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Instituto de Ciência e Tecnologia

AMANDA MARIA DE OLIVEIRA DAL PIVA

INFLUÊNCIA DA ESPESSURA DA CERÂMICA NO COMPORTAMENTO BIOMECÂNICO, SOBREVIVÊNCIA E NA TRANSLUCIDEZ DE COROAS MONOLÍTICAS

2020

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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.

Área: Prótese Dentária. Linha de pesquisa: Desempenho de materiais para reabilitação protética.

Orientadora: Prof. Dr. Marco Antonio Bottino

Coorientador: Prof. Dr. Rodrigo Othávio de Assunção e Souza

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“Realizar sonhos não é obra do acaso. Requer gestos conscientes. Muita disciplina e determinação. Além de uma boa pitada de sorte: estar preparado, no lugar certo e na hora certa. Repito, preparado, pois muitos não conseguem ter sorte, pois não estavam prontos para desfrutar a "sorte" na hora em que as circunstâncias poderiam favorecê-los". César Souza

SUMÁRIO

Dal Piva AMO. Influência da espessura da cerâmica no comportamento biomecânico, sobrevivência e na translucidez de coroas monolíticas [tese]. São José dos Campos (SP): Universidade Estadual Paulista (Unesp), Instituto de Ciência e Tecnologia; 2020.

RESUMO

Apesar do aumento do uso de coroas monolíticas, seu desempenho, em diferentes aspectos, ainda não foi determinado. Inicialmente, este projeto investigou o comportamento biomecânico de diferentes coroas monolíticas convencionais sobre dentes e a distribuição de tensões na camada de cimento (Artigo 1). Como objetivo principal, este estudo avaliou o efeito do princípio do mínimo preparo dental no comportamento biomecânico, confiabilidade e translucidez de coroas monolíticas posteriores em cerâmica. No entanto, para definir o substrato a ser utilizado para receber as coroas usinadas, uma análise complementar foi desenvolvida para observar o comportamento da restauração sobre diferentes substratos através da análise por elementos finitos (Artigo 2). E para o Artigo 3, cento e vinte e seis coroas foram fabricadas e divididas (n = 21 / gr) de acordo com o material (zircônia de alta translucidez -YZHT, silicato de lítio reforçado com zircônia - ZLS e cerâmica híbrida -HC) e espessura (0,5 – subgrupo .5 ou 1 mm – subgrupo 1). A concentração de tensão de tração foi calculada pelo método dos elementos finitos, as coroas adesivamente cimentadas foram fadigadas pelo teste step-stress para calcular a confiabilidade de missões a 600 e 900 N a 100.000 ciclos; e, a translucidez foi analisada em 10 discos de cada material e espessura. Maior concentração de tensão de tração foi observada em coroas mais finas e com módulo de elasticidade mais alto. As coroas YZHT foram suspensas quando a fadiga atingiu a carga de 1.500N, sendo utilizado Weibull 1-parâmetro para analisar os dados. A confiabilidade foi afetada apenas pela espessura em 900 N. ZLS.5 apresentou sobrevida semelhante à HC.5, que foi semelhante aos grupos que apresentaram 100% de sobrevivência. YZHT mostrou a maior resistência característica e dispersão de dados. ZLS1 (22,3 ± 1,4) apresentou maior translucidez que HC1 (19,2 ± 0,6) e YZHT1 (12,0 ± 2,9), enquanto ZLS.5 e HC.5 foram semelhantes (26,5 ± 2,3, 26,7 ± 2,2) e superiores a YZHT.5 (12,7 ± 1,2). O HC.5 combinou alta confiabilidade e translucidez com baixa concentração de tensão, produzindo melhor desempenho da coroa e preservação dos dentes.

Palavras-chave: Fadiga. Coroas monolíticas. Materiais dentários. Preparo dental mínimo.

Dal Piva AMO. Influence of ceramic thickness on biomechanical behavior, survival and translucency of monolithic crowns [doctorate thesis]. São José dos Campos (SP): São Paulo State University (Unesp), Institute of Science and Technology; 2020.

ABSTRACT

Despite the increased use of monolithic crowns, their performance in different aspects has not yet been determined. Initially, this project investigated the biomechanical behavior of different conventional monolithic crowns on teeth and the stress distribution in the cement layer (Article 1). As main purpose, this study evaluated the effect of minimal dental preparation principle on the biomechanical behavior, reliability and translucency of posterior monolithic ceramic crowns. However, to define the substrate to be used to receive the machined crowns, a complementary analysis was developed to observe the restoration behavior on different substrates using the finite element analysis (Article 2). And for Article 3, one-hundred twenty six crowns were divided (n=21/gr) according to the material (High translucent zirconia - YZHT, Zirconia reinforced lithium silicate - ZLS and Hybrid ceramic - HC) and thickness (0.5 or 1 mm). Tensile stress concentration was calculated using the finite element method, the crowns were adhesivelly cemented and step stress fatigued to calculate reliability for missions at 600 and 900 N at 100,000 cycles; and, the translucency was analyzed in 10 discs of each material and thickness. Higher stress concentration was found in thinner crowns and those with higher elastic modulus. YZHT crowns were suspended when fatigue reached 1,500N load, thus 1-parameter Weibull was used to analyse the data. Reliability was only affected by thickness at 900 N. ZLS.5 showed similar survival to HC.5, which was similar to the groups that presented 100% survival. YZHT showed the highest strength and data scattering. ZLS1 (22.3 ± 1.4) presented higher translucency than HC1 (19.2 ± 0.6) and YZHT1 (12.0 ± 2.9), whereas ZLS.5 and HC.5 were similar to each other (26.5 ± 2.3, 26.7 ± 2.2) and superior to YZHT.5 (12.7 ± 1.2). HC.5 combined high reliability and translucency with low stress concentration, yielding better crown performance and tooth preservation.

Keywords: Fatigue. Monolithic crowns. Dental Materials. Tooth minimal preparation.

1 INTRODUÇÃO

Em função dos problemas estéticos das próteses metalo-cerâmicas (Vichi et al., 2016) devido à presença do metal e sua opacidade, foram desenvolvidos novos sistemas cerâmicos que eliminaram a ocorrência de escurecimento da margem cervical (Prince et al., 1983). Associadas a uma melhor condutibilidade térmica, biocompatibilidade e estabilidade clínica, surgiram as restaurações *metal-free*.

Quando comparadas às cerâmicas policristalinas, as cerâmicas de maior conteúdo vítreo são mais estéticas (Gracis et al., 2015), porém, menos resistentes. A cerâmica à base de zircônia (ZrO_2) parcialmente estabilizada por óxido de ítrio (Y_2O_3) é um material policristalino sem fase vítrea (Valandro, Bottino, 2009; Bispo, 2015). A Y-TZP tradicional apresenta baixa translucidez (Shenoy, Shenoy, 2010), e pode necessitar de recobrimento das infraestruturas com cerâmicas estéticas para mascarar sua opacidade (Baldissara et al., 2010; Eisenburger et al., 2011). As cerâmicas Y-TZP possuem combinações de propriedades interessantes entre os materiais cerâmicos, tais como elevada tenacidade à fratura, alta dureza, resistência ao desgaste, estabilidade química e biocompatibilidade (De Aza et al., 2002; Guazzato et al., 2004). No entanto, a associação entre infraestrutura de zircônia e cerâmica vítrea de cobertura pode resultar em falhas coesivas ou adesivas da cerâmica de cobertura, como lascamento (*chipping*) ou delaminação (Sailer et al., 2007; Christensen, Ploeger, 2010; Brizuela-Velasco et al., 2016). Para evitar a ocorrência destas falhas, as restaurações monolíticas foram desenvolvidas (Sailer et al., 2007; Christensen, Ploeger, 2010; Silva et al., 2017).

Além de apresentar custo operacional reduzido, as restaurações monolíticas permitem preparos mais conservadores (Amer et al., 2014) que se adequam ao critério da odontologia minimamente invasiva (Dirxen et al., 2013; Amer et al., 2014; Fradeani et al., 2016; Silva et al., 2017; Nawafleh et al., 2017; Sieper et al., 2017; Weigl et al., 2018). Diversos avanços nos materiais dentários permitem que diferentes cerâmicas possam ser utilizadas para uma mesma indicação, por exemplo, uma zircônia de alta translucidez, um silicato de lítio reforçado por zircônia e uma cerâmica híbrida podem ser indicadas (El Zhawi et al., 2016; Shembish et al., 2016; Chirumamilla et al., 2016; Silva et al., 2017; Furtado de Mendonça et al., 2018; Yan et al., 2018; Dal Piva et al., 2018; Kashkari et al., 2019; Rosentritt et al., 2019; Schlenz et al., 2019; Bergamo et al., 2019) quando um mínimo preparo dental é necessário para a confecção de uma coroa total posterior.

Visando superar as desvantagens como desgaste do antagonista e mimetização da estética natural do dente, cerâmicas com diferentes microestruturas foram desenvolvidas com propriedades mecânicas melhoradas, apropriado desgaste e estética aceitável (Gracis et al., 2015; Silva et al., 2017). Porém, a grande variedade dos materiais cerâmicos dificulta para o clínico a seleção do material ideal para cada situação clínica, fazendo com que o critério de seleção geralmente seja baseado na compreensão de valores de resistência e translucidez do material, técnica de confecção da restauração e preferência cerâmica do laboratório. Assim, uma nova classificação para as cerâmicas foi sugerida baseada nas fases que compõem sua estrutura química: cerâmicas de matriz vítrea, policristalinas e as de matriz resinosa (orgânica) (Gracis et al., 2015). A cerâmica pré-sinterizada à base de silicato de lítio reforçada por zircônia (ZLS), Vita Suprinity (Vita Zahnfabrick, Bad Sackingen, Alemanha), é um exemplo de cerâmica vítrea que pode ser utilizada para a confecção de facetas, *inlays*, *onlays*, coroas monolíticas anteriores e posteriores sobre dente. Esta cerâmica apresenta microestrutura (Ramos et al., 2016) e propriedades (Elsaka, Elnaghy, 2016) semelhantes ao dissilicato de lítio, um material já consagrado no mercado. Já as cerâmicas chamadas híbridas ou de matriz resinosa (HC) consistem em uma matriz cerâmica inorgânica embebida em uma matriz polimérica (Chirumamilla et al., 2016; Ramos et al., 2016). A cerâmica Enamic (Vita Zahnfabrick, Bad Sackingen, Alemanha) apresenta em sua composição uma matriz polimérica que contém uretano dimetacrilato (UDMA) e trietileno glycol dimetacrilato (TEGDMA) (Gracis et al., 2015). As cerâmicas híbridas apresentam módulo elástico inferior às cerâmicas tradicionais (Coldea et al., 2013; Ramos et al., 2016; Silva et al., 2017), baixa dureza (Coldea et al., 2013; Albero et al., 2015), rápida usinagem e fácil polimento (Silva et al., 2017). Dentre suas indicações estão as facetas, *inlays*, *onlays* e as coroas sobre dente e implante. Frente a tantas opções cerâmicas para uma mesma indicação, questionamentos clínicos são levantados acerca de qual material selecionar e quais propriedades devem ser consideradas para a correta escolha do material.

A estética também é um importante fator a ser considerado durante a seleção do material restaurador. A busca por um material com alta resistência mecânica e propriedades ópticas aceitáveis são objetos de estudo em diversas investigações (Sun et al., 2014; Dhima et al., 2014; Nordahl et al., 2015; Sorrentino et al., 2016; Nawafleh et al., 2017; Sieper et al., 2017; Choi et al., 2017; Weigl et al., 2018; Bergamo et al., 2019). Apesar do aumento na utilização de coroas monolíticas, a performance dessas restaurações ainda necessita ser avaliada quando o princípio de preparo mínimo é considerado (Worni et al., 2017; Bergamo et al., 2019), assim como qual material deve ser utilizado nesses preparos conservadores. Pouco se sabe sobre o desempenho de coroas monolíticas com espessuras mínimas. No entanto, é relatado que a espessura oclusal mínima sugerida pelo fabricante para coroas posteriores monolíticas é de 0.5 mm para a YZHT e 1 mm para a ZLS e HC. E que, a espessura da restauração influencia na resistência mecânica (Nakamura et al., 2015; Sun et al., 2014; Nawafleh et al., 2017; Choi et al., 2017; Tsuyuki et al., 2018; Yin et al., 2019; Gierthmuehlen et al., 2019), distribuição de tensões (da Fonseca et al., 2018a, 2018b; Tribst et al., 2018) e translucidez (Wang et al., 2013; Sulaiman et al., 2015; Stawarczyk et al., 2016; Tong et al., 2016; Church et al., 2017; Silva et al., 2017).

As avaliações *in vitro* de coroas monolíticas utilizam coroas anatômicas e preparos dentais a fim de simular os modos de falhas observados clinicamente (Coelho et al., 2009; Lorenzoni et al., 2010; Bonfante et al., 2010; Silva et al., 2011; Sun et al., 2014; Dhima et al., 2014; Nordahl et al., 2015; Sorrentino et al., 2016; Nawafleh et al., 2017; Furtado de Mendonça et al., 2018; Kashkari et al., 2019; de Paula et al., 2019; Schlenz et al., 2019) quando avaliados sob testes de fadiga (Peterson et al., 1998; Zhang, Lawn, 2004; Guess et al., 2010; Tribst et al., 2019). O teste de vida em fadiga acelerado ou *Step-stress accelerated-life test* (SSALT) é amplamente utilizado para avaliar o tempo de vida de restaurações (Silva et al., 2008; Coelho et al., 2009; Bonfante et al., 2010a, 2010b; Silva et al., 2011; El Zhawi et al., 2016; Bergamo et al., 2019). Quando o teste SSALT é utilizado em conjunto com uma análise de distribuição de tensão, eles permitem inferências sobre áreas críticas para a origem de trincas.

O objetivo do presente estudo foi avaliar o efeito da espessura da cerâmica no comportamento biomecânico, sobrevivência e translucidez de coroas posteriores monolíticas em três diferentes cerâmicas para CAD/CAM. As hipóteses consistiram em que o tipo de preparo e o material restaurador não mudariam (1) o comportamento biomecânico, (2) a sobrevivência e (3) a translucidez das coroas.

2 ARTIGOS

2.1 Artigo – Dal Piva AMO, Tribst JPM, Borges ALS, Souza ROAE, Bottino MA. Modelamento e análise CAD/FEA de diferentes restaurações do tipo coroas totais monolíticas / *CAD-FEA modeling and analysis of different full crown monolithic restorations**

RESUMO

Objetivos: Investigar a influência de diferentes materiais nas coroas monolíticas posteriores usando a Análise por Elementos Finitos 3D (FEA). **Métodos:** Doze (12) modelos 3D de dentes restaurados adesivamente com diferentes coroas de acordo com o material e seu módulo de elasticidade foram analisados: resina acrílica, poliéter-éter-cetona, resina composta, cerâmica híbrida, silicato de lítio reforçado com zircônia injetável e usinável, cerâmica feldspática, disilicato de lítio, liga de ouro, liga de cobalto-cromo (Co-Cr), zircônia tetragonal estabilizada parcialmente com ítria e alumina. Todos os materiais foram assumidos como se comportando elasticamente durante toda a deformação. Os resultados na linha de restauração e cimentação foram obtidos usando a tensão máxima principal. Além disso, os critérios de tensão máxima de cisalhamento foram utilizados para a linha de cimentação. **Resultados:** Materiais restauradores com maior módulo de elasticidade apresentam maior concentração de tensões no interior da coroa, principalmente na superfície interna. Por outro lado, materiais com menor módulo de elasticidade permitem a passagem de tensão para o cimento, aumentando a tensão de cisalhamento nessa camada. Materiais mais rígidos promovem valores de pico de tensão mais altos. Significado: Materiais com módulo de elasticidade mais alto, como Co-Cr, zircônia e alumina, permitem maior concentração de tração na superfície interna da coroa e maior tensão de cisalhamento na camada de cimento, facilitando a descolagem da coroa.

Palavras-chave: Cerâmicas. Análise por elementos finitos. Coroas monolíticas. Propriedades dos materiais. Materiais dentários.

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ABSTRACT
Objectives: *To investigate the influence of different materials for monolithic full posterior crowns using 3D-Finite Element Analysis (FEA).* ***Methods:*** *Twelve (12) 3D models of adhesively-restored teeth with different crowns according to the material and its elastic modulus were analyzed: Acrylic resin, Polyetheretherketone, Composite resin, Hybrid ceramic, pressable and machinable Zirconia reinforced lithium silicate, Feldspathic, Lithium disilicate, Gold alloy, Cobalt-Chromium alloy (Co-Cr), Zirconia tetragonal partially stabilized with yttria, and Alumina. All materials were assumed to behave elastically throughout the entire deformation. Results in restoration and cementing line were obtained using maximum principal stress. In addition, maximum shear stress criteria was used for the cementing line.* ***Results:*** *Restorative materials with higher elastic modulus present higher stress concentration inside the crown, mainly tensile stress on an intaglio surface. On the other hand, materials with lower elastic modulus allow stress passage for cement, increasing shear stress on this layer. Stiffer materials promote higher stress peak values.* ***Significance:*** *Materials with higher elastic modulus such as Co-Cr, zirconia and alumina enable higher tensile stress concentration on the crown intaglio surface and higher shear stress on the cement layer, facilitating crown debonding.*

Keywords: Ceramics. Finite element analysis. Monolithic crowns. Material properties. Dental materials

1. Introduction

The indication of full crowns in molars is a treatment that mainly aims to restore masticatory function due to the magnitude of the occlusal forces present in this region [1]. Noble metallic crowns considered as the gold standard have been widely used [2], [3], [4], [5]. However, with the aesthetic improvement of restorative materials and the possibility of using dental ceramics instead of metals for the same indication, metallic crowns have lost their popularity. In order to minimize the occurrence of failures of the covering ceramics in both metal-ceramic crowns and full ceramic crowns [4], [6], ceramic materials were developed with the possibility to be used in a monolithic way. Although the main motivation for the use of ceramic crowns is to mimic an improved dental structure versus metals [7], there is no consensus on which ceramic has the best indication in the manufacture of these monolithic restorations [7], [8], [9]. For example, feldspathic or glass-ceramics may be quite successful in the anterior region [2], as well as a considerable percentage of survival up to 10 years [10]. However, when in posterior crowns, they do not present survival percentage as high as zirconia crowns [4], [5].

Toughness consists in a property of the materials defined by the amount of plastic and elastic deformation energy required to fracture a material. The fracture toughness corresponds to the energy required to propagate critical defects in a structure, directly related to the stress/strain curve [11]. Manufacturers' caution regarding the material indication exists since all ceramic materials have adequate toughness to withstand the masticatory loads; however, they can fail, therefore, a tough material is generally resistant but, a resistant material is not always tough [11]. The presence of humidity, temperature and continuous incidence of mastication with pH variations make the oral medium an arduous survival environment, causing even the most resistant materials to be degraded in the long term [12], [13]. In this sense, noble metals are still a restorative alternative due to their ductility and absence of oxidation in the oral environment. Thus, toughness does not seem to be the only factor responsible for the longevity of the restoration, as ceramics are as close to the metals or even higher in flexural strength. Therefore, materials with a different composition proposal have come to draw the attention of dentists, because perhaps a material that is not as resistant as zirconia could respond better to the masticatory loads and thus adapt and survive. With this intention, polymer infiltrated ceramics with a resin matrix were developed. This polymer infiltration could be able to absorb chewing and be a better option in the long term [8]. There are many materials with distinct characteristics that share the indication of rehabilitating posterior full crowns, from resins in the manufacture of temporary restorations to highly resistant ceramics. Thus, the possibility of using materials with elastic modulus from 2 GPa to a ceramic with a 100 times greater elastic modulus raises the question of how these restorations behave mechanically. Understanding the mechanical behavior of restorations and if this mechanism can be based on the restorative material choice is not clear and is not part of the daily routine of the dentist. This is because an extremely tough material can be used with the guarantee of the crown's structural durability; moreover, a brittle material can be chosen to dampen the masticatory loads. These materials share the possibility of being used in the same indication with the same anatomy onto a standard dental preparation and often being cemented in a similar way, making the restorative procedure routine for whichever material is the dentist's choice. However, can the material's behavior during function influence the longevity of the treatment? The objective of this study was to evaluate the stress regions of the restoration and the cementing line according to the restorative material used (12 levels) in posterior monolithic total crowns using non-linear 3D finite element analysis. The alternative hypothesis was that there would be no difference on the stress distribution in the restorations and cementing line, regardless of the material used.

2. Materials and methods

2.1. Finite element analysis (FEA) pre-processing

A human molar model was created using modeling software (Rhinoceros version 5.0 SR8, McNeel North America, Seattle, WA, USA). For this, anatomical lines referring to the occlusal grooves and surrounding crown bases were constructed so that each face was obtained following anatomical conditions. After creation of the surfaces, they were fixed to form a volumetric solid of a first maxillary molar. Next, the crown was separated from the root and a total crown preparation was constructed with 5.5 mm of height and 12° of occlusal convergence in the axial walls.

The external layer of the dental preparation was subsequently duplicated and used as a base for making the cementing line with 0.1 mm of thickness. This allows all the contacting faces of the preparation and the cement to be the same in number and shape and thus reduce the interference during the mathematical analysis. The external surface of the cement was used as a base for the inner surface of the crown. The final geometries were: monolithic crown, cement line, dental preparation, periodontal ligament and fixation cylinder (Fig. 1). All bodies were considered volumetric solids.

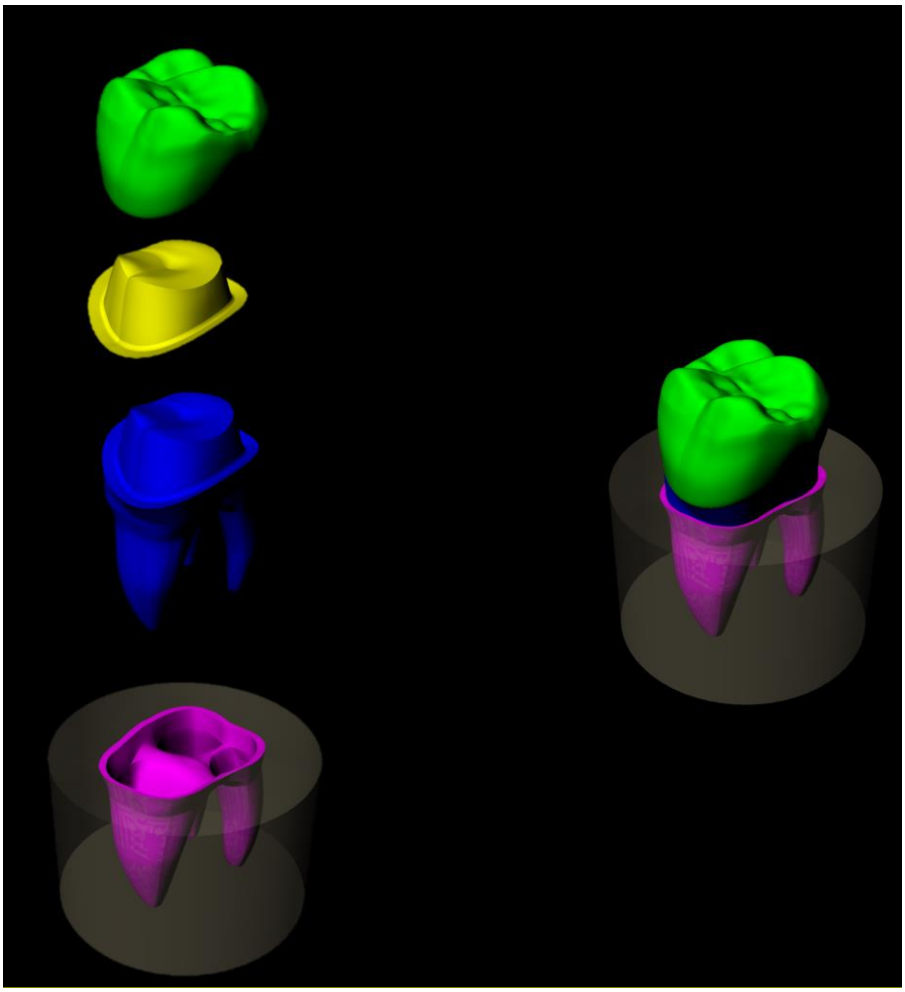

Fig. 1. 3D FEA model of a tooth: (a) monolithic crown; (b) cementing line; (c) tooth remnant; (d) periodontal ligament; (e) restored tooth.

2.2. FEA solution

2.2.1. Mesh generation

The geometries were imported into ANSYS software CAE (ANSYS 17.2, ANSYS Inc., Houston, TX, USA) in STEP format and tetrahedral elements formed the mesh. A convergence test of 10% mesh control determined the mean number of 95,263 elements and 169,672 nodes.

2.2.2. FEA processing

The materials and structures properties were attributed to each solid component with isotropic, homogeneous and linearly elastic behavior. Young's modulus and Poisson's ratio were reported (Table 1) [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29] and all contacts were ideally cast.

2.2.3. Loading and fixations

Load application (600 N) occurred similar to the methodology by Ausiello et al. [16] which considered the contact between food bolus and tooth surface during the closing phase of the chewing cycle (Fig. 2). A cylinder base was selected for the system fixation condition, ensuring only the movement constraint on the Z axis so that the deformation generated in all directions could be computed.

Table 1. Mechanical properties of materials and structures used in this study.

Material/Structure	Young's modulus (GPa)	Poisson's ratio
Enamel [14]	84.1	0.33
Dentin [15]	18.6	0.32
Food bolus [16]	3.41 ($\times 10^{-3}$)	0.10
Alumina [17]	314	0.22
Zirconia [18]	200	0.31
Lithium disilicate [19]	95	0.25
Poliuretano [20]	3.6	0.3
Composite resin [21]	11	0.28
Hybrid ceramic [22]	34.7	0.28
Pressable ZLS [23]	70	0.23
Feldspar [22]	48.7	0.23
PEEK [24]	3.70	0.40
Gold alloy [25]	91	0.32
CoCr alloy [26]	220	0.30
Acrilic Resin [27]	2.7	0.35
Usinable ZLS [23]	70	0.23
Periodontal ligament [16]	0.15 ($\times 10^{-3}$)	0.45
Resinous cement [28,29]	7.5	0.3

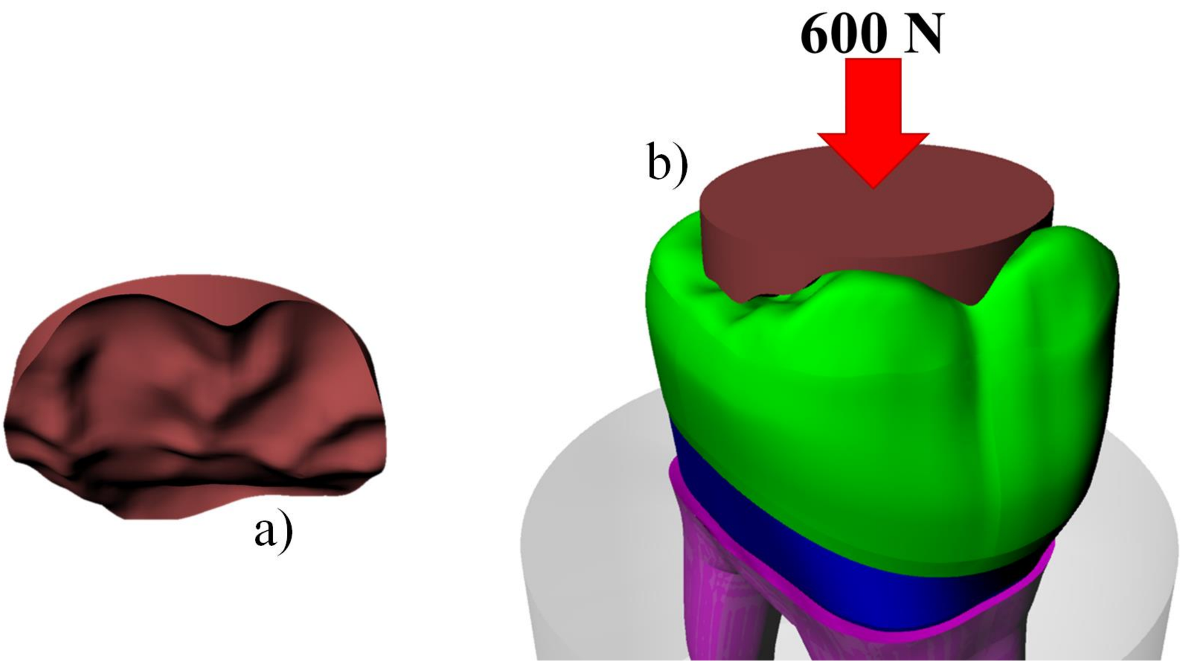

Fig. 2. Food modeling and load application: (a) bolus on the occlusal surface; (b) occlusal load.

2.3. FEA pos-processing

In order to evaluate the stress distribution generated by masticatory loads in the restored teeth, finite element analysis (FEA) has been used due to specimen standardization, low cost, and because it is a numerical method that offers a means to find an approximate solution [16], [30], [31], [32]. Some terms are very common when this computational method is used such as stress and stress concentration. Stress consists of the response of the atoms and molecules to a load applied in the evaluated structure [11]. Herein, results in restoration and cementing line were obtained using maximum principal stress (tensile stress results in MPa). In addition, maximum shear stress criteria was used for the cementing line.

Stress concentration is defined as a ratio of peak stress to nominal/average stress in the concerned region [33]. Thus, the stress concentration (SC) in the crown intaglio surface and on the cementing line were calculated according to the formula: SC=Sp/aS, where, “Sp” corresponds to the stress peak value and aS, to the average stress values in the concerned regions, in MPa. Strength property consists in the necessary force to fracture a structure with known area [34]. Thus, the failure risk (Fr) of the restoration and cementing line were calculated according to the formula: Fr=Sp/Strength. The restoration failure risk consisted on the material highest peak divided per its tensile strength. For the cementing line, its cohesive failure risk was evaluated by the stress peak to tensile strength ratio and the adhesive failure risk, was calculated by the stress peak to the bond strength to dentin ratio.

3. Results

The results generated in maximum principal stress show the tensile stress pattern generated in three regions of the prosthetic crown (occlusal face, sagittal cut and internal surface) through a stress map (Fig. 3). The stress distribution in the restoration was impaired directly proportional to the elastic modulus of the restorative material. Considering the stresses generated in the perspective cementing line (Fig. 4), the stress distribution was improved with the increase of elastic modulus of the restorative material used in the crown for tensile and shear criteria’s. By isolating the inner region of the crown, it is possible to observe that the higher the elastic modulus of the restorative material, the higher the tensile stress peak values (Fig. 5). The same behavior was observed for maximum shear stress on cement layer, with few areas of higher stress (Fig. 4), but higher peaks of shear stress (Fig. 5). Stress concentration results are summarized in Table 2 [17], [35], [36], [37], [38], [39], [40]. This finding suggests that the higher the stress concentration ratio the best is the stress distribution. This fact can be justified because the peak will never be equal to the average value. Therefore, a notable difference between stress peak and average stress values will result in values greater than 1. Thus, acrylic resin showed the best stress concentration for the crown (7.14). For the cementing line, the best behavior was found for the alumina crown (3.33), followed by zirconia and CoCr alloy (3.22). Considering the crown failure risk, hybrid ceramic showed the lowest risk (0.01) while alumina (0.06) showed the highest. For the cementing line, all materials showed proportionally (±40%) higher cohesive failure risk (0.15–0.21) in comparison to adhesive failure risk (0.06–0.09), with the worst performance for the alumina crown and the best performance for the composite resin crown.

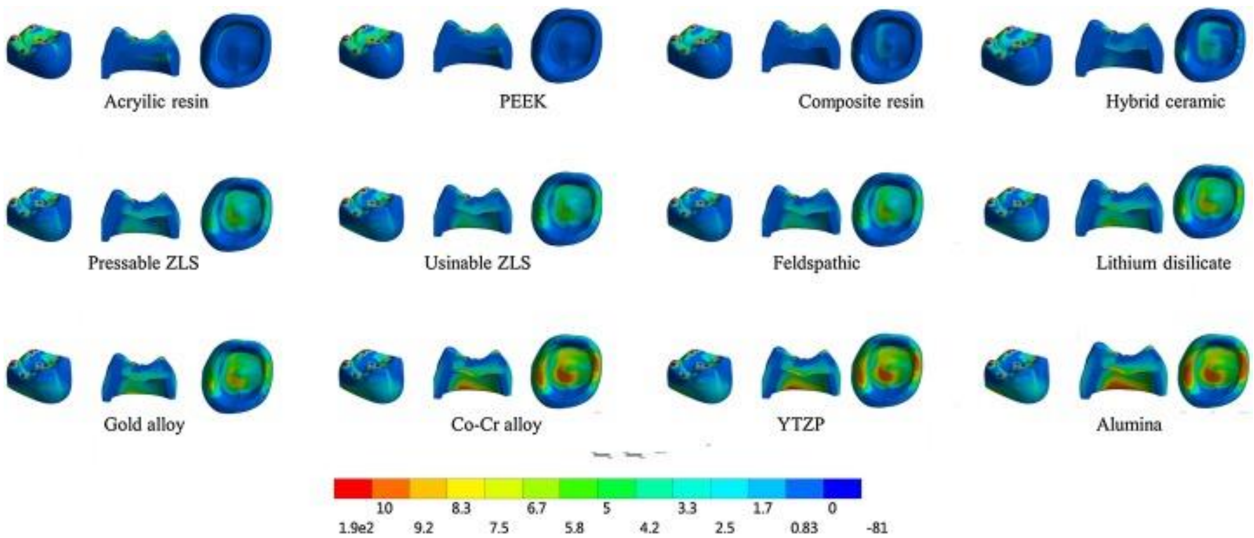

Fig. 3. Stress generated in monolithic crowns; (a) acrylic resin, (b) PEEK, (c) composite resin, (d) hybrid ceramic, (e) pressable ZLS, (f) ZLS CAD, (g) feldspathic, (h) lithium disilicate, (i) gold alloy, (j) CoCr alloy, (k) YTZP and (l) alumina.

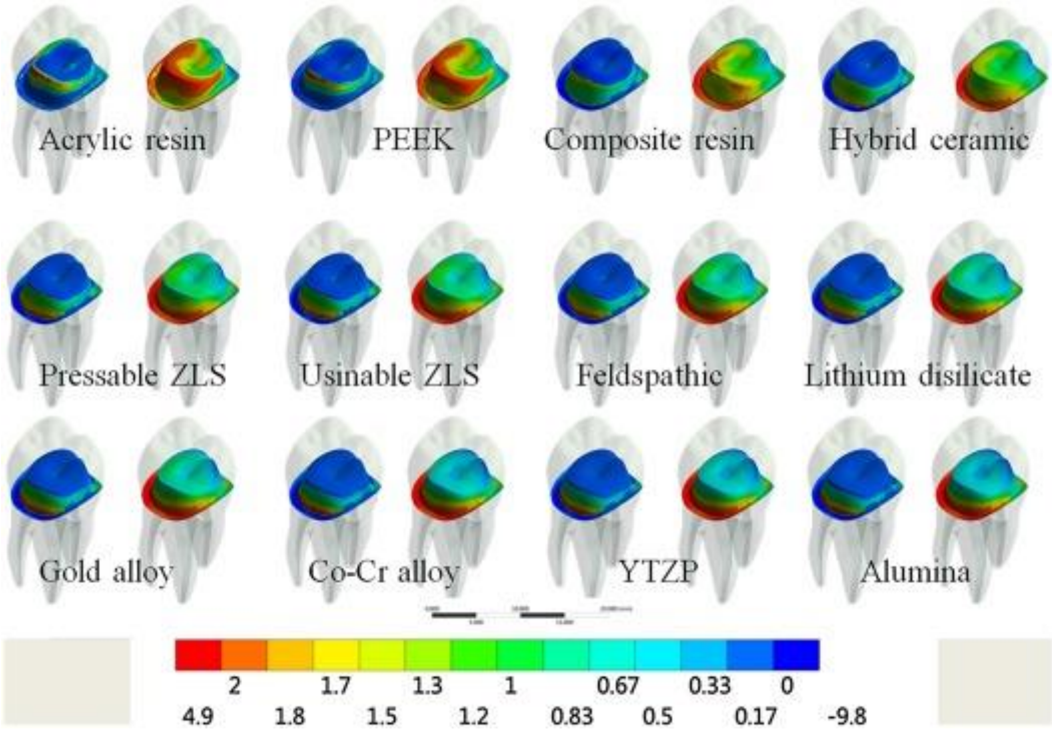

Fig. 4. Tensile and shear stresses generate on cementing line according to the monolithic crowns, respectively: (a) acrylic resin, (b) PEEK, (c) composite resin, (d) hybrid ceramic, (e) pressable ZLS, (f) ZLS CAD, (g) feldspathic, (h) lithium disilicate, (i) gold alloy, (j) CoCr alloy, (k) YTZP and (l) alumina.

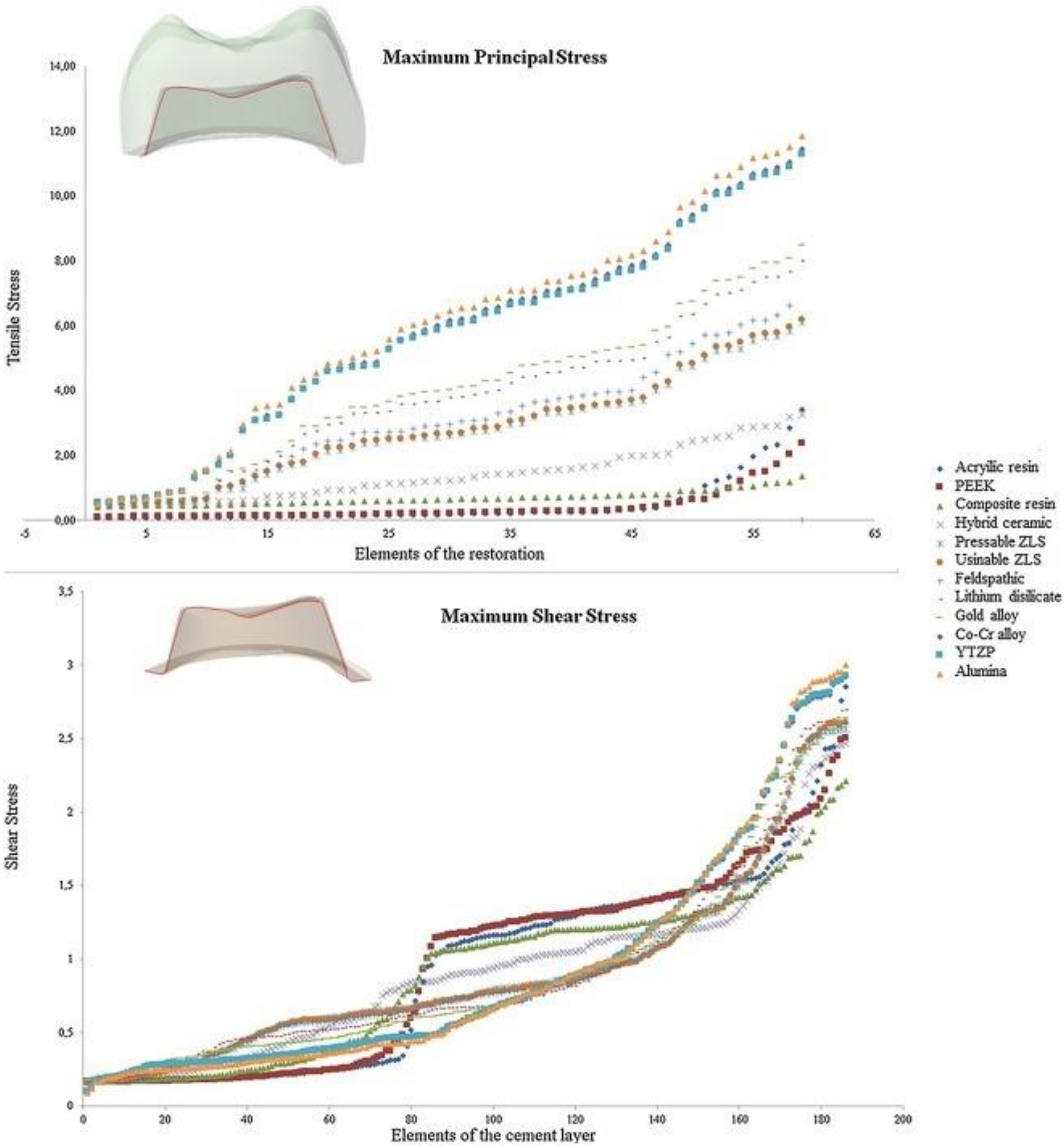

Fig. 5. Maximum principal stress (MPa) distribution along the crown internal surface and Maximum shear stress (MPa) distribution along the cementing layer external surface.

Table 2. Tensile strength of the materials simulated in this study, stress peak, average stress, stress concentration ratio and failure risks for crown and cementing line.

	Crown					Resin cement				
Material	**Tensile strength**	**Stress Peak**	**Average Stress**	**SC**	**Failure risk**	**Stress Peak**	**Average Stress**	**SC**	**Failure risk**	
									C	**A**
Alumina [17]	193	11.86	6.02	1.97	0.06	3	0.91	3.3	0.21	0.09
CoCr alloy [35]	680	11.44	5.75	1.99	0.02	2.92	0.91	3.22	0.20	0.08
Zirconia [36]	745	11.28	5.66	1.99	0.02	2.93	0.91	3.22	0.20	0.09
Lithium disilicate*	173±9	7.99	3.76	2.13	0.05	2.69	0.9	3	0.19	0.08
Gold alloy [37]	462	8.48	4.01	2.11	0.02	2.64	0.88	2.99	0.18	0.08
Pressable ZLS*	180±11	6.1	2.76	2.21	0.03	2.56	0.89	2.87	0.18	0.07
Usinable ZLS*	159±18	6.18	2.83	2.18	0.04	2.61	0.89	2.93	0.18	0.08
Feldspathic *	123±7	6.62	3.05	2.17	0.05	2.6	0.89	2.91	0.18	0.08
Hybrid ceramic*	227±23	3.26	1.42	2.29	0.01	2.46	0.89	2.76	0.17	0.07
Composite Resin [38]	45	1.35	0.68	1.98	0.03	2.21	0.89	2.49	0.15	0.06
PEEK [39]	54	2.38	0.4	5.91	0.04	2.5	0.94	2.67	0.17	0.07
Acrylic Resin [40]	79	3.41	0.48	7.14	0.04	2.85	0.92	3.09	0.20	0.08

Legend: Stress concentration ratio (SC), Coehsive (C) and Adhesive (A).

4. Discussion

The purpose of this study was to evaluate the stressed regions in the posterior monolithic crown and in the cementing line according to the restorative material. The results demonstrated that there is a significant difference between the biomechanical behavior as a function of the material used in the monolithic restoration, rejecting the alternative hypothesis. This study revealed that the observed values in the colorimetric stress scale of the crowns were considerably lower than the values of the critical stress of the materials used to build the crowns. Thus, it is suggested that there will be no fracture occurrence during occlusion. These results may be supported by similar findings in the literature for such materials [7], [8], [41]

For posterior monolithic crowns, different classes of materials may be used such as: acrylic resin generally used for temporary prosthesis; Polyetheretherketone (PEEK) polymer is an alternative resilient material [42], a hybrid ceramic that emerged with the objective of associating the composite resin and feldspathic ceramic qualities; zirconia reinforced lithium silicate, a material structurally similar to lithium disilicate reinforced with zirconia particles [22], [43], [44]; lithium disilicate [45]; noble metal alloys; yttria-tetragonal zirconia polycrystal (YTZP); and alumina-based ceramics are some possible treatment examples to be found in an oral environment. The higher stress peaks in the crowns were observed in the materials with higher elastic modulus corroborating with previous studies [9], [19]. Considering the observed stress peaks and although it does not show a risk of fracture for the materials, it can be harmful when located in the lower portion of the total crowns since this region lies in addition to the layer of resinous cement and a detachment of the prosthetic piece could be initiated in these stressed regions. This assertion is mainly of concern for YTZP, which in addition to having high elastic modulus presents poor adhesive properties [46], suggesting a worse prognosis. Case reports have already been documented in the literature [12], [47], supporting this theory. Still evaluating the stresses in the crowns in a sagittal section, it is possible to observe a tensile zone present on the intaglio surface of the crowns, validating our model since it is in this region that the propagation of crack in brittle materials begins [48], [49], justifying the results obtained in the restoration intaglio surface. Brittle materials have low fracture toughness, whereas materials that undergo plastic deformation such as metals present higher levels of fracture toughness, but also fail due to tensile forces [50], [51]. In this study, it was observed that the Cr–Co alloy concentrated more stress than the gold alloy and acted similarly to the ceramics of larger elastic modulus.

A previous study that evaluated total crowns on different substrates found that nanoceramic resin crowns with an elastic modulus of 12 GPa are more likely to fatigue the cementing line than lithium disilicate crowns. Such an inference is similar to the present results. However, the authors did not simulate a cement layer and reported that the stress at the interface may have occurred due to the difference between the elastic modulus of the restorative material and the substrate [50]. This explanation of the difference in elastic modulus does not seem to be responsible for the stress accumulation in the intermediate material (cement layer). Only when the restorative material was the hybrid ceramic and composite resin whose elastic modulus is similar to dentin did it reduce the difference in the rigidity between crown and tooth, and no mechanical benefit was obtained for the cement. Herein, these materials and also PEEK showed the lowest cement cohesive failure risk, which corresponds to the best mechanical benefit for the cement. Several FEA investigations that studied total crowns and the influence of restorative materials simplify the cementing line by using perfectly bonded contacts between the structures and consider that an ideal cementation has occurred [9], [50], [51]. Although this simplifying this method is possible, facilitates processing and speeds up the analysis for the crown, inferences on detachment and cohesive failure of the cement should be performed in situations where the cement has been simulated as an individual structure because the presence of the cement can modify the system mechanical behavior [41], [52], [53], as seen in the results herein.

The cementing layer was modeled with a thickness of 100 μm, according to the literature [54], [55]. This layer is relevant for studies since cohesive failures on this layer can occur in the long term [56], and thus allow restoration displacement. The results herein corroborates with this sentence since cohesive cementing line failure risk was superior than adhesive failure to dentin, regardless the crown material (Table 2). Referring to Fig. 4, it is possible to note that the more rigid the crown, the less tensile stress reaches the cement, as this crown was able to concentrate the stress itself. This behavior suggests that the group restored with crown with higher elastic modulus minimizes damage in the cement layer; however, they increase the both evaluated cement failure risks. Nevertheless, when correct cementation is done, the cement line is minimal, which means that the differences between the groups are few, even though they are significant. According to the colored graphs, the difference of at most 2 MPa makes it impossible to predict if the groups would clinically present very different behavior that could promote cement fracture. But, using the formula to calculate the failure risk, it was possible to suggest that alumina crowns showed the higher failure risk for the cement. Despite this limitation, the ability of materials with low elastic modulus to allow the passage of stress to the cement is noticeable, and therefore careful cementation should always be indicated, since in these cases the cement will be more stressed and could compromise the mechanics of the restoration and its longevity when in larger thicknesses.

In this paper higher stress peak was proportional to the higher possibility of failure. However, it is important to notice that it is not a rule. Thus, stress peak and also average values should be always evaluated. Here, the highest stress peak and the highest failure risk were found for the crown in alumina. As reported in the literature, failures involving monolithic crowns are related to the cementing layer, thus, cohesive and adhesive failure risks were evaluated for this layer. As the same cement was simulated in all conditions, its tensile strength [57] and bond strength to dentin [58] available in the literature were used. This demonstrates that the failure criteria of the adhesive layer's integrity can be directly connected with the shear action of the surrounding axial walls. Thus, these results support the importance of evaluating the adhesive resistance in tests that evaluate this type of resultant stress. The generated tensile stress on the total crowns appears to be inversely proportional to the cement layer, but the higher peaks of shear stress were present when rigid crowns were used. Basically, the loss of total crown adhesion seems to be related to the extremes of the simulated groups. Therefore, crowns with high elastic modulus exhibit their internal surface traction from the resin cement, and crowns with low elastic modulus allow more areas of shear stress in the same cementing layer. In order to promote more durable adhesion and to maintain the total crown in position, a topographic modification by chemical or physical agents of the inner face of the crown increases the adhesive resistance between the crown and cement, which makes the shear stress insufficient to overcome the adhesive strength obtained after surface treatment as the elastic modulus of the crown is still the same, yet it is assumed that the stress still exists of such magnitude.

The crown in acrylic resin is used in dentistry as a temporary restoration and although it allows the cement to concentrate tensile and shear stresses, its indication is very concise and the practicality of making restorations makes this material practical for use in several cases. However, PEEK is a relatively new material in dentistry and is handled by the CAD/CAM machining process [59]. Although it is indicated for crowns or infrastructures [59], its elastic modulus is low compared to most of the materials available with the same indication, and its mechanical behavior when used as a total crown is close to the mechanical behavior of the acrylic resin in the analysis of the generated stresses, but, with lower cement failure risk. The crowns in composite resin and hybrid ceramic demonstrate an elastic modulus that approaches the dentin structure and the resin cement, and although they are not capable of reducing tensile stresses in the cementing line as much as a zirconia crown, they are capable of not concentrating tensile stress on its inner face, thus suggesting interesting survival since these regions are the first regions to fail in a total crown [16], [60]. Hybrid ceramic presented the lowest failure risk for the crown and for the cement line. For the correct decision-making in selection of the materials for patients other properties should be considered such as wear resistance, degradation, fatigue resistance, toughness, aesthetics. Therefore, hybrid ceramic monolithic crown showed the best mechanical behavior being suggested as the best monolithic crown for posterior region.

5. Conclusion

Within the limitations of this study, it is possible to conclude that the hybrid ceramic showed more promising mechanical behavior results for posterior monolithic crown with lower failure risks.

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2.2 Artigo – Dal Piva AMO, Tribst JPM, Borges ALS, Melo RM, Bottino MA. Influência do design do substrato para testes mecânicos *in vitro* / *Influence of substrate design for in vitro mechanical testing**

RESUMO

INTRODUÇÃO: O objetivo deste estudo foi avaliar a influência do material do simulador de substrato dental e a presença da raiz e do ligamento periodontal na distribuição do tensão em uma coroa monolítica cimentada adesivamente.

MATERIAL E MÉTODOS: Cinco (5) modelos 3D de acordo com o material e a forma do simulador de substrato foram modelados com o software CAD para a análise não linear por elementos finitos (FEA): Dente com e sem ligamento periodontal - subgrupo "pl" (grupos Tooth + pl e Tooth- pl), dente usinado em resina epóxi (ER) com e sem câmara pulpar - subgrupo "pc" (ER + pc e ER-pc) e substrato simplificado em resina epóxi sem câmara pulpar e raízes (SiER). Em seguida, coroas monolíticas em silicato de lítio reforçado com zircônia foram modeladas cimentadas adesivamente sobre cada substrato. Os sólidos foram importados no formato STEP para o *software* de análise e o contato entre dentes e cilindro foi considerado perfeitamente aderido; enquanto que os contatos envolvendo o cimento resinoso foram considerados não separados. Os materiais foram considerados isotrópicos, linearmente elásticos e homogêneos. Uma carga axial (600 N) foi aplicada à superfície oclusal e foram solicitados resultados em tensão máxima principal (MPa) na restauração.

RESULTADOS: FEA revelou que todos os substratos avaliados mostraram a superfície do entalhe da coroa como a região mais estressada. A tensão média e os picos de tensão foram semelhantes nas restaurações cimentadas nos substratos Tooth + pl, Tooth-pl e ER+pc, mas 13% maior em comparação aos substratos ER-pc e SiER.

CONCLUSÕES: Substratos simplificados podem ser usados para avaliar o comportamento posterior da coroa completa sem ligamentos e raízes periodontais, uma vez que a rigidez da amostra seja levada em consideração.

Palavras-chave: Análise por elementos finitos. Carga axial. Análise numérica assistida computadorizada. Coroas monolíticas. Estudo metodológico.

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ABSTRACT

BACKGROUND:The goal of this study was to evaluate the influence of dental substrate simulator material, and the presence of root and periodontal ligament on the stress distribution in an adhesively-cemented monolithic crown.

MATERIAL AND METHODS: Five (5) 3D models according to the substrate simulator material and shape were modeled with CAD software for conducting non-linear finite element analysis (FEA): Tooth with and without periodontal ligament - subgroup "pl" (groups Tooth+pl and Tooth-pl), machined tooth in epoxy-resin with and without pulp chamber - subgroup "pc" (ER+pc and ER-pc) and simplified epoxy-resin substrate without pulp chamber and roots (SiER). Next, adhesively-cemented monolithic crowns in zirconia reinforced lithium silicate were modeled over each substrate. The solids were then imported in STEP format to the analysis software and the contact between teeth and cylinder was considered perfectly bonded; whereas, the contacts involving the resin cement were considered as non-separated. The materials were considered isotropic, linearly elastic, and homogeneous. An axial load (600 N) was applied to the occlusal surface and results of maximum principal stress (MPa) on the restoration were required.

RESULTS: FEA revealed that all evaluated subtracts showed the crown intaglio surface as the most stressed region. The average stress and stress peaks were similar for restorations cemented onto Tooth+pl, Tooth-pl and ER-pc substrates, but, 13% higher in comparison to ER-pc and SiER substrates.

CONCLUSIONS: Simplified substrates can be used to evaluate posterior full crown behavior without periodontal ligaments and roots, since the rigidity of the specimen is taken into account. Key words:Finite element analysis, axial loading, computed assisted numerical analisys, monolithic crowns,methodological study.

Keywords: Finite element analysis. Axial loading. Ccomputed assisted numerical analisys. Monolithic crowns. Methodological study.

Introduction

The field of materials science advances in developing new materials that often require new research to predict their behavior in use. Among dental materials, ceramics are widely used due to high aesthetics and mechanical properties (1). Thus, in respecting their limitations and following correct clinical application, ceramic restorations present promising results with high survival rates (2,3).

It is quite common for dental materials to be released on the market prior to clinical trials. Therefore, in searching for relevant information and short-term results, companies and researchers use laboratory studies which are most often fatigue tests (4-11). But when an experimental study is performed, several factors must be taken into account such as sample design, testing methods, data analysis and possible outcomes (4). Thus, several guides have been launched in order to standardize and guide researchers in developing sound studies that can be compared due to their methodological standardization (12,13). However, it takes a certain amount of time for this to become common practice.

In considering the studies of mechanical fatigue on ceramic crowns, preparation design and substrate materials can vary. Epoxy resin filled with woven glass fibers is a commonly used dentin-like material (5-7,14). This material was first presented in 2010 as having similar elastic and adhesive properties to wet dentin (15). Despite its characteristics, studies have used other materials as a tooth substitute (8-11), such as ivory (16), acrylic resin (17,18), typodont (19), metal (20) and composite resins (21,22). However, it is known that there are differences in the failure modes obtained in different specimen forms. For this reason, the question arises whether epoxy resin and the presence of dental root (s) would influence the restoration's mechanical properties. Few studies report the use of a dental preparation made of epoxy resin containing roots (5,23). Other variables are often simulated in laboratory tests, but have not been evaluated yet, which also lead to the following questions: should the substrate copy the tooth anatomy? Should a tooth be used or can a dentin-like material be used instead? Should the presence of the root (s) be considered? Or should the periodontal ligament be simulated?

Another point to consider is the stress distribution. If the distribution is not homogeneous, regions with stress peak values may concentrate and lead to failure of the material/structure (24,25). For evaluation of the stress distribution generated by masticatory loads in full crown restorations, finite element analysis (FEA) has been used (9,25) due to the ease of specimen standardization, low cost, and because it is a numerical method that offers an approximate solution (26). Thus, the goal of the present study was to evaluate the influence of substrate type (a dentin-like epoxy vs tooth), considering the presence of root (with and without) and the presence of periodontal ligament simulator (with and without) on the biomechanical behavior of full single monolithic crown restorations. The hypotheses were that: 1) the presence of the root, 2) the periodontal ligament, and 3) the type of substrate, would not interfere in the stress distribution in the restoration.

Materials and methods

Generation of the Geometric Models

A 3D model of a sound tooth was scanned (InEos, Sirona Dental Systems GmbH, Bensheim, Germany) generating a stereolithographic file. The file was exported to CAD Rhinoceros software (Rhinoceros version 5.0 SR8, McNeel North America, Seattle, WA, USA). The generation of the geometric model followed the methodology in Dal Piva et al. (25), with similar characteristics. The model was replicated in five models for *in vitro* mechanical testing of molar crown simulation, according to the abutment preparation related in the literature (Table 1). A preparation for a full-monolithic molar crown was designed with 5.5 mm of height and 12 degrees of occlusal convergence in the axial walls for all groups. Next, a 70-µm thick cement layer was created (27) between the intaglio surface of the restoration and the external bonding surface of the abutment.

Table 1 - Group distribution according to the substrate design, average (aS) and stress peak values (Sp) in MPa and stress concentration factor (SC) obtained in the restoration.

Group Description	**aS**	**Sp**	**SC**
Tooth+pl: A human tooth embedded into acrylic resin with a simulated periodontal ligament (Polyether based elastomer, 100 µm)	50.1	52.0	1.04
Tooth-pl: A human tooth embedded into acrylic resin without a simulated periodontal ligament	50.2	51.9	1.03
ER+pc: A tooth made of epoxy resin and root with the exact geometry of dentin root.	50.1	52.0	1.04
ER-pc: A solid epoxy resin root similar to a dye manufactured in a CAD/CAM facility.	45.5	47.2	1.04
SiER: A solid epoxy substrate without an anatomic root.	45.6	47.4	1.04

Finite element analysis (FEA)

Five different abutment preparations (Fig. 1) were obtained to determine the substrate influence on the crown behavior during a mechanical test. The crown model was defined to simulate zirconia reinforced lithium disilicate glass-ceramic [Vita Suprinity, Vita Zhanfabrick, Bad Säckingen, Germany, (E) = 70 GPa and Poisson ratio (ν) = 0.23] (28), embedded in the acrylic resin presented [E = 2.7 GPa and ν = 0.35] by a dentin root [E = 18.6 GPa and ν = 0.32] or by an epoxy root [E = 18 GPa and ν = 0.30] (29). The incorporated resin cement had E = 6 GPa and ν = 0.30 (linear shrinkage = 2.7%) (27).

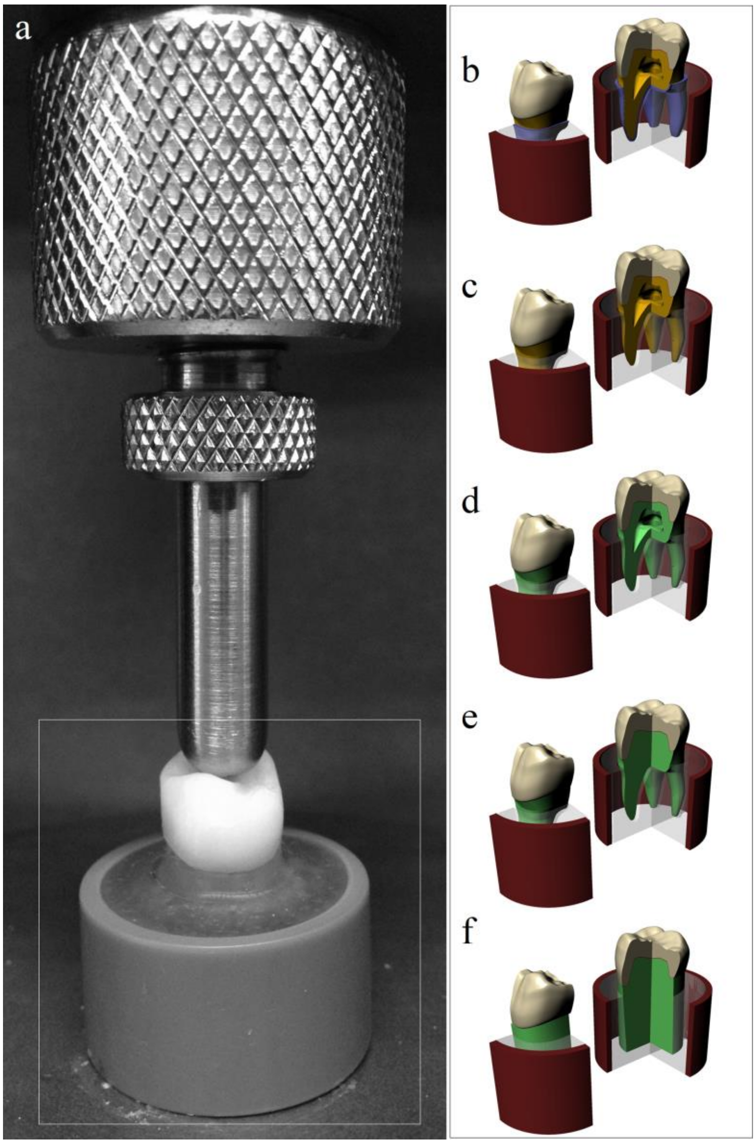

Figure 1 (A-F) - Illustration of the in vitro specimen and the modeling substrates design. (A) In vitro specimen embedded in acrylic resin. (B) Tooth+pl: A human tooth embedded into acrylic resin with a simulated periodontal ligament. (C) Tooth-pl: A human tooth embedded into acrylic resin without a simulated periodontal ligament. (D) ER+pc: A tooth made of epoxy resin and root with the exact geometry of dentin root. (E) ER-pc: A solid epoxy resin root similar to a dye manufactured in a CAD/CAM facility. (F) SiER: A solid epoxy substrate without an anatomic root.

The models were imported through STEP format to the analysis software (ANSYS 17.2, ANSYS Inc., Houston, TX, USA), in which they were divided into mesh composed by nodes (mean value = 183,147, standard deviation = 22,189) and tetrahedral elements (mean value = 102,510, standard deviation = 10,256) (Fig. 2). The aspect ratio of mesh metrics presented average of 1.82 with a standard deviation of 0.49. Mechanical properties of each structure/material were inserted into the analysis software and each material was considered isotropic and homogeneous. Non-linear contact were considered as "Non-separated" between restoration/resin cement/tooth, in which the target and contact surfaces are tied for the remainder of the analysis, although sliding is permitted (26). The contact between the tooth and the fixation cylinder was considered perfectly bonded. Model fixation occurred at the base of the acrylic resin cylinder in all groups and an axial load of 600 N (32,34) was applied to the occlusal surface considering the tripoidism concept (26). A mesh convergence test (10%) was performed to guarantee that the mesh would not interfere in the results (30). To determine the average stresses, stress peaks and stress concentration factors, one hundred highest peaks were observed in each restoration.

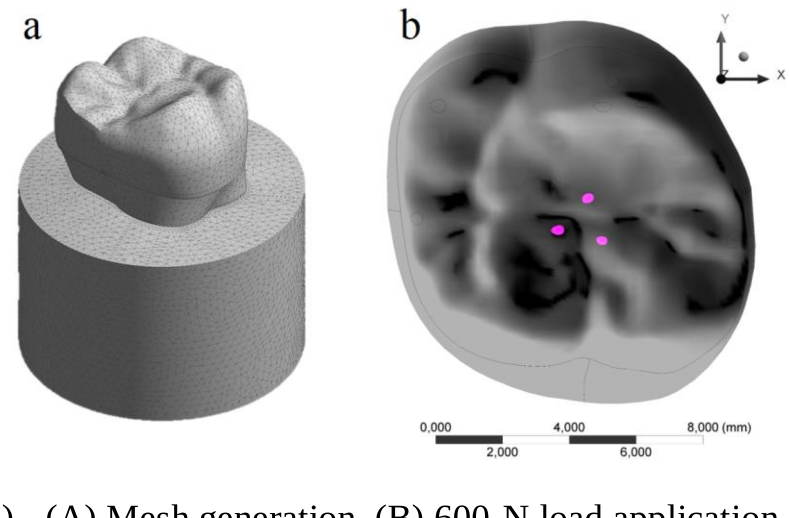

Figure 2 (A-B) - (A) Mesh generation. (B) 600-N load application area/points.

Results

Maximum principal stresses were obtained for the crown, being the object of the study. Data was summarized through colorimetric isolines which allows the visualization of the limit between each stress fringe. Tensile stress (MPa) peaks were also recorded to determine the stress concentration factor, being calculated by the ratio of stress peak and average stress (25). Figure Figure 3 is a sagittal view of the sectioned crown and demonstrates the decrease of red fringe and the consequent reduction of stress magnitude for epoxy-resin groups without pulp-chamber. The same behavior was observed for the crown intaglio surface showing the same stressed region, but with a decrease in the stress magnitude. Table 1 demonstrates that the average stress and stress peaks were close for the restorations cemented onto Tooth+pl, Tooth-pl and ER+pc substrates. ER-pc and SiER substrates showed similar stress values between them, however they were 13% lower than the other groups. Considering the stress concentration factor, all groups showed similar results near 1.0, which means suitable stress distribution.

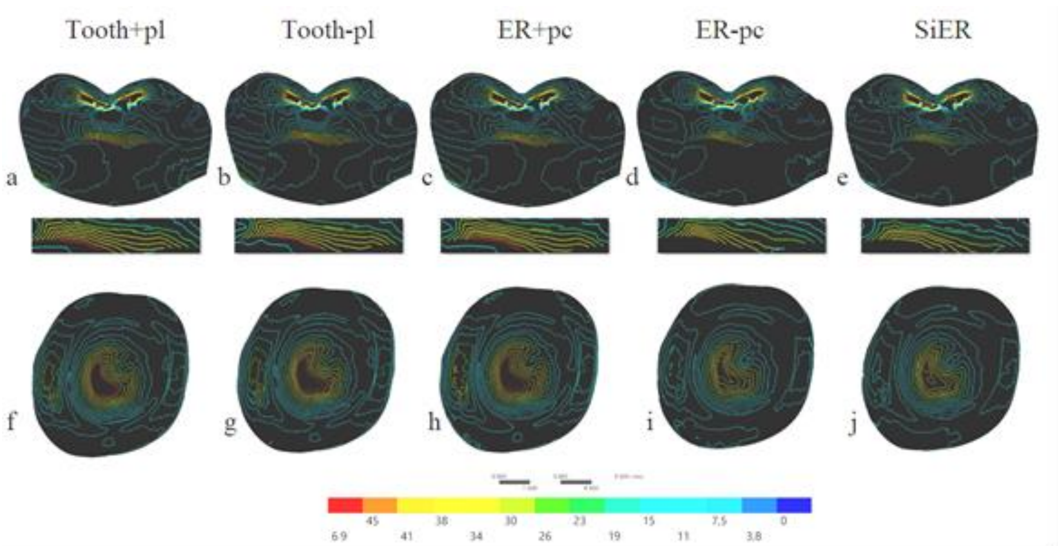

Figure 3 (A-J) - Maximum principal stress isolines in crown restoration sagittal view (A-E) and in crown restoration intaglio surface (F-J) according to the substrate design: Tooth+pl, Tooth-pl, ER+pc, ER-pc and SiER.

Discussion

In an attempt to more accurately mimic the structures found in the oral environment and their micromovements, some authors have made their samples with recently extracted fresh human teeth and have also used an elastomeric material to make a synthetic periodontal ligament between the root and the inclusion resin (31-33). However, the results show that this laboratory step is not necessary for studies evaluating posterior monolithic crowns. Preparing the periodontal ligament is performed in two steps: first, the tooth is coated by a layer of removable material such as wax acting as a spacer between the dental root and the inclusion substrate; and in the second step after polymerization of the inclusion material, the wax gives space to the elastomer. The use of curved or divergent roots makes this procedure impossible, as it would be impossible to remove the root after polymerization of the resinous substrate around the roots. In addition, most commonly used materials to replace the periodontal ligament in laboratory studies are liquid silicone and polyether. These materials do not present any mechanical properties in common with the human periodontal ligament, since they have an approximately 10x greater elastic modulus (34), little or no adhesion to the dental substrate and minimal tear resistance. Since periodontal ligament simulation adds more laboratory steps during specimen preparation, restricts the use of teeth with favorable root anatomy for removal and insertion and does not contribute to render more reliable results to the oral findings, some authors began to ignore this step in their studies (35-37). Also, ligament confection can introduce bias into the study due to the different types of materials and their homogeneity, in addition to the thickness of the simulated ligament which can influence the obtained results. Thus, the direct inclusion of fresh human teeth enables using teeth with different anatomies and root forms and still uses the same human tissue found in the oral medium as substrate. These studies still depend on the approval of a research ethics committee to be conducted and the search for nearby anatomies is reported as part of the methodology. Other authors justify that they did not make the synthetic periodontal ligament due to the fact that other authors have not done so, while other authors do not omit the lack of this laboratory stage, but also do not discuss it. The results herein show that there is no difference in the tensile stress map for the crown in both sagittal or internal views in comparing the restorations in specimens with and without synthetic periodontal ligament. This finding is in agreement with previous studies (38,39) which did not simulate the periodontal ligament because there was no difference in the mechanical behavior of the restorations. In contrast, creating a synthetic periodontal ligament has been defended as being necessary to modify the fracture pattern of dental roots of anterior teeth (40), but this was not evaluated in this study.

In order to simplify the preparation of laboratory specimens even more, some authors have used similar materials to dental tissues as substrates for cementing the restorations. Among these materials, epoxy resin filled with woven glass fibers stands out as dentin-like material having scientific support (5-7,14,15). The simplification disregards the tooth anatomy, standardizes the samples dimension and shape (since the samples are machined) without the need for an ethics committee approval. By observing the results of the present study, it is possible to observe that the crown cemented on the epoxy-resin or tooth in fact behaves in a similar way, presenting the same map of tensile stresses with almost identical stress peaks. Thus, it can be estimated that a crown adhesively-cemented on an epoxy-resin or on a tooth (with or without synthetic periodontal ligament) will fail similarly due to the same axial force distribution.

One of the characteristics of the human tooth is the presence of the pulp chamber and the root canals that are filled with dental pulp (41). In general, studies that used synthetic substrates replacing a human tooth in the laboratory tests do not report the presence or absence of the pulp chamber space. Plus, there are no studies which evaluated the pulp chamber space influence on the resulting compressive forces in indirect restorations. Benazzi *et al.* (41) evaluated the effect of increasing or decreasing the pulp chamber space on the stress distribution in a healthy human tooth. But, when the increase of the pulp chamber space was simulated, anatomical alterations of the root dentin reduced the tensile stress concentration in the internal portion of the enamel and increased the stresses in the crown's cervical third. There are reports on the dental remnant between restoration and pulp chamber, but the geometries were too simplified (often disks) (42,43).

One of the simulated groups in this theoretical study was a coronary preparation made in epoxy-resin without the pulp chamber or root canals, which would be the closest to a specimen machined from a solid resin cylinder. Figure Figure 3 allow for verifying that the crown deforms less in the presence of an anatomical root without pulp chamber and also concentrates less tensile stress, suggesting a smaller possibility of failure for this type of specimen. In spite of this, the isolines in the colorimetric maps delimit the same tensile regions as in the other groups, but with smaller magnitude fringes. Thus, a specimen made in that model may take longer to fail or even fail at higher loads due to a reduction of approximately 10% of the maximum tensile values. However, the critical regions of possible fracture origin are the same in all evaluated groups. Finally, the complete simplification of the specimen using a dentin substitute without periodontal ligament, pulp chamber, root canals or anatomic roots is also possible (10). This is the most easily attainable specimen type due to its various simplifications, keeping only the crown anatomy as a similar geometry to that found in the oral environment. Regarding the biomechanical results, this specimen behaves like the previous one, decreasing the stress magnitudes due to the increased rigidity of the system, but allowing the same areas to be stressed during the test. A notable difference between stress peak and average stress values will result in values greater than 1 (32). All simulated subtracts herein showed similar stress concentration factors near to 1, suggesting a lower difference between average and peak values (i.e. homogeneous stress distribution). Thus, all evaluated subtracts showed very similar behavior.

When evaluating a laboratory specimen that simulates a posterior crown (Fig. 1), we often do not know the effects of various types of substrates on supporting the restoration. This theoretical manuscript aimed to gather all kinds of laboratory specimens that mimic an anatomical structure, as well as to show the simplifications which are often omitted or forgotten in order to challenge them and show what happens when the same load is applied in different specimens. Our goal was not to demean what has already been done, but rather to help and support specimen preparation in future studies. However, the theoretical results expressed herein should be extrapolated with caution, since the effects on anterior teeth, the results generated during oblique loading or results in the dental root were not considered. Moreover, the materials were considered isotropic, absent from defects and with homogeneous structures derived from the applied methodology.

From this study, it is possible to conclude that it is not necessary to make a synthetic periodontal ligament for investigations using molar full crowns, and the use of dental preparations may be performed with a dentine-like material without roots since the greater rigidity of the specimen is taken into account.

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2.3 Artigo – Dal Piva AMO, Tribst JPM, Jalkh EBB, Anami LC, Bonfante EA, Bottino MA. Preparação dentária mínima para coroas monolíticas posteriores em cerâmica: efeito no comportamento biomecânico, confiabilidade e translucidez. / *Minimal tooth preparation for posterior monolithic ceramic crowns: effect on the biomechanical behavior, reliability and translucency**

RESUMO

Objetivo. Apesar do aumento do uso de coroas monolíticas, seu desempenho ainda não foi determinado quando se considera o princípio da preparação mínima dos dentes (MTP). O objetivo deste estudo foi avaliar o efeito da MTP no comportamento biomecânico, confiabilidade e translucidez das coroas monolíticas posteriores em cerâmica. **Materiais e métodos.** Para avaliar o desempenho das coroas monolíticas, os análogos da dentina foram usinados usando dois modelos de preparações (redução de 0,5 ou 1 mm) para receber as coroas dos primeiros molares. Cento e vinte e seis coroas foram divididas (n = 21 / gr) de acordo com o material (zircônia translúcida alta -YZHT, silicato de lítio reforçado com zircônia - ZLS e cerâmica híbrida -HC) e espessura (0,5 ou 1 mm). A concentração de tensão de tração foi calculada pelo método dos elementos finitos. As coroas foram cimentadas de maneira adesiva e desgastadas por esforço escalonado para calcular a confiabilidade de missões a 600 e 900 N a 100.000 ciclos. A translucidez foi analisada em 10 discos de cada material e espessura. **Resultados.** Maior concentração de tensão foi encontrada em coroas mais finas e com módulo de elasticidade mais alto. As coroas YZHT foram suspensas quando a fadiga atingiu a carga de 1.500N, sendo utilizado um parâmetro Weibull para analisar os dados. A confiabilidade foi afetada apenas pela espessura de 900 N. ZLS.5 apresentou sobrevida semelhante à do HC.5, semelhante aos grupos que apresentaram 100% de sobrevida. YZHT mostrou a maior força e dispersão de dados. ZLS1 (22,3 ± 1,4) apresentou maior translucidez que HC1 (19,2 ± 0,6) e YZHT1 (12,0 ± 2,9), enquanto ZLS.5 e HC.5 foram semelhantes (26,5 ± 2,3, 26,7 ± 2,2) e superiores a YZHT.5 (12,7 ± 1,2). **Conclusão.** O HC.5 combinou alta confiabilidade e translucidez com baixa concentração de tensão, produzindo melhor desempenho da coroa e preservação dos dentes.

Palavras-chave: Fadiga. Confiabilidade. Coroas monolíticas. Materiais dentários. Desgaste dos dentes.

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ABSTRACT
Purpose. *Despite the increased use of monolithic crowns, their performance has yet to be determined when the minimal tooth preparation (MTP) principle is considered. The goal of this study was to evaluate the effect of MTP on the biomechanical behavior, reliability and translucency of posterior monolithic ceramic crowns.* ***Materials and methods.*** *Dentin analogues were machined using two preparation designs (0.5 or 1 mm reduction) to receive first molar crowns in order to evaluate the monolithic crown performance. Next, 126 crowns were divided (n=21/gr) according to the material (High translucent zirconia - YZHT, Zirconia reinforced lithium silicate - ZLS and Hybrid ceramic - HC) and thickness (0.5 or 1 mm). Tensile stress concentration was calculated using the finite element method. The crowns were adhesivelly cemented and step stress fatigued to calculate reliability for missions at 600 and 900 N at 100,000 cycles. Translucency was analyzed in 10 discs of each material and thickness.* ***Results.*** *Higher stress concentration was found in thinner crowns and those with higher elastic modulus. YZHT crowns were suspended when fatigue reached 1,500N load, thus 1-parameter Weibull was used to analyse the data. Reliability was only affected by thickness at 900 N. ZLS.5 showed similar survival to HC.5, which was similar to the groups that presented 100% survival. YZHT showed the highest strength and data scattering. ZLS1 (22.3 ± 1.4) presented higher translucency than HC1 (19.2 ± 0.6) and YZHT1 (12.0 ± 2.9), whereas ZLS.5 and HC.5 were similar to each other (26.5 ± 2.3, 26.7 ± 2.2) and superior to YZHT.5 (12.7 ± 1.2).* ***Conclusion.*** *HC.5 combined high reliability and translucency with low stress concentration, yielding better crown performance and tooth preservation.*

Keywords: Fatigue. Reliability. Monolithic crowns. Dental materials. Tooth wear.

1. Introduction

The use of metal-ceramic prostheses is continuously decreasing, as metal-free restorations seem to reduce the occurrence of cervical margin darkening (Prince et al., 1983). However, monolithic restorations were developed to avoid chipping or delamination of veneering ceramics (Sailer et al., 2007; Christensen, Ploeger, 2010; Silva et al., 2017). In addition to having reduced operating cost (Guess et al., 2010), monolithic restorations enable more conservative preparations with thinner restorations, which meet the criteria of minimally invasive dentistry (Dirxen et al., 2013; Amer et al., 2014; Fradeani et al., 2016; Silva et al., 2017; Nawafleh et al., 2017; Sieper et al., 2017; Weigl et al., 2018).

Advances in dental materials enable different ceramics to be used for the same indication; e.g., high translucent zirconia, reinforced glass ceramics and hybrid ceramics may be indicated (El Zhawi et al., 2016; Shembish et al., 2016; Chirumamilla et al., 2016; Silva et al., 2017; Furtado de Mendonça et al., 2018; Yan et al., 2018; Dal Piva et al., 2018; Kashkari et al., 2019; Rosentritt et al., 2019; Schlenz et al., 2019; Bergamo et al., 2019) when a minimal dental preparation is required to make a posterior crown. According to the manufacturer, 4-6% yttria stabilized tetragonal zirconia polycrystal with high translucency (YZHT, Vita Zahnfabrick, Bad Sackingen, Germany) has similar chemical composition and mechanical properties to conventional translucent zirconia (Nordahl et al., 2015; Vichi et al., 2016), thus enabling its use in monolithic form. Ceramics with different microstructures were developed with optimized mechanical properties, appropriate wear behavior and acceptable aesthetics to overcome disadvantages of the antagonist dentition wear and to match natural tooth aesthetics (Gracis et al., 2015; Silva et al., 2017). Zirconia reinforced lithium silicate (ZLS) is an exemple of reinforced glass-ceramic (Elsaka, Elnaghy, 2016; Ramos et al., 2016) which can be used for laminate veneers, inlays, onlays, anterior and posterior crowns. Hybrid ceramic (HC) consists of an inorganic ceramic matrix embedded in a polymeric matrix (Chirumamilla et al., 2016; Ramos et al., 2016), with lower elastic modulus than traditional ceramics (Coldea at al., 2013; Ramos et al., 2016; Silva et al., 2017), low hardness (Coldea at al., 2013; Albero et al., 2015), fast machining, and easy polishing (Silva et al., 2017). laminate veneers, inlays, onlays and crowns are among its indications. In facing different materials for the same indication, clinical questions arise about which material to select and which properties should be considered for the correct material choice.

Despite the increase in posterior monolithic crowns use, their performance has yet to be determined when minimal tooth preparation is considered (Worni et al., 2017), as well as which material should be used in these conservative preparations. The occlusal minimal thickness for posterior monolithic crowns suggested by the manufacturer is 0.5 mm for YZHT and 1 mm for ZLS and HC. The restoration thickness influences the mechanical strength (Nakamura et al., 2015; Sun et al., 2015; Nawafleh et al., 2017; Choi et al., 2017; Tsuyuki et al., 2018; Yin et al., 2019; Gierthmuehlen et al., 2019), stress distribution (da Fonseca et al., 2018a,b; Tribst et al., 2018) and translucency (Wang et al., 2013; Sulaiman et al., 2015; Stawarczyk et al., 2016; Tong et al., 2016; Church et al., 2017; Silva et al., 2017). As aesthetics are an important factor in selecting a material, the search for a restorative material with high mechanical and desired optical properties has been the focus of several studies (Sun et al., 2014; Dhima et al., 2014; Nordahl et al., 2015; Sorrentino et al., 2016; Nawafleh et al., 2017; Sieper et al., 2017; Choi et al., 2017; Weigl et al., 2018; Bergamo et al., 2019).

Posterior monolithic crown failure rate data is very limited with no clinical trial available for ZLS. However, a survival rate of 100% after 2 years (Fasbinder et al., 2010) and 83.5% after 10 years follow-up (Rauch et al., 2018) have been reported for lithium disilicate, since biological and technical complications such as debonding and crown fracture were observed (Cortellini, Canale, 2012; Reich et al., 2013; Rauch et al., 2018). An up to 5-year laboratory survey of 29,808 zirconia monolithic posterior crowns showed a 0.69% failure rate (Sulaiman et al., 2016) and a high success rate of 100% after 23.8 months for 56 posterior crowns without cracking or debonding (Worni et al., 2017), and a 98.5% success rate in another study due to marginal discoloration of one crown after 1 year (Konstantinidis et al., 2018). The authors suggested that the minimal occlusal thickness of zirconia should be limited to 0.5 mm to withstand occlusal loads (Worni et al., 2017). For the hybrid ceramic, a 2-year follow-up of 35 monolithic posterior crowns with minimal occlusal thickness of 1-1.5 mm reported a 96.8% survival rate. The authors reported the loss of one crown which was fabricated for a previously cracked tooth (Chirumamilla et al., 2016). Information on the influence of the preparation type following the principle of tooth minimum preparation on the survival of thin monolithic crowns is still scarce (Weigl et al., 2018; Bergamo et al., 2019), as well as which material should be used in these conservative preparations.

Testing of anatomically-relevant crowns and tooth preparations tend to simulate clinical fracture modes (Coelho et al., 2009; Lorenzoni et al., 2010; Bonfante et al., 2010; Silva et al., 2011; Sun et al., 2014; Dhima et al., 2014; Nordahl et al., 2015; Sorrentino et al., 2016; Nawafleh et al., 2017; Furtado de Mendonça et al., 2018; Kashkari et al., 2019; de Paula et al., 2019; Schlenz et al., 2019) when evaluated under fatigue (Peterson et al., 1998; Zhang, Lawn, 2004; Guess et al., 2010; Tribst et al., 2019). The step-stress accelerated-life test (SSALT) has been widely used to evaluate the lifetime of restorations (Silva et al., 2008; Coelho et al., 2009; Bonfante et al., 2010a,b; Silva et al., 2011; El Zhawi et al., 2016; Bergamo et al., 2019). Inferences on restoration critical fracture initiation sites are enabled when SSALT fatigue is associated with the stress distribution analysis. This study evaluated the effect of tooth minimum preparation on the biomechanical behavior, reliability and translucency of posterior monolithic crowns of three different CAD/CAM all-ceramic materials. The hypotheses tested were that the preparation type and ceramic material would not change the crown's: (1) biomechanical behavior; (2) reliability; or (3) translucency.

2. Materials and Methods

2.1.1.1 Step stress acelerated life test (SSALT)

2.1.1.2 Specimen preparation

First, one hundred twenty-six (126) abutments were machined in epoxy resin (G10, Protec, São Paulo, Brazil) (Dal Piva et al., 2019) using CAD/CAM (Computer Aided Design/Computer Aided Machine) technology. Half of the abutments received a 5 mm high axial wall preparation (conventional) for posterior monolithic crown and the other half received 5.5 mm (conservative). The difference in the whole thickness of the preparations was uniformly defined as 0.5 mm. Both preparations presented rounded internal angles, chamfer preparation, and total occlusal convergence of 20° (Corazza et al., 2013). The abutments were cleaned in an ultrasonic bath with distilled water for 5 min and embedded in acrylic resin (25 mm Ø x 20 mm height) up to the cementoenamel junction.

A thin layer of titanium dioxide-based powder (Ivoclar Vivadent, Schaan, Liechtenstein) was sprayed onto each abutment for scanning (inEos Blue, inLab SW4.2, Sirona, Benshein, Germany) and subsequent crown design. A crown was generated after delimiting the end of the conservative preparation by an individual biogeneric command. This same crown was then used as the standard through the biogeneric copy option, by which the software generated an anatomically similar crown to the conservative on the conventional preparation. The following ceramic blocks were milled using the Cerec inLab (5884742 D329, Sirona for Dental Systems, Benshelm, Germany): High translucency zirconia HT (YZHT), Vita Suprinity (ZLS) and Vita Enamic (HC) (all from Vita Zahnfabrik, Bad Säckingen, Germany). Next, the restorations were separated from the remaining blocks with the aid of a diamond blade and fine-grained diamond bur under abundant irrigation. After cleaning in an ultrasonic bath with isopropyl alcohol for 5 min, YZHT and ZLS ceramic restorations were cleaned and sintered (1450 °C, Infire HTC speed, Sirona) or crystallized (840 °C, Vacumat 600MP, Vita Zahnfabrik, Bad Säckingen, Germany) according to manufacturer's instructions. All crowns were polished using the 2-stage polishing system with pre- (7000–12,000 rpm speed for 15 s) and high-gloss polishers (4000–8000 rpm for 15 s).

The G10 abutments were conditioned with 10% hydrofluoric acid for 60s, washed with air/water jet for 30 s, and then dried before receiving the adhesive system (Kelly et al., 2010) (ED primer A + B, Kuraray Medical, Tokyo, Japan). The crowns were sandblasted with 50µm alumin oxide (10 s, 10 mm and 2.5 Bar), etched with phosphoric acid during 5s for surface cleaning and then a silane agent (Clearfil Ceramic Primer, Kuraray Medical) was applied for 60s. Panavia F 2.0 self-etching resin cement (Kuraray Medical) was manipulated in 1:1 ratio and applied onto the intaglio surface of the crowns, which were then placed on the respective abutment and kept in a 750g weight for 5 min. Excess cement was removed and then the cement was light cured (Valo, Ultradent Products, Utah, USA) for 20s on each face. The finished specimens were immersed in distilled water and stored at 37 °C for 24h before the fatigue test. Figure 1 shows a flowchart of the study design and methods.

2.1.1.3 Fatigue test

Prior to the SSALT, three specimens per group were submitted to single load to fracture test (1000 kgf, 0.5 mm/min) in a universal testing machine (DL-1000, EMIC, São José dos Pinhais, Brazil). The profiles used in the SSALT were determined from the mean load value (in N) of each group. The samples were randomly distributed among 3 profiles: mild, moderate, and aggressive (Bonfante et al., 2010; Stijacic et al., 2015) in the ratio of 3:2:1, according to the load increase and number of cycles (Fig. 2). The samples were positioned on a fatigue machine (Instron Electropuls E3000 Linear Torsion system, USA) and a fatigue load was delivered (6 mm diameter, stainless steel, water, 10 Hz) on the occlusal fossa (Nicolaisen et al., 2014; Villefort et al., 2017). The load value and the number of cycles until the specimen failure or suspension were used for statistical analysis. Either bulk or cohesive fracture of the crowns was determined as the failure criterion. Representative failed crowns were subjected to fractographic analysis under polarized light (Stereo Discovery.V20, Carl Zeiss, LLC, USA) and scanning electron microscopes (SEM) (XL 20, Philips, Eindhoven, the Netherlands) to identify the failure origin, following the guidance described by Scherrer et al. (2017).

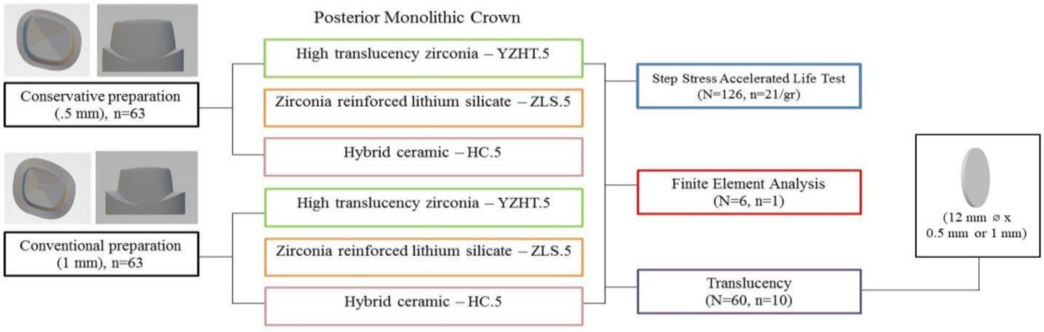

Figure 1. Study flowchart shows two preparation designs (0.5mm and 1mm) and testing of 3 materials under Step Stress Accelerated Life Testing (n=18/group), Finite Element Analysis of tensile stress concentration and Translucency (n=10 discs).

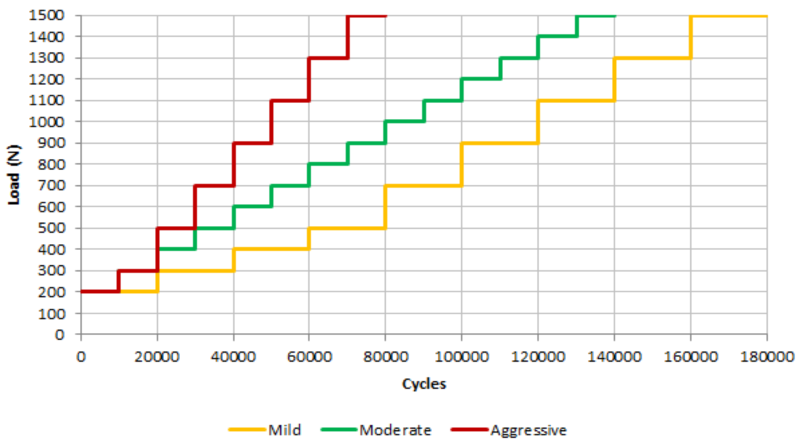

Figure 2. Step Stress Accelerated Life Test (SSALT) load profiles starting at 200 N and finished at 1,500 N.

2.1.2 Finite Element Analysis (FEA)

2.1.2.1 Pre-processing

A three-dimensional (3D) model of an upper first molar was used to evaluate the tensile stress of the monolithic crown. The model containing root, periodontal ligament, medullary and cortical bones (Dal Piva et al., 2018) was imported to Rhinoceros CAD software (version 5.0 SR8, McNeel North America, Seattle, USA). A cross-section was made at the cementoenamel junction to separate root and crown, and then a conservative preparation following the *in vitro* specimen dimension was modeled to receive the crown with minimum occlusal thickness of 0.5 mm. The conventional preparation was generated from the conservative with a reduction of 0.5 mm in all directions. A crown with minimal occlusal thickness of 1 mm was also generated. The cement layer was modeled with 80 µm for both conditions.

2.1.2.2 Pos-processing

The volumetric solids were imported to the analysis software (ANSYS 17.2, ANSYS Inc., Houston, USA) in STEP (STandard for the Exchange of Product model data) format. A mesh convergence test (10%) determined 169,672 nodes and 95,263 tetrahedral elements for the conventional preparation; and 173,428 nodes and 101,112 elements for the conservative preparation. A static structural analysis was used and the material properties were reported for each solid component as isotropic and homogeneous (Table 1). The groups were divided according to the crown occlusal minimum thickness and the ceramic material (high translucent zirconia, zirconia reinforced lithium silicate and hybrid ceramic). The contacts were considered perfectly bonded between the bodies and the fixation was defined on the base of the cortical bone. The loading was similarly applied (600 and 900 N) as performed in the *in vitro* test (Fig. 3). The Maximum Principal Stress criterion was used to assess the distribution of tensile stresses in the monolithic crowns.

Table 1- Elastic modulus (*E*) and Poisson ratio (*v*) of the materials and structures simulated in this study.

Material/Structure	***E* (GPa)**	***v***	**Reference**
Enamel	84.1	0.33	Roscoe et al., 2013
Dentin	18.6	0.32	Monteiro et al., 2018
Periodontal ligament	0.069	0.45	Monteiro et al., 2018
High translucency zirconia	210	0.33	Vita Zhanfabriek
Zirconia reinforced lithium silicate	65.6	0.23	Ramos et al., 2016
Hybrid ceramic	34.7	0.28	Ramos et al., 2016
Resin cement	7.5	0.25	Jongsma et al., 2012

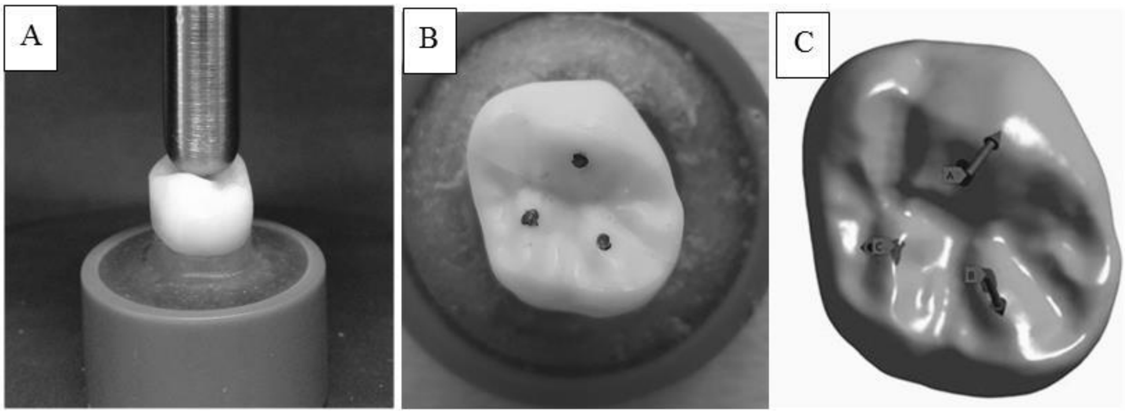

Figure 3. A) Shows loading in the central fossa and B) the tripodization occlusal scheme used during the SSALT and C) FEA.

2.1.3 Translucency

Ten (10) discs from each group (6mm Ø x 0.5mm and 1mm) were polished with sandpaper up to #1200 grit under water cooling (Vichi et al., 2016) in an automatic precision polishing equipment

(EcoMet™/AutoMet™250, Buehler, Illinois, USA). A spectrophotometer (CM2600d Konica Minolta, Japan) was used with D65 illuminant in reflectance mode, 100% UV, observer angle at 2º, specular reflection, small area view of 3 mm Ø and with the presence of polyethylene glycol (Caneppele et al., 2015). The translucency was calculated applying the formula $[(L_B - L_W)^2 + (a_B - a_W)^2 + (b_B - b_W)^2]^{1/2}$, where the subscripts B and W refer to black and white backgrounds (Vichi et al., 2016).

2.2 Data analysis

Tensile stress results (MPa) in the crown were organized with identical scale for direct comparison in a color graph. Tensile stress peaks were exported from the occlusal surface and are summarized in Table 2. The crowns were suspended after the fatigue test (i.e. not failing at 1,500N) were submitted to a single load to fracture test. However, suspension analysis was also performed using Weibayes (1-parameter Weibull) analysis (Weibull ++, Synthesis 9, Reliasoft, Tucson, AZ, USA) and an estimated Beta (β) value (Abernethy, 2007; Nicholls, Lein, 2009; Paula et al., 2015). The estimated survival probability of each group at loads 600 and 900 N at 100,000 cycles was calculated. Weibull modulus (m) and characteristic strength (σ) considering 62.3% failure were also determined for samples that were subjected to single load to failure testing after fatigue. Translucency data were submitted to one-way ANOVA and Tukey test, all with $\alpha = 5\%$.

3. Results

3.1 SSALT

YZHT crowns were suspended after not failing the SSALT up to 1,500N, and underwent single load to fracture testing. Weibull analysis showed a difference between the mean values of characteristic strength according to the thickness for these two groups (Table 2). The load at failure for the remaining groups that presented failures during fatigue was also used to determine the characteristic strength and Weibull modulus (Table 2). Use-level probability Weibull plots show the probability of failure as a function of cycles for the different groups presenting failures and some suspensions under SSALT (Fig. 4A), and suspensions only (YZHT, Fig. 4B).

Table 2 – Stress peaks, Weibull modulus (*m*), characteristic strength (σ) and confidence intervals. The statistical differences were determined based on the confidence interval (CI).

Groups	**Stress peak (MPa)**			
	600 N	**900 N**	***m* (CI)**	**σ (CI)**
YZHT.5	88.1	129.1	5.8 (4.3 – 7.8)	3.370 (3.141 – 3.615)[B]
YZHT1	60.2	87.7	3.8 (2.8 – 5.1)	5.323 (4.783 – 5.925)[A]
ZLS.5	72.1	109.4	7.2 (5.9 – 15.8)	1.499 (1.481 – 1.515)[C]
ZLS1	56.2	84.7	27.5	1.500[C]
HC.5	55.3	90.8	35.9 (24.4 – 52.7)	1.452 (1.361 – 1.535)[C]
HC1	52.4	84.9	20.2	1.500[C]

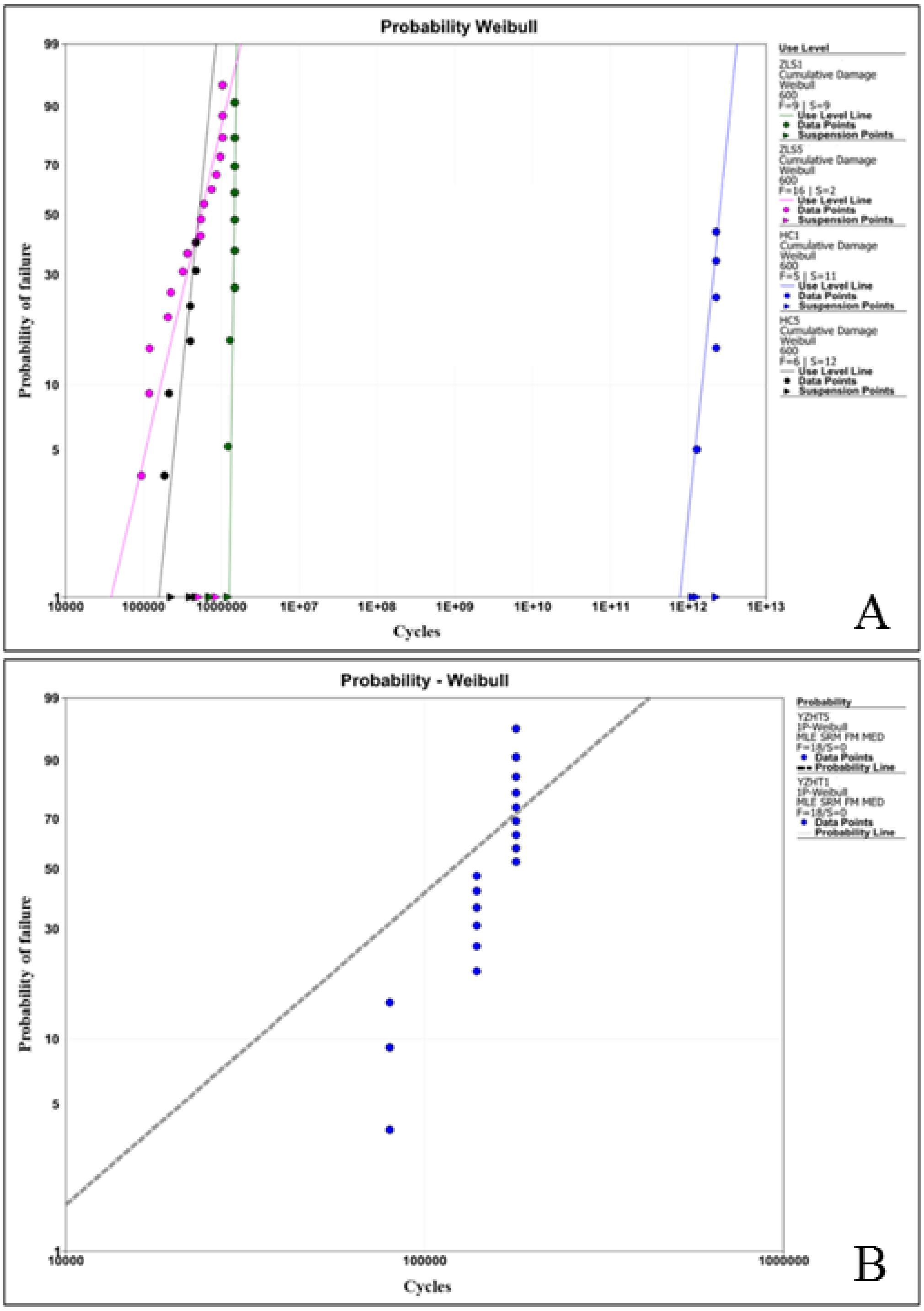

Figure 4. A) 2 - parameter probability Weibull plot for HC.5, HC1, ZLS.5 and ZLS1 groups; (B) Weibull plot probability showing Weibayes projection line for groups in YZHT.

YZHT crowns showed 100% reliability, and the highest characteristic strength (Table 2). The reliability for ZLS and HC was only influenced by thickness at 900 N (Table 3). No difference was observed for reliability between crown materials of 1 mm thickness. ZLS.5 showed similar survival as HC.5 at 900 N, which was similar to the groups that survived 100%. The Weibull shape factor (beta value) showed that the failures were influenced by fatigue and damage accumulation (Bonfante et al., 2010a): ZLS.5 (1.5; 0.6-3.6), HC.5 (3.6; 1.3-9.8), ZLS1 (27.5; 13.5-55.9) and HC1 (20.2; 9.3-38.4).

Table 3 - Reliability under 100,000 fatigue cycles. Similar letters indicate an absence of statistical difference between groups in the same row.

Load (N)	**Reliability (%)**	**ZLS.5**	**ZLS1**	**HC.5**	**HC1**
600	Upper bound	100	100	100	100
	Reliability	95[a]	100[a]	100[a]	100[a]
	Lower bound	81	100	93	100
900	Upper bound	90	100	100	100
	Reliability	76[b]	100[a]	97[a,b]	100[a]
	Lower bound	50	100	83	100

3.2 Failure mode

Fractography analysis of bulk fractured crowns showed that the failure was originated from the occlusal surface and propagated towards the cementation surface, eventually spreading to the margins of the split restoration, which was confirmed by the fractographic marks (Figs. 5-7).

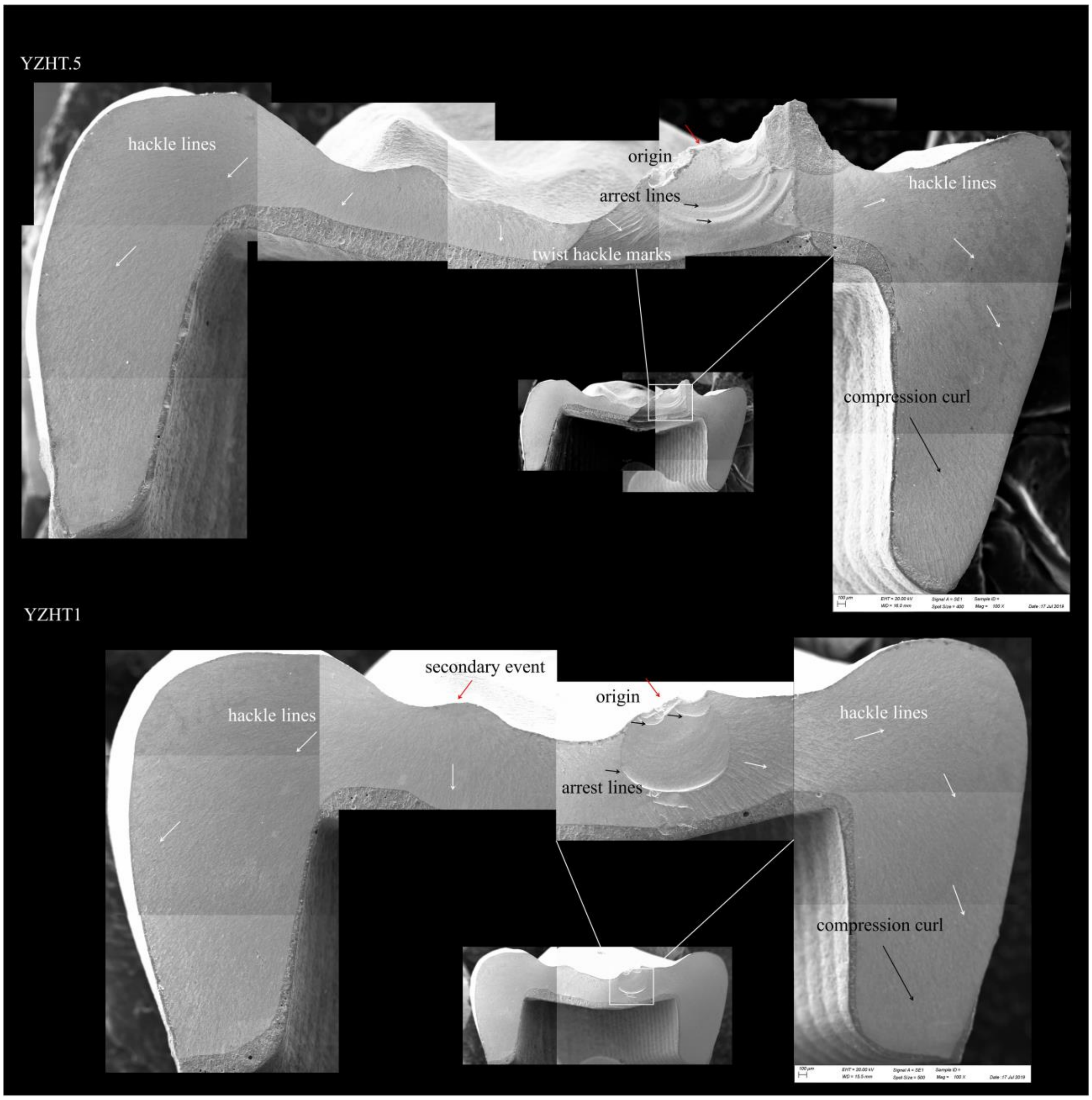

Figure 5. Fractographic analysis of representative YZHT of 0.5 and 1 mm crowns. Compression curl, twist hackle marks, arrest and hackle lines determined that the crack started on the occlusal surface (red arrow) and propagated (white arrowns) to the bottom of the restoration. The specimens were evaluated under 40x and 100x magnifications.

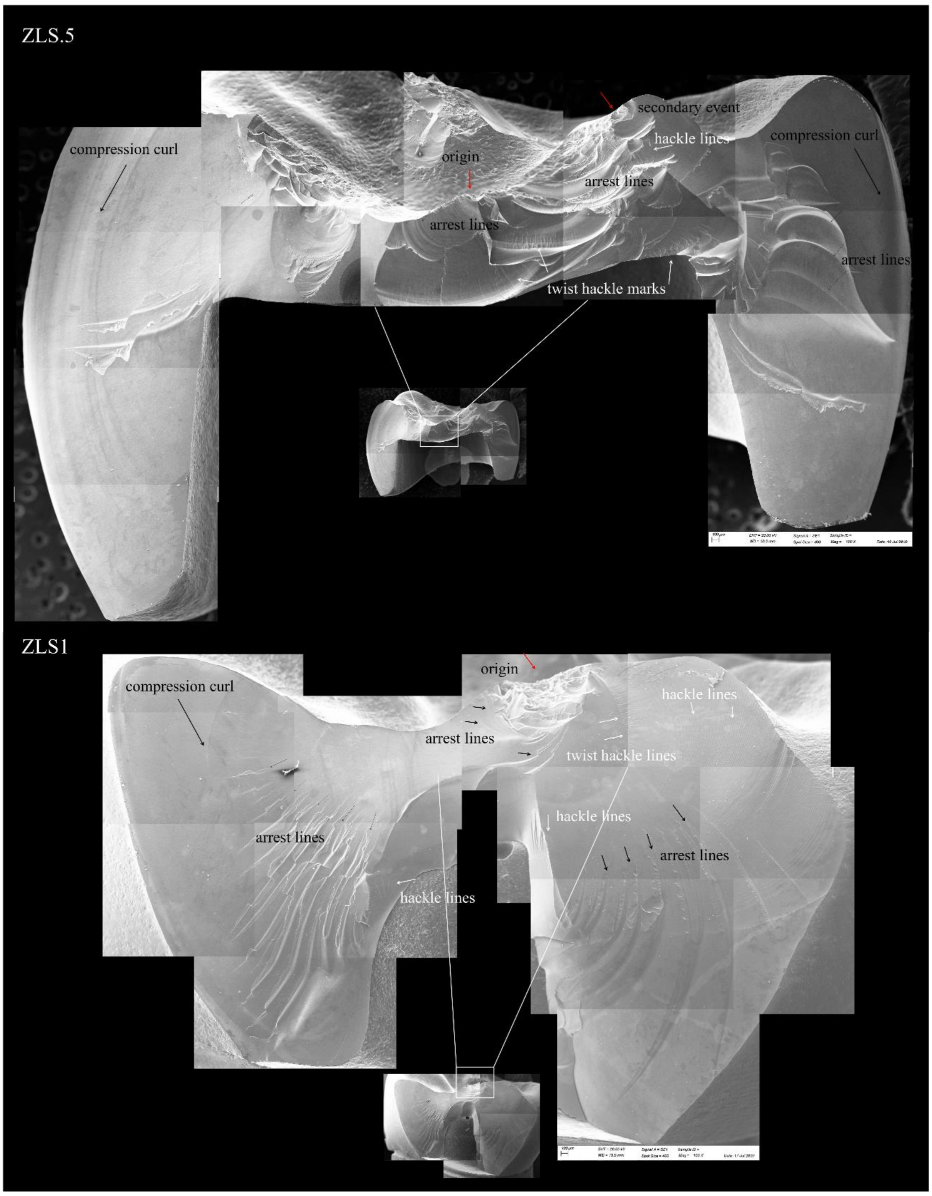

Figure 6. Fractographic analysis of representative ZLS 0.5 and 1 mm crowns. Compression curl, twist hackle marks, arrest and hackle lines determined that the crack started on the occlusal surface and propagated through to the bottom of the restoration. The ZLS crowns showed many arrest lines which indicate the failure origin. However, the damage accumulation in fatigue experiments could generate events other than the origin, i.e. secondary event(s). The specimens were evaluated under 40x and 100x magnifications.

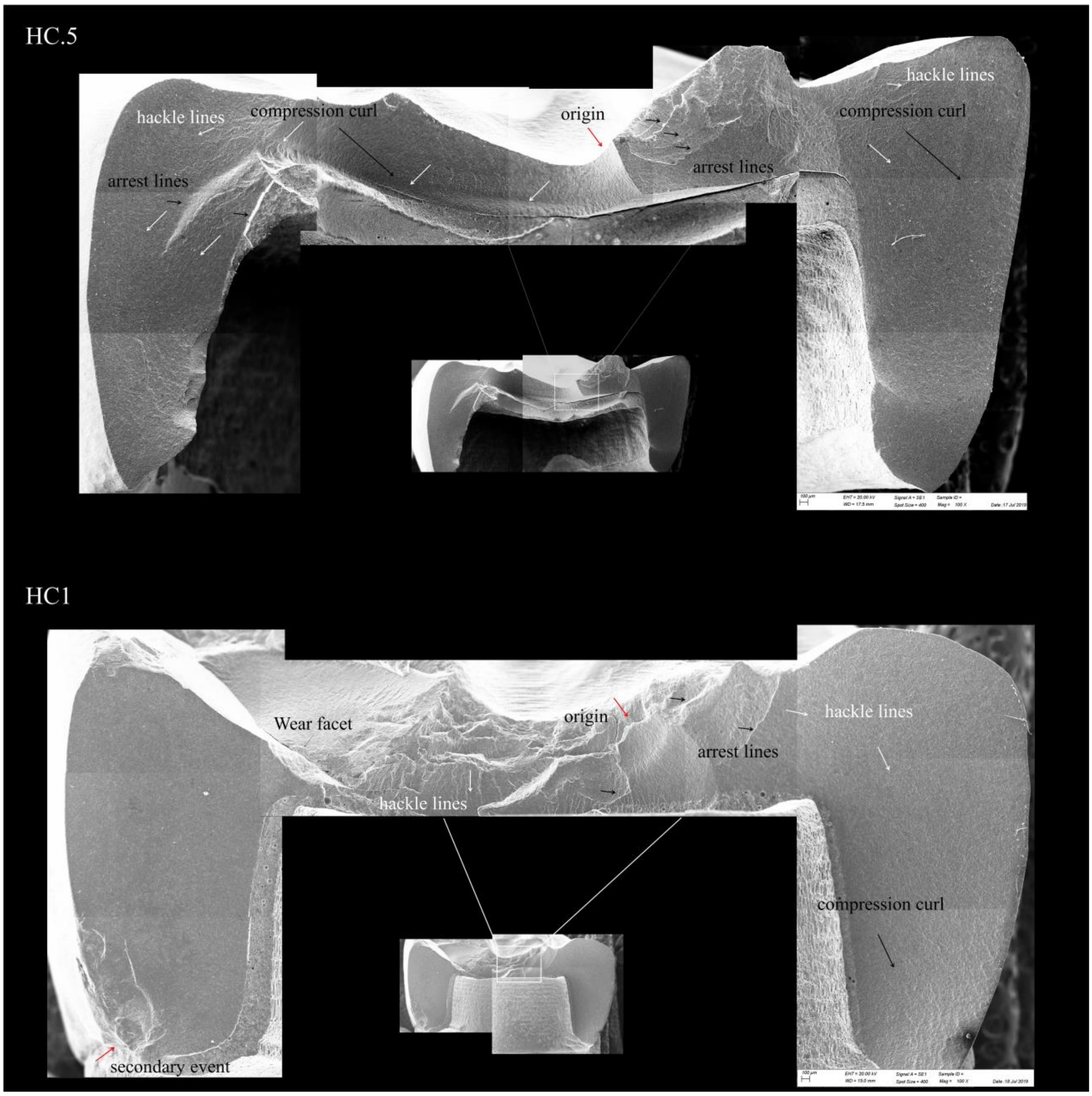

Figure 7. Fractographic analysis of representative HC crowns. Compression curl, arrest and hackle lines determined that the crack started on the occlusal surface (red arrow) and propagated (white arrowns) to the bottom of the restoration. The specimens were evaluated under 40x and 100x magnifications.

3.3 FEA

Thinner crowns concentrated more stress compared to thicker restorations. The higher the ceramic elastic modulus (HC < ZLS < YZHT), the higher the stress concentration in the crown. The peak tensile stress values for both loads are summarized in Table 2. The stress concentration regions in all conditions were compatible with the generated tensile strength as a response of the load application, as well as the intaglio surface.

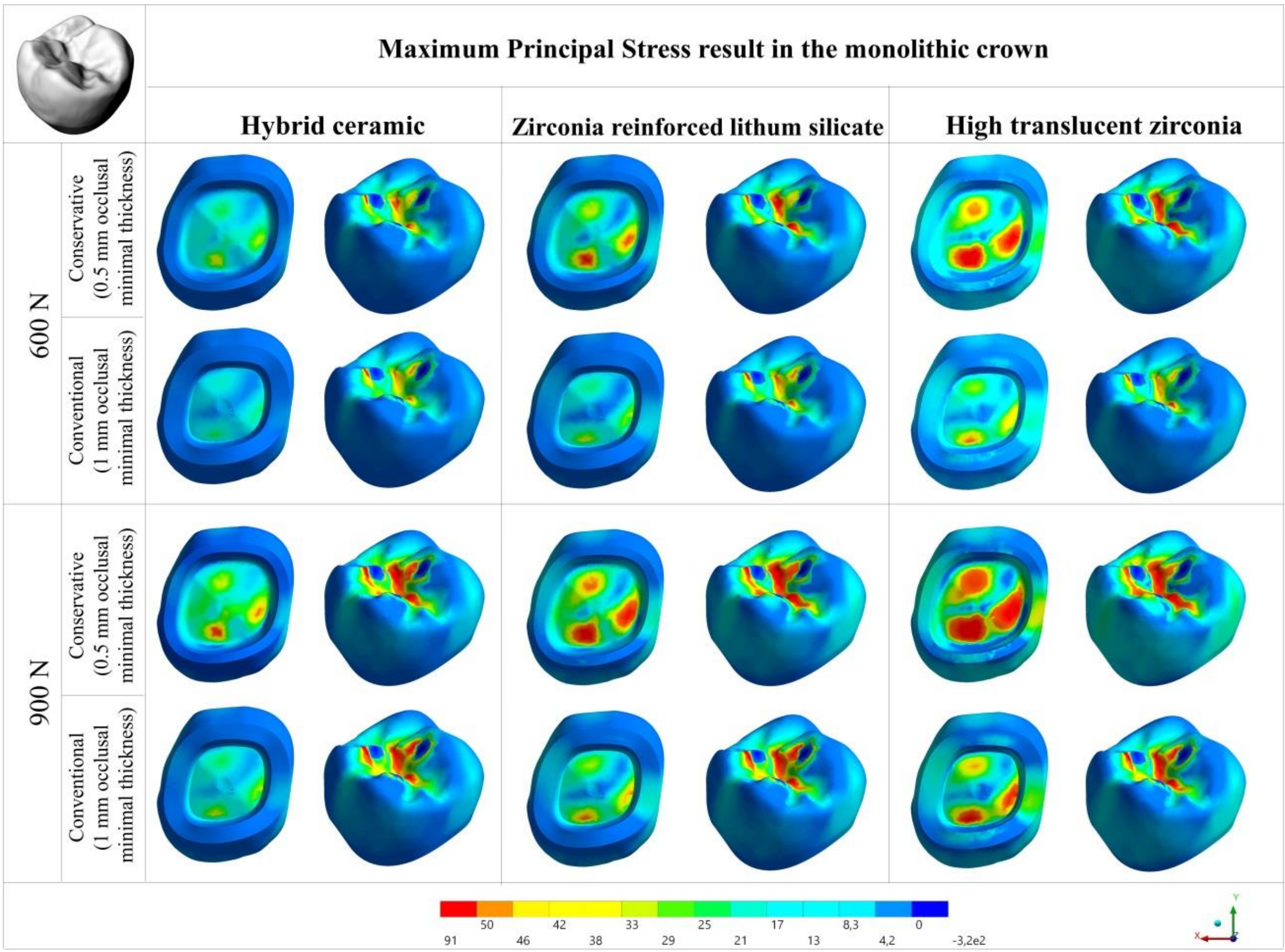

Figure 8. Tensile stress results (MPa) in the crown according to the material, preparation type and loading.

3.4 Translucency

One-way ANOVA showed thickness influence on the TP for ZLS and HC ($F = 23.3$, $p < 0.001$; $F = 98.2$, $p < 0.001$), however, not for YZHT ($F = 0.3$, $p = 0.551$). Table 4 summarizes the grouping distribution according to the Tukey test.

Table 4. Mean, standard deviation and Tukey test for translucency results, according to the material and thickness.

Group	**0.5 mm**	**1 mm**
YZHT	12.7 ± 1.2^{b}	12.0 ± 2.9^{c}
ZLS	26.5 ± 2.3^{a}	22.3 ± 1.4^{a}
HC	26.7 ± 2.2^{a}	19.2 ± 0.6^{b}

4. Discussion

The goal of this study was to evaluate the effect of minimal tooth preparation on the biomechanical behavior, reliability and translucency of posterior monolithic all-ceramic crowns. According to the stress maps generated by the FEA, it was observed that the minimum thickness and the material's elastic modulus influenced the crowns' biomechanical behavior, leading to rejection of the first hypothesis regarding biomechanical behavior.

FEA is widely used to investigate stress distribution across the components of complex structures (Imanishi et al., 2003; Ha, 2015; da Fonseca et al., 2018a,b; Tribst et al., 2018; Dal Piva et al., 2018). The 0.5 mm crowns presented more stress due to the lower material volume (da Fonseca et al., 2018a,b; Tribst et al., 2018) with the highest stress concentration at the bottom of the fissure where areas with the lowest thickness are located (Imanishi et al., 2003; Dal Piva et al., 2018). The stress magnitude was directly proportional to the increase in the material's elastic modulus (Penteado et al., 2019; Dal Piva et al., 2018). This finding corroborates a previous study which evaluated 12 monolithic posterior crowns and observed that HC presented lower failure risk (Dal Piva et al., 2018). In this study, fractographic analysis showed telltale marks indicating that the failure origin was located in the area with higher tensile stress concentration, corroborating the FEA results.

The crowns' survival was influenced by the thickness, partially rejecting the second hypothesis since no difference was observed for crowns in different material with the same occlusal thickness, which is different from previous studies (Peterson et al., 1998; Jassin, Majeed, 2018; Sagsoz, Yanıkoglu, 2018). The results show 100% survival for YZHT crowns, corroborating the minimum thickness suggested by Worni et al. (2017). There was no difference between the crowns survival at 600N, which is considered the maximum bite force value in the molar region (Imanishi et al., 2003; D'souza et al., 2017). However, HC.5 and YZHT.5 crowns were similar to 1mm crowns at 900 N in simulating a condition of parafunction (Teixeira et al., 2012). While ZLS.5 presented similar characteristic strength to HC, it showed lower reliability and higher failure probability at 900N.

Most of the available studies on monolithic crowns performed single load to failure testing and reported that the higher the restoration thickness, the higher is the load to fracture (Sun et al., 2014; Nakamura et al., 2015, 2016; Nordahl et al., 2015; Sorrentino et al., 2016; Choi et al., 2016; Sieper et al., 2017; Jassin, Majeed, 2018; Tsuyuki et al., 2018; Nakamura et al., 2018; Bankoğlu Güngör, Karakoca Nemli, 2018; Gierthmuehlen et al., 2019; Yin et al., 2019). This study only observed this pattern for YZHT crowns. The lifetime of all-ceramic restorations is related to the slow crack growth due to the occlusal loads and humidity to which the ceramics are subjected to during fatigue (Ramos 2016; Melo 2019). However, different from the present study, Sorrentino et al. (2016) did not observe the influence of thickness on the fracture load of zirconia crowns. However, the authors performed a monotonic load-bearing test on crowns with different occlusal thicknesses (0.5, 1, 1.5, and 2 mm) without shape standardization since each crown was manufactured for a different dental abutment. Nevertherless, the load to fracture of a monolithic zirconia crown exceeds the maximum physiological occlusal loads (Sun et al., 2014; Nordahl et al., 2015; Sorrentino et al., 2016; Gierthmuehlen et al., 2019; Bankoğlu Güngör, Karakoca Nemli, 2018). Also the HC and ZLS in thicknesses of 1 and 1.5 mm have higher fracture load values than physiological loads (Choi et al., 2017; Sieper et al., 2017; Jassin, Majeed, 2018). The HC crowns in this study showed similar behavior and compatible with thicker crowns under both loads. The use of HCs has the advantage of adequate stress distribution, easy machinability and repair (Silva et al., 2017). Although presenting the lowest load to fracture value (Sieper et al., 2017; Jassin, Majeed, 2018), the biomechanical behavior HC seems to be its advantage, as it withstands greater damage tolerance (Coldea et al., 2013; El Zhawi et al., 2016) under fatigue. A previous study reported lower reliability for ZLS in 0.5 mm thickness and that this crown should be indicated with caution (Bergamo et al., 2019).

Güngör, Nemli (2018) evaluated the load to failure of different monolithic and bilayered crowns after thermo-mechanical aging. The authors suggested that HC should be indicated for premolars and anterior region because they did not survive fatigue; however, the crown thickness was not informed. Using a similar aging protocol Gierthmuehlen et al. (2019) tested HC crowns in 1 and 1.5 mmm thickness and indicated 1 mm for the posterior region since it showed mean load to failure of 2,367 N, even after aging. However, the authors measured the crown thickness considering the cusp area, which may not represent the thinnest area. Full HC crowns have been suggested for patients with parafunctional activity (Dirxen et al., 2013; El Zhawi et al., 2016); however, no information was specified for their minimal thickness. These promising results for HC corroborates a 1-year follow-up study which indicates this material to perform restorations ranging from 0.5 to 1.5 mm (Dirxen et al., 2013). This behavior could be explained due to the damage tolerance (Choi et al., 2017) because its interpenetrating polymer network (Dirxen et al., 2013) limits crack propagation due to a strengthening mechanism which consists of a crack bridge zone formation followed by plastic deformation and secondary cracking (Wegner et al., 2001).

In comparing YZHT.5 and HC.5, some factors could influence the material choice such as the antagonist wear, color stability (Dirxen et al., 2013) and marginal adaptation (Silva et al., 2017; Konstantinidis et al., 2018). Both ceramics present similar color stability (Konstantinidis et al., 2018) and it is well known that HC shows very low antagonist wear. Recent research has reported that polished zirconia can show acceptable antagonist wear rate (Stawarczyk et al., 2016; Lohbauer, Reich, 2017) and the use of polishing rubbers could decrease surface roughness and biofilm formation on this material (Dal Piva et al., 2018; Contreras et al., 2018). In addition, the HC presents the advantages of adjustment and repair convenience/ease with composite resin (Ferreira da Silva et al., 2018).

The translucency was also influenced by the thickness and material, rejecting the third hypothesis. The results reported no difference for the translucency of HC and ZLS at 0.5 mm. YZHT showed lower translucency for both thicknesses, corroborating previous studies (Wang et al., 2013; Church et al., 2017) and disagreeing with a previous study that reported that the smaller the zirconia thickness, the greater the light propagation (Sulaiman et al., 2015). Despite the inferior color mismatch of zirconia (Konstantinidis et al., 2018), patient satisfaction with zirconia shade has been reported. The translucency of YZHT is achieved due to a decrease in grain size and impurities (Kim et al., 2013; Zhang, 2014; Tong et al., 2016), alumina percentage, the phase in which the material is presented (Zhang, 2014; Sulaiman et al., 2015), in addition to sintering time and temperature (Ebeid et al., 2014). In view of the great clinical interest in sufficiently resistant monolithic materials to enable minimal tooth preparation, Vichi et al. (2016) observed that high translucency zirconia promotes the best combination in terms of translucency and strength when used at thicknesses between 0.5 and 1 mm.

The limitations of this study are related to non-simulation of all factors present in the oral cavity such as pH and temperature variation, biofilm formation, sliding loads, and parafunctional habits. Different antagonists may also induce different mechanical responses in materials (Weber et al., 2018). Nevertheless, this study showed that differences in survival probability of the evaluated crowns were only observed at 900N, suggesting that future clinical studies of the materials investigated herein are warranted.

5. Conclusion

Based on this study’s limitations, it is possible to conclude that thinner crowns with high elastic modulus concentrated more tensile stresses, while crowns in hybrid ceramic and in high translucency zirconia with 0.5 mm minimal thickness showed similar survival to crowns at 1 mm. Furthermore, the hybrid ceramic showed similar translucency to the glass-ceramic at 5 mm minimal thickness, and superior to the high translucency zirconia. Therefore, the hybrid ceramic crown with 0.5 mm occlusal minimal thickness associates high reliability and translucency with low stress concentration, yielding better crown performance for minimal tooth preparations.

Acknowledgements

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3 CONSIDERAÇÕES GERAIS

É comprovada a incessante busca pelo material odontológico que melhor associe propriedades estéticas e resistência mecânica para suportar cargas mastigatórias e exigências do paciente. Deste modo, através de ensaios laboratoriais ou clínicos, os dados científicos servem para guiar os cirurgiões dentistas quanto à melhor indicação dos materiais odontológicos.

Este projeto teve como objetivo avaliar o desempenho de coroas monolíticas em diferentes espessuras e materiais. Inicialmente, observamos que dependendo do material (artigo 1) diferentes comportamentos podem ser observados na restauração, na linha de cimentação e no dente. E que, a utilização de um substrato simplificado (artigo 2) não influencia na distribuição de tensões pela estrutura da restauração. Deste modo, utilizou-se e sugere-se um substrato simplificado para realização de ensaios laboratoriais com coroas anatômicas (artigo 3).

Outro ponto relevante discutido foi o fato de diferentes materiais poderem ser utilizados para uma mesma indicação. E que, para uma coroa final, o uso de uma material cerâmico menos rígido é favorável para todo o sistema. Este achado foi corroborado pela análise de sobrevivência das coroas em cerâmica híbrida (independente da espessura) que apresentaram comportamento sob fadiga semelhante às cerâmicas de zircônia de alta translucidez e silicato de lítio com reforço de zircônia com 1 mm de espessura mínima na face oclusal. Durante a investigação, não houveram falhas adesivas e as cargas necessárias para fraturar as coroas foram superiores às cargas fisiológicas de mastigação. Deste modo, os três materiais avaliados apresentaram sobrevivência adequada mesmo com diferentes distribuições de tensões e translucidez. Porém, a cerâmica híbrida com espessura mínima de 0,5 mm combinou alta sobrevivência e translucidez com baixa concentração de tensão, produzindo melhor desempenho da coroa e possibilitando maior preservação do substrato dental através do preparo mais conservador.

Sendo assim, trabalhos clínicos em longo prazo deverão ser conduzidos a fim de se observar a taxa de sucesso de diferentes coroas monolíticas. E que se possível, a análise fractográfica dos espécimes fraturados deve ser realizada com o objetivo de determinar o real motivo que gerou a falha da restauração. Exceto para possíveis casos de descimentação, onde a recimentação da peça possa ser indicada.

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ANEXO A – Comprovante do artigo 1 publicado

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CAD-FEA modeling and analysis of different full crown monolithic restorations

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ABSTRACT

Objectives. To investigate the influence of different materials for monolithic full posterior crowns using 3D-Finite Element Analysis (FEA).

Methods. Twelve (12) 3D models of adhesively-restored teeth with different crowns according to the material and its elastic modulus were analysed: Acrylic resin, Polyetheretherketone, Composite resin, Hybrid ceramic, pressable and machinable Zirconia reinforced lithium silicate, Feldspathic, Lithium disilicate, Gold alloy, Cobalt–Chromium alloy (Co–Cr), Zirconia tetragonal partially stabilized with yttria, and Alumina. All materials were assumed to behave elastically throughout the entire deformation. Results in restoration and cementing line were obtained using maximum principal stress. In addition, maximum shear stress criteria was used for the cementing line.

Results. Restorative materials with higher elastic modulus present higher stress concentration inside the crown, mainly tensile stress on an intaglio surface. On the other hand, materials with lower elastic modulus allow stress passage for cement, increasing shear stress on this layer. Stiffer materials promote higher stress peak values.

Significance. Materials with higher elastic modulus such as Co–Cr, zirconia and alumina enable higher tensile stress concentration on the crown intaglio surface and higher shear stress on the cement layer, facilitating crown debonding.

ANEXO B – Comprovante do artigo 2 publicado

Influence of substrate design for *in vitro* mechanical testing

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Abstract

Background: The goal of this study was to evaluate the influence of dental substrate simulator material, and the presence of root and periodontal ligament on the stress distribution in an adhesively-cemented monolithic crown.
Material and Methods: Five (5) 3D models according to the substrate simulator material and shape were modeled with CAD software for conducting non-linear finite element analysis (FEA): Tooth with and without periodontal ligament - subgroup "pl" (groups Tooth+pl and Tooth-pl), machined tooth in epoxy-resin with and without pulp chamber - subgroup "pc" (ER+pc and ER-pc) and simplified epoxy-resin substrate without pulp chamber and roots (SiER). Next, adhesively-cemented monolithic crowns in zirconia reinforced lithium silicate were modeled over each substrate. The solids were then imported in STEP format to the analysis software and the contact between teeth and cylinder was considered perfectly bonded; whereas, the contacts involving the resin cement were considered as non-separated. The materials were considered isotropic, linearly elastic, and homogeneous. An axial load (600 N) was applied to the occlusal surface and results of maximum principal stress (MPa) on the restoration were required.
Results: FEA revealed that all evaluated subtracts showed the crown intaglio surface as the most stressed region. The average stress and stress peaks were similar for restorations cemented onto Tooth+pl, Tooth-pl and ER+pc substrates, but, 13% higher in comparison to ER-pc and SiER substrates.
Conclusions: Simplified substrates can be used to evaluate posterior full crown behavior without periodontal ligaments and roots, since the rigidity of the specimen is taken into account.

Key words: *Finite element analysis, axial loading, computed assisted numerical analisys, monolithic crowns,methodological study.*

ANEXO C – Comprovante do artigo 3 submetido

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