



UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
Campus de São José dos Campos
Instituto de Ciência e Tecnologia

AMIR MOHIDIN DEMACHKIA

**RESTAURAÇÕES *ENDOCROWN* EM PRÉ-MOLARES:
influência das paredes remanescentes da estrutura dentária e
materiais restauradores na resistência à fadiga**

***ENDOCROWN RESTORATIONS IN PREMOLARS: influence of
remaining axial walls of tooth structure and restorative materials on
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fatigue resistance***

Tese apresentada ao Instituto de Ciência e Tecnologia, Universidade Estadual Paulista (Unesp), Campus de São José dos Campos, como parte dos requisitos para obtenção do título de DOUTOR, pelo Programa de Pós-Graduação em ODONTOLOGIA RESTAURADORA.

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BANCA EXAMINADORA

Profa. Dra. Renata Marques de Melo Marinho (Orientadora)

Universidade Estadual Paulista (Unesp)

Instituto de Ciência e Tecnologia

Campus de São José dos Campos

Prof. Dr. Lafayette Nogueira Júnior

Universidade Estadual Paulista (Unesp)

Instituto de Ciência e Tecnologia

Campus de São José dos Campos

Prof. Dr. Cesar Rogério Pucci

Universidade Estadual Paulista (Unesp)

Instituto de Ciência e Tecnologia

Campus de São José dos Campos

Profa. Dra. Lais Regine da Silva Concilio

Universidade de Taubaté (Unitau)

Profa. Dra. Camila da Silva Rodrigues

Universidade Federal de Pelotas

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RESUMO

Este estudo teve como objetivo avaliar o efeito da estrutura dentária remanescente e dois materiais diferentes de restauração CAD/CAM no desempenho à fadiga e no modo de falha de pré-molares tratados endodonticamente restaurados por *endocrowns*. Um total de 90 pré-molares superiores foram tratados endodonticamente e divididos aleatoriamente de acordo com o número de paredes axiais remanescentes, e os materiais restauradores foram divididos em 6 grupos (n = 15); quatro paredes restantes restauradas com zircônia ultratranslúcida 5Y-PSZ (grupo Fo-Z) e dissilicato de lítio (grupo Fo-L), três paredes restantes restauradas com 5Y-PSZ (grupo Th-Z) e dissilicato de lítio (grupo Th-L) e duas paredes restantes restauradas com 5Y-PSZ (grupo Tw-Z) e dissilicato de lítio (Tw-L). As restaurações foram cimentadas adesivamente e os espécimes foram submetidos a cargas de fadiga gradual em seu longo eixo (carga inicial: 200 N, frequência: 20 Hz). Uma carga incremental de 100 N por 10.000 ciclos foi aplicada com um pistão metálico de Ø 6 mm até a falha. A carga de falha por fadiga (FFL) e o número de ciclos de falha (CFF) no momento da falha foram registrados e analisados estatisticamente por ANOVA 2 fatores e teste de Kaplan-Meier ($\alpha = 0,05$). Os espécimes fraturados foram examinados em estereomicroscópio em 8× e 25× e os modos de falha foram determinados como reparáveis ou catastróficos. FFL e CFF foram significativamente influenciados pelo material restaurador ($p < 0,05$). As restaurações de 5Y-PSZ apresentaram FFL (Fo-Z = 1487 N, Tw-Z = 1427 N, Tw-Z = 1533 N) e probabilidade de sobrevivência significativamente maiores quando comparadas com dissilicato de lítio (Fo-L = 1060 N, Th-L = 940 N, Tw-L = 1000 N). O número de paredes remanescentes não afetou o comportamento de fadiga ou modo de falha dos corpos de prova. Das restaurações de dissilicato de lítio, 51% tiveram falhas reparáveis, enquanto 95% das restaurações de zircônia ultratranslúcida 5Y-ZP tiveram falhas catastróficas. *Endocrowns* de zircônia apresentaram melhor desempenho em fadiga do que *endocrowns* de dissilicato de lítio, independentemente do número de paredes remanescentes do eixo. *Endocrowns* de pré-molares de dissilicato de lítio e 5Y-PSZ apresentaram maior FFL do que as cargas mastigatórias normais.

Palavras-chave: Cerâmicas. CAD/CAM. Fadiga. Falha de restaurações dentárias. Análise de elementos finitos.

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ABSTRACT

This study aimed to evaluate the effect of the remaining tooth structure and two different CAD/CAM restoration materials on the fatigue performance and failure mode of endodontically treated premolars restored with endocrowns. A total of 90 maxillary premolars were endodontically treated and divided randomly according to the number of remaining axial walls, and the restorative materials were divided into 6 groups ($n = 15$); four remaining walls restored with ultratranslucent zirconia 5Y-PSZ (group Fo-Z) and lithium disilicate (group Fo-L), three remaining walls restored with 5Y-PSZ (group Th-Z) and lithium disilicate (Group Th-L), and two remaining walls restored with 5Y-PSZ (group Tw-Z) and lithium disilicate (Tw-L). The restorations were cemented adhesively and the specimens were subjected to stepwise fatigue loading along the long axis (initial load: 200 N, frequency: 20 Hz). An incremental step load of 100 N per 10,000 cycles was applied with a Ø6-mm metallic piston until failure. The fatigue failure load (FFL) and number of failure cycles (CFF) at the time of failure were recorded and statistically analyzed with two-way ANOVA and the Kaplan-Meier test ($\alpha = 0.05$). Fractured specimens were examined under a stereomicroscope at 8 $\times$ and 25 $\times$ and failure modes determined as repairable or catastrophic. FFL and CFF were significantly influenced by restorative material ($p < 0.05$). 5Y-PSZ endocrowns showed significantly higher FFL (Fo-Z = 1487 N, Th-Z = 1427 N, Tw-Z = 1533 N) and survival probability when compared with lithium disilicate (Fo-L = 1060 N, Th-L = 940 N, Tw-L = 1000 N). The number of remaining walls did not affect the fatigue behavior or failure mode of the specimens. Of the lithium disilicate restorations, 51% had repairable failures, while 95% of ultratranslucent zirconia 5Y-ZP restorations had catastrophic failures. Zirconia endocrowns showed better fatigue performance than lithium disilicate endocrowns, regardless of the number of remaining axis walls. Lithium disilicate and 5Y-PSZ premolar endocrowns showed higher FFL than the normal masticatory loads.

Keywords: Ceramics. CAD/CAM. Fatigue. Dental restoration failures. Finite element analysis.

1 INTRODUCTION

Endodontically treated teeth (ETTs) associated with extensive substance loss subsequent to trauma, caries, or wide access cavity preparation have a high risk of fracture (Reeh et al., 1989; Sedgley, Messer, 1992; Dietschi et al., 2008). Accordingly, any treatment of such teeth should take into account remaining tooth structure, tooth location, masticatory forces, and restorative material (Faria et al., 2011). Traditionally, the treatment for extensively damaged ETTs has been a post-and-core and cuspal coverage with a crown. However, in this type of treatment, post-space preparation of the intact coronal and intracanal tooth structure is needed, increasing the risk of root perforation and stripping or weakening of the tooth (Schwartz, Robbins, 2004; El Ghoul et al., 2019; Hassouneh et al., 2020). Therefore, extreme care should be taken during post-space preparation to avoid these risks (Kfir et al., 2020).

Contemporary dental treatment emphasizes the preservation of sound tooth structure as much as possible, even when restoring endodontically treated teeth. In this context, endocrown restorations (first described by Pissis in 1995) consisting of a monoblock indirect restoration with a crown extending from the intaglio surface that represents the core have become popular as an alternative to conventional post-and-core and crown restorations. The crown covers the coronal part to protect the remaining tooth structure, and the core occupies the pulp chamber to provide retention and stability to the restoration after bonding with adhesive while sealing the obturated canals (Pissis, 1995; Bindl, Mörmann, 1999). Endocrowns have gained reliability and popularity in the last few years because of improvements in adhesive systems and ceramic materials (Dietschi et al., 2008; El-Damanhoury et al., 2015; Fages et al., 2017; Munoz-Sanchez et al., 2021). A recent systematic review that included 41 articles (8 clinical studies, 33

in vitro studies) concluded that molar endocrown restorations can be considered an alternative to conventional crowns; however, additional studies are required for premolar endocrowns (Govare, Contrepois, 2020).

The development in computer-aided design/computer-aided manufacturing technologies (CAD/CAM) and ceramic materials has allowed the fabrication of endocrown restorations from different materials, including resin nanoceramic, lithium disilicate ceramic, hybrid ceramic, and zirconia. These materials have different microstructures, esthetic properties and moduli of elasticity, ranging from 10 GPa for composite resin blocks to 250 GPa for zirconia (Zhu et al., 2017). The fracture resistance of molar endocrowns from these materials has been studied, with conclusions that lithium disilicate and resin nanoceramic endocrowns had higher fracture resistance than zirconia-reinforced lithium disilicate or hybrid ceramic (Gresnigt et al., 2016; El Ghouli et al., 2019). In contrast, EL-Damanhoury et al. (2015) reported that resin nanoceramic endocrowns showed higher fracture resistance and a more favorable failure mode than lithium disilicate or feldspathic ceramic, but Dartora et al. (2019) reported no difference between the lithium disilicate and hybrid ceramic (El-Damanhoury et al., 2015; Dartora et al., 2019). However, studies on the biomechanical behavior of ultratranslucent yttria-stabilized zirconia when used as an endocrown to restore premolars are lacking. Translucent zirconia, mainly 4Y- and 5Y-PSZ has become more popular in recent years and, because of their lower toughness and fracture resistance, are typically indicated in similar clinical situations as lithium disilicate (Zhang, Lawn, 2018). Translucent zirconias were developed to overcome the esthetic limitation (high opacity) of 3Y-TZP zirconia by including a transparent phase. Translucency was achieved by adding 4 mol% (4Y-PSZ) or 5 mol% (5Y-PSZ) yttria, which is required to stabilize the cubic phase at room temperature. Although translucent zirconias are weaker than 3Y-TZP zirconia as the cubic phase does not undergo a stress-induced

transformation, they are indicated for use as a monolithic restoration in esthetic areas. (Pereira et al., 2018; Zhang, Lawn, 2018; Pereira et al., 2019).

Incidence of pulp involvement from extensive interproximal caries is commonly encountered, leading to endodontic treatment. In this situation, one or two proximal walls with intact buccal and lingual walls are often destroyed (Barallat et al., 2022). To our knowledge, information about the effect of missing proximal walls on the biomechanical behavior of premolars restored with endocrowns are lacking. Thus, the question remains: Does the number of remaining walls affect the fatigue behavior of the tooth/restoration complex and their failure mode?

Therefore, our study aimed to evaluate the effect of the remaining axial wall number (four, three, and two) and two CAD/CAM materials, lithium disilicate ceramic and ultratranslucent 5 mol% yttria stabilized zirconia (5Y-PSZ) on the fatigue resistance and failure mode of endodontically treated maxillary premolars restored with endocrowns. The null hypotheses of the study were that the endocrown material would have no influence on the fatigue failure load and failure mode and that the remaining walls of tooth structure would have no influence on the fatigue failure and failure mode.

2 LITERATURE REVIEW

2.1 Endocrown

In the past, it had been thought that ETT become more brittle and weaker than vital teeth due to the changes in dentin properties, making it essential to protect them with full coverage crowns. Post and core were also commonly used, not just to give retention to the core and crown but also to strengthen the tooth. However, the later discovery that post placement might jeopardize the tooth fracture resistance, made the preservation of the remaining sound tooth structure crucial for its long-term success (Schwartz, Robbins, 2004; El Ghouli et al., 2019). Therefore, Modern philosophy of Partial coverage restorations without post placement such as endocrown has been suggested as alternative to the post and core associated with full coverage (Dietschi et al., 2008).

In 1995, Pissis presented a ‘monobloc’ technique to restore ETT with free metal crown extended into the pulp chamber for retention instead of utilizing metal post and core, aiming to improve the esthetic appearance of the final restoration (Pissis, 1995). The term ‘endocrown’ was used for the first time by Mörmann et al., in 1998. The authors had been motivated by the breakthrough in CAD/CAM technology, which allows to fabricate a complex form of the internal surface of the indirect restorations (defect oriented custom shape of the fitting surface of the restoration), to study the fracture strength of ceramic crown restorations restoring ETT molars prepared with different forms simulating different destructed teeth conditions that are frequently encountered clinically. The groups included conventional crown preparation with 1.5 mm occlusal reduction, conventional crown preparation with excessive occlusal reduction 3.5mm, conventional crown preparations with mesio-occlusodistal cavity on the occlusal surface, and endocrown preparations (5.5 mm occlusal

reduction). The study concluded that endocrowns and classical crowns with high ceramic thickness showed the highest fracture resistance, due to their higher ceramic thickness (Mörmann et al., 1998). The authors then clinically examined 19 endocrown restoration (4 premolars and 15 molars) (Bindl et al., 1999) over a period of 1 to 3 years. only one crown was shown to fail after 28 months due to recurrent caries in the floor of the pulp chamber. In a successive clinical study in 2005, the authors compared the survival rate of felspathic ceramic restorations restoring premolars and molars with classical preparation, reduced height, and endocrown preparation. After a mean follow-up of 55 months, the survival rate of restorations on molars with classical, reduced, and endocrown preparation was 94.6%, 92.1%, and 87.1%, respectively. For premolars, the survival rate was significantly lower in endocrown (68.8%) compared with classical (97%) and reduced preparation (92.2%). The lower survival rate of premolar endocrown was attributed to the lower surface area available for bonding compared to molars.

In a retrospective clinical study, Belleflamme et al. (2017), evaluated the survival and success rate of 99 endocrowns, that restored 58 molars and 41 premolars. After a mean follow-up of 44 months, the survival and success rates were 99% and 89.9% respectively, with nine failures in molars and only one in premolar. Among the reasons for failures in molars, two were attributed to debonding, two to fracture, three to periodontitis, and two to recurrent caries. Whereas for the premolar, the failure was attributed to ceramic fracture. The authors indicated, that out of three fractures, two were just minor chippings that originated from the occlusal contact point, while the only major fracture was detected in a bruxer patient (it was not possible to distinguish whether the fracture was in premolar or molar) (Belleflamme et al., 2017).

Fages et al. (2017) evaluated the survival rate of 235 felspathic endocrowns and 212 full crowns on molar teeth. After a mean follow up of 55

months, only 6 failures were detected, indicating a 98,66% survival probability. Their results revealed five ceramic chippings in full crown restorations and one in an endocrown. Other types of failures such as retention loss, recurrent caries, and tooth fracture were not observed. (Fages et al., 2017)

Among the laboratory studies, various authors evaluated the fracture strength of molars restored by endocrowns and those with conventional approaches. In a study by Biacchi and Bastin (2012) the fracture strength of molars restored with glass ceramic endocrowns and subjected to 135° oblique load showed higher fracture strength than those restored with fiber post, composite core and full coverage crown (Biacchi and Basting, 2012). In another study, Hamdy (2015) evaluated the fracture strength of molars restored with lithium disilicate endocrowns fiber post with full coverage crown, inlay and onlay (Hamdy, 2015). He found that endocrowns and fiber post with full coverage crown showed the highest fracture resistance with no significant difference between the two groups. Furthermore, onlays were shown to have better fracture resistance than inlays. The percentage of restorable failures in full coverage crowns, endocrowns, onlays and inlays were 90%, 80%, 80% and 30%, respectively (Hamdy, 2015).

Mange et al. (2014) compared the fatigue performance and fracture resistance of molar teeth restored with nanoceramic endocrowns, crowns with 2mm core build up with no post, and 4mm core build up with no post (Magne et al., 2014). The survival rate of the endocrowns, crowns with 4mm core, and crowns with 2 mm core were 53%, 87%, and 87%, respectively. After that, the survived samples were loaded to failure. The results showed no statistical difference between all groups. However, all samples showed catastrophic failures.

In a finite element analysis (FEA), Dejak and Mlotkowski (2013) evaluated the stress concentration in molars restored with leucite-reinforced

ceramic endocrowns, fiber posts with full crowns, and metal posts with full crowns (Dejak, Młotkowski, 2013). The authors have reported that the stress concentration in the dentin and luting cement of teeth restored with endocrowns were lower than those restored with fiber post or metal post and full coverage crown. Therefore, it was concluded that molars restored with ceramic endocrowns are less susceptible to failure compared to the conventional treatment.

Restored premolar teeth are known to be more susceptible to fracture than molars, due to their steep inclined cusp, narrow clinical crown and subjection to lateral forces (Salis et al., 1987). Therefore, several *in vitro* studies have been conducted comparing the fracture resistance of premolars restored with endocrowns and post and core and crown. Chang et al. (2009) evaluated the fracture resistance and failure mode of premolars restored with leucite ceramic endocrowns and fiber post and core and full crown (Chang et al., 2009). Their results showed that premolar endocrowns subjected to axial load have higher fracture resistance than post and core with a full crown. The failure mode was shown to be unfavorable in most of the samples. Similar results were observed in a study conducted by Atash et al. (2017), that showed the higher fracture resistance of endocrowns compared to premolars restored with fiber post or metal post and full crown (Atash et al., 2017). However, most of the favorable fractures were observed in the group of fiber posts, while most of the endocrowns and metal posts showed unfavorable failures. Contradicting the results of previous studies, Guo et al. (2016) reported that fracture resistance was similar in premolars restored with lithium disilicate endocrowns and fiber posts with full ceramic crowns (Guo et al., 2016).

Rocca et al. (2018) evaluated the marginal adaptation and fatigue failure load of premolars restored with lithium disilicate endocrowns with different core lengths (0, 2, 4mm) and fiber posts with ceramic crowns (Rocca et al., 2018).

The marginal adaptation was evaluated for all samples before and after the hermos-mechanical cyclic loading. Survived samples were then subjected to stepwise fatigue test. The authors reported that marginal adaptation of full crowns and endocrowns with 2 and 4mm cores were not affected by the hermos-mechanical aging. In addition, all samples survived the aging except four samples of endocrowns with 0 mm core length, due to early debonding. Regarding fatigue resistance, although endocrowns displayed fatigue resistance similar to post and core with full crowns, it was higher in endocrowns with 2 and 4mm core lengths.

Anterior teeth are smaller and receive higher non-axial forces compared to posterior teeth, which increases their susceptibility to restoration failure. This may explain the low number of studies on endocrowns restoring anterior teeth, even though the results were promising. In an *in vitro* study, Sebastia et al. (2014) demonstrated no significant differences in fracture strength of maxillary incisors that were restored with endocrowns fabricated from composite or ceramic, and full crowns (composite or ceramic) with different fiber posts lengths (5mm and 10mm). However, the endocrowns and short fiber posts groups showed higher number of repairable fractures compared to long fiber posts (Ramírez-Sebastià et al., 2014). Similar results were found in a study by Gungor et al. (2017), in which the fracture strength of maxillary incisors restored with different post and crown materials were not different compared to those restored with endocrowns (Güngör et al., 2017).

Recent advances in CAD/CAM technology have enabled fabrication of indirect endocrown restorations from different ceramic blocks with reduced fabrication time compared to the conventional technique. However, differences in microstructure and mechanical properties of ceramic endocrowns can affect stress distribution and biomechanical behavior of the endocrowns / tooth complex (Tribst et al., 2018). El Ghoul et al. (2018) evaluated the fracture

resistance to axial and lateral loading on molars restored with endocrowns fabricated from different ceramic materials (lithium disilicate, resin nano ceramic, and zirconia reinforced lithium disilicate glass material) (El ghoul et al., 2018). They concluded that the fracture resistance was highest in lithium disilicate and nano ceramic under axial load, while under lateral load it was highest in lithium disilicate. However, the majority of irreparable failures were in lithium disilicate, especially under lateral load. In a similar study by Gresnigt et al. (2016), similar results were obtained even after performing immediate dentin sealing (IDS) (Gresnigt et al., 2016).

A study by Hassouneh et al. (2020), evaluated the fracture resistance of premolars restored with resin nano ceramic, lithium disilicate and translucent zirconia (3Y-TZP) endocrown, subjected to 45-degree load direction. They concluded that nano-ceramic endocrown demonstrated higher fracture resistance and repairable failures compared to lithium disilicate and feldspathic ceramic (Hassouneh et al., 2020). In another study by Dartora et al. (2019), the fatigue strength of molars restored with different endocrown materials (lithium disilicate glass ceramic, polymer-infiltrated ceramic network, direct resin composite) was evaluated (Dartora et al., 2019). Their results showed no significant differences in fatigue failure load and number of cycles among the groups. In addition, most of the failures were repairable among the different materials.

Regarding endocrown preparation design, the general guidelines according to most of the reports are (Hays et al., 2017):

- a. 2 to 3mm occlusal reduction
- b. 2mm axial wall thickness
- c. 90-degree butt joint
- d. Supragingival margins whenever possible
- e. Flat pulpal floor

However, there are no specific guidelines regarding the amount of core length for adequate fracture resistance and failure mode. Hayes et al. (2017), evaluated the effect of lithium disilicate endocrown core extension (2, 3 and 4mm) on the fracture resistance of molars. The samples were subjected to monotonic load at 45° to the long axis of the tooth (Hayes et al., 2017). The authors concluded that endocrowns with 2 and 4 mm core length showed higher fracture resistance than those with 3mm core length, with majority of the samples showing catastrophic failures. In another study by Dartora et al. (2018), lithium disilicate endocrowns restoring molars with 3 and 5mm core extensions showed higher fracture resistance than those with 1mm core extension (Dartora et al., 2018).

Enhorn et al. (2017), studied the effect of ferrule inclusion to the endocrown preparation design on the fracture resistance of lower molars (Enhorn et al., 2017). The groups included butt joint endocrown preparations with 1mm and 2mm ferrule heights. The results showed that preparation with ferrule demonstrated higher fracture resistance than butt joint endocrowns. Moreover, while the catastrophic failure rate was least (63%) for 1mm ferrule, it was 100% for 2mm ferrule, with the butt joint showing 83% catastrophic failure. In a similar study, Taha et al. (2017) evaluated the effect of preparation design (1mm ferrule, butt joint) and occlusal thickness (2mm, 3.5mm) on the fracture resistance of polymer infiltrated ceramic endocrowns (Taha et al., 2017). The authors reported that endocrowns restored molars with ferrule exhibited higher fracture resistance than endocrowns with butt joint preparation. However, there was no effect of differences in restoration thickness (3.5mm, 2mm) on fracture resistance. Failure mode was also not affected by the preparation design and occlusal thickness. In confirmation with these results, Tribst et al. (2019) concluded that lithium disilicate or leucite ceramic endocrowns with different occlusal thicknesses (1.5, 3, 4.5mm) restoring molars with different tooth

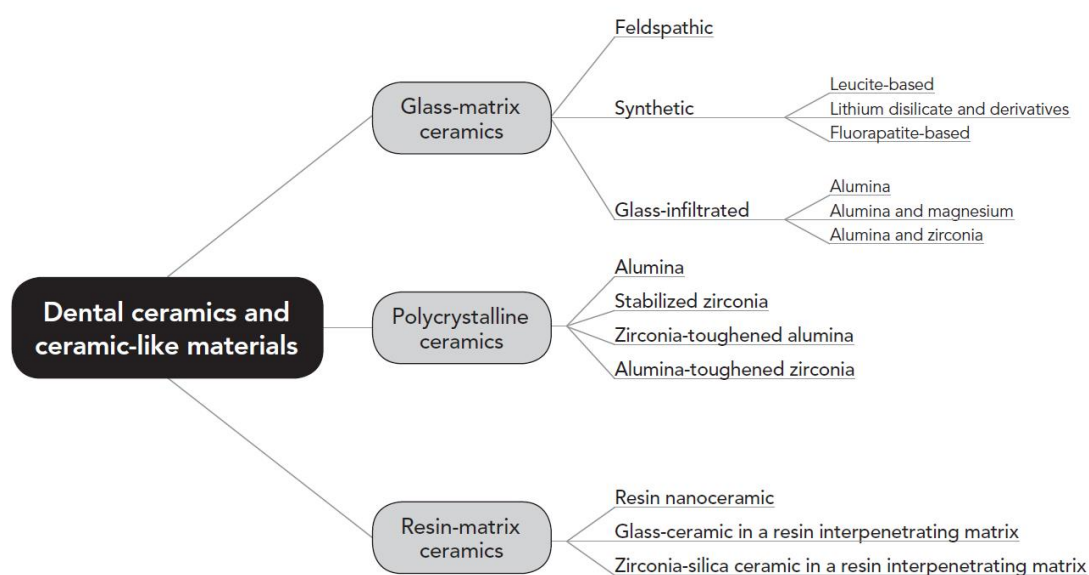
structure heights (4.5, 3, 1.5mm) did not affect the fracture resistance (Tribst et al., 2019).

2.2 Dental ceramics

Patients' increasing demand for highly esthetic restorations over the years has accelerated the development of ceramic restorations that mimic the optical properties of natural teeth, are biocompatible and have excellent mechanical properties (Guess et al., 2011; Beier, Dumfahrt, 2014).

Dental ceramics can be classified according to the microstructure, fabrication technique, clinical indications, translucency, firing temperature and ability to be etched. A popular classification by Gracis et al. (2015) describes ceramic materials as: a) Glass-matrix ceramic, b) Polycrystalline ceramic, and c) Resin-matrix ceramic, as shown in Figure 1 (Gracis et al., 2015).

Figure 1- Ceramic Classification



Source: Gracis et al., 2015

2.2.1 Glass-matrix ceramic

Feldspathic ceramic was the first glass matrix ceramic introduced in dentistry. It is composed mainly of quartz (silica), clay/kaolin, feldspar. The low percentage of leucite crystal appeared as a reaction product of potassium feldspar and glass, increasing the strength of the ceramic and control the coefficient of thermal expansion making it suitable for veneering over the metal substrate (Gracis et al., 2015). Its high esthetics can be attributed to the glass matrix with a very low crystal amount. However, the main shortcoming of this material is its low mechanical properties, limiting its use to anterior full crowns, facial laminate veneers, or as a veneering material over metal or ceramic substrate (Kelly, Benetti 2011; Sailer et al., 2015).

Over the past years, dental ceramic industries have developed numerous synthetic ceramics that commonly include silicone dioxide (SiO_2), potassium oxide (K_2O), sodium oxide (Na_2O), and aluminum oxide (Al_2O_3) with different amount of crystals in the glassy matrix, aiming to increase the flexural strength of ceramic, while maintaining the optical properties (Gracis et al. 2015; Warreth and Elkareimi, 2020). In the late '90s, IPS Empress 2 was developed and became the first lithia-based glass ceramic (Zhang et al., 2023). It was composed of 65% of lithium disilicate, small needle-shaped crystals embedded in a glass matrix, with a 1 vol% porosity (Zarone et al., 2019). It was later modified by adding 70% of smaller and more uniformly distributed lithium disilicate (IPS e.max Press), resulting in improved mechanical properties (flexural strength: 360 - 480 MPa; hardness: 5.8 GPa; modulus of elasticity: 95 GPa;) (Zarone et al., 2019; Warreth, Elkareimi, 2020). In addition to its improved mechanical properties, lithium disilicate also is an etchable ceramic. Therefore, applying 5% of hydrofluoric acid for 20s made it possible to selectively dissolve the glass

content, forming porous surface that provide micromechanical bond, and exposing hydroxyl groups to provide chemical bond with the resin cement via silane (Ramakrishnaiah et al., 2016).

Initially, IPS e.max press was introduced as ceramic ingot, to be pressed in a mold following the lost wax technique. However, the development of CAD/CAM technology in 2006 and the two step ceramic crystallization made it possible to fabricate Lithium disilicate ceramic in a block form (IPS e.max CAD) (Fasbinder et al., 2010). The block is produced in a pre-crystallized stage (blue), which contains 40% metasilicates (Li_2SiO_3) and lithium disilicate nuclei ($\text{Li}_2\text{Si}_2\text{O}_5$). The Pre-crystallized form has flexural strength of 130 MPa, which is important to be able to mill the material faster with less wear and damage to the milling bur and machine (Teja, Teja, 2015; Willard, Chu, 2018). After milling, the material is crystalized by heating at 840-850 °C under vacuum to transform metasilicates crystal into lithium disilicate (70%), giving the final optical and mechanical property to the material (Willard, Chu 2018; Zarone et al., 2019). Lithium disilicate ceramic has been indicated for inlays, onlays, laminate veneers, crowns and three unit bridges (posterior and anterior) (Warreth, Elkareimi, 2020).

Starting in 2013, new variants of lithia-based glass ceramics have been introduced to the market. Examples of these include Obsidian blocks by Glidewell Laboratories, which is a lithium silicate glass ceramic, and Celtra Du blocks by Dentsply, which is a biphasic lithium disilicate/lithium silicate ceramic (Zhang et al., 2023).

2.2.3 Polycrystalline ceramic

Polycrystalline ceramics do not contain any glassy components. Instead, their crystals are densely packed into regular arrays, resulting in higher toughness and strength compared to ceramics with a glass matrix. However, due to their dense structure and the absence of glass, etching polycrystalline ceramics with hydrofluoric acid becomes challenging.

Zirconia (ZrO_2) is a polymorphic inert material that exhibits different crystalline forms at different temperature; a) monoclinic zirconia (M) that is stable at room temperature up to 1170°C , b) tetragonal zirconia (T) that is stable from 1170°C to 2370°C , c) cubic zirconia (C) that is stable between 2370°C and 2680°C (Zhang, Lawn, 2018). Tetragonal or cubical phase can be stabilized at room temperature by alloying zirconia with other oxides (stabilizer) such as yttrium oxide (Y_2O_3), magnesium oxide (MgO) and calcium oxide (CaO). Of the different stabilizers, yttrium oxide (Y_2O_3) has shown perfect results regarding strength and toughness (Kelly and Denry, 2008; Zhang and Lawn, 2018). In regard to the microstructure, zirconia can be classified into; a) fully stabilized zirconia (FSZ), which is totally in a cubic phase (FSZ) and can be obtained by adding more than 8 mol% of Y_2O_3 , b) partially stabilized zirconia (PSZ), which is a multiphase zirconia, consisting of cubic crystals as the major phase and tetragonal or monoclinic particles as the minor phase, and can be obtained by adding small amount of Y_2O_3 , c) tetragonal zirconia polycrystal (TZP), which is mainly of tetragonal phase, and formed by adding 2 to 3 mol% Y_2O_3 (Piconi, Maccauro, 1999; Vagkopoulou et al., 2009; Gracis et al., 2015).

Conventionally, 3Y-TZP is indicated for indirect restorations, due to the exceptional mechanical properties (flexural strength 1200 MPa) and transformation toughening. The transformation from tetragonal to monoclinic

crystal at the crack tip, accompanied with 4% expansion, thereby hindering the crack propagation.(Vagkopoulou et al., 2009; Gracis et al., 2015). However, 3Y-TZP is a very opaque material (birefringent), due to the non-cubic crystals structure, leading to light scattering from crystal boundaries (Zhang, 2014). Therefore, 3Y-TZP is widely used as core and veneered with feldspathic ceramic (bilayer technique). The main disadvantage of the bilayer technique is the ceramic chipping and delamination, due to the weak bond between the zirconia core and the covering ceramic (Sax, 2011; Pang et al., 2015). In addition, an invasive preparation is needed to accommodate the opaque core and thick veneering ceramic (Zhang, 2014).

In order to overcome the optical properties drawback of 3Y-TZP, translucent zirconia has been developed by adding a higher amount of yttria [4 mol% (4Y-PSZ) or 5 mol% (5Y-PSZ)], resulting in a highly cubic phase zirconia [partially-stabilized zirconia (PSZ)]. The optical properties is enhanced by allowing light transmittance with less scattering from the grain boundaries (Zhang et al., 2019). This advancement in PSZ translucency with multilayer shade availability resulted in PSZ with higher translucency than low translucent lithium disilicate (Baldissara et al., 2018), allowing practitioner to utilize it in a monolithic configuration in esthetic areas similar to lithium disilicate (Souza et al., 2018).

The main drawback of PSZ compared to 3Y-TZP is the low mechanical properties as the cubic phase does not undergo the transformation toughening (Zhang et al., 2019).

In addition to the importance of the mechanical properties of the zirconia ceramic, adhesion of resin cement to zirconia and tooth structure is an essential factor for clinical success, especially in non-retentive cases (resin bonded FPD) where the restoration relies on micromechanical and chemical bonding. In contrast to silicate ceramic, zirconia is a polycrystal acid resistant material and

could not be salinized to achieve adequate bond strength with the resin cement. Hence micromechanical, chemical or combination of both surface treatment has been suggested (Melo et al., 2015). Employing AlO_3 air blasting is a micromechanical approach to increase the surface roughness of the zirconia which consequently increase the wettability of the resin and enhance the bond strength. Chemical surface alteration is achieved by infiltrating silica on zirconia surface followed by salinization using sol-gel technique (Campos et al., 2016).

2.3 Fatigue Tests

Fatigue is “the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations.” Intraoral ceramic restorations are brittle materials that fracture suddenly due to fatigue without a significant plastic deformation (Bonfante, Coelho, 2016). For this reason, materials should be tested in conditions as similar to the oral environment as possible. When testing fatigue, loading can be applied as static (constant load until fracture), dynamic (increasing load at constant rate until fracture), and cyclic (loading and un-loading with constant frequency and load value) (Bonfante, Coelho, 2016).

Various tests can be employed to evaluate the mechanical behavior of dental ceramics. *Fatigue life/limit* of a given material indicates the stress below which the material will not fail for infinite number of cycles. To determine fatigue life, the starting applied load must be sufficient to induce material failure. When the failure of a sample is observed, the applied load for the new sample is lowered until a load is reached where the sample resists infinite cycles.

For every sample, the applied load and fatigue cycles are counted and saved to draw the S-N Wöhler curve (S: Stress magnitude, N: Cycles to failure). This test provides the best vision for the material behavior for a whole service life. The disadvantages of this test are the high number of samples needed and the unpredictability of the number of cycles that will cause material failure (time consuming test) (Kelly et al., 2017).

To overcome the time consumption of the fatigue life test, accelerated fatigue tests such as staircase, stepwise and step-stress can be used. In *staircase* test, two to four samples are subjected to single monotonic load until failure to define the initial load, which is 50-70% of the monotonic load. First the sample is tested starting from the predetermined initial load for a number of cycles that the material is likely to be subjected during its expected life. In dentistry, 100.000 cycles and frequency of 5Hz has been widely used. The staircase starts after the first inversion. If the specimen fails, the next specimen will be tested at lower load level according to the preselected step size (10% of initial fatigue load). If the specimen passes (survives), the next specimen will be tested at a higher load level according to the preselected step size (10% of initial fatigue load) (Amaral et al., 2017; Bonfante, Coelho, 2016).

Step-stress is an accelerating fatigue test that assume the fatigue life and failure behavior of a given material at regular conditions by data collected from accelerated stress levels. In this test, initial load and final load is determined firstly by assigning 3 samples to monotonic test and 30% of the mean value is used as initial load and 60% of the same value is used as the end load. The samples are fatigued in 3 different step size profiles (mild, moderate, aggressive), that means the sample that assigned to mild profile (low step size) will be subjected to more cycles to reach the same load of a sample assigned to aggressive (high step size) or moderate profile (Bonfante, Coelho, 2016).

Step-wise is test is another an accelerating fatigue test, where initial load is determined by monotonic test that performed on a small number of samples, in which 60% of the mean of the fracture strength of tested samples. Then, the samples will receive cyclic load for a number of predetermined cycles (10,000 to 50,000 cycles). At the end of the cycles, if the sample survive, the load will be increased according to predetermined load increment and it will be subjected again to new cycle. This will be repeated until failure of the sample or until reach a predetermined number of cycles (Anami et al., 2016; Magne et al., 2014)

3 PROPOSITION

This study aimed to evaluate the effect of the remaining tooth structure and two different CAD/CAM restoration materials on the fatigue strength and failure mode of endodontically treated premolars restored with endocrowns.

H0: The endocrown materials and remaining walls of tooth structure would have no influence on the fatigue failure load and failure mode of the restoration / tooth complex

4 MATERIAL AND METHODS

Information on the materials, manufacturers, and composition of the materials used in this study are listed in Table 1.

Table 1 – Materials used in this study

Material	Company	Composition
IPS e.max CAD	Ivoclar AG, Schaan, Liechtenstein	SiO ₂ , Li ₂ O, K ₂ O, P ₂ O ₅ , ZrO ₂ , ZnO, other and coloring oxides
Ultratranlucent multilayered zirconia	Kuraray Noritake Dental Inc., Tokyo, Japan	ZrO ₂ , 9% Y ₂ O ₃ , other oxides
FGM etching gel	FGM, Joinville, SC, Brazil	5% hydrofluoric acid (main component)
Monobond Plus	Ivoclar AG, Schaan, Liechtenstein	Alcohol solution of silane methacrylate, phosphoric acid methacrylate, and sulfide methacrylate
Multilink Automix (Ivoclar Vivadent)	Ivoclar Vivadent, Schaan, Liechtenstein	Dimethacrylates, HEMA, barium glass filler, Ba-Al-Fluoro-Silicate glass, ytterbium trifluoride, highly dispersed silica, catalysts and stabilizer, and pigments
Multilink Primer A	Ivoclar AG, Schaan, Liechtenstein	Water and initiators
Multilink Primer B	Ivoclar Vivadent, Schaan, Liechtenstein	Phosphonic acid acrylate, hydroxyethyl methacrylate, methacrylate mod, polyacrylic acid, stabilizer
Aluminum Oxide	Polidental Indústria e Comércio, Cotia, SP	Aluminum Oxide (50 µm)
Tetric N-Bond Universal	Ivoclar AG, Schaan, Liechtenstein	Methacrylates, ethanol, water, highly dispersed silicon dioxide, initiators, and stabilizers.

Source: Prepared by author according to the information offered by the manufacturers (2022).

4.1 Experimental design

Upon ethical approval by the scientific research committee (SRC No: 001-06-2020), a total of 90 human maxillary first premolars of similar dimensions (maximum deviation of 10% from the means was accepted) (Taha, Spintzyk et al., 2018), with complete roots, and without caries, fractures, and visible cracks were selected. Tooth dimensions were measured buccolingually and mesiodistally at the cemento-enamel junction (CEJ) with digital calipers. The teeth were cleaned and stored in 0.1% thymol at 4°C. Sample size was calculated based on the means and standard deviations of a pilot study, which showed that $n = 15$ was sufficient for the study with a power of 80% at 5% significance level.

After selection, the teeth were numbered and assigned randomly using an online software program* to 6 groups ($n = 15$) according to the remaining walls and restorative materials:

Group (Fo-L): Four remaining walls restored with lithium disilicate;

Group (Fo-Z): Four remaining walls restored with ultra-translucent zirconia;

Group (Th-L): Three remaining walls restored with lithium disilicate;

Group (Th-Z): Three remaining walls restored with ultra-translucent zirconia;

Group (Tw-L): Two remaining walls restored with lithium disilicate;

Group (Tw-Z): Two remaining walls restored with ultra-translucent zirconia.

The teeth were attached to a dental surveyor and embedded in plastic tubes filled with auto-polymerizing epoxy resin 2 mm apically to the proximal CEJ and oriented perpendicularly to the ground. The crowns were then cut under

*www.randomizer.org

coolant irrigation parallel to the occlusal surface with a low-speed diamond disc (IsoMet 1000, Buehler, Lake Bluff, EUA), 3 mm coronal to the proximal CEJ.

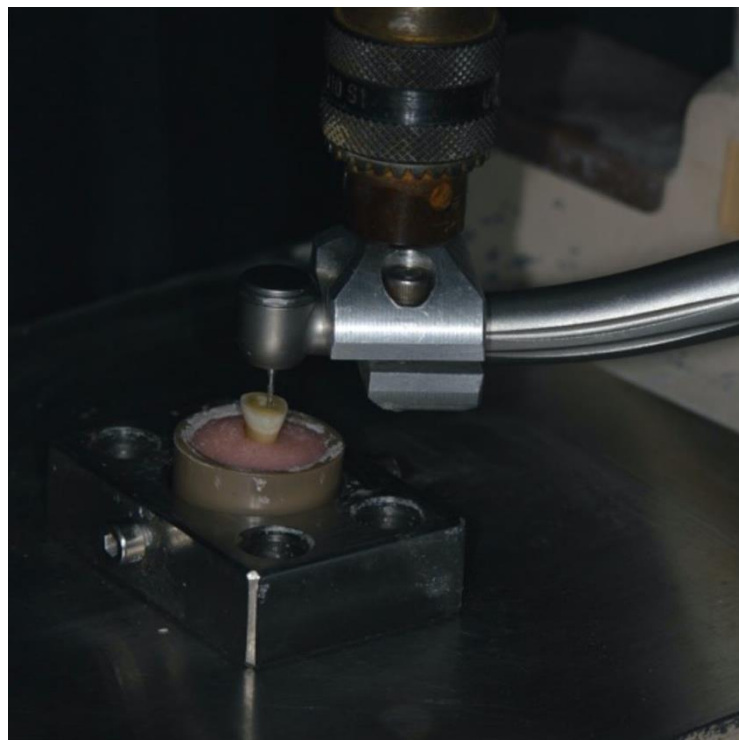
4.2 Endodontic treatment

The access cavity was made with a high-speed diamond rotary instrument (1014; KG Sorensen, San Jose, SP, Brazil). The teeth were endodontically treated to master file F1 using a Protaper system (Dentsply-Maillefer; Ballaigues, Switzerland), and a single cone F1 (Dentsply-Maillefer; Ballaigues, Switzerland) was cemented with a eugenol-free root canal sealer. After obturating the canals, a light polymerizing self-adhesive agent (Tetric N-Bond Universal, Ivoclar AG, Schaan, Liechtenstein) was applied to the orifices and floor of the pulp chamber and polymerized for 20 seconds using a Light Emission Diode (LED) polymerization device (Valo, Ultradent Products, Inc, South Jordan, Utah, USA). A layer of composite resin (Ceram.x, Dentsply Sirona, Bensheim, Germany) was then applied to seal the canal orifices, flatten the floor of the pulp chamber, and establish a uniform cavity depth of 3 mm (Filtek Z350, 3M ESPE, Neuss, Germany).

4.3 Tooth preparation

The teeth were prepared keeping a 2-mm wall thickness all around with a divergence of 6° using a tapered round-end diamond rotary instrument (2135; KG Sorensen, San Jose, SP, Brazil) mounted to a high-speed handpiece, which was attached to a dental surveyor parallel to the floor by a device designed by the authors to standardize the tooth preparation (Figure 2). The diamond rotary instrument was changed after every five preparations.

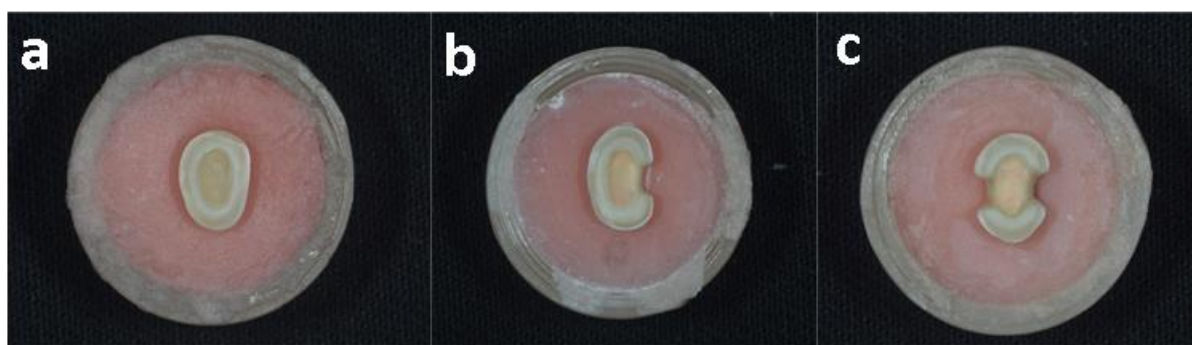
Figure 2 – Endocrown tooth preparation



Legend: High-speed handpiece attached to the holder, attached to the surveyor arm.
Source: Prepared by the author.

Thirty teeth were kept without further preparation (Fo-) (Figure 3a), while the remaining teeth received further preparation according to their group. For the teeth in group (Th-), the mesial wall was removed to the CEJ level, keeping the teeth with three remaining walls (Figure 3b). For the teeth in group (Tw-), mesial and distal walls were removed, keeping the teeth with two remaining walls (Figure 3c).

Figure 3 – Groups according to the remaining tooth structure



Legend: (a) Teeth with four remaining walls (Fo-), (b) Teeth with three remaining walls (Th-), (c) Teeth with two remaining walls (Tw-).

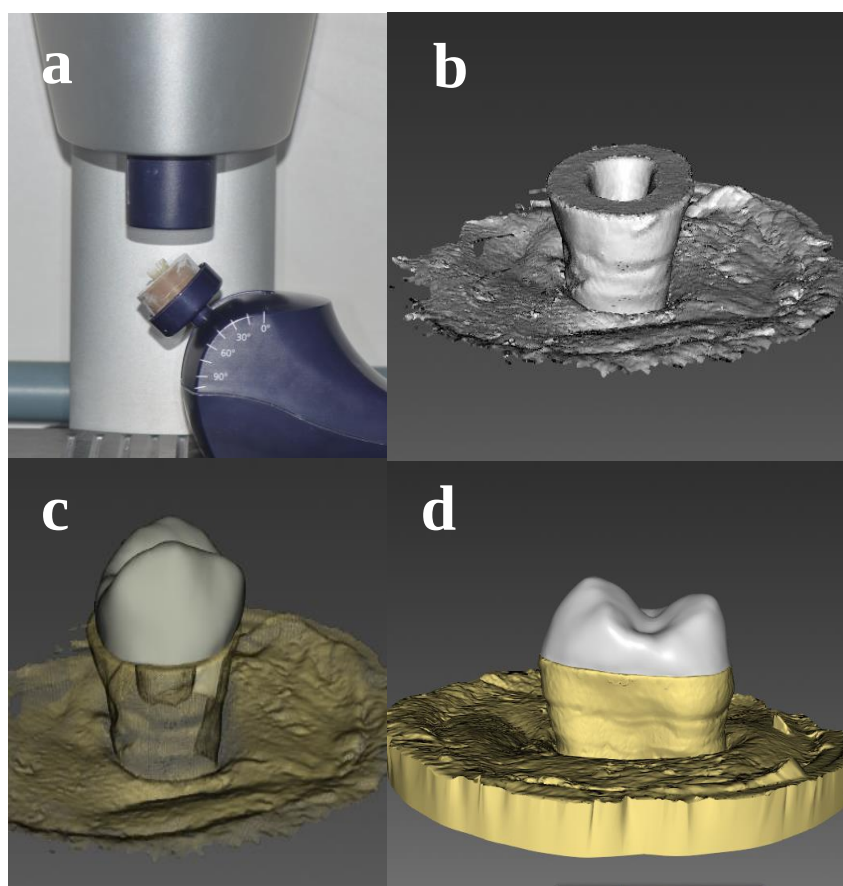
Source: Prepared by the author.

4.4 Fabrication of endocrowns

The teeth were scanned using a laboratory scanning device (Cerec InEos Blue cam, Dentsply Sirona, Bensheim, Germany). Virtual models were then obtained, and margins were determined in the CEREC CAD/CAM software program (Dentsply Sirona, Bensheim, Germany). In order to standardize the restoration form and occlusal anatomy in all specimens, one endocrown restoration was automatically generated by the software program and edited to ensure a 6 mm and 5 mm occlusal thickness from the preparation butt joint to

the buccal and lingual cusp tip respectively and 4 mm from the central groove; the cement space was set to 80 μm . The designed restoration was then exported and saved in STL file format, imported, and adapted to all the previously scanned specimens using only the “position” tools (translation and rotation) and without any editing of the previously saved original shape (Figure 4) (Magne et al., 2010).

Figure 4 – Endocrown design process usin CAD/CAM



Legend: (a) Scanning of the samples by extra-oral scanner, (b) scanned sample, (c) previously designed crown imported to the scanned sample, (d) restoration before exportation to CAM system.

Source: Prepared by the author.

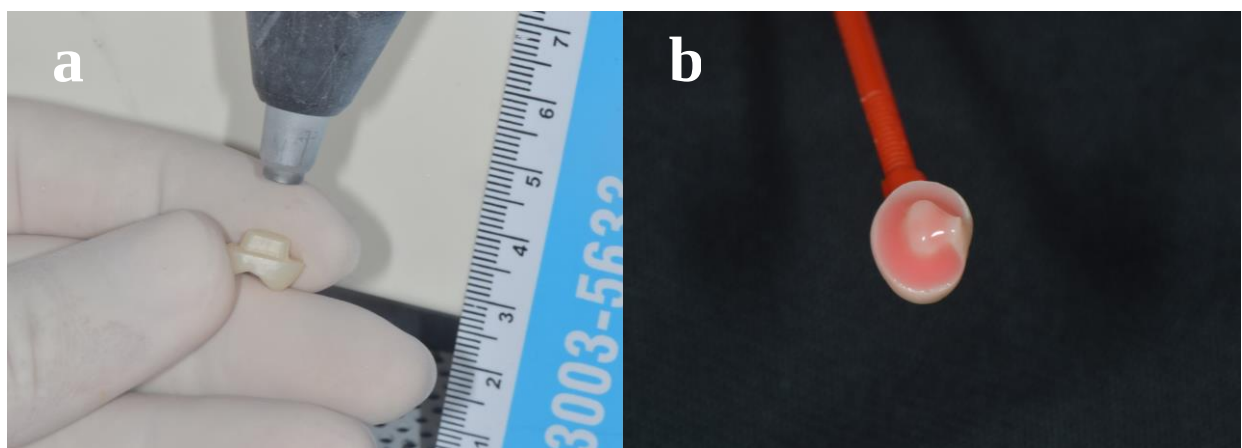
Lithium disilicate endocrown restorations (IPS e.max CAD, Ivoclar AG, Schaan, Liechtenstein) were milled with the CEREC MXCL milling machine (inLab MC-XL, Dentsply Sirona, Bensheim, Germany). The restorations were then crystallized in a ceramic furnace (Ivoclar AG, Schaan, Liechtenstein) according to the manufacturers' instructions (Gold et al., 2018). Endocrowns were milled from pre-sintered ultra-translucent 5 mol% yttria stabilized zirconia disks 5Y-PSZ (KATANA UTML, Kuraray Noritake Dental Inc., Tokyo, Japan) using a CAD/CAM milling machine (inLab MC-X5, Dentsply Sirona, Bensheim, Germany) and were then sintered according to the manufacturers' instructions (Cokic et al., 2020).

4.5 Bonding procedure

The intaglio surfaces of lithium disilicate restorations were etched with a 5% hydrofluoric acid gel (FGM, Condac, FGM, Joinville, Brazil) for 20 seconds and then washed with water and air dried. The fitting surface of the ultra-translucent zirconia 5Y-PSZ restorations was airborne-particle abraded with 50- μm aluminum oxide (Al_2O_3) (Polidental Indústria e Comércio, Cotia, SP) at 2.5 bar at a 10-mm distance for 4 seconds and then cleaned in an ultrasonic bath of 99% isopropanol for 3 minutes and air dried as shown in (Figure 5). The surface conditioning and cementation procedure were similar for both materials (lithium disilicate and 5Y-PSZ): A universal primer (Monobond N, Ivoclar AG, Schaan, Liechtenstein) was applied on the intaglio surfaces for 60 seconds and a gentle stream of oil-free air was used to dry and remove excess. Self-etching primer (Multilink primer A & B, Ivoclar AG, Schaan, Liechtenstein) was mixed according to the manufacturers' instructions, applied on the tooth surface,

scrubbed with a microbrush for 15 seconds, and gently air dried. After the surface treatments, the restorations were cemented with a resin cement (Multilink N Automix, Ivoclar AG, Schaan, Liechtenstein). All restorations were seated under a constant load of 7.8kg by using a metallic device which consisted of a dead weight resting on a vertical pin, which rested on the occlusal surface. After the removal of excess cement with a cotton pellet, each specimen was then light polymerized for 60 seconds using LED polymerization light (Ultradent Products, Inc, South Jordan, Utah, USA) after removing the occlusal load. The specimens were stored in distilled water at 37 °C for 24 hours before the fatigue test. Figure 6 summarize the cementation process after ceramic surface treatment.

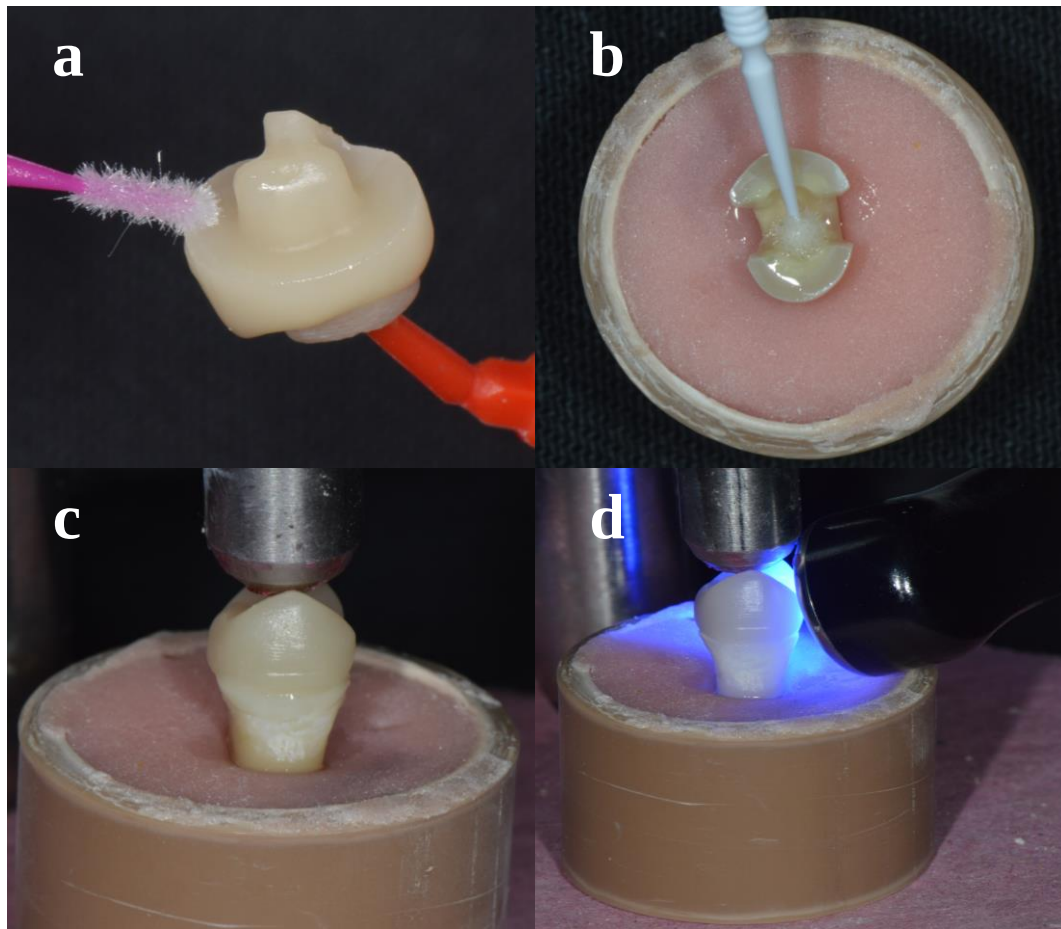
Figure 5 – Ceramic surface treatment



Legend: (a) Sandblasting of the fitting surface of 5Y-PSZ with 50-µm Al_2O_3 (b) Hydrofluoric acid etching to lithium disilicate ceramic

Source: Prepared by the author.

Figure 6 – Cementation Process



Legend: (a) universal primer application on the fitting surface of ceramics. (b) Self etching primer application on tooth structure. (c) cementation of endocrown under constant load. (d) photo polymerization of the resin cement.

Source: Prepared by the author.

4.6 Fatigue failure load test (Step-wise fatigue test)

The specimens were placed in a chamber filled with distilled water and subjected to a stepwise fatigue test by an electrodynamic testing machine (Instron ElectroPuls E3000, Instron Corp, Norwood, Mass, USA) using a Ø6-mm-cylindrical stainless-steel piston at a loading frequency of 20 Hz. The load was applied vertically along the tooth axis. The specimens were placed in the load chamber in the same position in relation to the metal piston to ensure standardized occlusal contact at the buccal and lingual cusp slopes. The stepwise test parameters were an initial load of 200 N, a fixed increment of 100 N, and 10,000 cycles per step (Velho, Dapieve et al., 2022). At first, a load of 200 N was applied for 5000 cycles to accommodate the settling of the piston on the specimen. After that, the load was increased following the predetermined increment every 10,000 cycles until specimen fracture. The data of fatigue failure load (FFL) and the number of cycles for failures (CFF) at the failure moment were collected for statistical analysis.

4.7 Failure and fractography analysis

After the fatigue test, all specimens were examined visually under a stereomicroscope at magnifications of 8× and 25×(Stereo Discovery V20; Carl Zeiss, Gottingen, Germany) to determine the fracture origin. One representative specimen from each material were cleaned in ultrasonic bath of 70%, 80%, and 99% isopropanol for 3 min, respectively, then in distilled water and dried. After that, representative specimen of each material was gold coated and examined

under scanning electron microscopy (SEM) (Inspect S50, FEI, Brno, Czech Republic) at different magnifications starting from 30× up to 200× to identify the fracture origin and fractographic marks in a high definition image. Failure modes were classified into three types; Type I: Only ceramic fracture or ceramic and tooth fracture above the CEJ, Type II: Ceramic and tooth fracture below the CEJ (non-repairable) and Type III: Split fracture, ceramic and tooth split vertically (non-repairable).

4.8 Finite element analysis

Previously validated upper first premolar was chosen in this study. The STL file of the validated premolar was opened using CAD software (Rhinoceros 5.0 McNeel North America, USA). 3D volumetric solid model was then created by outlining the anatomical structure (anatomical lines) to create surfaces and joining surfaces together to form NURBS volume. Each surface was made from three or four anatomical lines. The constructed model included Enamel, dentin, pulp chamber, and periodontal ligament. The model was fixed in a polyurethane cylinder. The model was then replicated and prepared simulating different endocrowns preparation designs (four remaining axial walls, three remaining axial walls, two remaining axial walls) Preparation dimensions was similar to the samples used in the *in vitro* study conducted by the author.

For structural analysis, the models were exported as STEP file to ANSYS software (ANSYS 17.2, ANSYS Inc., Houston, TX, EUA). The contacts were considered perfectly bonded between the structures. Each model was replicated to receive different ceramic endocrown materials (LD and 5Y-PSZ) with similar dimensions to the samples used in the previous *in vitro* study

conducted by the author. Eighty microns of resin cement layer was included in this step. In addition, 1 mm composite layer thickness was placed over the floor of the pulp chamber as a flattening procedure. The mesh was generated automatically, which composed of tetrahedra elements 312774 and node 446740. The convergence test (10%) was performed to assure the least possible influence on the results.

Mechanical properties of all materials and structures were inserted into the software (Table 2) and each material was considered homogenous, elastic and isotropic. The model fixation was placed at the base of the cylinder with fixed zero nodal displacements. Axial occlusal load 200 N was applied with occlusal contacts at buccal and lingual slopes similar to what was done in the *in vitro* test. Maximum principal stress was analyzed on endocrowns restoration, cement layer and tooth structure in colorimetric scale for qualitative comparison between the different groups.

Table 2 – Materials used in this study

Material	Modulus of elasticity (GPa)	Poisson ratio	References
Enamel	70	0.30	Dejak et al., 2012
Dentin	18	0.31	Dejak et al., 2012
Multilink N	5	0.29	Firidinoğlu et al., 2012
Composite resin	19	0.32	Papadogiannis et al., 2008
Polyurethane	3.6	0.30	Souza et al., 2015
5Y-PSZ	210	0.30	Ma et al., 2016
Lithium Disilicate	95	0.23	Ma et al., 2016

4.9 Data analysis

For statistical analysis, the IBM SPSS Software (IBM, Armonk, NY, USA) was used. The influence of the factors “restorative material” and “remaining tooth walls” on the fatigue behavior and the interaction between these two factors was evaluated by a two-way ANOVA test ($\alpha = 0.05$). FFL and CFF data were then subjected to survival analysis (Kaplan Meier with Mantel-Cox (log-rank) post-hoc tests ($\alpha = 0.05$)). The survival rates were then tabulated at each step for both FFL and CFF.

The chi-square test of independence with the Z post hoc test using a Bonferroni correction was performed ($\alpha = 0.05$) to evaluate the association between failure mode and restorative material or number of remaining walls.

The maximum principal stress (MPS) distribution in dental tissues, restorations and cement layer were analyzed, and the peak values of the maximum tensile/shear stress were determined.

5 RESULTS

5.1 Survival analysis

Two-way ANOVA showed a statistical influence for the “restorative materials” (FFL – $p < 0.001$, $F = 136.95$; CFF – $p < 0.001$, $F = 134.19$) and no influence for the “remaining walls” (FFL – $p = 0.16$, $F = 1.89$; CFF – $p = 0.14$, $F = 2.01$); no significant differences were found for the interaction between the two factors (FFL – $p = 0.40$, $F = 0.93$; CFF – $p = 0.44$, $F = 0.82$).

FFL and CFF were significantly influenced by the restorative material, in which the highest values of FFL and CFF were presented by the groups restored with ultra-translucent zirconia (Table 3) (Figure 7).

Table 3 – Mean fatigue failure loads (FFL) in Newtons, number of cycles for failure (CFF), with respective 95% confidence interval (CI)

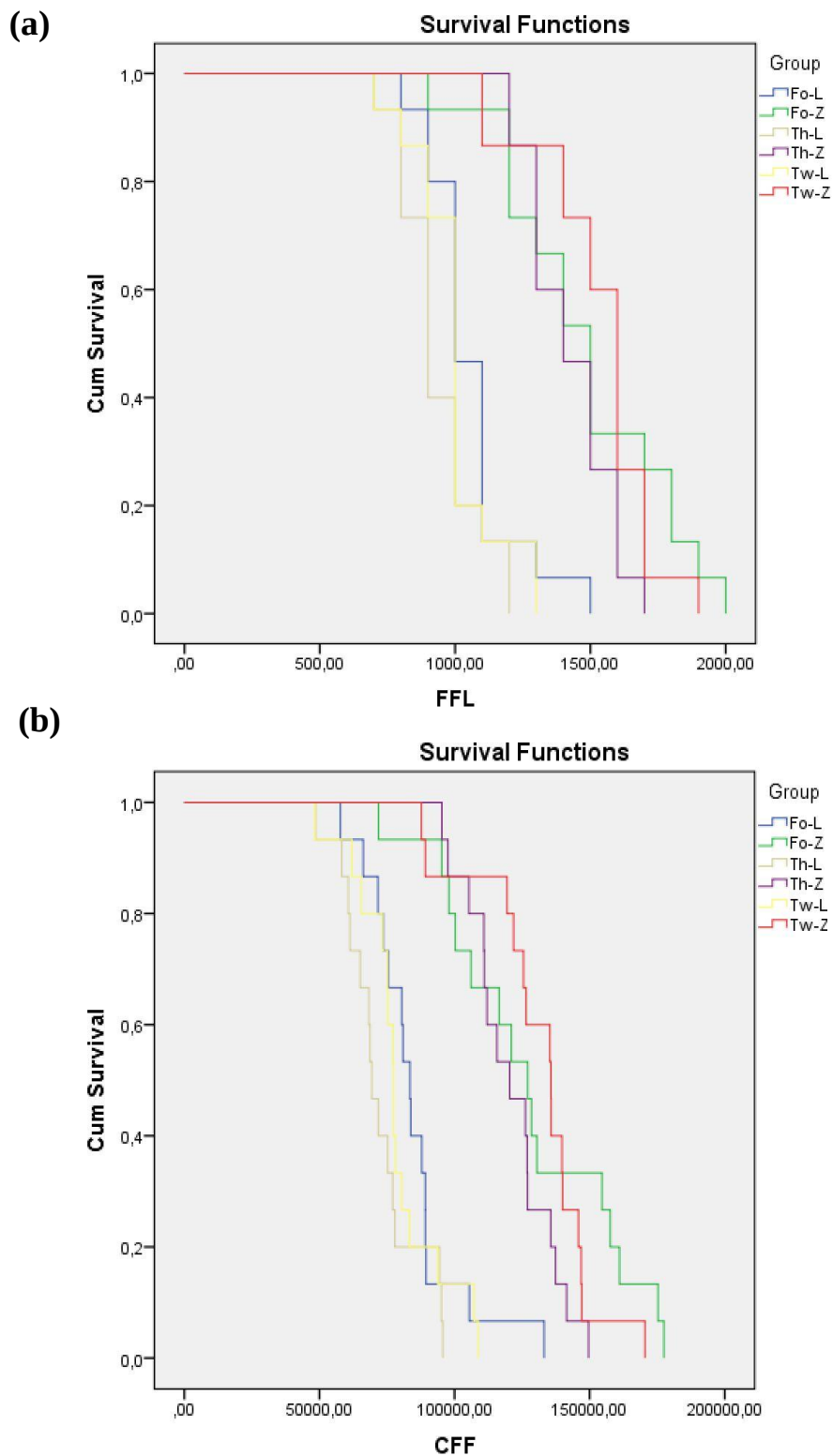
Groups	FFL	CFF
	Mean (CI)*	Mean (CI)*
Fo-L	1060.00 (974.89 – 1145.11) ^B	84519.33 (75617.44 – 93421.23) ^B
Fo-Z	1486.67 (1331.43 – 1641.90) ^A	128067.73 (112108.37 – 144027.09) ^A
Th-L	940.00 (866.41 – 1013.58) ^B	72521.47 (65462.58 – 79580.35) ^B
Th-Z	1426,67 (1346.73 – 1506.61) ^A	120827.27 (112730.53 – 128924.00) ^A
Tw-L	1000.00 (921.13 – 1078.86) ^B	78901.20 (71015.22 – 86787.18) ^B
Tw-Z	1533.33 (1424.01 – 1642.65) ^A	131143.00 (120324.99 – 141961.01) ^A

Different letters indicate statistical differences on each column for each considered outcome.

* Kaplan-Meier and Mantel-Cox (log-rank) tests for FFL and CFF.

Source: Prepared by the author.

Figure 7 - Survival plots obtained by Kaplan–Meier and Log-rank tests



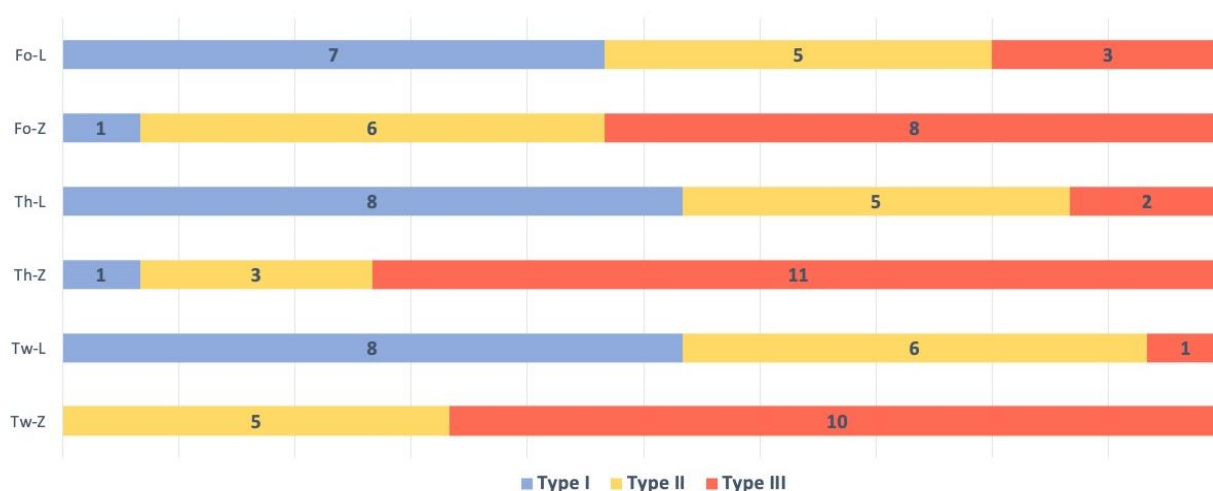
Legend: (a) Survival plots according to the steps of fatigue failure loads (FFL) in Newtons, (b) number of cycles for failure (CFF) in which each specimen failed.

Source: Prepared by the author.

5.2 Failure analysis

Regarding failure modes, the chi-square test of independence showed an association between failure mode and restorative material ($\chi^2 = 32,88$, $p < 0.001$) but not between failure mode and remaining tooth walls ($\chi^2 = 0.91$, $p = 0.92$). Non-repairable failure (type II and III) were predominant (95%) in the ultra-translucent zirconia groups, while repairable failures (type I) were (51%) in the lithium disilicate groups (Figure 8 and 9). The origin of the fracture was at the occlusal surface beneath the contact with the piston in all failed specimens. Detailed fractographic marks and direction of the crack propagation were determined under SEM (Figure 10).

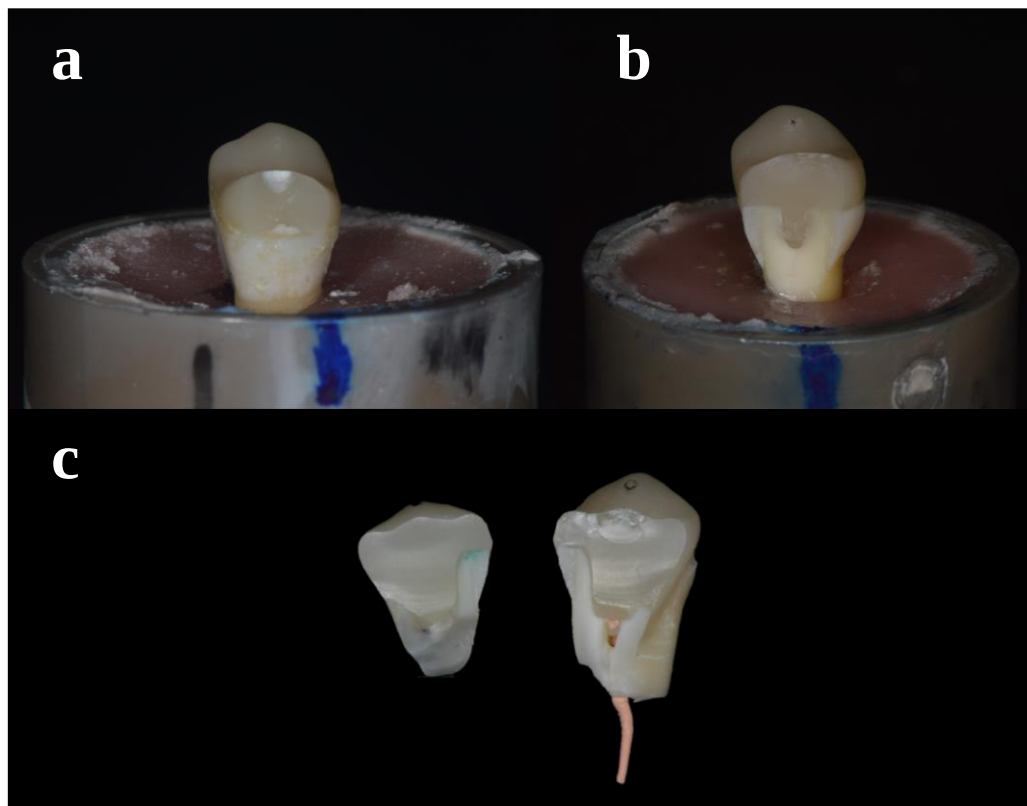
Figure 8 - Number of samples per group for each type of failure



Legend: Number of samples per group for each type of failure.

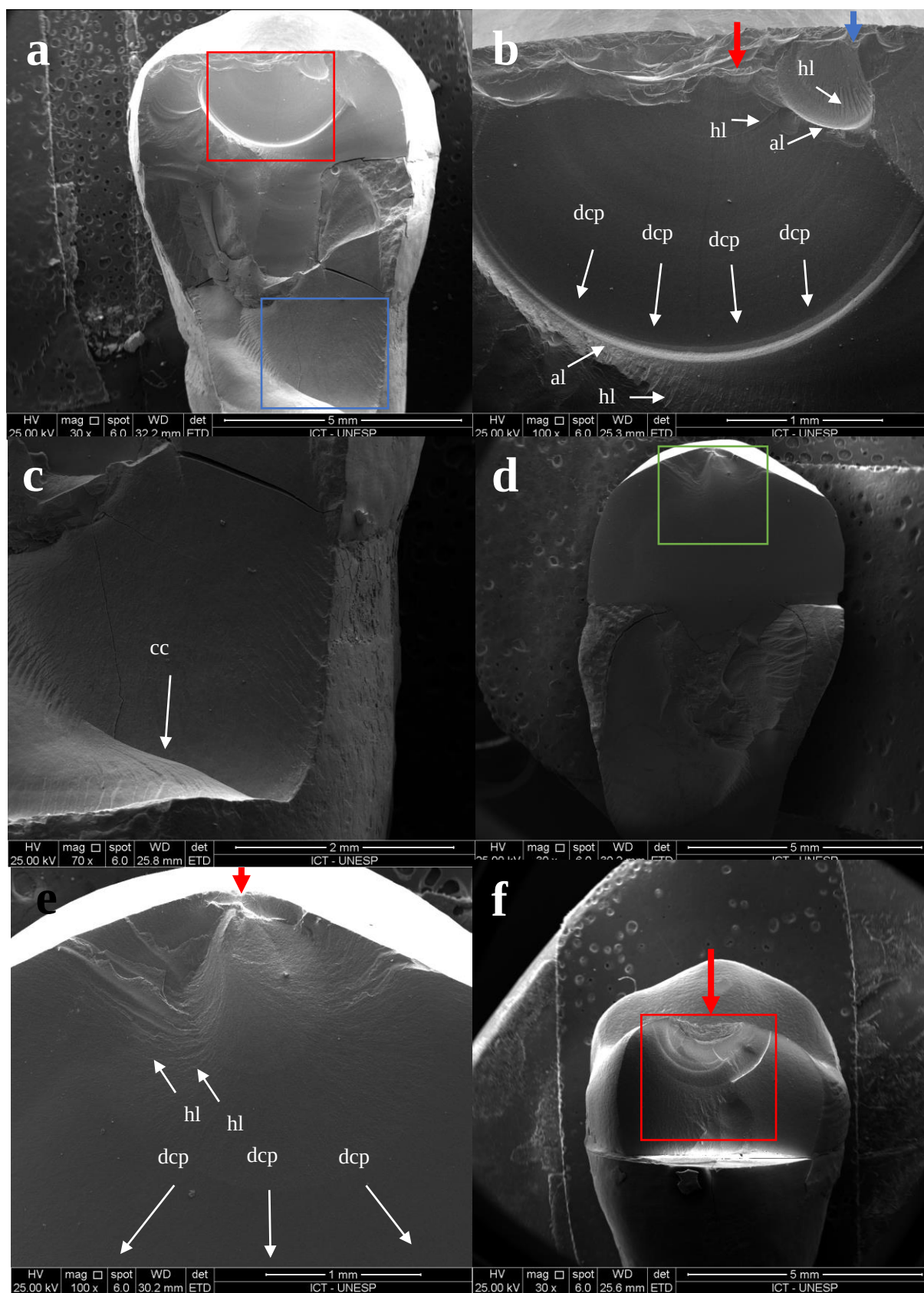
Source: Prepared by the author.

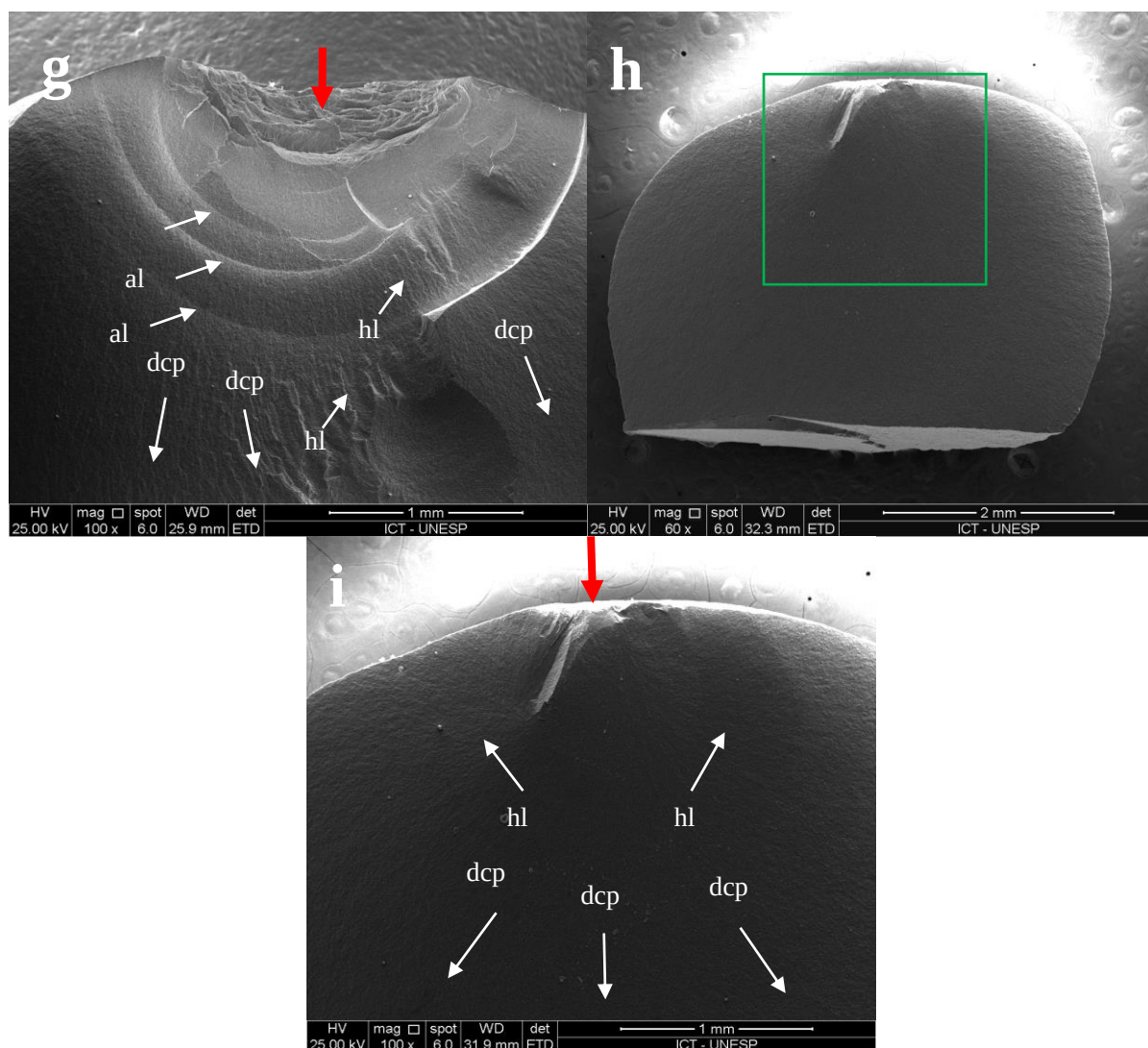
Figure 9 - Representative images of different failure modes



Legend: (a) Type I failure: ceramic fracture, (b) Type II failure: ceramic and tooth fracture below the CEJ, (c) Type III failure: splitting fracture.
Source: Prepared by the author.

Figure 10 - SEM analysis of representative fractured samples





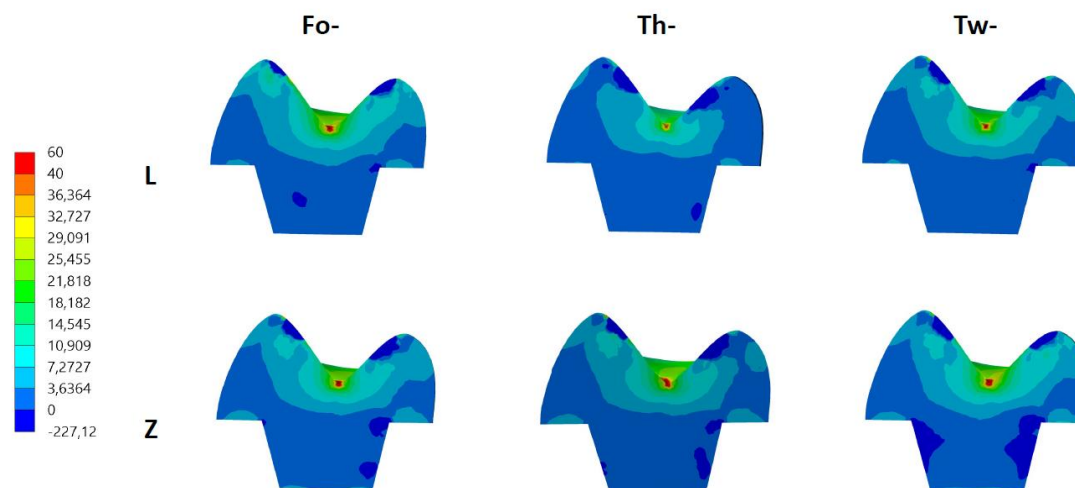
Legend: (a) general view of the fractured zirconia endocrown. (b) Red arrow indicates the main fracture origin at the occlusal area, followed by large arrest line (al) along the direction of crack propagation (dcp), which indicated by Hackle lines (hl), started from the top of restoration toward the apical region. Blue arrow indicates a secondary fracture origin. (c) compression curl (cc) at the bottom of the fracture. (d) general view of the palatal fractured fragment of the zirconia endocrown. (e) Red arrow indicates the main fracture origin at the occlusal area. Hackle lines (hl) indicating the direction of crack propagation. (f) general view of the fractured lithium disilicate endocrown. White arrow at the buccal cusp indicates the worn ceramic surface due to the piston contact. (g) Red arrow indicates the main fracture origin at the occlusal area, followed by multiple arrest lines indicating different fracture events along the fatigue time (al). Hackle lines (hl) started from the top of restoration toward the apical region indicating the direction of crack propagation (dcp). (h) general view of the palatal fractured fragment of lithium disilicate endocrown. (i) Red arrow indicates the main fracture origin. (hl) and (dcp) are labelled with white arrows.

Source: Prepared by the author.

5.3 Finite element analysis

Maximum principal stress (MPS) under 200 N axial load was analyzed in the endocrowns, cement layer, and dental structure. Regarding the restorative materials (Figure 11), the occlusal axial load generated high stresses at the central groove for both materials. Additionally, it can be observed that the 5Y-PSZ material resulted in higher stresses covering larger areas, such as the base of the endocrown core and the buccal and lingual butt joint interface, compared to the lithium disilicate groups. However, Lithium disilicate transmitted higher stresses to the cementation material over a larger area (Figure 12). Specifically, high stresses were concentrated at the palatal and buccal butt joint areas, the palatal area of the base of the core, and at the gingival line angle of the proximal box. While, in 5Y-PSZ higher stresses were localized at the palatal region in the base of the restoration core. Regarding the tooth structure, in both lithium disilicate and 5Y-PSZ, stresses were highly concentrated at the buccopulpal and palatopulpal line angles. However, higher stresses values were observed in teeth restored with 5Y-PSZ (Figure 13). Peaks of MPS for restorations, cement layer, and tooth structure are presented in (Figure 14, 15,16).

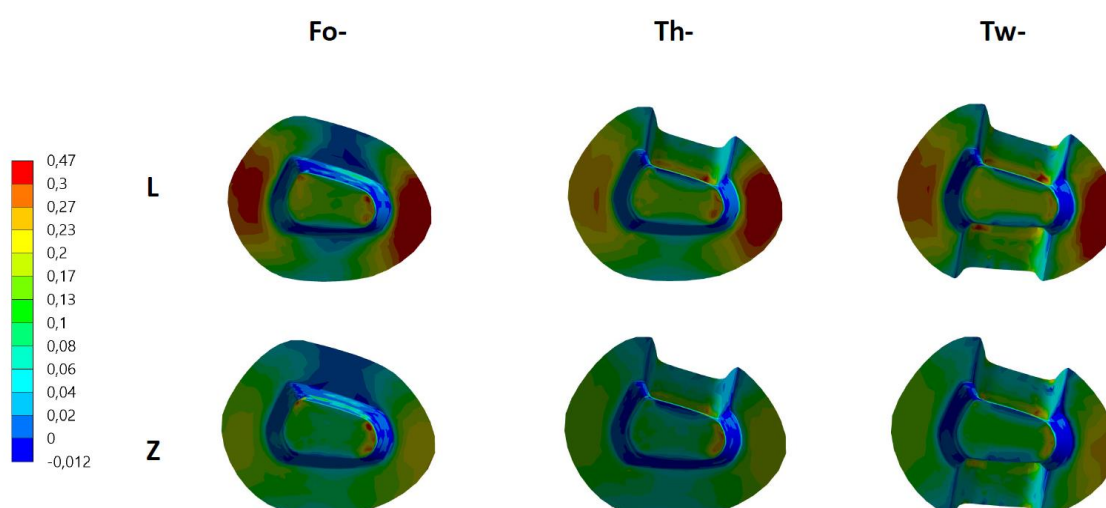
Figure 11 - MPS at the ceramic restoration



Legend: Sectional view showing the distribution of the stress according to the number of remaining axial walls (Fo: Four, Th: Three, Tw: Two walls), and ceramic material (L: Lithium disilicate, Z: 5Y-PSZ).

Source: Prepared by the author.

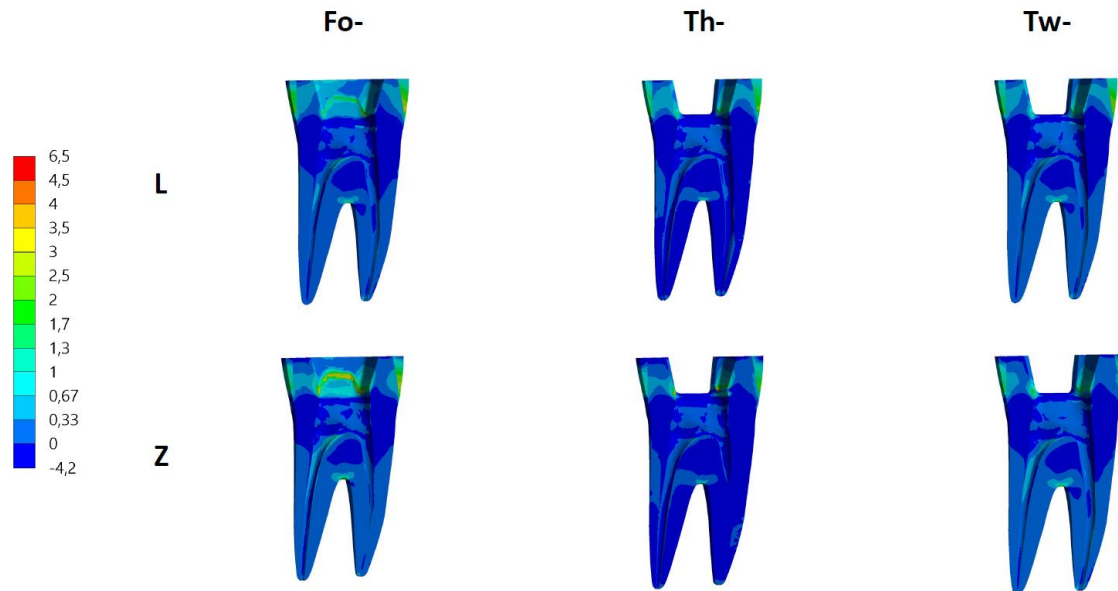
Figure 12 - MPS at the cementation layer



Legend: Distribution of the stress in the cementation layer according to the number of remaining axial walls (Fo: Four, Th: Three, Tw: Two walls), and ceramic material (L: Lithium disilicate, Z: 5Y-PSZ).

Source: Prepared by the author.

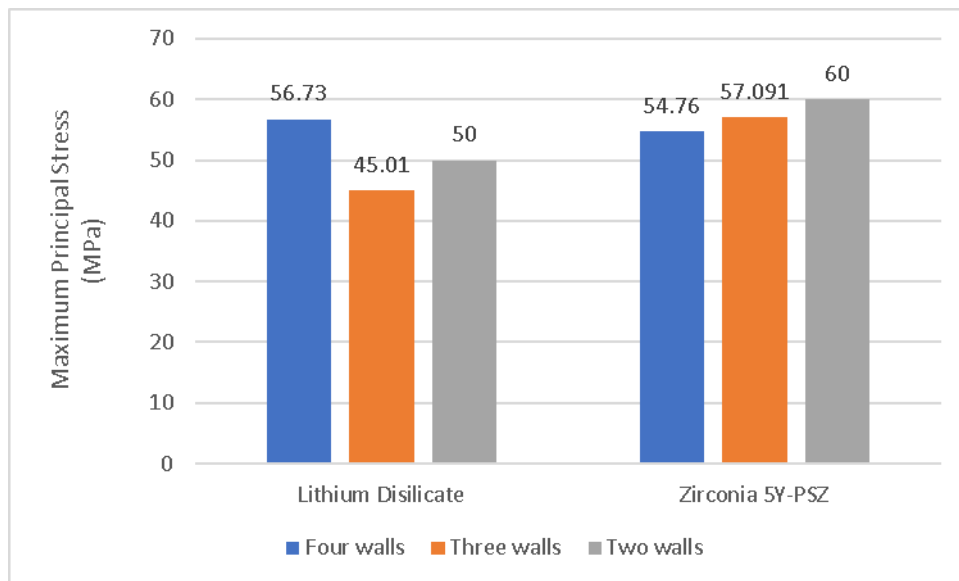
Figure 13 - MPS at the remaining tooth structure



Legend: Sectional view showing the distribution of the stress according to the number of remaining axial walls (Fo: Four, Th: Three, Tw: Two walls), and ceramic material (L: Lithium disilicate, Z: 5Y-PSZ).

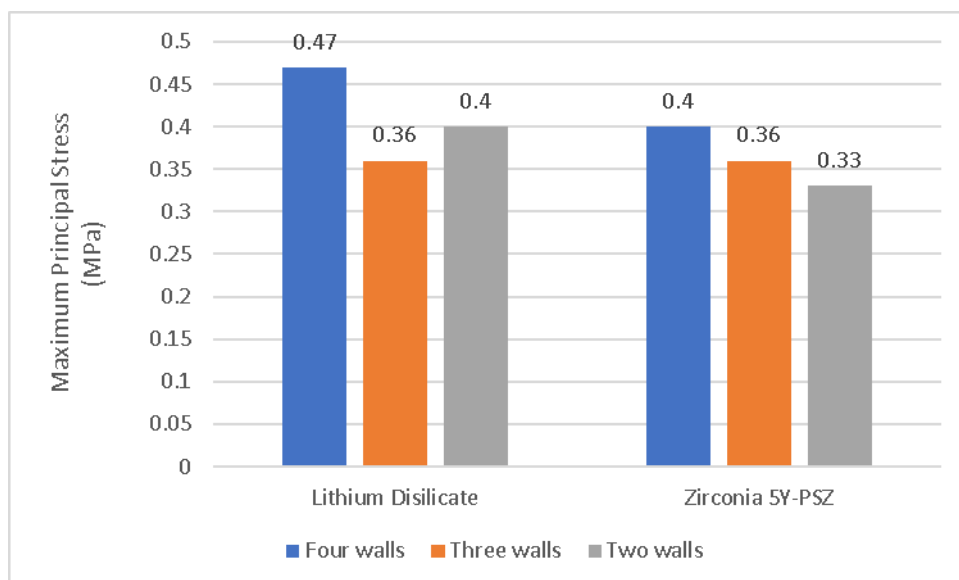
Source: Prepared by the author.

Figure 14 - Stress peaks calculated at restoration materials



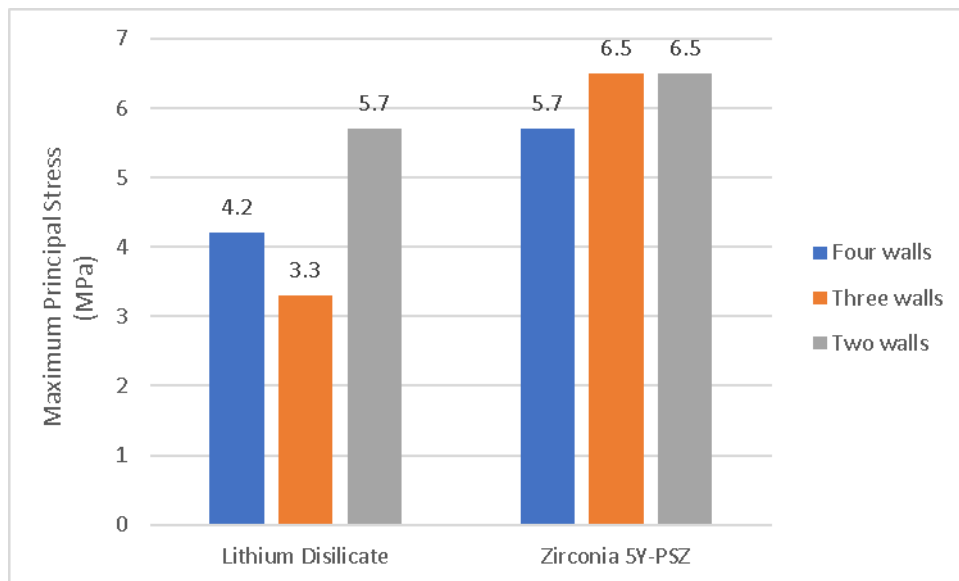
Source: Prepared by the author.

Figure 15 - Stress peaks calculated at cementation layer



Source: Prepared by the author.

Figure 16 - Stress peaks calculated for tooth structure



Source: Prepared by the author.

6 DISCUSSION

The aim of the present study was to evaluate the fatigue behavior and failure mode of endodontically treated maxillary premolars with different remaining axial walls (four, three, two) restored with a monolithic lithium disilicate LD or ultra-translucent zirconia 5Y-PSZ endocrown. The conventional endocrown group that restored teeth with four walls was considered a control group since many previous studies demonstrated that this condition presents higher (Biacchi, Basting, 2012; Atach et al., 2017) or similar fracture resistance (Hamdy, 2015; Guo et al., 2016) when compared with teeth restored with fiber post and full coverage crown. The results revealed that the 5Y-PSZ endocrown demonstrated a significantly higher fatigue failure load compared with the lithium disilicate endocrown and that the failure mode was significantly affected by the restoration material. However, the remaining walls of the tooth structure did not affect the fatigue load and failure mode. Hence, the first part of null hypothesis was rejected, and the second part of null hypothesis was not rejected.

Unlike metals, ceramics are brittle materials that fracture suddenly without a significant plastic deformation. Intraoral ceramic fracture has been mainly attributed to fatigue failure, which results from repetitive loading with low magnitude (mastication), leading to crack formation with slow growth in the presence of moisture (Monteiro et al., 2018; Kelly, 1999). Therefore, the fatigue test (low load with a high number of cycles) replicates the clinical situation better than a monotonic test (single load to failure), which does not reflect the load behavior and magnitude of the intraoral dynamic condition (Bonfante, Coelho, 2016; Magne et al., 2014; Zhang et al., 2013). In this study, specimens were subjected to a stepwise cyclic loading accelerated fatigue test, with increasing load increment (100 N) every 10,000 cycles until failure. An

accelerated fatigue test was chosen instead of a traditional fatigue test (low load with high number of cycles) to reduce the time and cost of the test (Pereira et al., 2018; Magne et al., 2014; Madruga et al., 2019; Rocca et al., 2016). Nevertheless, different mechanical tests, either dynamic or static, simple or complicated, provide valuable information about the mechanical performance as long as their design and interpretation are clinically relevant.

Strength and fracture toughness of ceramic materials are interrelated properties since ceramics with high toughness has high strength values. While strength values are often associated as indicators of structural performance for brittle dental materials comparison (Kelly, 1995), the fracture toughness is more related to an inherent material property, which describes structural performance of a single material (Kelly, 2004).

Most of the dental materials can be described as complex materials with different structures joined via interfaces. This characteristic is significant because when fracture toughness is said to be an intrinsic property, one adopts the material as homogeneous and isotropic (Soderholm, 2010). Therefore, the fracture toughness assessment of heterogeneous materials with bonded interfaces are much more complicated than that of homogeneous isotropic materials. The major cause is that the crack propagation initiate different failure modes at the adhesive interface, modifying the failure mode of the specimen (Soderholm, 2010). Therefore, in complex geometries, such as the present bonded endocrown restorations, fatigue strength evaluation is necessary as a method for determining the long-term performance (as most materials will not fail immediately as a result of their initial properties), indeed showing how the same restorative material can be affected by the preparation design.

Although the 5Y-PSZ zirconia has lower flexural strength than 3Y-TZP because tetragonal→martensitic transformation is limited in the 5Y-PSZ zirconia, its flexural strength is still 34% higher than that of lithium disilicate

(Kwon et al., 2018). The increased fracture strength explains the higher fatigue load and number of cycles until failure of the zirconia endocrowns compared with lithium disilicate. Consistent with the result of the present study, Ahmad et al. 2022, reported that a 4Y-PSZ endocrown showed higher fracture strength than lithium disilicate for restoring maxillary premolar with a butt joint preparation design (Ahmed et al., 2022). However, in that study, the group of premolars prepared with a ferrule exhibited similar fracture strength between the 4Y-PSZ endocrown and lithium disilicate. A possible explanation for the increase in load capacity of lithium disilicate, comparable with translucent zirconia, was the increased surface area in the ferrule preparation (Lawson et al., 2019; Aldesoki et al., 2022). Hassouneh et al. 2020, investigated the load to failure of premolars restored with endocrowns fabricated from different CAD/CAM materials, reporting no significant difference between lithium disilicate (547.4 ± 141.5 N) and translucent zirconia (460 ± 112 N) (Hassouneh et al., 2020). In addition, the mean fracture strength values were much lower than those of the present study. Unlike in the present study, Hassouneh et al., 2020, used a load to failure testing protocol and a 45° load direction, which makes their loading scenario worse.

Masticatory force in the premolar region has been reported to range from 222 to 445 N, reaching 800 N in bruxer (Widmalm and Ericsson, 1982; Nishigawa et al., 2001). Based on the Kaplan–Meyer survival probability, in the present study, all teeth restored with 5Y-PSZ would have 100% probability of exceeding 800 N without failing, while teeth with 4, 3, and 2 remaining walls restored with lithium disilicate would have 93%, 73%, and 87% survival probability of exceeding the same load, respectively. Thus, from the survival probability viewpoint, both materials should withstand normal occlusal forces; therefore, these materials can be indicated in similar clinical situations, and 5Y-PSZ may be more suitable for the higher occlusal loads. The caution would be

that near 1000 N loading the restoration (5Y-PSZ) tends to fracture catastrophically and the teeth fracture alike.

The present *in vitro* study showed that the majority of the zirconia endocrowns (95%) presented non-repairable failure, while 49% of lithium disilicate presented non-repairable failure and 51% repairable failure. Based on the FEA analysis conducted in this study, 5Y-PSZ presented higher stress concentration in the restoration and tooth structure in comparison to lithium disilicate under the same conditions. This can be attributed to the extremely high modulus of elasticity (210 MPa) of 5Y-PSZ, which can explain the high percentage of catastrophic failures in the teeth restored with 5Y-PSZ. Therefore, despite the importance of survival probability and fracture strength of restorative materials in material selection, the modulus of elasticity should also be considered when choosing a restorative material. These findings were consistent with a previous study that reported the highest percentage of non-repairable failure in zirconia endocrowns when compared to lithium disilicate and resin composite endocrowns (Hassouneh et al., 2020). In contrast, Ahmed et al. (2022) reported that all teeth restored with lithium disilicate and zirconia endocrowns exhibited non-repairable failures. The author applied a static load at 150° to the long axis of the teeth, which was a destructive load that intensified the stress at the cervical area (De Kuijper et al., 2020). Clinically, teeth are subjected to load in different directions (complex loads). In the present study, cyclic loading was applied in the long axis of the teeth, simulating occlusal loading in the posterior teeth during mouth opening and closing (Borden et al., 2018); in addition, a single contact point was used between the piston and each cusp ridge on the occlusal surface to ensure a stable piston/tooth contact during the test (Rocca et al., 2016; Rocca et al., 2018).

In type I and II failures, all restorations fractured on the lingual cusp. These results are consistent with a previous FEA study conducted by Zhu et al.,

2017, which also reported significant stress concentration on the lingual wall of maxillary premolars restored with endocrowns when subjected to axial load (Zhu et al., 2017). The uneven stress concentration on the buccal and lingual walls might be related to the dissimilarity in height and shape between the buccal and lingual cusp (Palamara et al., 2000).

The height of remaining tooth structure has been reported not to affect the fracture strength of molars restored with endocrowns (Tribst et al., 2019). However, circumferential walls cannot be always achieved. Therefore, in the current study, different numbers of remaining walls were evaluated, and the number of remaining walls (4, 3 or 2) did not affect the fatigue strength. This finding conflicted with a previous study reporting that the remaining tooth structure of premolars restored with fiber posts, cores, and cast crowns significantly affected the fracture strength (Smaran et al., 2013). These conflicting findings can be related to the difference in the restorative procedure and components, as in the post-and-core procedure, post space preparation is needed before cementation, which requires removal of intracanal tooth structure leading to tooth weakening. Further, the fewer bonded interfaces in a monoblock restoration (endocrown, cement, and dentin) transmit less stress to the tooth structure when compared with a multicomponent restorative procedure (post, core, cement, crown, and dentin) (Helal, Wang, 2019). Nevertheless, our FEA analysis revealed that as the number of remaining axial walls decrease, the accumulated stress in the tooth structure increases, suggesting that teeth with less remaining tooth structure may fail earlier than those with more remaining tooth structure. This finding is supported by a previous FEA analysis, which found that molars with greater height in their axial walls experienced less stress concentration in the tooth structure compared to molars with shorter axial walls (Tribst et al., 2019).

In the present study, extracted premolars with different remaining walls

were evaluated to represent different common clinical scenarios, though using natural teeth was expected to increase the variability (Hassouneh et al., 2020). In order to provide standardization, premolars with similar mesiodistal dimensions at the CEJ were selected, and 10% of deviation from the means was accepted. For further standardization, tooth preparation, restoration design, and restoration cementation were performed by the same operator. The endocrown occlusal anatomy and thickness were standardized among all specimens with the CEREC software program by importing a previously designed endocrown to each scanned tooth without any editing of the shape and thickness of the restoration. Hence, similar contacts between the piston and occlusal surface were developed for all the specimens.

An attempt was made to replicate the clinical scenario in this *in vitro* study, but some limitations were still present, including that the periodontal ligament was not simulated by placing an elastic material between the resin block and root surfaces of the teeth. However, this simulation was not used because it is difficult to standardize the thickness of the material and it might be displaced during the cyclic loading test. Moreover, the specimens were only subjected to axial load, while clinically, it is a complex load (axial and nonaxial). Further studies should investigate the mechanical behavior of the worst scenario cases of restoring posterior teeth with more extensive damage such as with only one remaining wall, or anterior teeth.

7 CONCLUSIONS

Within the limitations of the present study, the following conclusions can be drawn:

- a) Ultra-translucent zirconia 5Y-PSZ endocrowns in premolars had a higher fatigue load to failure than lithium disilicate, regardless of the number of remaining axial walls.
- b) Number of remaining axial walls did not affect the fatigue failure load.
- c) Both tested materials showed acceptable survival probability, but lithium disilicate failed before zirconia restorations.
- d) The failure mode was predominantly non-repairable in 5Y-PSZ restorations.

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