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Original article

Evaluation of Fracture Toughness of Monolithic and Multilayered Zirconia for Prosthodontic Restorations: An *In-Vitro* Study

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The purpose of this in-vitro study was to compare the fracture toughness of monolithic zirconia and multilayered zirconia, two commonly used materials in prosthodontic restorations. Fracture toughness is a key mechanical property that determines a material's resistance to crack propagation under stress, which is crucial for the longevity and performance of dental restorations. A total of 20 zirconia discs (10 monolithic and 10 multilayered) were fabricated using Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology. The discs were subjected to loading and fracture toughness was measured using the indentation method with a Vickers micro-hardness tester. The fracture toughness values for monolithic zirconia (Group 1) were significantly higher than those for multilayered zirconia (Group 2), with mean values of 5.394 ± 0.378 MPa·m$^{1/2}$and 4.358 ± 0.394 MPa·m$^{1/2}$, respectively ($p < 0.0001$). These findings suggest that monolithic zirconia offers superior mechanical performance, making it a more suitable material for high-stress applications, while multilayered zirconia may be preferred for anterior restorations, where esthetics are prioritized. The study highlights the trade-off between mechanical strength and esthetic appeal in the selection of zirconia materials for dental restorations and provides valuable insights for optimizing material choice in clinical prosthodontics.

Introduction

The development of advanced materials in the field of fixed prosthodontics has significantly impacted the longevity and performance of dental restorations. Zirconia, specifically, has emerged as a popular material due to its excellent mechanical properties, including high strength and fracture toughness, making it an ideal choice for dental crowns and bridges [1]. Monolithic zirconia, fabricated from a single block of material, offers superior strength and minimal risk of delamination [2]. However, recent advancements have introduced multi-layered zirconia, which combines different layers with varying properties to improve esthetics while attempting to maintain structural integrity [3].

Fracture toughness is a critical parameter for evaluating the performance of dental materials, as it determines a material's ability to resist crack propagation under stress [4]. The fracture resistance of zirconia restorations can be influenced by several factors, including the material's composition, the number of layers, the manufacturing process, and the conditions under which the prostheses are subjected to mechanical forces during function [5]. Monolithic zirconia, while known for its strength, may lack the aesthetic properties of natural teeth, leading to the introduction of multi-layer zirconia systems [6]. These multi-layer systems, which incorporate a more translucent surface layer, attempt to balance both strength and esthetic appeal [7]. This paper aims to evaluate and compare the fracture toughness of monolithic and multi-layer zirconia in prosthodontics restoration applications. By investigating the mechanical performance of these two different zirconia structural, the study intends to provide insights into the optimal material choice for dental restorations, considering both functional and aesthetic demands. The findings will contribute to a better understanding of the strengths and limitations of these materials in clinical settings, ultimately guiding future advancements in prosthetic dentistry.

Materials and Methods

Materials

Two types of zirconia materials were used in this study: monolithic zirconia and multi-layered zirconia. Both materials were selected based on their widespread use in fixed prosthodontics and

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their relevance to the clinical question of fracture toughness. The following materials were used in the experiment: Monolithic Zirconia: group (1) Material: Noritake Kurary Composition: Fully dense zirconia with a uniform microstructure designed for strength and durability. Multi-layered Zirconia: group (2) Material: Noritake Kurary Composition: A multi-layered zirconia with a translucent surface layer and a stronger core. The core has a higher density compared to the surface. Both materials were processed using the same CAD/CAM milling technique for consistency.

Sample Preparation

A total of 20 zirconia discs (10 monolithic and 10 multi-layered) were fabricated for the study. Each disc had the following dimensions: Diameter: 10 mm Thickness: 1.5 mm The cylindrical discs were designed using AutoCAD software. The geometric specifications were exported and saved in stereolithography (STL) file format, a widely accepted 3D model format compatible with Computer-Aided Design and Manufacturing (CAD/CAM) systems [8], and milled from zirconia blocks using a milling machine.

Milling was carried out according to a standardized protocol based on the manufacturer's guidelines, ensuring uniform production of cylindrical specimens. The CAD design parameters were standardized across all samples to ensure uniformity in size and shape [9]. After milling, the samples were sintered in sintering furnace, following the manufacturer's sintering protocol. This process ensures complete densification and finalization of the zirconia material's crystalline phase. The multi-layered samples underwent a multi-stage sintering process [10].

Fracture Toughness Testing

Each disc was then subjected to loading using micro hardness tester Digital Display Vickers Micro-hardness Tester (Model HVS-50, Laizhou Huayin Testing Instrument Co., Ltd. China) with a Vickers diamond indenter and a 20X objective lens The load at failure and the crack length were recorded for each sample.

Fracture Toughness measurement

Fracture toughness was determined by the indentation technique. Three indentations were made on each specimen at widely separated locations with a load of 500 gram for 20 seconds in a micro hardness tester. The basis of the indentation technique is a series of cracks that form under heavy loading in a brittle material around a Vickers diamond indenter. When viewed superiorly the cracks appear to emanate from each of the corners of the indentation. The size of these cracks, expressed by the surface dimension "c" increases with an elevating indentation load and is an inverse function of fracture toughness. The fracture toughness was calculated IN table [1] with the following formula:

$$K_{IC} = 0.016\,(E/H)^{0.5}\,(P/c^{1.5})$$

where K_{IC} is the fracture toughness, **C** is the crack length (measured from the center of the indentation) figure [1], **P** is the applied indenter load**,** **H** is the Vickers hardness, a is the half diagonal of the indentation, and **E** is the elastic modulus. A notch was introduced at the center of each zirconia disc using a diamond blade to create a controlled crack initiation point.

Table 1. Fracture toughness measurement

Gr_1	G2
K_{IC} (MPa.m$^{1/2}$)	K_{IC} (MPa.m$^{1/2}$)
4.897852	4.495849
4.842875	4.063913
5.12665	4.096041
5.331516	3.966574
5.889485	4.051111
5.276552	4.111072
5.882472	4.188859
5.344402	4.626889
5.636317	5.087202
5.71679	4.89154

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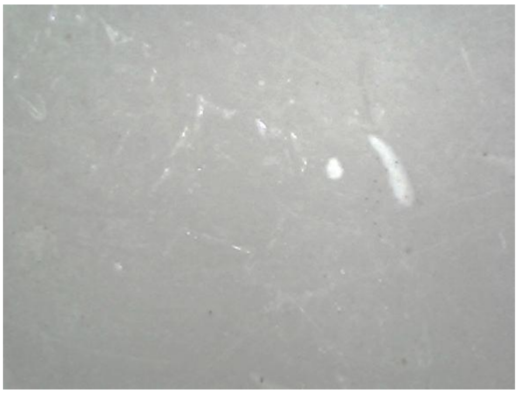

Figure 1. Crack length

Statistical Analysis

The fracture toughness values of the two groups (monolithic and multi-layered zirconia) were compared using a student's t-test. The significance level was set at $p < 0.05$. The data were analyzed using using Graph Pad Instat (Graph Pad, Inc.) software for windows. In addition, descriptive statistics (mean, standard deviation) were calculated for the fracture toughness of both material groups. This analysis aimed to determine whether there were statistically significant differences between the two groups in terms of their fracture toughness values.

Results

Fracture toughness ($MPa.m^{1/2}$) results (Mean±SD) for both groups are summarized in table [2]. It was found that *Gr (1)* recorded statistically *significant* higher mean value (*5.394 ± 0.378* $MPa.m^{1/2}$) than *Gr (2)* (*4.358 ± 0.394* $MPa.m^{1/2}$) as proven with student t-test ($p = 0.0001 < 0.05$) (Table 2).

Table 2. Comparison of fracture toughness ($MPa.m^{1/2}$) results between both groups

Variable		Descriptive statistics		t-test
		Mean±SD	95% CI (low-high)	P value
Material group	Gr_1	5.394 ± 0.378	5.124 – 5.665	<0.0001*
	Gr_2	4.358 ± 0.394	4.076 – 4.640	

*CI; confidence intervals. *; significant (p < 0.05). ns; non-significant (p>0.05)*

Discussion

The evaluation of fracture toughness in zirconia discs designed using CAD/CAM technology revealed a notable difference in the mechanical properties of monolithic versus multi-layered zirconia. Specifically, when considering discs with a diameter of 10 mm and a thickness of 1.5 mm, monolithic zirconia exhibited superior fracture toughness compared to multi-layered zirconia, which aligns with several studies in the field [11-13].

Monolithic zirconia is known for its inherent strength due to its uniform microstructure and dense crystalline phase. This material typically possesses a high fracture toughness because it lacks interfaces between layers, which are potential sites for crack initiation and propagation [14]. The homogeneity of monolithic zirconia contributes to its ability to resist crack growth, making it more reliable under high-stress conditions, especially in discs with a relatively thin 1.5 mm thickness, which would be more vulnerable to crack initiation in a multi-layered configuration. Additionally, monolithic zirconia benefits from its high flexural strength, which further reduces the likelihood of failure under masticatory forces [15], and the fracture strength of 4-unit gradient multilayered zirconia 5Y-TZP/3Y-TZP was significantly higher than bilayered zirconia 3Y-TZP when both were subjected to fracture resistance tests after mastication simulation [16].

On the other hand, multi-layered zirconia systems are designed to optimize both strength and esthetic properties, incorporating layers with different mechanical characteristics. The surface layer of multi-layered zirconia typically has a higher translucency, which enhances the esthetic appeal, particularly in restorations visible in the smile zone. However, this translucency is often achieved at the cost of the material's fracture toughness, as the surface layer is usually less dense and has a lower strength compared to the underlying core [17]. This gradient in material properties can create weak interfaces between the layers, which may become sites of stress concentration, ultimately reducing the overall fracture resistance compared to monolithic zirconia.

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The fracture toughness of multi-layered zirconia can also be influenced by the design and fabrication process. CAD/CAM technology allows for highly precise manufacturing of both monolithic and multi-layered zirconia discs, but the multi-layered systems may still face challenges related to the bonding between layers during the sintering process [18]. Even with advanced techniques, these interfaces may not be as strong as the single-phase structure of monolithic zirconia, making the material more prone to delamination or failure under load, particularly in thinner designs like the 1.5 mm discs evaluated in this study. Interestingly, while monolithic zirconia outperforms multi-layer zirconia in terms of fracture toughness in the context of this study, it should be noted that multi-layered zirconia still offers significant advantages in terms of esthetics, particularly in restorations requiring high translucency [19,20]. Therefore, the choice between these two materials should be based on a balance of mechanical performance and aesthetic requirements. In clinical situations where strength and durability are paramount, such as in posterior restorations or patients with bruxism, monolithic zirconia may be the superior choice. Conversely, for anterior restorations or patients where esthetics play a critical role, multi-layered zirconia may be preferred, even with the slight compromise in fracture toughness.

Conclusion

while monolithic zirconia exhibits higher fracture toughness in discs of 10 mm diameter and 1.5 mm thickness, multi-layered zirconia remains a viable option depending on clinical needs. Future research should explore the performance of these materials under a broader range of clinical scenarios, including different loading conditions and long-term wear studies, to provide more comprehensive guidance for material selection in fixed prosthodontics.

Conflict of interest. Nil

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المستخلص

ان الهدف من هذه الدراسة المخبرية المقارنة هو تقييم صلابة الكسر لكل من الزيركونيا الأحادية الطبقة والزيركونيا متعددة الطبقات، وهما مادتان مستخدمتان بشكل شائع في ترميمات الأسنان. تُعتبر صلابة الكسر خاصية ميكانيكية رئيسية تحدد مقاومة المادة لتكاثر الشقوق تحت الضغط، وهو ما يعتبر أمرًا ضروريًا لضمان طول عمر وكفاءة الترميمات السنية. تم تصنيع 20 قرصًا من الزيركونيا (10 أحادية الطبقة و10 متعددة الطبقات) باستخدام تقنية التصميم بمساعدة الكمبيوتر والتصنيع بمساعدة الكمبيوتر . الزيركونيا الأحادية الطبقة والزيركونيا متعددة الطبقات خضعت الأقراص لاختبار صلابة، وتم قياس صلابة الكسر باستخدام طريقة الإدخال مع جهاز اختبار الصلابة الميكروية (Vickers). أظهرت نتائج الدراسة أن قيم صلابة الكسر للزيركونيا الأحادية الطبقة (المجموعة 1) كانت أعلى بشكل ملحوظ من تلك الخاصة بالزيركونيا متعددة الطبقات (المجموعة 2)، حيث كانت القيم المتوسطة 5.394 ± 0.378 $MPa•m^{1/2}$ و4.358 ± 0.394 $MPa•m^{1/2}$ على التوالي ($p < 0.0001$). تشير هذه النتائج إلى أن الزيركونيا الأحادية الطبقة توفر أداءً ميكانيكيًا أفضل، مما يجعلها مادة أكثر ملاءمة للاستخدام في التطبيقات ذات الضغط العالي، بينما قد تكون الزيركونيا متعددة الطبقات مفضلة للترميمات الأمامية حيث تكون الجمالية هي الأولوية. تبرز الدراسة التوازن بين القوة الميكانيكية والجاذبية الجمالية في اختيار مواد الزيركونيا للترميمات السنية، وتقدم رؤى قيمة لتحسين اختيار المواد في مجال طب الأسنان التعويضي.

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