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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.

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 [2–5]. However, with the aesthetic improvement of restorative materials and the possibility of using dental ceram-

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ics 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 [7–9]. 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.

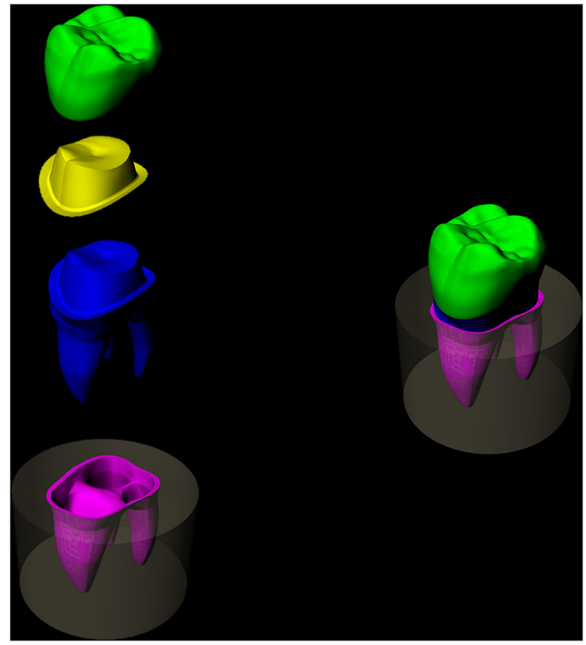

Fig. 1 – 3D FEA model of a tooth: (a) monolithic crown; (b) cementing line; (c) tooth remnant; (d) periodontal ligament; (e) restored tooth.

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.

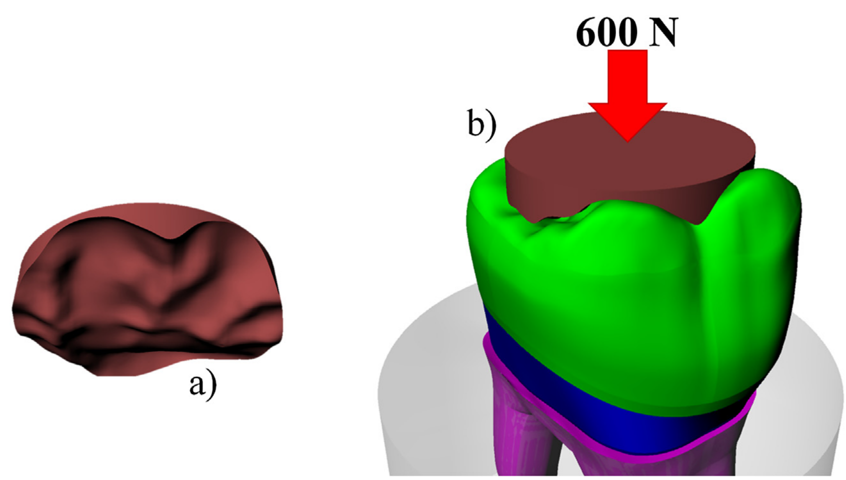

Fig. 2 – Food modeling and load application: (a) bolus on the occlusal surface; (b) occlusal load.

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 ($\times10^{-3}$)	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 ($\times10^{-3}$)	0.45
Resinous cement [28,29]	7.5	0.3

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) [14–29] and all contacts were ideally cast.

2.2.3. *Loading and fixations*

Load application (600 N) occurred similar to the methodology by Ausielo 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.

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 [16,30–32]. 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: $SC = \frac{Sp}{aS}$, 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: $Fr = \frac{Sp}{Strength}$. 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 pros-

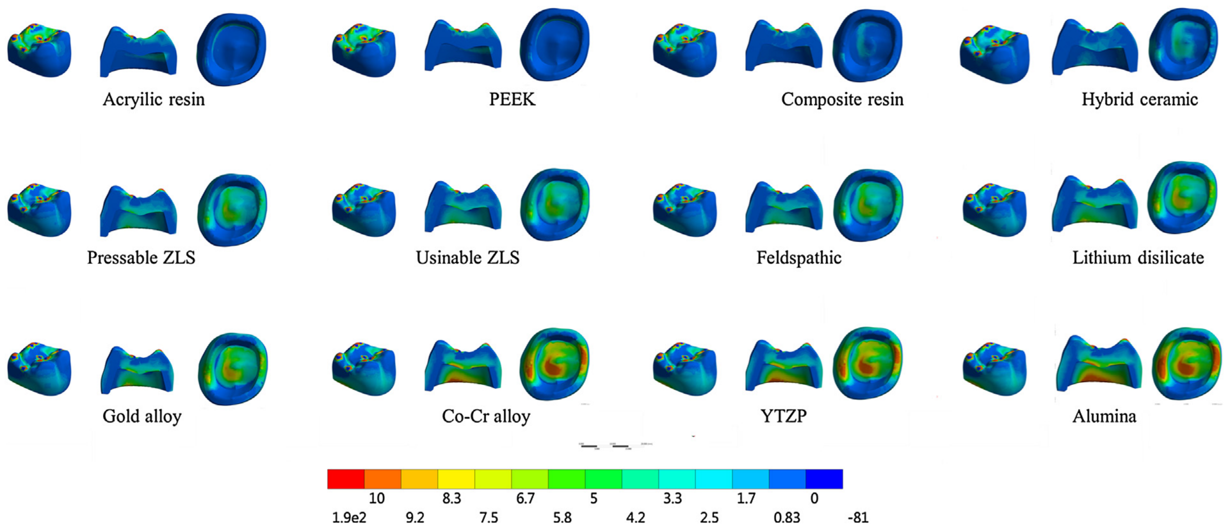

Fig. 3 – Stress generated in monolithic crowns; (a) acrylic resin, (b) PEEK, (c) composite resin, (d) hybrid ceramic, (e) pressable ZLS, (f) ZLS CAD, (g) feldspathic, (h) lithium disilicate, (i) gold alloy, (j) CoCr alloy, (k) YTZP and (l) alumina.

thetic 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 [17,35–40]. 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

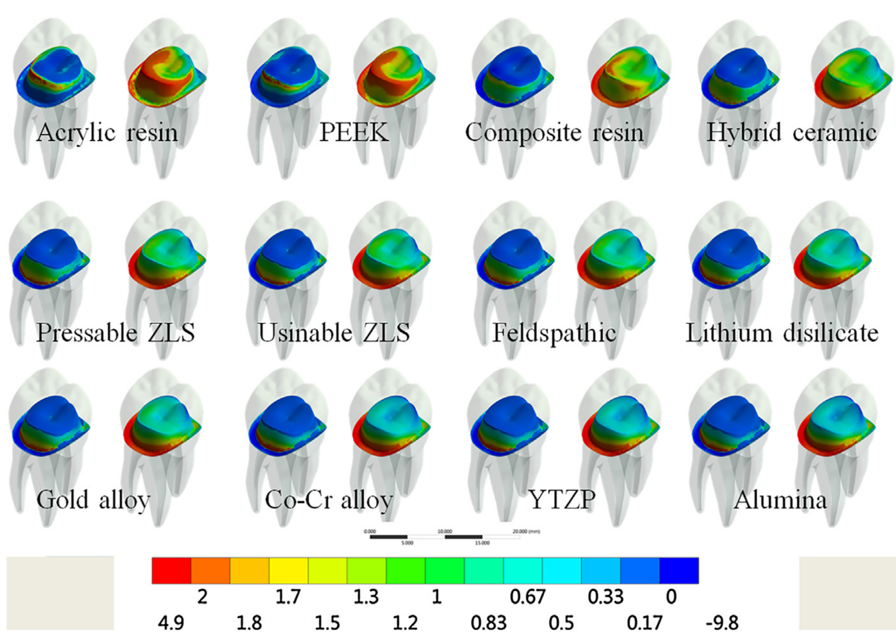

Fig. 4 – Tensile and shear stresses generate on cementing line according to the monolithic crowns, respectively: (a) acrylic resin, (b) PEEK, (c) composite resin, (d) hybrid ceramic, (e) pressable ZLS, (f) ZLS CAD, (g) feldspathic, (h) lithium disilicate, (i) gold alloy, (j) CoCr alloy, (k) YTZP and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

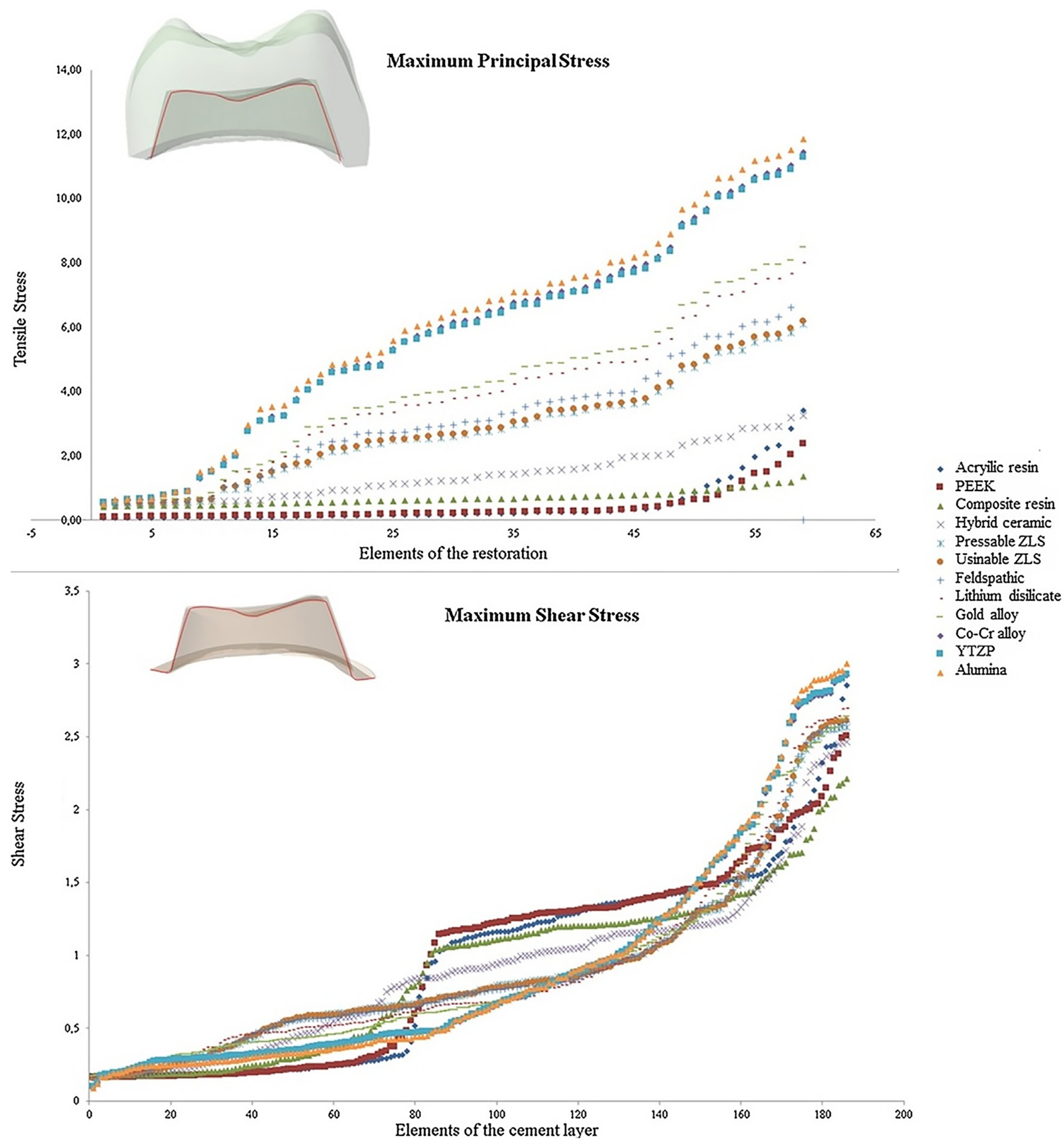

Fig. 5 – Maximum principal stress (MPa) distribution along the crown internal surface and Maximum shear stress (MPa) distribution along the cementing layer external surface.

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.

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

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.

Material	Crown				Resin cement				Failure risk	
	Tensile strength	Stress peak	Average stress	SC	Failure risk	Stress peak	Average stress	SC	Cohesive	Adhesive
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[a]	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[a]	180 ± 11	6.1	2.76	2.21	0.03	2.56	0.89	2.87	0.18	0.07
Usinable ZLS[a]	159 ± 18	6.18	2.83	2.18	0.04	2.61	0.89	2.93	0.18	0.08
Feldspathic[a]	123 ± 7	6.62	3.05	2.17	0.05	2.6	0.89	2.91	0.18	0.08
Hybrid ceramic[a]	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

[a] The tensile strength values were obtained by the authors following Della Bona et al. [38] methodology.

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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