAM) technology were evenly divided into two groups, each with distinct feather-edge margin thicknesses: 0.5 mm (group 1) and 0.4 mm (group 2). These crowns were securely cemented onto customized polymethyl methacrylate (PMMA) dies using a universal restorative glass ionomer. Subsequently, the crowns underwent a compressive axial loading test, controlled by an innovative AET crack detection system rooted in the principles of non-destructive laboratory testing.
Fractographic analysis was conducted to determine the location of crack or eventual fracture.

Results: The proportion of MZCs with a crack was statistically higher than the proportion with a fracture in the whole sample ($p<0.001$). In addition, the results showed that the crowns in group 1 exhibited higher loading values than those in group 2. The mean loading capacity in group was 911.2 N ± 614.7 N. Two locations of crack and fracture were registered: occlusal and marginal. No statistical association was observed between the two groups for the location of cracks or fractures.

Conclusions: The feather-edge crowns with a 0.5 mm margin thickness had a higher loading capacity than those with a 0.4 mm. However, the latter supports loads that exceed occlusal force in the oral cavity suggesting that 0.4 mm feathered edge MZCs may be a valid and less invasive alternative to thicker margins.
The novel load-to-fracture AET setup proved effective in detecting early crack initiation, suggesting it as a promising method for assessing the mechanical properties of brittle materials prior to failure, potentially impacting the field of dentistry.However more advanced research is needed to enhance the accuracy of the proposed technique.

Clinical implications: The examined MZC demonstrates the ability to withstand occlusal forces in a patient's mouth, offering clinical practitioners the option of embracing minimally invasive dentistry through the use of 0.4 mm feather-edge MZC in their treatment options. Furthermore, the positive results from the innovative acoustic emission testing technique, facilitating early crack detection, indicate a promising future for studying the behavior of brittle materials in dental laboratory testing.

Keywords: Zirconia, multilayered, feather edge, load bearing, acoustic emission testing.

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The authors declare no conflicts of interest.

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TESTER LA RÉSISTANCE DES COURONNES ZIRCONES MONOLITHIQUES MULTICOUCHES AVEC DES LIMITES EN PLUME FINES : ÉTUDE PILOTE AVEC UN NOUVEAU TEST ACOUSTIC

Introduction: Peu de recherches ont exploré les caractéristiques mécaniques des couronnes en zircone monolithique multicouche (CZM) récemment introduites avec un design de limites cervicales en forme de plume. De plus, la plupart des techniques conventionnelles d'évaluation du comportement mécanique des céramiques dentaires cassantes reposent sur des tests destructifs, rendant impossible l'évaluation précise des valeurs réelles de résistance en raison de l'incapacite de la détection prématurée des fissures.

Objectifs: L'objectif principal de l'étude était d'évaluer la resistance des couronnes en zircone monolithique multicouche translucide avec des épaisseurs de limites en forme de plume de 0,4 mm et 0,5 mm. De plus, la recherche a introduit une nouvelle technique novatrice de test d'émission acoustique (TEA) non destructive au laboratoire pour identifier les premières fissures dans les céramiques dentaires.

Méthodes: Quarante couronnes en zircone multicouche produites à l'aide de la technologie de conception et de fabrication assistées par ordinateur (CAO/FAO) ont été réparties uniformément en deux groupes, chacun avec des épaisseurs de limite en forme de plume distinctes : 0,5 mm (groupe 1) et 0,4 mm (groupe 2). Ces couronnes ont été solidement cimentées sur des dies en polyméthacrylate de méthyle (PMMA) à l'aide d'un ciment a verre ionomère universel . Par la suite, les couronnes ont subi un test de charge axiale compressive, contrôlé par un système innovant de détection des fissures (TEA) basé sur les principes des tests de laboratoire non destructifs. Une analyse fractographique a été réalisée pour déterminer l'emplacement de la fissure ou éventuelle fracture.

Résultat: La proportion de CZM avec une fissure était statistiquement plus élevée que la proportion avec une fracture dans l'ensemble de l'échantillon ($p<0{,}001$). De plus, les résultats ont montré que les couronnes du groupe 1 présentaient des valeurs de charge plus élevées que celles du groupe 2. La capacité de charge moyenne dans le groupe 2 était de 911,2 N ± 614,7 N. Deux emplacements de fissure et de fracture ont été enregistrés : occlusal et marginal. Aucune association statistique n'a été observée entre les deux groupes pour l'emplacement des fissures ou des fractures.

Conclusions: Les couronnes ZM avec des limites cervicales en forme de plume avec une épaisseur de limite cervicale de 0,5 mm présentaient une capacité de charge plus élevée que celles avec une épaisseur de 0,4 mm. Cependant, ces dernières supportent des charges dépassant la force occlusale dans la cavité buccale, suggérant que les CZM en forme de plume de 0,4 mm pourraient constituer une alternative valide et moins invasive aux limites plus épaisses. Le nouveau dispositif de test TEA de charge à la rupture s'est révélé efficace pour détecter les premières fissures, suggérant qu'il pourrait être une méthode prometteuse pour évaluer les propriétés mécaniques des matériaux cassants avant leur défaillance, potentiellement impactant le domaine de la dentisterie. Cependant, des recherches plus avancées sont nécessaires pour améliorer la précision de la technique proposée.

Implications cliniques: La CZM examinée démontre la capacité de résister aux forces occlusales , offrant aux praticiens cliniques la possibilité d'adopter une dentisterie invasive minimale grâce à l'utilisation de CZM en forme de plume de 0,4 mm dans leurs options de traitement. De plus, les résultats positifs de la nouvelle technique d'émission acoustique, facilitant la détection précoce des fissures, indiquent un avenir prometteur pour l'étude du comportement des matériaux cassants dans les tests de laboratoire dentaire.

Mots-clés: Zircone, multicouche, limite en forme de plume, capacité de charge, test d'émission acoustique.

Introduction

Contemporary dentistry is embracing a minimally invasive approach, marked by the evolution from zirconia veneered with porcelain crowns to full-contour restorations using monolithic zirconia. These crowns, known as Monolithic Zirconia Crowns (MZCs), have become pioneers in minimally invasive dentistry due to their excellent mechanical and optical properties [1, 2]. This transition addresses the issue of chipping failure associated with veneering ceramics, offering metal-free restorations with enhanced esthetics and biocompatibility [2-4].

Monolithic multilayer translucent zirconia crowns are a recent development that combines various shades and translucencies to achieve a more natural appearance [5]. Monolithic multilayer zirconia exhibits a notably higher level of translucency when compared to other types of monolithic zirconia materials. However, further tests including thermo-cycling, fractographic analysis and biocompatibility are needed to determine the mechanical behavior and clinical performance of this novel zirconia [5]. The fracture resistance of monolithic zirconia crowns is directly related to their thickness.

Furthermore, tooth preparation and finish line design play an important role in determining the strength of all-ceramic crowns [1]. Tooth preparation with a horizontal margin has a visible finish line in shoulder or chamfer form. However, a vertical preparation (also known as feather-edge or knife-edge) is one where the finish line is no longer represented by a line but by an area with no identifiable margin on the prepared tooth [4]. Thus, vertical preparation is a less invasive tooth preparation. This particular finish line design safeguards the periodontal tissues by retaining the utmost coronal and radicular tooth structures [1, 6].

Flexural Strength and fracture toughness tests are commonly employed to evaluate the mechanical properties of ceramic crowns. In both tests, a load is applied to a specimen using a universal testing machine [7]. While these tests offer valuable insights into the overall strength and performance of ceramic material, they rely on catastrophic failure. Non-destructive testing methods play a crucial role in identifying early internal defects in ceramic crowns before irreversible damage takes place [8-10].

Non-destructive testing (NDT) is a method used to examine materials without causing damage. Acoustic emission testing (AET) is a specific NDT approach for dental ceramics [11], relying on the detection of elastic waves produced by the rapid release of energy during early crack initiation. This laboratory technique enables real-time monitoring of structural integrity by offering insights into the fracture or damage process [12-14].

Few studies have reported load-to-crack tests on MZCs. with on feather-edge margin design.to evaluate and analyze the behavior of such crowns and their critical point of failure, a load-to- crack test was performed using a novel AET.

The aim of this study was to evaluate the effect of the 0.4mm thin feather edge margin design on the load- bearing capacity of posterior monolithic multilayer zirconia crowns compared to 0.5 thickness.

Materials and Methods

Forty monolithic crowns (Nacera Pearl®, Multi-layered Zirconia Multi-Shade C) were tested in the experiment, evenly distributed into two groups based on different margin thicknesses. Specifically, twenty crowns featured a uniform margin thickness of 0.5 mm (group 1), while the remaining twenty had a thickness of 0.4 mm (group 2). Group 1 samples were labeled alphabetically, and group 2 samples were labeled numerically. The study employed blind assessment for unbiased evaluation (Table 1).

An operator milled a single intact artificial mandibular first molar (Frasaco®) with a turbine handpiece and diamond burs of different diameters. The occlusal surface area was reduced by 1.5 mm [8] (functional cusps). The axial walls were tapered by 4 degrees and reduced by 1.2 mm (Komet® 8862). The artificial tooth was prepared with a feather-edge margin. All edges were rounded and polished by a handpiece micromotor, silicone polishing burs of different grain diameters and a polishing brush with a polishing paste (Dialux® blanc). The tooth that had been prepared was subsequently placed horizontally along the customized metallic mold's axis, which held cold-cure acrylic resin, with dimensions measuring 2.5 x 2.5 x 3 mm³.

The die (artificially prepared tooth and acrylic base) was scanned by a laboratory scanner (Dental Wings, Exocad, 3 Shape®). The file was processed using computer-aided design (CAD) software (Mayka Den-

Table 1: Fabrication method of MZCs in both groups and chemical composition

Fabrication method	Crown Material	Chemical Composition in %	
(Yenadent)	Zirconia (Nacera Pearl)	ZrO2+HfO2+Y2O3	> 99%
		Y2O3	4.5% - 6%

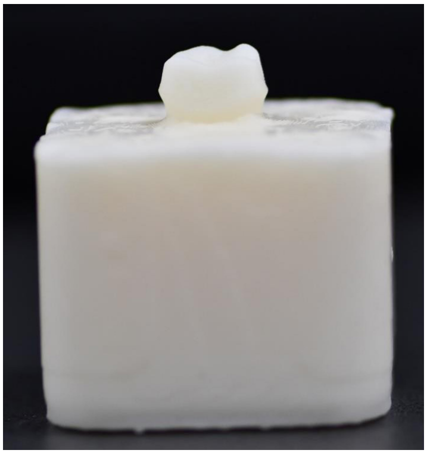

Figure 1. PMMA die.

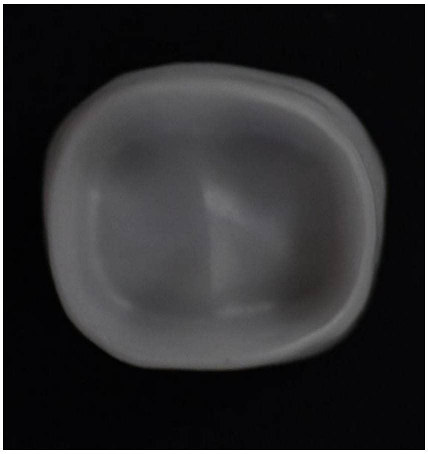

Figure 2. Posterior feather edge full monolithic zirconia crown.

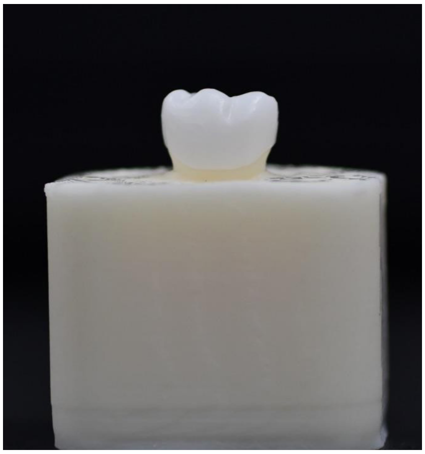

Figure 3. Zirconia crowns on PMMA base.

tal V6, Picasoft®), where the virtual 3D model was configured according to the specified guidelines for zirconia-based all-ceramic crowns, with the exception of setting the marginal thickness. It was fixed at 0.5 mm feather-edge for the first group and at 0.4 mm for the second group. By using the gap thickness tool in the CAD software, a space of 40 microns dedicated to the cement was formed. Based on the CAD die, twenty polymethylmethacrylate (PMMA) dies (Figure 1) were printed (Formlabs 2®, Massachusetts, USA) by a 3D printing machine (Yenadent®) for group 1 and twenty PMMA dies for group 2 (Table 2).

The MZCs of groups 1 and 2 were milled in a milling unit (Yenadent®) from four monolithic multilayered zirconia discs B2/B3 98mm x 16mm (Nacera Pearl®) (Figure 2). The MZCs were sintered at 1500°C in a sintering furnace according to the manufacturer's instructions.

The MZCs were cemented onto the PMMA dies with a universal restorative glass ionomer by the same operator in the two groups. After mechanically mixing a capsule of resin modified glass ionomer (GC Fuji II® capsules) in a dental amalgamator, an applicator gun was used to coat the inside of the MZC. A 1 mm rubber sheet was placed between the V-shape indenter and the crown to prevent direct contact

Table 2: Samples description

Group	Restorative Material	Fabrication method	Feather edge limit thickness	Die Material	Cementation by glassionomer
1(n=20) 2(n=20)	Monolithic Y- TZP translucent multilayered zirconia	CAD-CAM	0.5 mm 0.4 mm	PMMA	Capsules

damage and ensure the distribution of forces [1]. In order to stabilize the sample on the die, a universal testing machine was used to apply a 20 Newton vertical load on the occlusal surface and excess cement was eliminated. The load was maintained for a duration of 15 minutes till setting time. This procedure was repeated by the same operator for each MZC-PMMA die cementation (Figure 3). All samples were stored in an incubator for 7 days before mechanical testing [3].

No mechanical aging procedure was conducted. However, in agreement with the international organization of standardization, a thermocycling procedure was carried out. It consisted of 500 cycles alternating between 5 and 55°C. The immersion time in each bath was 20 seconds and the transfer time 5 seconds [3, 9, 10].

To prevent Hertzian damage, a 2 mm urethane rubber cylinder was also placed between the indenter and the crown. A V-shaped two-plane indenter was used to create an axial load of the occlusal surface of the specimens [3]. The compressive load was applied at a crosshead-speed of 0.5 mm per minute until the detection of the crack sound. To consolidate the crown with its PMMA die and prevent any noise interference, a preload of 20 Newton was applied to the specimen. After reaching this desired load, the recordings were re-initialized, and the desired test was started [3].

A high sensitivity microphone (MiniSPL®, NTI) was fixed at 1 centimeter from the sample in the UTM to detect the slightest noise change. The microphone, which has a sensitivity of 20 ±2 milliVolt/Pascal, was connected to an amplifier (Avalon Design 737®) integrated to a motherboard (chipset). A custom-fabricated "cut-off" switch system was integrated in the UTM to ensure non-destructive testing. Once the sound travels through the amplifier, the switch is initiated to turn off the modified UTM and therefore, stop the loading on the specimen. The microphone was programmed to listen to the machine's noise as "normal" and to be on the lookout for any other sound. Thus, the chipset detected the audio signal of the UTM as a normalized signal. The same chipset detects the emission of the crack sound and triggers a stop command that is sent to the machine. All the samples were loaded until the machine stopped and the values were automatically registered in Newton [11]. The microphone was placed at 1 mm from the specimen to detect the slightest noise change. During the test, to prevent external sound interferences, noise cancellation was ensured by corrugated foam sheets (Cactus®,USA).

Fractographic analysis of all the MZCs was conducted in an optical stereomicroscope (Leica ®Microsystems) under three magnifications: 6.4, 10 and 16x. Photographs of the all the samples were registered in various positions and analyzed to determine the location of the crack or eventual fracture [12].

The statistical analyses for the study were performed with SPSS Statistics for Windows, version 25.0 (IBM® Corp). Independent samples t-test was conducted to examine whether there was a significant difference in the load means between the two tested groups (Group 1 and Group 2). The assumption of equal variances was checked with Levene's test for equality of variances. Pearson chi-square test was used to compare the fracture type between the two groups. Additionally, Fisher's exact test was used to compare the location of the crack and the location of the fracture when it occurred. In every situation, a p-value less than 0.05 was considered statistically significant.

Results

The load-to-fracture testing machine was explored to see if it could detect cracks and prevent catastrophic failure of the dental crowns. Out of the whole sample (N=40), 20 (50%) had a crack and 16 (40%) had a fracture. A cross-tabulation was performed to assess the relationship between the presence of a crack and the occurrence of a fracture (Table 3). The results showed that all crowns with a crack did not exhibit a fracture during the testing (*: Sample size).

Table 3. Evaluation of the presence of crack and fracture in the whole sample

	No Fracture (n)	Fracture (n)	Total (N*)
No Crack (n)	4 (10%)	16 (40%)	20 (50%)
Crack (n)	20 (50%)	0 (0%)	20 (50%)
Total (N*)	24 (60%)	16 (40%)	40 (100%)

*: Population

A significant difference between the means of the two groups tested (groups 1 and 2). The fracture/crack load in group 1 was found to be significantly greater than the one observed in group 2 (p-value=0.034) (Table 4). The factor being compared between the groups (load) had a significant impact on the outcome, with group 1 demonstrating a greater load bearing capacity compared to group 2.

Table 4. Comparison of fracture load between group 1 and 2

Groupe		n	Mean	Std. Deviation
Load [N*]	1	20	1139.686	359.442
	2	20	911.200	296.479

*: Newton

There was no significant association found between group 1 and group 2 regarding the location of crack and/or fracture, whether it was occlusal or marginal (p-value=1.06).

The higher ration of crack to fracture revealed a high sensitivity of the AET technique.

Discussion

The study aimed to assess the mechanical performance of translucent multilayered monolithic zirconia crowns (MZCs) with different feather-edge margin thicknesses and introduce a novel acoustic technique for crack detection. The investigation utilized an in vitro approach, providing valuable insights into the behavior of these crowns under occlusal forces.

Monolithic zirconia is often used in dentistry due to its superior strength, biocompatibility, and durability [13, 14]. It is a single-piece restoration processed by CAD/CAM with no porcelain overlay, making it highly cost-effective and predictable [15, 16].

In general, translucent monolithic zirconia comes in three composition types, with the highest esthetic quality found in high-concentration yttria (5Y), followed by medium concentration yttria (4Y) and low concentration yttria (3Y) [17]. The yttria concentration plays a direct role in determining the esthetic appearance and mechanical properties of monolithic zirconia crowns (MZCs). Studies have shown that higher translucency is inversely proportional to fracture resistance [18, 19]. Various factors, including crown type, die preparation, and fabrication method, also contribute to the load at fracture [17].

The multilayer zirconia crowns in this study were fabricated with an occlusal thickness higher than 0.7 mm to ensure optimal fracture resistance and low stress value [2, 16, 20]. Vertical preparation feather-edge margins, were chosen for their less invasive nature, and for their improved periodontal tissue protection. Feather-edge margins allow an adequate fit of crowns and create a natural-looking transition with the tooth, improving both esthetics and function [21, 22]. They also help prevent plaque accumulation and enhance the overall performance of zirconia crowns, especially in areas subjected to heavy masticatory forces [23].

The choice of the die material is crucial during the load-to-failure tests to accurately evaluate the mechanical performance of restorative materials. The die material should simulate the behavior of natural teeth. PMMA resin, used as a die material, has a modulus of elasticity of 2100.05 ± 114.28 Megapascal approximately which is comparable to the modulus of dentin and enamel [24, 25]. In this study, PMMA/MZC specimens were used in load-to-fracture tests. In this study assessed three variables on the MZCs: crack and/or fracture detection, load value at crack or fracture and location of crack and/or fracture. An acoustic system with a microphone was used to detect the initiation of a crack in the material [26]. This allows non-destructive testing. This technique is a non-invasive type of testing that involves examining materials without causing damage [27, 28]. In brittle materials such as zirconia non-destructive load testing techniques are especially useful, because they prevent irreversible catastrophic failures [29]. Acoustic testing utilizes sound waves to detect and measure faults or defects in the material. NDT provides insight into the mechanical behavior of brittle material [26] (Figure 4).

The statistical analysis showed that a higher proportion of crowns had cracks compared to fractures in both groups. The acoustic testing machine successfully stopped before crown failure indicating its effectiveness in detecting cracks. The load-bearing values recorded in this study with the aid of crack detection were more accurate and comparable to those occurring in the oral cavity [1,30]. Four samples in one group did not fracture or crack, but were still included in the statistical analysis because the recorded loads were higher than mean masticatory force [31-33].

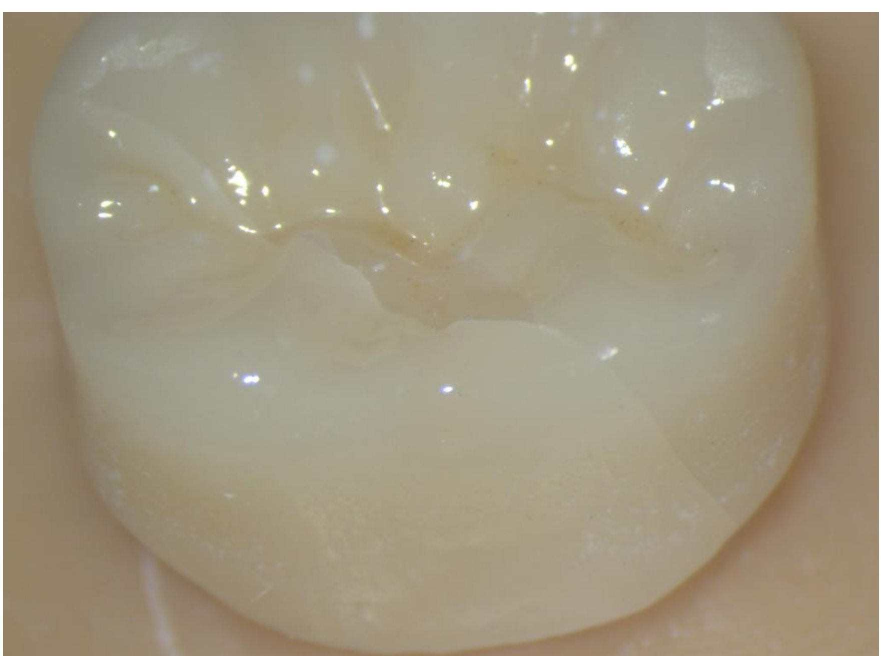

Figure 4. Sample O in group 1 showing occluso-marginal crack.

Different types of fractures and fissures were registered during the loading of MZCs [34, 35]. The present study aimed to compare the location of cracks and fractures. Fractographic analysis revealed various types of fractures and fissures during the loading of the crowns. Due to the small sample size, statistical analysis for occlusal crack location could not be conducted in both groups. Further research with a larger sample size is recommended.

In our investigation into the mean fracture load comparison between 0.4mm and 0.5mm thick zirconia crowns, our findings align with existing evidence emphasizing the significance of zirconia crown thickness in influencing fracture resistance. Notably, research by Sripetchdanond et al. [36] observed a substantial enhancement in fracture resistance by increasing zirconia crown thickness from 0.5mm to 1mm. Similarly, Schmitter et al. [36] demonstrated increased fracture resistance when thickness was raised from 0.4mm to 0.6mm. These collective results, including our own study, underscore the positive correlation between thicker zirconia crown margins and improved fracture resistance, supporting the importance of considering thickness in crown design [36].

Regarding the resistance of 0.4mm thick zirconia to occlusal forces, our study's findings are consistent with previous research. A study by Tan et al. [37] evaluated the fracture resistance of 0.4mm thick zirconia restorations and reported that they exhibited high fracture resistance and could withstand occlusal forces. Another study by Al-Rabab'ah et al. compared the fracture resistance of 0.4 mm thick zirconia crowns to that of lithium disilicate crowns and found that the zirconia crowns exhibited higher fracture resistance. Thus, the results of our study support the findings of these studies and suggest that 0.4mm thick zirconia restorations can withstand occlusal forces [38].

Concerning the AET, our findings align with previous studies.Wang et al. conducted a comparison between acoustic testing and dye penetration testing for crack detection in dental ceramics and reported higher sensitivity and specificity with acoustic testing compared to dye penetration testing. This finding aligns with our study's observations of significantly lower fracture loads identified using a AET in comparison to fracture loads determined without a AET, indicating the effectiveness of acoustic testing in early crack detection [39].

While the study shows promising results, it acknowledges some limitations. Mechanical aging was not conducted, and the emphasis was on initial observations and data collection, lacking an assessment of the long-term effects of mechanical aging. A comprehensive analysis could benefit from comparing these specimens with a control group that undergoes testing without AET to establish the acoustic system's reliability. Additionally, enhancing the study's power and obtaining more precise data on crack and fracture locations would be possible with a larger sample size.

Conclusion

In summary, this study offers valuable insights into the mechanical characteristics of feather-edge MZCs with varying margin thicknesses. 0.4 mm and 0.5 mm crowns were affected occlusally and marginally, when subjected to occlusal force. The results indicate that 0.4 mm feathered edge multilayered MZCs could serve as a viable and minimally invasive option compared to thicker margins. The novel load-to-fracture AET setup proved effective in detecting early crack initiation, suggesting it as a promising method for assessing the mechanical properties of brittle materials prior to failure, potentially impacting the field of dentistry. Continued more extensive research is essential to substantiate these initial findings across different clinical contexts.

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Ethical considerations

The protocol was accepted by the Ethical Committee of the "Université Saint Joseph", Beirut, and the study was carried out at their Dental Biomaterials Laboratory in the Innovation and Sport Campus. The load-to-crack experiment took place in a controlled laboratory setting. The materials used in vitro were resin, acrylic resin, monolithic zirconia, PMMA and glass-ionomers. No human participants or live animals were included in this study; therefore, certain ethical considerations were not applicable. This research respected the guidelines and ethical standards through strict study methodology, proper data management, and accurate documentation of findings.

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