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Compressive strength of connectors with different areas in three-unit polychromatic monolithic zirconia fixed partial dentures

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ABSTRACT

Objective: To compare the compressive strength of connectors with different areas in three-unit fixed partial dentures (FPDs) fabricated from three types of polychromatic monolithic zirconia using CAD/CAM technology. **Materials and methods:** An *in vitro* experimental study was conducted with 30 FPD samples fabricated from three brands of polychromatic monolithic zirconia: IPS e.max® ZirCAD MT Multi (Ivoclar Vivadent; Schaan, Liechtenstein), Katana™ Zirconia Super Translucent Multi Layered (STML) (Noritake Dental Supply; Okayama, Japan), and Ceramill® Zolid fx Multilayer (Amann Girrbach; Koblach, Austria). For each brand, 10 specimens were fabricated and subdivided into two subgroups according to connector area: 9 mm^2 (n = 5) and 12 mm^2 (n = 5). The specimens were subjected to compressive strength testing in a universal testing machine (CMT-5L, LG; Anyang, South Korea), applying a vertical load at the center of the pontic until fracture occurred. The obtained data were analyzed using the Kruskal-Wallis and Mann-Whitney U tests. **Results:** The 12 mm^2 connectors showed significantly greater compressive strength than the 9 mm^2 connectors, regardless of the brand used (medians of 1557.76 N [IQR: 425.54 N] vs. 1180.40 N [IQR: 708.32 N]; $p = 0.024$). Katana™ Zirconia STML and IPS e.max® ZirCAD MT Multi zirconia achieved higher strength values than Ceramill® Zolid fx Multilayer for both connector sizes ($p < 0.05$). **Conclusions:** Connector area significantly influenced the compressive strength of polychromatic monolithic zirconia FPDs. The 12 mm^2 connectors exhibited greater strength, and Katana™ Zirconia STML and IPS e.max® ZirCAD MT Multi showed better performance compared with Ceramill® Zolid fx Multilayer. These findings suggest that increasing connector area may favor the clinical longevity of restorations.

Keywords: fixed partial dental prosthesis; monolithic zirconia; compressive strength; CAD/CAM technology.

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INTRODUCTION

The clinical success of a fixed partial denture (FPD) depends on multiple factors, such as the position of the missing tooth, the available space, and the connector dimensions; these variables influence both the restoration design and the selection of the restorative material (1,2). These factors are critical in multi-unit restorations, where connector structural integrity and stress distribution determine the durability of the FPD.

For decades, metal-ceramic prostheses have been regarded as the gold standard due to their high survival rates, reaching approximately 94% at 5 years (3,4). However, they present limitations such as possible metal exposure in the cervical region, allergic reactions, gingival tissue pigmentation caused by metallic ion release (5), and compromised esthetics due to the grayish, opaque appearance of metal, so they do not reproduce the natural translucency of dental tissues (6).

In this context, all-ceramic FPDs have gained preference because of their high biocompatibility and superior esthetics compared with metal-based prostheses (1,7). Among ceramic materials, zirconia has emerged as one of the most relevant in dentistry because of its remarkable mechanical properties (6), including high flexural strength (>1000 MPa) and considerable fracture toughness (6,8). Nevertheless, clinical failures, especially in the connector region, still represent a significant challenge (8).

The clinical behavior of zirconia is closely related to its crystalline structure. This material exhibits three principal phases: i) monoclinic, at room temperature; ii) tetragonal, above 1170 °C; and iii) cubic, from 2370 °C to its melting point at 2680 °C (9–11). During cooling, the transition from the cubic phase to the monoclinic phase—through the tetragonal phase—may generate a volumetric increase of up to 5%, inducing internal stresses and crack formation (11–13). To prevent this transformation, stabilizing oxides (yttrium, cerium, or magnesium) are added, allowing the material to maintain its tetragonal and cubic phases at room temperature (9–12).

According to its composition and phase proportions, zirconia is classified into four types (7). Type I corresponds to yttria partially stabilized tetragonal zirconia polycrystalline (3 mol%), which provides high mechanical strength and clinical reliability. Type II maintains a similar structure but with variations in the content and distribution of aluminum oxide (Al_2O_3). Type III is fully stabilized with yttria (5 mol%) and exhibits a mixed cubic-tetragonal structure with 50% cubic phase content; this increases its translucency (14–16), although it reduces its mechanical properties (7,11). Type IV zirconia (stabilized with 4 mol% yttria) provides a balance between strength and translucency, with flexural strength values close to 900 MPa and moderate translucency (~30%). These properties make it a viable alternative for extensive monolithic restorations, in which connector design and dimensions are determining factors for clinical durability (7,16).

Among the most relevant complications of zirconia FPDs are fractures in the connector region and chipping or delamination of the veneering ceramic in non-monolithic restorations (5,11,17). Connectors require adequate dimensions because they are areas prone to fracture, particularly in the presence of more than one pontic (13–18). Larsson et al. (19) demonstrated that four-unit FPDs with connectors of at least 4 mm^2 exhibit significantly greater fracture resistance. Similarly, finite element analyses have shown that increasing connector height reduces stress levels within the connector area (8,19,20). Hamza et al. (8) reported that larger connector dimensions result in higher flexural strength. On the other hand, since fractures usually originate in the gingival region of the connector, a rounded design is recommended to optimize stress distribution (10,20,21).

Chipping represents another frequent complication, with rates of up to 15% at two years and between 13% and 15% over periods of three to five years (22,23). This issue prompted the development of monolithic zirconia restorations, which offer advantages such as lower manufacturing costs, increased safety, elimination of veneering ceramic shrinkage, and reduced thickness requirements, allowing for less invasive tooth preparations.

Consequently, type IV monolithic zirconia restorations have emerged as a promising alternative to metal-ceramic FPDs. Nevertheless, there is still no consensus in the literature regarding the ideal minimum connector dimensions for these restorations, despite their direct influence on clinical longevity. Therefore, the objective of this in vitro study was to compare the compressive strength of connectors with different areas in three-unit type IV polychromatic monolithic zirconia fixed partial dentures (FPDs).

MATERIALS AND METHODS

This in vitro experimental study was conducted using 30 three-unit polychromatic monolithic zirconia fixed partial dentures (FPDs) designed to replace the maxillary right second premolar. The sample size was determined with a statistical power of 80% and a margin of error of 5%. The effect size calculation was based on the study by Plengsombut et al. (9), who reported statistically significant differences among groups with a minimum of five specimens per group. Only samples meeting the required dimensions and showing no visible defects or signs of fracture were included.

Materials and experimental groups

Three commercial brands of polychromatic monolithic zirconia were used: IPS e.max® ZirCAD MT Multi (Ivoclar Vivadent; Schaan, Liechtenstein), Katana™ Zirconia Super Translucent Multi Layered (STML) (Noritake Dental Supply; Okayama, Japan), and Ceramill® Zolid fx Multilayer (Amann Girrbach; Koblach, Austria). For each brand, ten specimens were fabricated and distributed into two subgroups (n = 5): one with rounded 9 mm^2 connectors and the other with 12 mm^2 connectors.

Fabrication of master models

To simulate a three-unit FPD, a master model was fabricated with two abutments corresponding to the maxillary right first premolar and first molar. Each abutment was designed using computer-aided design (CAD) software (Figure 1A), with 1.5 mm axial reductions, 2 mm occlusal reductions, a 12° taper, and a 1.2 mm chamfer finish line.

The digital master models were printed using a computer-aided manufacturing (CAM) system with additive manufacturing technology (M2 Cusing, Concept Laser; Lichtenfels, Germany), employing a cobalt-chromium (Co-Cr) alloy. After that, they were fixed into acrylic blocks with an inter-abutment distance of 7 mm to simulate the space of the missing maxillary right second premolar (Figure 1B). Each block was scanned using an intraoral scanner (Primescan, Dentsply Sirona; Bensheim, Germany) and reprinted through 3D CAM in Co-Cr (M2 Cusing, Concept Laser; Lichtenfels, Germany), incorporating a rigid metallic base (Figure 1C).

Specimen fabrication

The definitive master model was scanned using a laboratory scanner (inEos X5, Dentsply Sirona; Bensheim, Germany) (Figure 2A). Based on the file obtained, the frameworks were designed using DentalCAD® (exocad; Darmstadt, Germany), where the connectors were defined according to the dimensions assigned to each group (Figures 2B, 2C, and 2D).

The FPDs were milled from polychromatic zirconia discs in a partially sintered state. Due to material shrinkage during this process, the frameworks were machined approximately 30% larger than their final dimensions. Subsequently, sintering was performed in an inFire HTC Speed furnace (Dentsply Sirona; Bensheim, Germany) using a conventional cycle at 1510 °C for eight hours; after this period, the restorations reached their definitive dimensions (Figure 3).

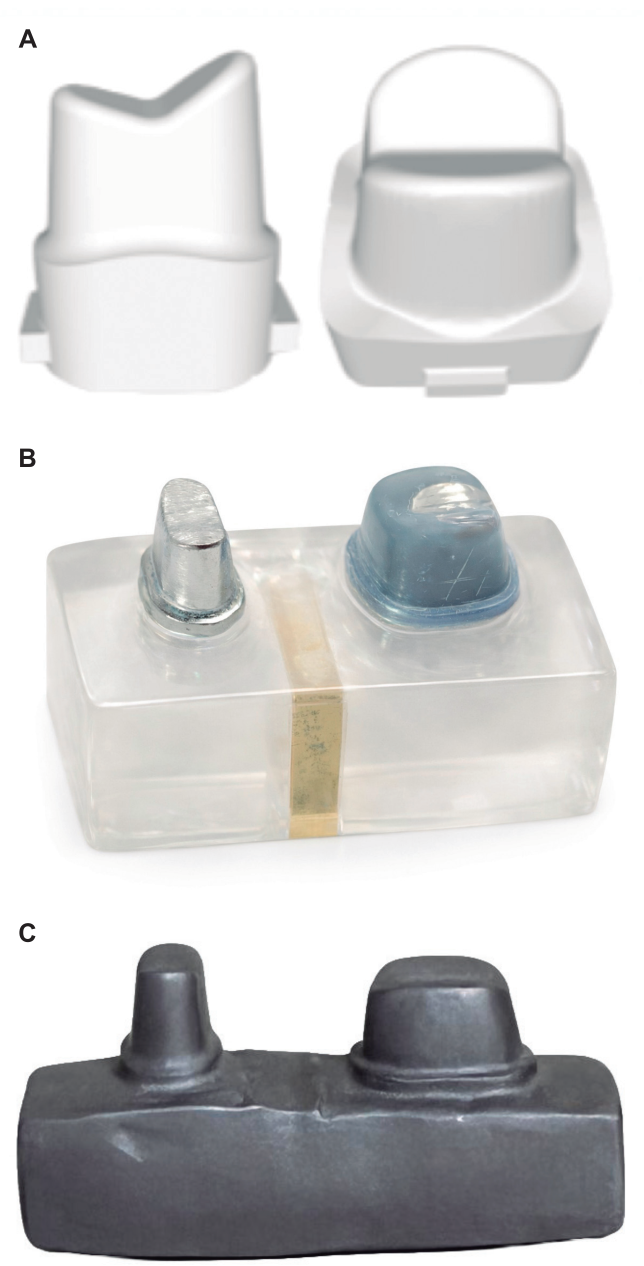

Figure 1. A) CAD software design; B) Master model in acrylic block; C) Master model with Co-Cr base.

Finally, the frameworks were passively seated on the master model without cementation to ensure stability and allow removal during mechanical testing.

Strength testing

The specimens underwent strength testing using a universal testing machine (CMT-5L, LG; Anyang, South Korea). A vertical load was applied at the center of the pontic through a 4.2 mm diameter steel ball at a speed of 0.75 mm/min until fracture of the FPDs occurred.

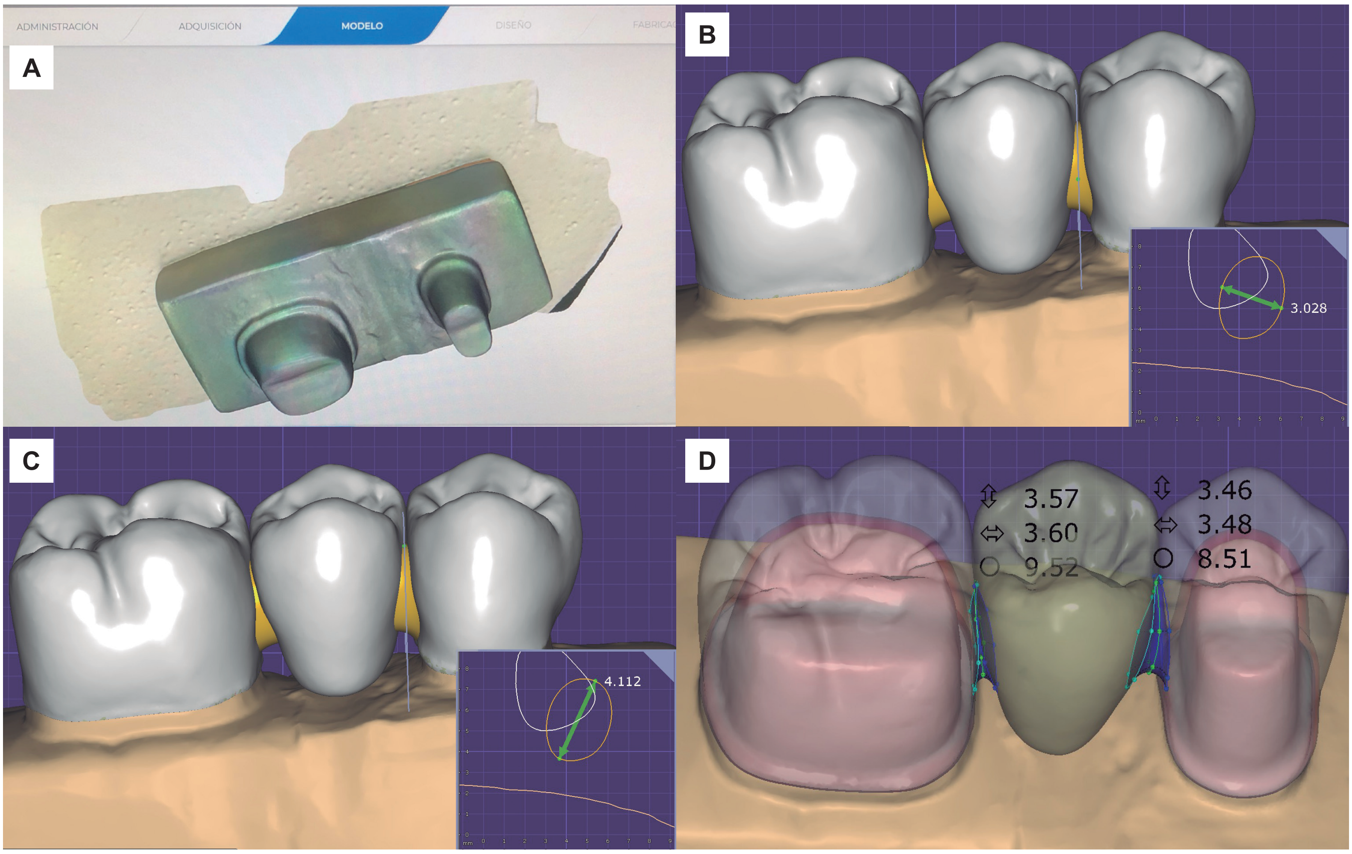

Figure 2. A) Scanning of the master model; B) Design of fixed partial dentures with a 9 mm^2 connector diameter; C) Design of fixed partial dentures with a 12 mm^2 connector diameter; D) Internal view of the fixed partial denture design.

Figure 3. IPS e.max® ZirCAD MT Multi fixed partial denture framework with a 12 mm^2 connector diameter.

Statistical analysis

Data analysis was performed using Stata v. 14.0 (StataCorp®; College Station, Texas, USA). Data normality was assessed using a histogram, which revealed a non-normal distribution. Compressive strength among the three brands was compared for the 9 mm^2 and 12 mm^2 connectors using the Kruskal-Wallis test. Additionally, a post hoc test was applied to identify differences among zirconia brands within each connector type. Similarly, the medians obtained for the 9 mm^2 and 12 mm^2 connectors were compared using the Mann-Whitney U test. For all analyses, a 95% confidence level was established.

Ethical considerations

The study was evaluated by the Institutional Ethics and Research Committee of the Stomatology Program at Universidad Científica del Sur. In accordance with the board resolution regarding precision standards for exemption from the Ethics Committee, the study was approved under registration No. 232-2020-POS8.

RESULTS

The results demonstrated that FPDs with 12 mm^2 connectors exhibited significantly greater compressive strength than those with 9 mm^2 connectors (medians: 1557.76 N versus 1180.40 N, respectively; $p = 0.024$), regardless of the zirconia used (Table 1).

When analyzing the performance of each brand, significant differences were identified among the three evaluated options for both connector sizes. For the 9 mm^2 connectors, Katana™ Zirconia STML achieved the highest strength value (1577.39 N), followed by IPS e.max® ZirCAD MT Multi (1326.26 N) and

Ceramill® Zolid fx Multilayer (811.13 N) (p = 0.006). For the 12 mm² connectors, Katana™ Zirconia STML again demonstrated the highest compressive strength (1788.61 N), followed by IPS e.max ZirCAD MT Multi (1700.91 N) and Ceramill® Zolid fx Multilayer (1335.77 N) (p = 0.016) (Table 1).

Table 1. Comparison of compressive strength according to zirconia type and connector area.

Connector area size	Zirconia type	Median (N)	IQR	P-value*	Median (N)	IQR	p-value**
9 mm²	Ceramill® Zolid fx Multilayer	811.13	135.41				
	IPS e.max® ZirCAD MT Multi	1326.26	368.68	0.006	1180.40	708.32	
	Katana™ Zirconia STML	1577.39	72.05				0.024
12 mm²	Ceramill® Zolid fx Multilayer	1335.77	150.84				
	IPS e.max® ZirCAD MT Multi	1700.91	236.70	0.016	1557.76	425.54	
	Katana™ Zirconia STML	1788.61	232.95				

N: Newton; IQR: Interquartile range.
* Kruskal-Wallis test.
** Mann-Whitney U test.

Statistical comparisons indicated that Ceramill® Zolid fx Multilayer presented significantly lower values compared with Katana™ Zirconia STML and IPS e.max ZirCAD MT Multi for both 9 mm² and 12 mm² connectors ($p < 0.05$). In contrast, no significant differences were observed between Katana™ Zirconia STML and IPS e.max® ZirCAD MT Multi for either of the evaluated connector sizes ($p > 0.05$) (Table 2).

Regarding the effect of connector area according to zirconia brand, only Ceramill Zolid FX Multilayer showed significant differences between the 9 mm² and 12 mm² connectors (p = 0.009), whereas Katana™ Zirconia STML and IPS e.max® ZirCAD MT Multi did not show significant variations between both connector sizes ($p > 0.05$) (Table 2).

Table 2. Compressive strength according to zirconia type and connector size.

Connector area size	Zirconia type	p-value
9 mm²	Ceramill® Zolid fx Multilayer vs. Katana™ Zirconia STML	0.001*
	Ceramill® Zolid fx Multilayer vs. IPS e.max® ZirCAD MT Multi	0.014*
	Katana™ Zirconia STML vs. IPS e.max® ZirCAD MT Multi	0.179*
12 mm²	Ceramill® Zolid fx Multilayer vs. Katana™ Zirconia STML	0.003*
	Ceramill® Zolid fx Multilayer vs. IPS e.max® ZirCAD MT Multi	0.017*
	Katana™ Zirconia STML vs. IPS e.max® ZirCAD MT Multi	0.262*
9 mm² vs. 12 mm²	Ceramill® Zolid fx Multilayer	0.009**
	Katana™ Zirconia STML	0.250**
	IPS e.max® ZirCAD MT Multi	0.117**

* Dunn's post hoc test.
** Mann-Whitney U test.

Regarding the fracture pattern, the most frequent fracture location was observed in the pontic and abutment regions, occurring in 24 specimens (80.0%). Of these, 11 fractures (45.8%) corresponded to 9 mm² connectors, whereas 13 fractures (54.2%) were associated with 12 mm² connectors. In addition, 4 fractures (13.3%) were observed exclusively in the distal abutment, all associated with 9 mm² connectors; and one fracture (3.3%) simultaneously involved the pontic and the mesial abutment in a specimen with a 12 mm² connector.

DISCUSSION

Esthetic demands in dentistry have increased considerably, even for rehabilitations in the posterior region.

However, the selection of restorative materials should not prioritize esthetics alone, since mechanical performance is crucial to ensuring clinical longevity. In this context, type IV zirconias represent an optimal alternative for the fabrication of monolithic FPDs, as they provide a balance between optical properties and mechanical strength, particularly when the available prosthetic space is limited (1,24).

This study evaluated the compressive strength of 9 mm² and 12 mm² connectors in FPDs fabricated with three types of type IV monolithic zirconia: Ceramill® Zolid fx Multilayer, Katana™ Zirconia STML, and IPS e.max® ZirCAD MT Multi. The selection of these brands was based on their comparable microstructural and esthetic characteristics, as well as their widespread use in prosthetic rehabilitations.

Unlike studies based on ceramic bars subjected to flexural testing (9), the present investigation employed an anatomical FPD design based on the proposal of Hamza et al. (8) in order to faithfully reproduce clinical conditions. This approach avoids the overestimation of strength observed in rigid laboratory configurations and enables a more realistic stress distribution (25). Experimental designs with immovable supports tend to artificially increase load-bearing capacity, which may lead to overestimation of the material's strength (19,25).

Following this analytical approach, rounded connectors were selected, since several investigations have demonstrated that this design offers greater resistance to occlusal loading than sharp configurations (9,19,20,26). Hamza et al. (8) demonstrated that a rounded curvature radius of 0.6 mm, in 2×3 mm and 3×3 mm samples, exhibited significantly greater strength than a radius of 0.1 mm. Similarly, Hafezeqoran et al. (27) reported that sharp designs are not advisable in areas subjected to high stress levels, especially when occlusogingival height is limited.

Regarding dimensions, the evidence indicates that the recommended connector areas for three-unit zirconia FPDs are generally around 16 mm² (4,23); however, manufacturers suggest a minimum cross-sectional area of 7 to 9 mm² for 3Y-TZP and 12 to 16 mm² for 4Y-PSZ and 5Y-PSZ (26). In this study, connector dimensions of 9 mm² and 12 mm² were evaluated, slightly smaller than conventional recommendations, to analyze mechanical behavior under more demanding conditions. This choice reflects common clinical situations in which anatomical or esthetic limitations require a reduction in the connector area.

The results demonstrated that increasing the connector cross-sectional area is associated with a significant increase in compressive strength. This behavior can be explained by the reduction in stress concentration resulting from a greater resistant volume. These findings are consistent with those reported by Salimi et al. (28), who observed that 4×4 mm connectors exhibited markedly greater strength than 3×3 mm connectors, concluding that connector size exerts a greater influence on strength than structural modifications. Similarly, Studart et al. (29) observed a higher incidence of fractures in connectors with smaller cross-sectional areas, and finite element analyses have shown reductions of up to 50% in stress levels when the height of these connectors is increased (4, 23). Collectively, these data reinforce the consensus that connector dimensions are determinant factors in mechanical strength. Similarly, Hafezeqoran et al. (27) reported strength increases exceeding 120% when comparing 9 mm² and 12 mm² connectors.

Analysis of the fracture pattern revealed that most failures were concentrated in the pontic and the junctions with the abutments, which are areas of greater stress accumulation under axial loading. This behavior underscores the need to optimize both the dimensions and geometry of the restoration (30).

Consistent with these findings, several in vitro studies have evaluated the strength of the analyzed brands using similar connector areas. For example, a study involving IPS e.max® ZirCAD MT Multi with 9 mm² connectors reported a mean strength of 1353.0 N ± 178.0 N, a result comparable to that found in this study (1372.63 N ± 293.01 N) (30). Similarly, Subsomboon and Urapepon (25) analyzed the effect of connector design on the strength of three types of monolithic zirconia—including Katana™ Zirconia STML (type IV zirconia)—and reported a mean strength of 1663.6 N ± 372.7 N for 9 mm² connectors, similar to the value obtained in this study (1601.01 N ± 315.20 N).

In the present study, Katana™ Zirconia STML exhibited the highest compressive strength, followed by IPS e.max® ZirCAD MT Multi and Ceramill Zolid fx Multilayer. These differences are attributable to microstructural characteristics: Katana™ Zirconia STML presents a multilayer gradient with a greater tetragonal phase content in the inner layers, favoring toughening through martensitic transformation. IPS e.max® ZirCAD MT Multi combines 3Y and 4Y phases to balance translucency and mechanical strength. In contrast, Ceramill® Zolid fx Multilayer contains a higher percentage of cubic phase, which improves light transmission but reduces toughening capacity, resulting in lower strength values (31).

It should be emphasized that the chemical composition and relative proportion of crystalline phases in the different generations of zirconia directly influence their mechanical strength. The most recent generations (types III and IV) incorporate a higher cubic phase content (4Y-TZP and 5Y-TZP), which increases translucency but reduces strength (7). However, regardless of the material type, connector geometry remains a critical determinant of stress distribution, as demonstrated by the findings of the present study.

In addition to evaluating the intrinsic properties of the material, it is essential to consider the expected clinical performance of the prosthesis. FPDs must withstand the occlusal forces generated by the patient, which depend on factors such as age, sex, and, primarily, the individual's dental status (32). Average occlusal force in adults ranges from 400 to 800 N in the posterior region (8,33). The values obtained in this investigation substantially exceeded this range, supporting the clinical feasibility of FPDs with 9 mm² and 12 mm² connectors for the replacement of a second premolar.

In addition, existing clinical studies further support this interpretation. A randomized clinical trial reported a 90% success rate for monolithic zirconia FPDs, whereas other reports indicated survival rates ranging from 96.7% to 100% (34); this corroborates the feasibility of using 9 mm² connectors in the posterior region. This high survival rate may be explained by the structural stability of zirconia and by the connector dimensions employed in those studies, which were 9 mm².

In the present in vitro study, limitations inherent to the differences between in vivo and in vitro environments are identified. These include the elastic modulus of supporting structures, oral cavity moisture conditions, thermal variations, intermittent dynamic loading, and the effects of cementation. Nevertheless, in vitro testing is fundamental for the preliminary evaluation of new dental materials before clinical application, thereby contributing to patient safety.

CONCLUSIONS

An increase in the connector area is positively correlated with greater compressive strength in monolithic zirconia fixed partial dentures (FPDs). In particular, frameworks fabricated with Katana™ Zirconia STML and IPS e.max ZirCAD MT Multi exhibited higher strength values, for both 9 mm² and 12 mm² connectors, compared with Ceramill™ Zolid fx Multilayer. These findings demonstrate that the microstructural variations among the evaluated zirconia materials significantly influence their mechanical performance. In the same way, they reinforce that appropriate connector design constitutes a determining factor in ensuring the clinical longevity of restorations.

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WGGP: conceptualization; writing of original draft, research, resources, project administration, writing - review & editing, funding acquisition. **AEG:** formal analysis, data curation, writing - review & editing, visualization. **AKS:** writing - review & editing, supervision. **GHM:** writing of original draft, writing - review & editing, supervision.

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