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Comparative stress evaluation of different types of prosthetic abutment and crown with an internal connection implant

Distribuição de tensões em implantes cone morse com coroas e intermediários confeccionados por diferentes materiais

Distribución del estrés en implantes con conexión interna con coronas e intermedios de diferentes materiales

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Abstract
The purpose of this study was to compare the stress distribution in two different types of crowns (zirconia and feldspatic ceramic) and three different types of abutments (poly-ether-ether-ketone, titanium and zirconia) at an upper central incisor, with the Finite Element Analysis (FEA). Five experimental groups were established: Group P-Zr/SA (PEEK/zirconia - without adhesion), Group P-Zr/CA (PEEK/zirconia - with adhesion), Ti-Zr Group (titanium/zirconia), Zr-Zr Group (zirconia/zirconia) and Zr-F Group (zirconia/feldspatic). An oblique loading was applied at the palatal surface of the crown in each model. All models were exported to a finite element analysis software, where Maximum stress (tensile), Minimum stress (compressive) and von Mises stresses values were obtained. The results showed that the P-Zr/SA and P-Zr/CA groups exhibited the highest von Mises stresses values in the implant, and these stresses were concentrated at the implant platform. In all abutments groups, the Maximum Principal stress location was at the hexagonal connection, and the P-Zr/SA and P-Zr/CA groups showed the lowest stress values. The P-Zr/CA and Zr-Zr groups exhibited better crown stress distribution (better dissipation). The von Mises stress location were similar in all groups in the screws, however the von Mises stress values were the highest in the P-Zr/SA and P-Zr/CA groups. It can be concluded in this study that the PEEK abutment does not have a better stress distribution in the crowns, implants and screws.
Keywords: Poly-ether-ether-ketone; Zirconia; Abutment; Stress distribution; Finite element analysis.

Resumo
O objetivo neste estudo foi comparar, por meio do método de elementos finitos (MEF), a distribuição de tensões em dois diferentes tipos de coroas (zircônia e cerâmica feldspática) e três tipos diferentes de intermediários protéticos

(PEEK, titânio e zircônia) em um incisivo central superior. Cinco grupos foram estabelecidos: P-Zr/SA (PEEK/zircônia - sem adesão), P-Zr/CA (PEEK/zircônia - com adesão), Ti-Zr (titânio/zircônia), Zr-Zr (zircônia/zircônia) e Zr-F (zircônia/feldspática). Em cada modelo foi simulada uma carga oblíqua de 100 N na face palatina. Todos os modelos foram exportados para um software de análise de elementos finitos (ANSYS Workbench 16), onde foram analisados os valores de tensão Máxima Principal (tração), Mínima Principal (compressão) e von Mises. Os resultados demonstraram que os grupos P-Zr/SA e P-Zr/CA tiveram os maiores valores de von Mises no implante, sendo que essas tensões se concentraram na plataforma do implante. Nos intermediários, em todos os grupos, a tensão Máxima Principal se concentrou na região da conexão sextavada, sendo que os grupos P-Zr/SA e P-Zr/CA apresentaram os menores valores. Os grupos P-Zr/CA e Zr-Zr apresentaram maior dissipação das tensões na coroa. Nos parafusos, a localização das tensões de von Mises foi similar em todos os grupos, sendo que os grupos P-Zr/SA e P-Zr/CA apresentaram os maiores valores. Concluiu-se neste estudo que o intermediário de PEEK não proporciona uma melhor distribuição de tensões nas coroas, implantes e parafusos.
Palavras-chave: Poliéter-éter-cetona; Zircônia; Intermediário; Distribuição de tensões; Método de elementos finitos.

Resumen
El objetivo de este estudio fue comparar, utilizando el método de elementos finitos (MEF), la distribución de tensiones en dos tipos diferentes de coronas (zirconia y cerámica de feldespato) y tres tipos diferentes de intermedios protésicos (PEEK, titanio y zirconia) en un incisivo central. Se establecieron cinco grupos: P-Zr/SA (PEEK/zirconia - sin adherencia), P-Zr/CA (PEEK/zirconia - con adherencia), Ti-Zr (titanio/zirconia), Zr-Zr (zirconia/ irconia) y Zr-F (zirconia/feldespato). En cada modelo, se simuló una carga oblicua de 100 N en la superficie palatina. Todos los modelos se exportaron a un software de análisis de elementos finitos (ANSYS Workbench 16), donde se analizaron los valores Máximo Principal (tracción), Mínimo Principal (compresión) y von Mises. Los resultados mostraron que los grupos P-Zr/SA y P-Zr/CA tenían los valores de von Mises más altos en el implante, y estas tensiones se concentraron en la plataforma del implante. En los intermedios, en todos los grupos, la tensión principal máxima se concentró en la región de la conexión hexagonal, teniendo los grupos P-Zr/SA y P-Zr/CA los valores más bajos. Los grupos P-Zr/CA y Zr-Zr mostraron mayor disipación de tensiones en la corona. En los tornillos, las tensiones de von Mises fue similar en todos los grupos, con los grupos P-Zr/SA y P-Zr/CA mostrando los valores más altos. En este estudio se concluyó que el PEEK intermedio no proporciona una mejor distribución de la tensión en las coronas, implantes y tornillos.
Palabras clave: Polieter-eter-cetona; Zirconia; Intermedio; Distribución de tensiones; Método de elementos finitos.

1. Introduction

Implant-supported single crowns are a valid and established alternative to conventional fixed dental prostheses (FPDs) for single-tooth replacement (Zembic et al., 2015). One of the most challenging scenarios for the dental practitioner is to give answer to the patient expectations with a good result of the implant integration, excellent esthetical crown incorporation in the dental arch and achieve a harmonious restoration that cannot be distinguished from natural teeth by the naked eye. This is particularly important and challenging in the anterior region of the jaw, which is its most exposed region (Gomes, Montero, 2011; Zembic et al., 2015).

A usable two-piece implant reconstruction is consisted of a titanium abutment attached to the implant with a titanium screw and a metal ceramic crown cemented to the abutment (Jemt, 1986; Ekfeldt et al., 2011). For many years, both the abutment and the implant were made from commercially pure titanium (Abrahamsson et al., 1998; Lindhe, Berglundh, 1998), mainly due to their biocompatibility, hardness and mechanical resistance (Linkevicius, Vaitelis, 2015). However, one major drawback of titanium abutments is that their dark gray color can cause a grayish discoloration of the peri-implant mucosa impairing the esthetic result of implant reconstructions (Sailer et al., 2009).

To overcome this problem, a variety of abutments and restorations differing in design and biomaterials have been introduced to achieve optimal mechanical, biological, and esthetic treatment outcomes (Bidra, Rungruanganunt, 2013). The alumina and zirconia abutments are biocompatible and allow a healthy adherence of the peri-implant mucosa (Abrahamsson et al., 1998; Linkevivius, Apse, 2008). However, because of better mechanical and optical properties when compared to alumina, zirconia is currently the ceramic of choice for different types of metal-free dental reconstructions, including crowns and prosthetic abutments (Zarone et al., 2011; Zembic et al., 2013). Although there are still few long-term clinical studies in the literature (> 5 years), it is known that the survival rate of zirconia abutments is comparable to titanium abutments (Ekfeldt et al., 2011; Jung et al., 2012; Lops et al., 2013; Zembic et al., 2013; Zembic et al., 2015).

PEEK (poly-ether-ether-ketone), is a dominant member of the PAEK (poly-aryl-ether-ketone) polymer family and was developed as a main substitute for the metallic components and implants of high-performance thermoplastic polymers, especially in cases of orthopedics and trauma (Sarot et al., 2010). This material is a high-performance thermoplastic polymer, biocompatible, with an elasticity module close to bone tissue (Schwitalla, Müller, 2013). It is an aesthetic material, with reduced degree of discoloration and less density than titanium (Tannous et al., 2012). These findings suggest that PEEK could substitute titanium as material for dental endosseous implants (Schwitalla, Müller, 2013; Najeeb et al., 2016). Currently, individual abutments on implants can be milled of PEEK (Skirbutis et al., 2017). A close match of elastic moduli of bone and PEEK surface reduces the stress shielding effects and encourage bone remodeling. Hence, PEEK could prove to be a viable alternative to titanium in constructing implant abutments (Najeeb et al., 2016).

Metal-ceramic restorations have been used in restorative dentistry for many years (Pjetursson et al., 2007). However, the use of metal under ceramics makes it difficult to reproduce the teeth natural aesthetics details, compromising the ceramic characteristics (Sailer et al., 2007). The drawback of such restorations is increased light reflectivity because of the opaque porcelain needed to mask the metal substrate (Heffernan et al., 2002). To overcome this challenge, polycrystalline ceramics are also used in the manufacture of indirect restorations (Sailer et al., 2007). Zirconia has a white color pigment with high opacity, in addition to its high mechanical properties (Vagkopoulou et al., 2009). The increased opacity of zirconia ceramics is useful in cases of masking darkened teeth, implant abutment or metallic cores (Heffernan et al., 2002; Vagkopoulou et al., 2009).

There are insufficient and conflicting reports in the literature on how the stresses are distributed in implants, abutments, crowns and screws, mainly associated with PEEK material (Sarot et al., 2010; Schwitalla, Müller, 2013; Kaleli et al., 2018). In addition, an increasing number of implant systems and restorative materials are available on the market, as well as an increased demand for more aesthetic restorations. Therefore, it is important to evaluate the performance of these implants and materials for a better understanding of the prosthetic treatment results.

The purpose of this study, using the finite element analysis (FEA), was to compare the stress distribution in two different types of restorative crowns (zirconia and feldspatic ceramic) and three different types of prosthetic abutments (PEEK, titanium and zirconia). The alternative hypothesis was that the PEEK abutment would exhibit a better stress distribution in the crowns, implant and screw, when compared to the titanium and zirconia abutments.

2. Methodology

Two three-dimensional anterior maxilla segments (25 mm height x 15 mm mesio-distal width x 15 mm bucco-palate depth) were created based on a cone-beam computed tomographic image (i-CAT Cone Beam 3D Dental Imaging System; Imaging Sciences International), reproducing a clinical situation with the absence of an upper central incisor, and replacement by implant-supported single crown in order to simulate the functional occlusal loading on osseointegrated implants. Each model consisted of a dental implant with 4.3 mm platform diameter and 11.5 mm in length, with a Morse taper prosthetic connection associated with a platform switching abutment. The abutments were represented by three different materials: PEEK, titanium and zirconia. The experimental groups were modeled with the aid of three-dimensional computer-aided design software (Solid Works 2013; Dassault Systèmes Solid Works Corp). Two types of prosthetic crowns were simulated in the software, a 2 mm thick feldspatic ceramic crown and a 2.0 mm thick polycrystalline ceramic crown (zirconia stabilized with yttrium) (Lava, 3M ESPE). Each prosthetic crown (feldspatic and zirconia) was cemented to one of the three types of abutments (PEEK, titanium, and zirconia), and five different models were created according to restoration and abutment material combinations: P-Zr/SA Group (PEEK/zirconia - without adhesion), P-Zr/CA Group (PEEK/zirconia - with adhesion), Ti-Zr Group (titanium/zirconia), Zr-Zr Group (zirconia/zirconia) and Zr-F Group (zirconia/feldspatic).

A 25µm thickness dual-polymerized resin cement (Rely X Ultimate, 3M ESPE, Saint Paul, MN, EUA) layer was defined between the restorative crown and abutment to simulate clinical conditions.

All the models were exported to FEA software (ANSYS Workbench 16, Ansys Inc., Canonsburg, PA, USA) for biomechanical analysis. All materials were considered isotropic, homogeneous, linearly elastic, and the materials Young modulus and Poisson ratio values were exported to the software (Table 1). The cortical bone and cancellous bone were separated and both bone structures were shown in different colors. The 3D implant model was placed in bone structure with 100% osseointegration and in a 2.0 mm subcrestal position. In each model, a 100 N oblique loading (45º) was performed on the palatal surface simulating the masticatory force that affects the upper incisor teeth. The loading was simulated using non-linear frictional contact elements with a 0.3 µm friction coefficient between the bone and the implant.

Table 1 - Young modulus and Poisson ratio of each material.

Material	Young modulus (GPa)	Poisson ratio	Reference
Cortical bone	13,7	0,30	24
Cancellous bone	1,37	0,30	24
Titanium	110	0,35	24
Zirconia	210	0,30	24
PEEK	3,5	0,36	24
Feldspatic ceramic	82,8	0,35	26
Resin cement	7,7	0,33	3M/ESPE

Source: Own authorship.

For regions that correspond to critical areas such as, implant-abutment and implant-bone tissue interfaces, a mesh refinement process was carried out with the number of nodes and elements gradually increasing. The total number of nodes and elements that were used in the finite element analysis for each group are described in Table 2.

Table 2 - Number of nodes and elements for each group.

Group	Nodes	Elements
P-Zr	760.603	506.193
Ti-Zr	732.046	570.162
Zr-Zr	681.477	401.359
Zr-F	722.875	462.114

Source: Own authorship.

The finite element analysis was used to determine the values of Maximum Principal stress (tensile) and Minimum Principal stress (compressive), von Mises stresses and the modified von Mises criteria. And the data analysis was performed in a quantitative and qualitative way.

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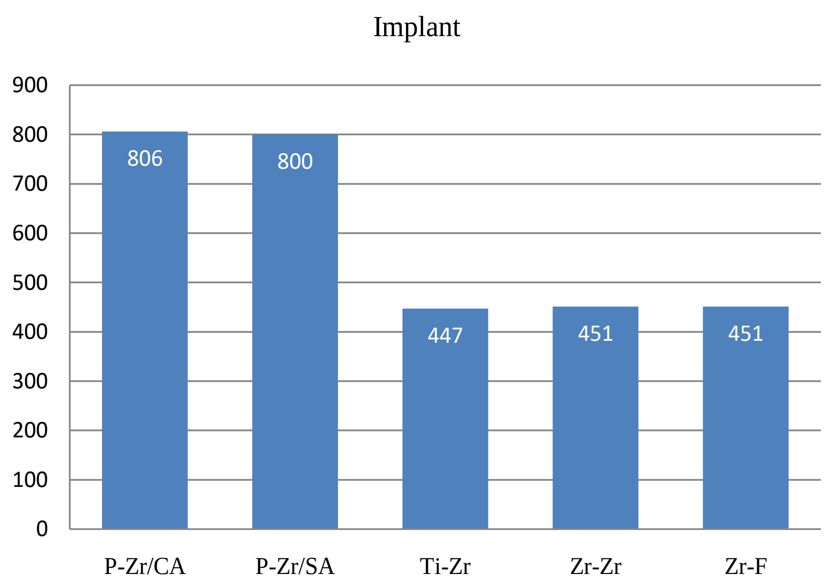
3. Results

The results are shown in the tables and figures below. The different abutment materials influenced in different ways the stress distribution in the implant, abutment, prosthetic crown and screw, under 100N palatal loading at 45º along the implant axis.

Implant

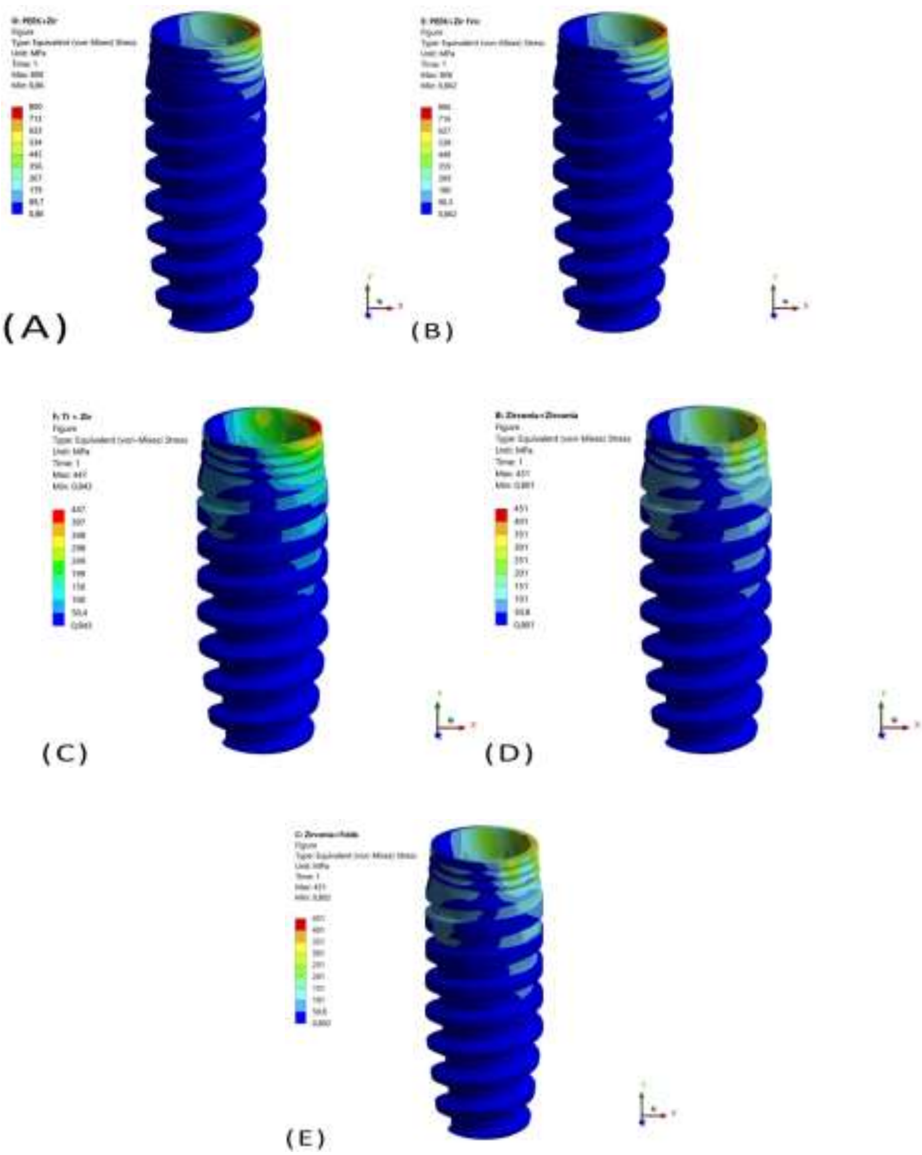
Regarding the von Mises stress implant values, the P-Zr/SA and P-Zr/CA groups showed the highest values, while the other groups exhibited intermediate values similar to each other (Figure 1). In the P-Zr/SA and P-Zr/CA groups, von Mises stress was concentrated at the buccal region of the implant platform (Figures 2A and 2B). In the Ti-Zr, Zr-Zr and Zr-F groups (Figures 2C, 2D and 2E) the stress was distributed more towards the center of the implant, but still with a greater concentration at the implant platform.

Figure 1 - Results of Von Mises stresses in the Implant (MPa).



Source: Own authorship.

Figure 2 - Distribution of the von Mises stress at different implant groups. (A) P-Zr/SA; (B) P-Zr/CA; (C) Ti-Zr; (D) Zr-Zr; (E) Zr-F.

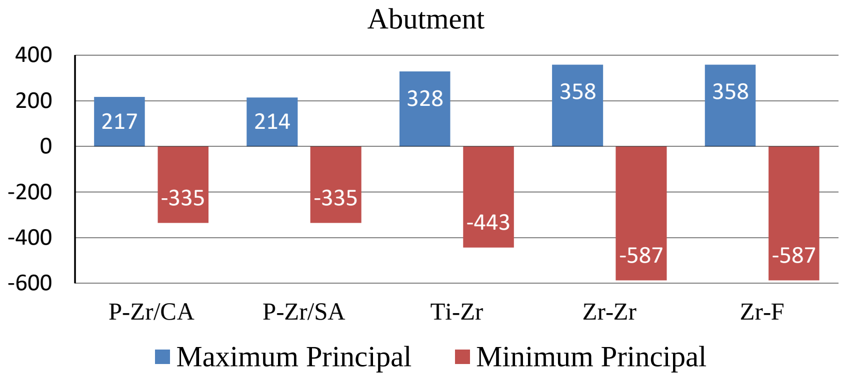


Source: Own authorship.

Abutment

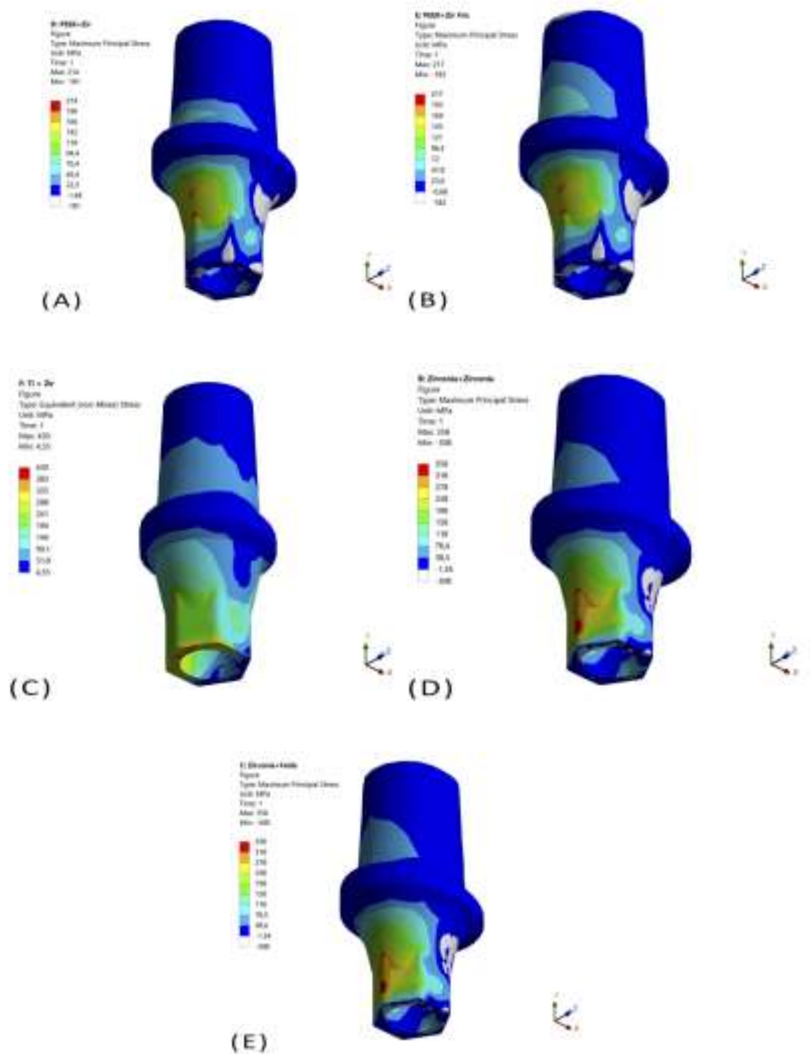
The P-Zr/SA and P-Zr/CA abutments groups exhibited the lowest tensile stress values when compared to the other analyzed groups. The Zr-Zr group and Zr-F group showed the highest tensile stress values and were similar to each other (Figure 3). In all groups the Maximum Principal stress (tensile) distribution concentrated at the hexagonal connection, in the opposite direction of the applied force (Figures 4A to 4E).

Figure 3 - Comparison of maximum (tensile) and minimum (compressive) principal.



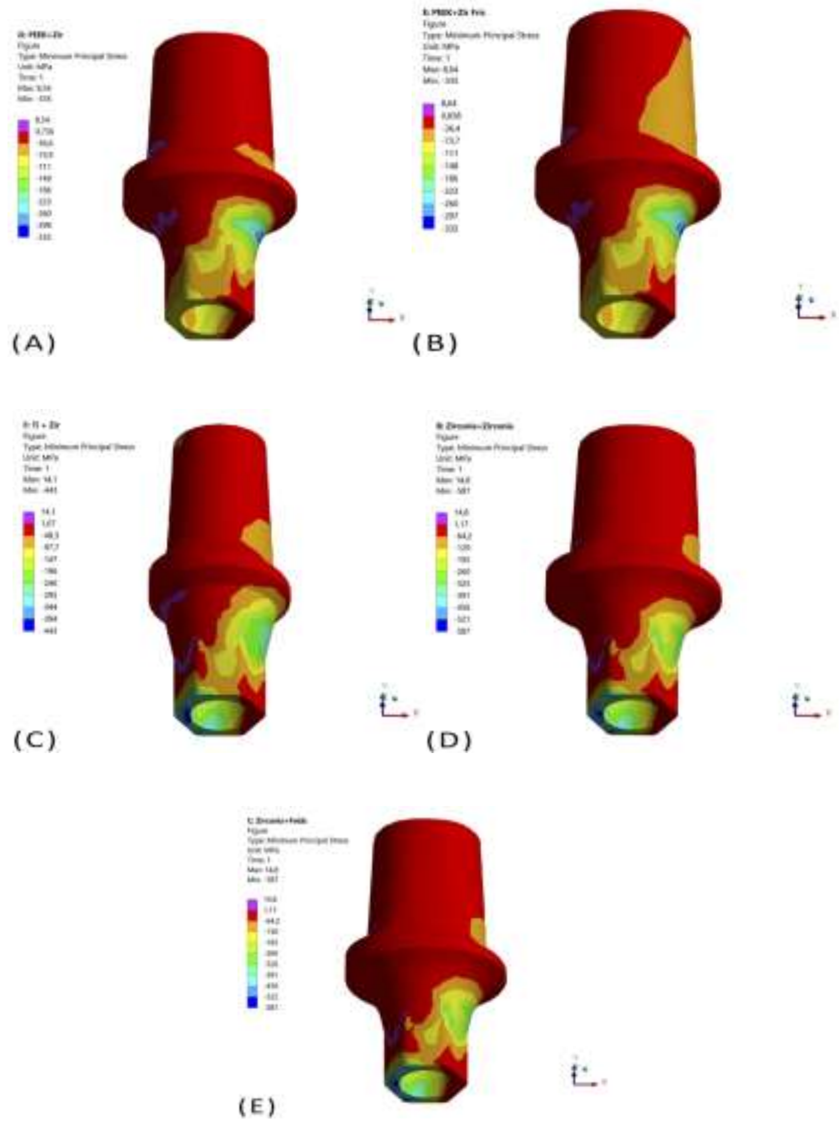
Source: Own authorship.

Figure 4 - Distribution of the Maximum Principal stress at different abutment groups. (A) P-Zr/SA; (B) P-Zr/CA; (C) Ti-Zr; (D) Zr-Zr; (E) Zr-F.



Source: Own authorship.

Figure 5 - Distribution of the Minimum Principal stress at different abutment groups. (A) P-Zr/SA; (B) P-Zr/CA; (C) Ti-Zr; (D) Zr-Zr; (E) Zr-F.



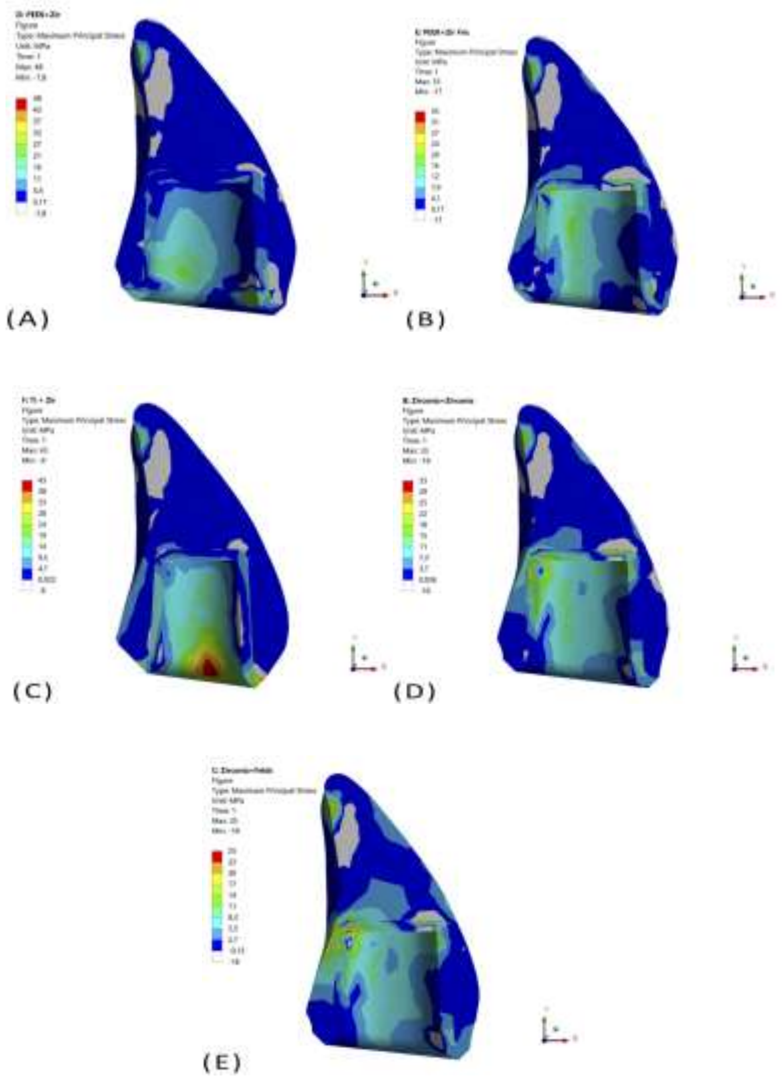
Source: Own authorship.

In all prosthetic abutments groups, the Minimum Principal stress (compression) distribution also concentrated at hexagonal connection, but, at the same direction as the applied force (Figures 5A to 5E). The P-Zr/SA and P-Zr/CA groups (Figures 5A and 5B) showed the lowest compressive stress values compared to the other analyzed groups (Figures 5C, 5D and 5E). The Zr-Zr and Zr-F groups (Figures 5D and 5E) displayed the highest compression stress values and were similar to each other (Figure 3).

Prosthetic Crown

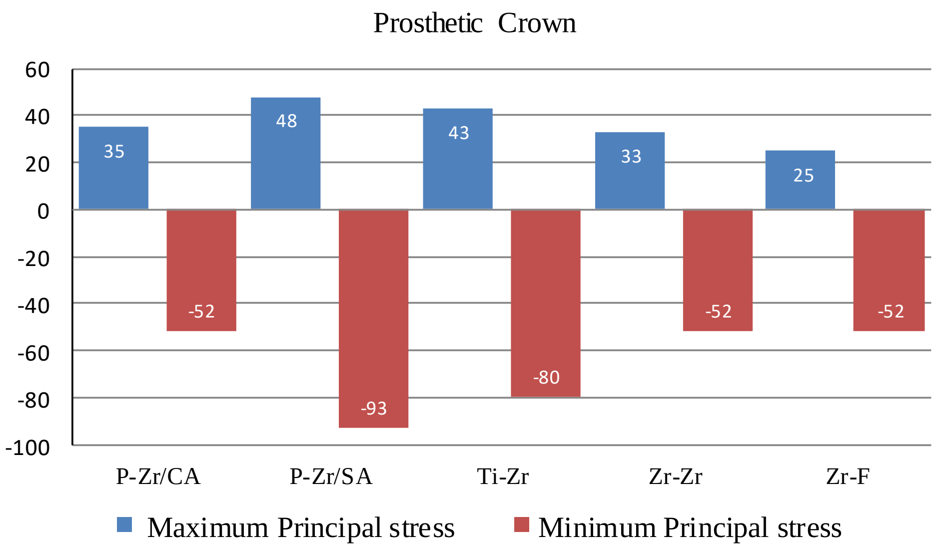
Regarding to restorative crowns, the P-Zr/CA and Zr-Zr groups (Figures 6B and 6D) showed better stress distribution (greater dissipation) inside the zirconia crown. The Ti-Zr group (Figure 6C) showed a higher Maximum Principal stress concentration at the cervical region. In the Zr-Zr and Zr-F groups (Figures 6D and 6E) the stress was concentrated at the palatal region of the crown. The P-Zr/SA group exhibited the highest Maximum Principal stress value, followed by the Ti-Zr group. The Zr-F group showed the lowest values (Figure 7).

Figure 6 - Distribution of the Maximum Principal stress at different crown groups. (A) P-Zr/SA; (B) P-Zr/CA; (C) Ti-Zr; (D) Zr-Zr; (E) Zr-F.



Source: Own authorship.

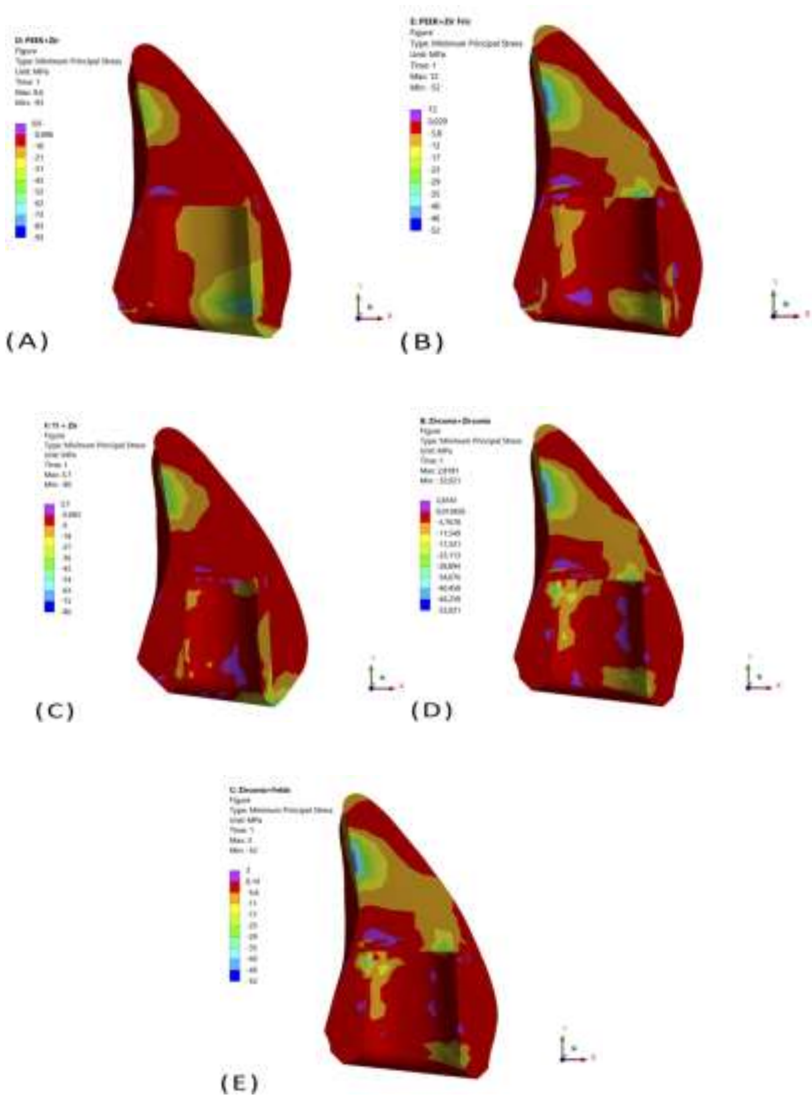
Figure 7 - Comparison of maximum (tensile) and minimum (compressive) principal stresses in the prosthetic crowns.



Source: Own authorship.

Concerning the Minimum Principal stress, similar forces distribution were obtained in the P-Zr/CA, Ti-Zr, Zr-Zr and Zr-F groups (Figures 8B to 8E), and, the stress distribution was at the interface area between crown and abutment (Figure 8A). The P-Zr/SA group showed the lowest compression stress value, while the groups P-Zr/CA, Zr-Zr and Zr-F exhibited the highest values (Figure 7).

Figure 8 - Distribution of the Minimum Principal stress at the different crown groups. (A) P-Zr/SA; (B) P-Zr/CA; (C) Ti-Zr; (D) Zr-Zr; (E) Zr-F.

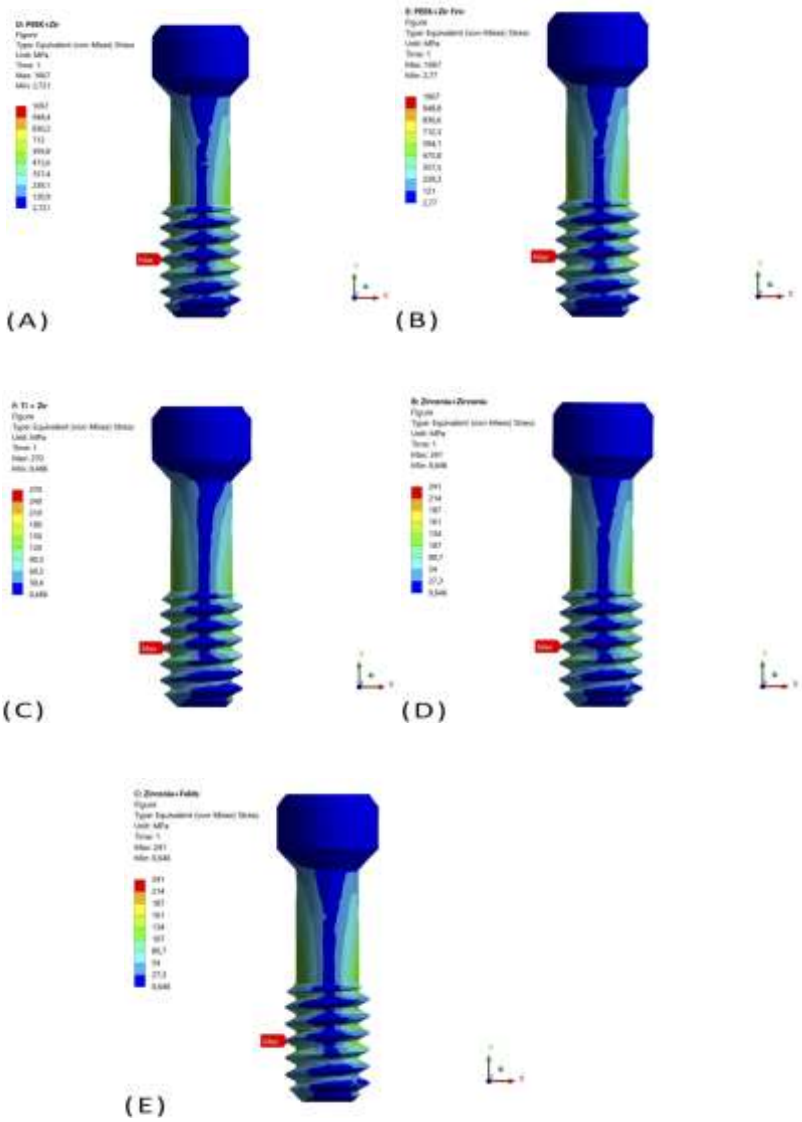


Source: Own authorship.

Abutment Screw

The von Mises stresses location at the abutment screw was similar in all groups (Figures 9A to 9E). With regard to the von Mises stress values, the P-Zr/SA and P-Zr/CA groups (Figures 9A and 9B) showed the highest values, while the Zr-Zr and Zr-F groups (Figures 9D and 9E) exhibited the lowest values (Figure 10).

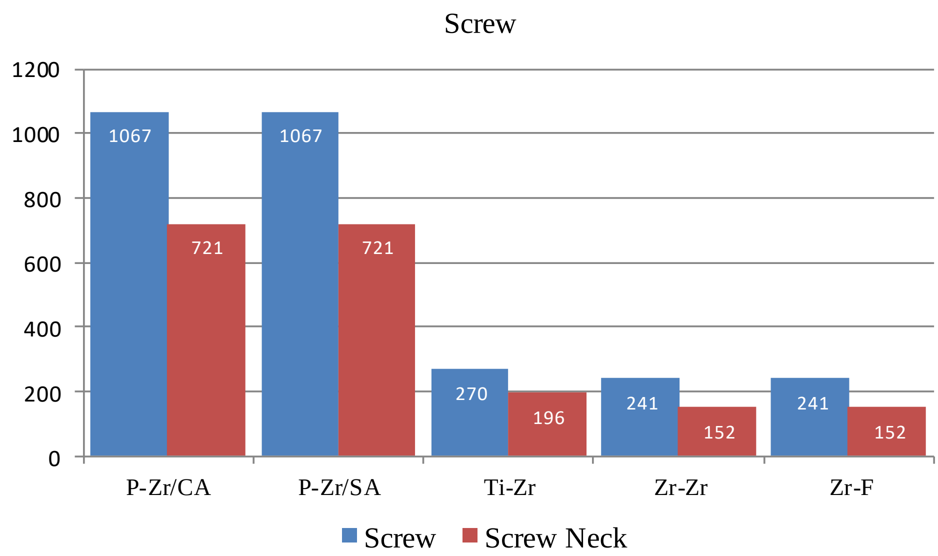
Figure 9 - Distribution of the von Mises stress at the different screw groups. (A) P-Zr/SA; (B) P-Zr/CA; (C) Ti-Zr; (D) Zr-Zr; (E) Zr-F.



Source: Own authorship.

When comparing the screw neck area values, the P-Zr/SA and P-Zr/CA groups showed the highest von Mises stress values, the Zr-Zr and Zr-F groups displayed the lowest values (Figure 10).

Figure 10 - Results of Von Mises stresses in the screw and screw neck (MPa).



Source: Own authorship.

4. Discussion

Results of the present study revealed that the analyzed abutments had different performances in the Maximum and Minimum Principal stresses values and distribution. Therefore, the hypothesis that PEEK abutment has a better stress distribution in crowns, implants and screws was rejected.

PEEK has a lower elasticity modulus when compared to titanium and zirconia (Table 1) and exhibits greater deformations (elastic and plastic) under a load, being less fragile than titanium and ceramic. Therefore, PEEK abutments receive lower stress values (Figure 3), and these stresses are better distributed and in more uniform way into its structure.

Due to the low elastic and plastic deformation (high fragility), zirconia concentrates the stresses at one point in the hexagon connection (Figures 4D and 4E), increasing the probability of a material failure in that region. When a stress is generated on a fragile material, this stress will cause a material fracture instead of promoting considerable deformation. It is important to note that, unlike ductile materials (titanium), PEEK and zirconia are fragile materials and exhibit different compressive strength and tensile strength values. Therefore, Maximum Principal and Minimum Principal stresses are analyzed on these materials instead of the von Mises stresses.

The use of PEEK abutment generated higher von Mises stresses values in the implant (Figure 1) concentrated in the implant platform area (Figures 2A and 2B). This may be explained, because PEEK has a low elasticity modulus and greater plastic deformation when compared to zirconia and titanium. In addition, abutment of lower elastic modulus will undergo greater deformation due to the absence of lateral contact with other structures, transferring the stresses to the implant and peri-implant bone tissue (Tretto et al., 2020).

Due to its ductile characteristic, the titanium abutment (Ti-Zr Group) transferred and concentrated greater stress at the crown cervical area (Figure 6C). The P-Zr/CA and Zr-Zr groups generated stresses with similar values (Figure 7) and distributions (Figures 6A and 6D, respectively) inside the zirconia crown. This is due to the fact that, the finite elements simulation in the present study, used cementing agent between the crown and the prosthetic abutment as a parameter, in which, dissipates and attenuates the tensions in the crown, resulting in approximate values. Several layers or structures play a role in transmitting masticatory forces to implants and peripheral bone, including the restorative crown, cement layer, inner screw, and abutment (Sevimay et al., 2005). Some of the transmitted energy is considered to be absorbed by the intermediate structures (Kaleli et al., 2018).

The cement used in the P-Zr/CA group attenuates part of the crown stresses (Maximum Principal and Minimum Principal). For this reason, the P-Zr/CA group showed lower stress values when compared to the group without cement (P-Zr/SA) (Figure 7). In addition, the structures (restorative crown and abutment) without adhesion act as a single, rigid body, avoiding the stress dissipation at the crown-abutment interfaces, resulting in a considerable increase stress concentration in the crown. This is due to the fact that, when the analyzed group does not use cement as a parameter, a FEA parameter simplification (linear analysis) is generated, therefore, higher stress values were observed (Dos Santos et al., 2017).

Regarding the prosthetic abutment screw, the P-Zr/SA and P-Zr/CA groups (Figure 10) exhibited the highest von Mises stresses values, due to the fact that the PEEK material displays greater deformations (elastic and plastic) when loaded. Therefore, it was observed a greater stress transfer to the screw (Figures 9D and 9E), this was not observed in Zr-Zr and Zr-F groups (Figures 9D and 9E), since zirconia has a high rigidity compared to PEEK.

The same implant stress results with PEEK abutment were observed in previous studies (Tretto et al., 2020; Tekin et al., 2019). However, our research showed opposite results when compared to two other studies (Sarot et al., 2010; Kaleli et al., 2018). The different abutment materials used in these studies did not result in any significant difference in the implant stress distribution between the groups. This may be related to the use of a titanium base (Ti-base abutment) that supported the zirconia and PEEK abutments; whereas in the present study the abutments were represented without the titanium base. However, in the qualitative analysis, it was observed a greater stress concentration at the implant platform, corroborating with our results.

Digital systems are available in almost all Dentistry areas (intra-oral scanners, digital images and CAD/CAM system). The FEA accurately determines the intensity and the way, which different stresses are distributed in a material without the need for physical prototypes, reducing the methodology costs (Srirekha, Bashetty, 2010; Trivedi, 2014). However, the FEA is a mathematical model and has some limitations, such as the difficulty in simulating the clinical variables involved in the implant-supported rehabilitation treatment. In addition, there is a limitation to simulate the biological tissues mechanical performance in situ, such as bone tissue, since bone has a viscoelastic characteristic, whereas materials, such as titanium, ceramic and PEEK, do not have this property (Geng et al., 2001). Materials, such as titanium, are ductile and have similar tensile and compressive strengths. In other hand, bone responds differently to tensile and compressive strengths, because it is a heterogeneous structure composed of collagen and hydroxyapatite nanoparticles. However, at FEA it is considered homogeneous (Dos Santos et al., 2017).

The results of this study provide an overview of the abutments biomechanical performance in virtual conditions. Future computational studies, in addition to laboratory and clinical evaluations, are needed to evaluate the mechanical performance of the PEEK abutments.

5. Conclusion

Within the limitations of this FEA study, it can be concluded that, the change in abutment material affected the stress distribution in the implant, restorative crown and abutment screw. The use of PEEK abutment generated higher stresses values in the implant. Zirconia and titanium abutments exhibited the best results when used with a titanium implant and zirconia or feldspatic ceramic crown, and also can be concluded that the peek material should not be used as a single dental implant abutment. Further clinical and laboratory studies are necessary to endorse the use of this material.

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