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Marcus Vinicius Rocha de Almeida

IMPLANTES DENTÁRIOS E PILARES EM PEEK: AVALIAÇÃO DA TENSÃO EM COROA UNITÁRIA IMPLANTOSUPORTADA NA REGIÃO ANTERIOR

DENTAL IMPLANT AND ABUTMENT IN PEEK: STRESS ASSESSMENT IN SINGLE CROWN RETAINERS ON ANTERIOR REGION

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Dissertação apresentada à Faculdade de Odontologia de Piracicaba da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Mestre em clínica odontológica, na área de Prótese Dental.

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Orientadora: Profª. Drª. Raissa Micaella Marcello Machado

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RESUMO

Implantes dentários em titânio e zircônia apresentam um módulo de elasticidade (ME) alto, favorecendo o fenômeno de “stress shielding”, perda óssea peri-implantar por falta de tensão fisiológica. O poli (eteretercetona) (PEEK) é um material alternativo, já utilizado na medicina por apresentar um ME próximo ao do osso. O método de análise por elementos finitos (AEF) é uma forma efetiva de avaliação que permite estudar a distribuição das tensões de forma virtual, capaz de apontar resultados prévios aos testes *in vitro* e *in vivo*. O objetivo desse estudo foi avaliar, por AEF, a distribuição de tensões em sistemas de implantes em PEEK como retentores de coroas unitárias em região anterior comparados a sistemas comercialmente disponíveis. Para isso cinco modelos foram criados, variando o material do implante e abutment: titânio (Ti), zircônia (Zr), PEEKp (PEEK puro), PEEKc (PEEK com fibra de carbono), PEEKv (PEEK com fibra de vidro). Os modelos foram montados, e uma carga de 50N a 30º foi aplicada no bordo incisal de forma virtual. A tensão de von Mises (σvM), foi avaliada para pilar, implante e parafuso do pilar, e tensão máxima principal (τmax) e principal mínima (σmin) foram avaliadas para o osso cortical e medular. Os menores valores na σvM no pilar foram observados no grupo PEEKp, sendo 70% menor comparada ao Ti e 74% menor comparada ao Zr. Para o implante a maior redução também ocorreu no grupo PEEKp sendo 68% menor que o Ti e 71% menor que o Zr. No parafuso do pilar houve aumento na tensão de pelo menos 33% no grupo PEEKc em relação ao Ti e de pelo menos 81% no mesmo grupo em relação a Zr. No osso cortical a maior τmax foi encontrada no PEEKp, sendo que houve aumento em todos os grupos PEEK comparados com Ti e Zr. Na σmin os maiores picos foram encontrados no grupo PEEKc. No osso alveolar, todos os grupos PEEK mostraram aumento de pelo menos 7%. Assim, pilares e implantes em PEEKc geram uma distribuição equilibrada de tensões entre si e no osso cortical, possibilitando futuras pesquisas *in vitro* e *in vivo* com este material.

Palavras-chave: Biomecânica, Implantes Dentários, Análise de elementos finitos.

Abstract

Dental implants in titanium and zirconia have a high elastic modulus (EM), favoring the stress shielding phenomenon, peri-implant bone loss by physiologic stimulus absence. Hence, the poly etheretherketone (PEEK) it's an alternative material, already used in areas of medicine by presents an elastic modulus (EM) similar to the bone. The finite element analysis method (AEF) is an effective form of evaluation that allows studying the stress distribution virtually, capable to provide results to *in vitro* and *in vivo* tests. The objective of this study is to evaluate, by FEA, the stress distribution in PEEK implant systems as retainers of single crowns in the anterior region compared to commercially available implant systems. For this, 5 models were created, varying the implant and abutment material: titanium (Ti), zirconia (Zr), PEEKp (pure PEEK), PEEKc (PEEK with carbon fiber), PEEKg (PEEK with glass fiber). The models were assembled, and a load of 50N at 30º was virtually applied to the incisal edge. The von Mises stress (σvM) was evaluated for abutment, implant and screw, and maximum principal stress (τmax) minimum principal stress (σmin) was evaluated for cortical and cancellous bone. The lowest values on abutment σvM was observed in PEEKp group compared to Ti, being 70% lower than Ti and 74% than Zr. On the implants, the major reduction also occurred in PEEKp, being 68% lower than Ti, and a 71% lower than Zr. In the abutment screws, a increase of at least 33% was found in PEEKc compared to Ti, and at least 81% compared to Zr. In the cortical bone the highest τmax values were in the PEEKp group compared to Ti and Zr. For σmin, the highest peak stress was found in the PEEKc. In the cancellous bone, all PEEK group showed increased in stress of at least 7%. Thus, abutments and implants made PEEKc generates the best stress distribution to each other and to the cortical bone.

Keywords: Biomechanics, Dental implant, Finite element analysis

Sumário

1.0 INTRODUÇÃO

Os implantes dentários amplamente utilizados em reabilitações orais tem como principal material o titânio (Ti), devido às suas características como biocompatibilidade, capacidade de osseointegração, e excelente comportamento biomecânico(Tretto et al. 2020; Aljawad 2013). Os componentes protéticos e seus respectivos parafusos de fixação confeccionados em Ti também são fundamentais, pois colaboram para a distribuição das tensões oclusais aos implantes e ao osso(Paula, Silva, and Moreira 2018; Vélez et al. 2020). O alto módulo de elasticidade (ME) do Ti em relação ao do osso, é um inconveniente em situações como fratura do implante por sobrecarga ou perda óssea peri-implantar por falta de estímulo mínimo a essa estrutura(Goiato et al., n.d.; Rahmitasari et al. 2017).

Alternativo ao Ti, os implantes em cerâmica foram sugeridos pela primeira vez em 1960, tendo o óxido de alumínio como primeiro material testado(Rodriguez et al. 2018). Entretanto, foram retirados do mercado devido à biomecânica insatisfatória(Rodriguez et al. 2018). O dióxido de zircônia, contudo, apresenta propriedades biológicas semelhantes ao Ti, e excelente comportamento mecânico em próteses dentárias(Kohal et al. 2004; Grize 2016; N. Cionca 2017). Esse material possui baixa condutividade térmica, alta resistência a flexão, é altamente resistente a fratura e à corrosão além de possuir cor favorável à sua aplicação em áreas estéticas (Kohal et al. 2004; Grize 2016; N. Cionca 2017). A desvantagem, entretanto, reside na deterioração da zircônia na presença de água, levando ao aparecimento de microfissuras que comprometem a sua interação com os tecidos peri-implantares, além de apresentar um alto ME(N. Cionca 2017; Grize 2016).

O ME é uma medida de rigidez/deformação elástica de um material, resultante da razão entre tensão aplicada e a deformação observada nesse material dentro da região elástica(Anusavice, Shen, and H. Ralph 2020). O ME, também conhecido como módulo de Young, é uma variável de extrema importância, uma vez que discrepância muito grande entre o ME do material do implante e do osso resulta no fenômeno chamado “stress shielding”. Este é caracterizado pela concentração da tensão no implante devido ao alto ME dos materiais de fabricação, diminuindo a tensão no osso(Souza et al. 2021; Qin et al. 2021; Brizuela et al. 2019). A ausência de estímulo mínimo no osso dificulta a remodelação e facilita a reabsorção óssea, resultando na redução do nível ósseo peri-implantar(Souza et al. 2021; Qin et al. 2021; Brizuela et al. 2019).

Neste sentido, o PEEK surge como uma alternativa aos materiais já conhecidos. Trata-se de polímero termoplástico de alta performance que foi disponibilizado para comercialização depois de ser comprovada a sua alta performance biológica e mecânica, com alta resistência à degradação *in vivo*(Schwitalla and Mu 2013). Essas características impulsionaram o uso do PEEK na medicina, em reconstrução de calvaria, como material de próteses de quadril e implantes na coluna vertebral, de forma alternativa ao Ti(Schwitalla and Mu 2013; Kurtz and Devine 2007), sobretudo, por apresentar ME próximo ao do osso(Rahmitasari et al. 2017; Yao et al. 2017; Qin et al. 2021). Sua aplicação na odontologia destaca-se pela baixa afinidade ao acúmulo de biofilme, boa capacidade de polimento, resistência a desgaste no meio oral, cor compatível com o dente, além do já citado ME próximo ao do osso(Bathala et al. 2019; Skirbutis et al. 2018; Schwitalla and Mu 2013). Por isso, o PEEK tem sido aplicado em infra estruturas de próteses parciais removíveis, próteses maxilares obturadoras e componentes protéticos em sistemas de implante(Skirbutis et al. 2018). Entretanto não está claro se a maior transferência de tensão causada pelo PEEK beneficia ou prejudica o tecido ósseo alveolar.

Estudos anteriores utilizaram análise de elementos finitos (AEF) como método para avaliar a distribuição de tensões entre implantes e osso adjacente(Fabris et al. 2022; Aljawad 2013). Este método *in sílico* permite transformar estruturas orais complexas como osso cortical e alveolar em elementos menores para avaliar o seu comportamento mecânico, dos implantes e dos componentes protéticos, com alta acurácia(Goiato et al., n.d.; Fabris et al. 2022; Macedo et al. 2017). A análise ocorre simulando aplicação de uma carga pré definida e a partir de funções matemáticas o comportamento do osso/implante/componentes do ponto de vista mecânico frente a essa carga é avaliado(Goiato et al., n.d.). Embora as estruturas orais não sejam homogêneas, isotrópicas, e suas condições de contorno serem limitadas, caracterizando uma limitação metodológica, o AEF é efetivo na avaliação da distribuição da tensão prévia aos testes *in vitro* e *in vivo*(Fabris et al. 2022), não eliminando, contudo, a necessidade de outros testes mecânicos posteriores.

Embora o PEEK seja bem indicado no âmbito da prótese(Schwitalla and Mu 2013; Bathala et al. 2019; Skirbutis et al. 2018), seu potencial para manufatura de implantes ainda precisa ser investigado em comparação ao Ti e à Zr. Um estudo recente encontrou altos picos de tensão na região cervical (~9.0 MPa) ao analisar implantes de Ti e Zr com terços cervicais revestidos em PEEK, submetidos a uma carga vertical de 100N e horizontal de 30N diretamente no pilar(Lee et al. 2012). O estudo considerou a carga como alta para as condições simuladas, podendo causar fratura do implante ou perda óssea. Outro estudo concluiu que implantes de corpo único em PEEK modificado por fibra de carbono as tensões transferidas ao osso são maiores em relação ao Ti e Zr(Fabris et al. 2022), aumentando o estímulo e consequente neoformação óssea. Além disso, em duas revisões sistemáticas recentes avaliaram a osseointegração do PEEK(Najeeb et al. 2016; Alotaibi et al. 2020) foi possível verificar que o material é capaz de promover proliferação e diferenciação celular, angiogênese e outros fatores importantes para a osteocondução. No entanto, mais testes, sobretudo os relacionados a tensão, devem ser executados para avaliar o potencial de osseointegração do PEEK(Najeeb et al. 2016; Alotaibi et al. 2020).

Diante dos achados mais atuais é possível identificar uma lacuna na literatura sobre a distribuição de carga em implantes e componentes em PEEK, especialmente considerando cada elemento do sistema. Nas avaliações *in silico* a simulação o mais próximo da condição clínica é fundamental para prover dados confiáveis, próximos à realidade, capazes de suportar estudos posteriores. Sendo assim, é necessário avaliar o comportamento do PEEK considerando o modelo de coroa dentária, pilar e parafuso separadamente, simulando uma condição clínica e que garante a reversibilidade da reabilitação, comparada ao implante de corpo único, ou até possibilidades protéticas diversas. Além disso, diante das diferenças na qualidade óssea que compõe a maxila(U. Lekholm 1985), é necessário compreender qual magnitude de tensão o PEEK é capaz de promover, de maneira que não induza perda óssea por sobrecarga, ao mesmo tempo que estimule o osso peri-implantar equilibradamente para evitar a perda por stress shielding. Ainda, sabendo-se que altura e diâmetro do implante são importantes para otimizar a cobertura óssea ao redor do mesmo, e resultar em uma melhor distribuição de tensões, é importante avaliar se PEEK, que tem um ME próximo ao osso, é capaz de promover uma tensão equilibrada para alcançar um resultado estético satisfatório, com estrutura peri-implantar preservada.

Dessa forma, esse estudo avaliou, por meio da análise de elementos finitos, a distribuição de tensões no complexo pilar/parafuso do pilar/implante/osso submetidos a uma carga oblíqua (30º) de 50N, na região de incisivo central superior em sistemas de implantes totalmente confeccionados em PEEK puro, PEEK reforçado com fibra de carbono e PEEK reforçado com fibra de vidro.

2.0 ARTIGO

Dental implant and abutment in PEEK: stress assessment in single crown retainers on anterior region

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Abstract

Objective: Stress distribution assessment by finite elements analysis in poly(etheretherketone) (PEEK) implant and abutment as retainers of single crowns in the anterior region.

Materials and Methods: Five 3D models were created, varying implant/abutment manufacturing materials: titanium (Ti), zirconia (Zr), pure PEEK (PEEKp), carbon fiber-reinforced PEEK (PEEKc), glass fiber-reinforced PEEK (PEEKg). A 50N load was applied 30º off-axis at the incisal edge of the upper central incisor. The Von Mises stress (σvM) was evaluated on abutment, implant/screw, and minimum principal stress (σmin) and maximum shear stress (τmax) for cortical and cancellous bone.

Results: The abutment σvM lowest stress was observed in PEEKp group, being 70% lower than Ti and 74% than Zr. On the implant, PEEKp reduced 68% compared to Ti and a 71% to Zr. In the abutment screws, an increase of at least 33% was found in PEEKc compared to Ti, and of at least 81% to Zr. For cortical bone, the highest τmax values were in the PEEKp group, and a slight increase in stress was observed compared to all PEEK groups with Ti and Zr. For σmin, the highest stress was found in the PEEKc. Stress increased at least 7% in cancellous bone for all PEEK groups.

Conclusion: Abutments and implants made by PEEKc concentrate less σvM stress, transmitting greater stress to the cortical and medullary bone.

Clinical relevance: The best stress distribution in PEEKc components may contribute to decreased stress shielding; in vitro and in vivo research is recommended to investigate this.

Keywords: PEEK, Biomechanics, Dental implant, Finite element analysis.

1.0 Introduction

Titanium (Ti) is the main material used to manufacture dental implants, prosthetic components, and abutment screws due to its biocompatibility and excellent biomechanical properties[1,2]. However, the mismatch between Ti and bone elastic modulus (EM) can lead to peri-implant bone loss and implant fracture by overload or "stress-shielding" – a phenomenon that causes crestal bone loss by the absence of mechanical stimulus[3–6]. Zirconia (Zr) implants, alternatives to Ti, have been applied with similar biological properties to Ti, like low thermal conductivity, high flexural resistance, high corrosion resistance, and suitable color for use in aesthetic areas[7,8]. On the other hand, its interaction with peri-implant soft and hard tissues is compromised due to microcracks caused by water exposure, and it also has a higher EM than Ti[7].

Several studies have focused on understanding the properties of dental implant materials and their ability to preserve the alveolar bone[9]. The finite element analysis (FEA) allows an *in silico* evaluation able to give directions to previous in vitro and in vivo studies about its mechanical properties[10]. Alternative materials, such as low EM polymers like poly (etheretherketone) (PEEK)[10], have been studied. This high-performance material has been used in medical areas like traumatology and orthopedics[10]. It is a polymer with excellent biological and mechanical performance and an EM close to the bone[4,11,12]. If used like a polymer matrix, PEEK mixed with carbon fiber (PEEKc) presents a high strength, toughness, and chemical resistance[14]. On the other hand, glass fiber in a PEEK (PEEKg) polymer matrix can improve the tensile strength and tensile modulus by 75%[15]. Thus, to take advantage of these improvements, PEEK has been used in implantology components and prostheses with good results[6, 16]. However, it was not tested as implant material in association with abutments also made in this polymer.

Despite all PEEK potential, few studies have been conducted on applying this material as an implant system, demonstrating that it can generate balanced stress to the bone [9,10]. One study found a higher stress peak (~4000 MPa) simulating oblique load in a one-piece PEEK implant[9]. Another evaluated stress in Ti implants with cervical area coverage in PEEK, finding ~9 Mpa[11]. Although an important finding, it's unclear which sufficiently balanced load can avoid marginal bone loss while containing the stress shielding phenomenon. In addition, any study evaluated stress distribution in two pieces of PEEK implant in the anterior region, in front of its aesthetic challenging an osseous quality - bone type III[17]. Thus, this study aimed to assess by FEA the stress distribution in abutment/abutment screw/implant/bone complex, above 50N oblique load, in upper central incisor in implant systems entirely manufactured in PEEK and its modification.

2.0 Material and Methods

Virtual models of maxillary central incisor zirconia crown, cement layer (70µm), cortical and cancellous bone models were created in computer-aided design (CAD) software (Dassault-Systems

SolidWorks Corp; Waltham, Massachusetts, USA)[14]. The morse taper implant (Ø 4.3mm x 8.5mm) and abutment (Ø 4.5mm x 4mm straight universal abutment) CADs were provided by the manufacture (Unitite Prime, S.I.N. Implant System, São Paulo, São Paulo, Brazil). The incisor crown was virtually cemented in the abutment screwed in a morse taper implant left 2 mm submerged into the bone to the assessments[9,14]. The maxillary bone segment is composed of cancellous bone surrounded by cortical bone with a thickness of 2 mm[9, 15,16]. The force application and bone dimension used in FEA were validated by past literature[17]. The factor evaluated was the abutment and implant manufacturing material, divided into five groups: Ti (control); Zr (control); PEEKp; PEEKc; PEEKg. The detailed description of each component of each group is shown in figure 1[9, 19–21].

After the assembly, the models were exported to finite element software (ANSYS Workbench 15.0; ANSYS Inc; Canonsburg, Pennsylvania, USA) to perform the analysis through numeric calculus. After 5% convergence analysis tolerance, a mesh of 0.8mm tetrahedral elements was defined (Figure 2)[16], and the EM and Poisson's ratio properties entered into the software are described in Table 1[9]. The components were considered homogeneous, isotropic, and linearly elastic[18,19]. Movements in the X, Y, and Z axes were prevented by remaining fixed on the lateral surface of the bone segment in both the cortical and cancellous portions, and interference detection tools were implemented to avoid analysis errors[20]. The contact condition between implant/abutment and implant/screw/abutment were considered “no separation”, and the crown/cement/abutment contacts as bonded.

The simulation was performed using a 30º off-axis [25] 50N static load[26, 27] at the incisal edge of the upper central incisor to simulate a clinical scenario and the physiological masticatory force on the anterior region (Figure 3)[19, 28]. The von Mises stress criteria were evaluated (σvM) for abutment, implant, and screw abutment; minimum principal stress (σmin) and maximum shear stress (τmax) were used for both cortical and cancellous bone[16]. The results of maximum stress values for each studied criterion were quantitatively compared in megapascals (MPa). In addition, qualitative analysis was carried out by color scale, where the highest stress peaks were represented by the warmest color (red) and the absence of stress by the coldest color (blue).

Table 1 – Material mechanical properties.

	Elastic modulus (GPa)	Poisson’s ratio
Titanium grade IV[9]	110	0.33
Zirconia[9]	210	0.3
PEEKp[9]	4.34	0.36
PEEKc[9]	19.7	0.42
PEEKg[9]	10.5	0.35
Cortical bone[9]	13.7	0.3
Cancellous bone[9]	1.37	0.3

(PEEKp) Pure PEEK; (PEEKc) PEEK reinforced with carbon fiber; (PEEKg) PEEK reinforced with glass fiber.

As failure criteria, this study will considerate the tensile strength (in MPa) to Ti grade IV (483), Zr (1.050), PEEKp (115), PEEKc (217), and PEEKg (158)[9]. To the cancellous and cortical bone, the limit considered 1-5 MPa and 100-190MPa respectively[21].

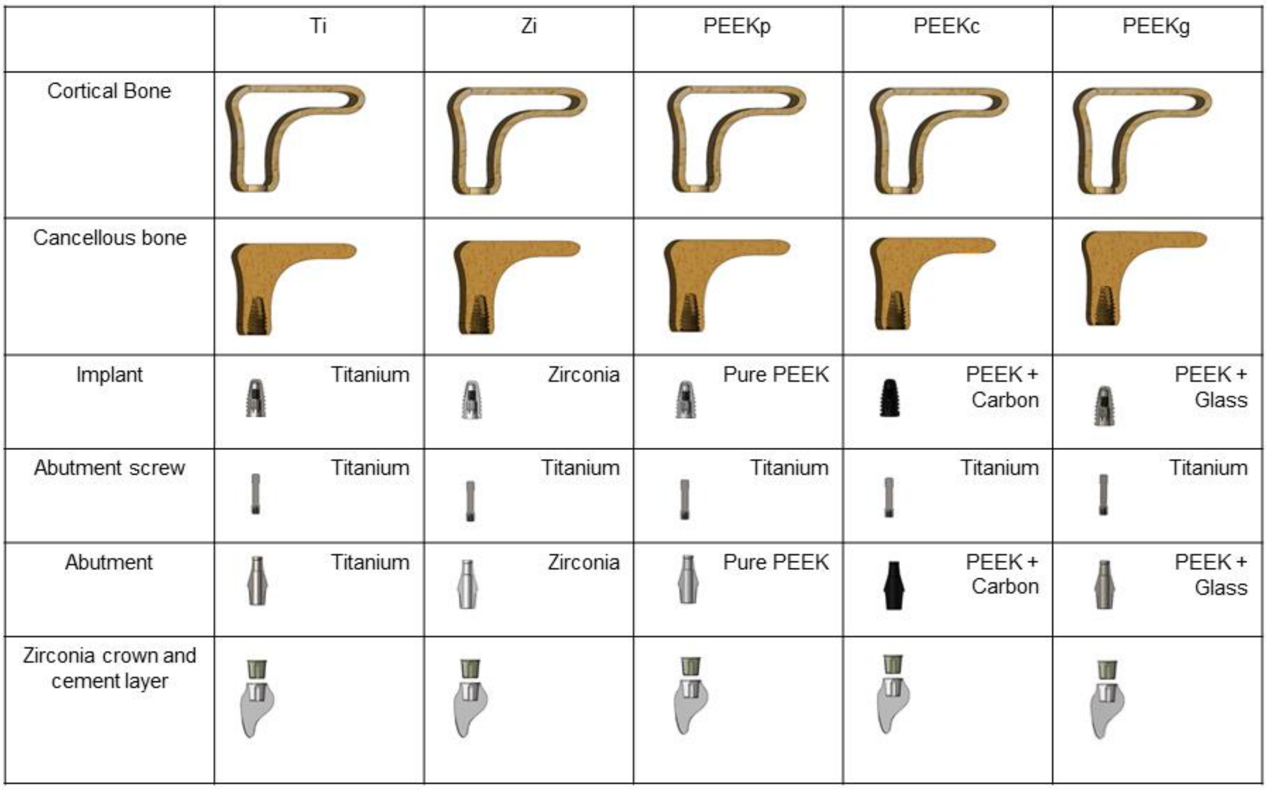

Figure 1. Description of the components of each group studied

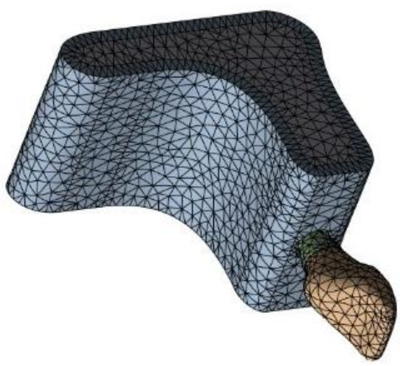

Figure 2. Isometric view of the final model mesh.

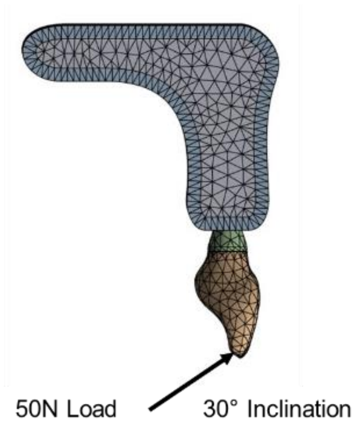

Figure 3. Load (50N) angulation (30º) applied at the lingual incisal edge.

3.0 Results

Results for stress distribution are presented in Tables 2 and 3. The abutment σvM lowest stress values were observed in PEEKp group, being 70% lower than Ti and 74% than Zr. For all groups the maximum peaks were observed in cervical inner portion of the abutment, on the interface with screw abutment, as shown in the figure 4. Meanwhile in the abutment screws, an increase of at least 33% was found in PEEKc compared to Ti, and of at least 81% compared to Zr. In this component, peaks stress was observed in the coronal portion of the screw abutment in the interface with the inner coronal abutment portion (figure 4). Regarding the implant, a 68% reduction was shown in the PEEKp compared to Ti, and a 71% reduction compared to Zr, localized in vestibular face of the coronal portion

The analysis of the cortical bone showed that the highest τmax values were in the PEEKp group, and a slight increase in stress can be observed when comparing all PEEK groups with Ti and Zr. For σmin, the highest stress was found in the PEEKc. Regarding cancellous bone, all PEEK groups showed an increase in stress of at least 7% in the PEEKp compared to Ti (τmax) and of at least 21% in the PEEKc compared to Ti (σmin). The sites of the stress peaks are shown in Figures 4 to 10. In the abutments, the screw joint was found to be the main stress location for all groups on the buccal side (Figure 4). In the screw abutments, the peak of stress was found in its collar for all groups on the opposite side (palatine) (Figure 5). In the implant, the inner cervical region concentrated stress peak for all groups, especially in the first three threads (Figure 6). In cortical bone, localized stress matched the three first threads (Figures 7 and 8); meanwhile, it was observed underneath cortical area in the cancellous bone (Figures 8 and 9).

Table 2: Von-Mises (σvM) (MPa) for abutment, implant and abutment screw and minimum principal (σmin) and maximum shear stress (τmax) (MPa) to cortical and cancellous bone.

	Ti	Zr	PEEKp	PEEKc	PEEKg
Abutment (σvM)	331.76	383.24	100.74	146.39	124.72
Implant (σvM)	299.92	328.94	94.742	188.84	150.31
Screw (σvM)	273.53	200.39	675.3	362.73	533.07
Cortical max (τmax)	10.826	9.5579	14.013	13.851	13.464
Cortical min (σmin)	19.646	18.222	12.977	21.738	18.225
Cancellous max (τmax)	5.5303	5.1701	5.9358	7.1045	6.6206
Cancellous min (σmin)	8.6543	7.906	13.172	10.497	10.93

(Ti) Titanium control group; (Zr) Zirconium control group; (PEEKp) pure poly(etheretherketone); (PEEKc) reinforced carbon fiber poly(etheretherketone); (PEEKg) reinforced fiber glass poly(etheretherketone).

Table 3: Comparison between Ti and Zr control groups and PEEKp, PEEKc e PEEKg (%).

	Ti x PEEKp	Ti x PEEKc	Ti x PEEKg	Zr x PEEKp	Zr x PEEKc	Zr x PEEKg
Abutment (σvM)	(-)70%	(-)56%	(-)62%	(-)74%	(-)62%	(-)67%
Implant (σvM)	(-)68%	(-)37%	(-)50%	(-)71%	(-)43%	(-)54%
Screw (σvM)	147%	33%	95%	237%	81%	166%
Cortical bone (τmax)	29%	28%	24%	47%	45%	41%
Cortical bone (σmin)	(-)34%	11%	(-)7%	(-)29%	19%	0.016%
Cancellous bone (τmax)	7%	28%	20%	15%	37%	28%
Cancellous bone (σmin)	52%	21%	26%	67%	33%	38%

(Zr) Zirconia control group; (PEEKp) pure poly(etheretherketone); (PEEKc) reinforced carbon fiber poly(etheretherketone); (PEEKg) reinforced fiber glass poly(etheretherketone), (-) stress decrease; (σvM) Von-Mises stress; (σmin) minimum principal stress; (τmax) maximum shear stress.

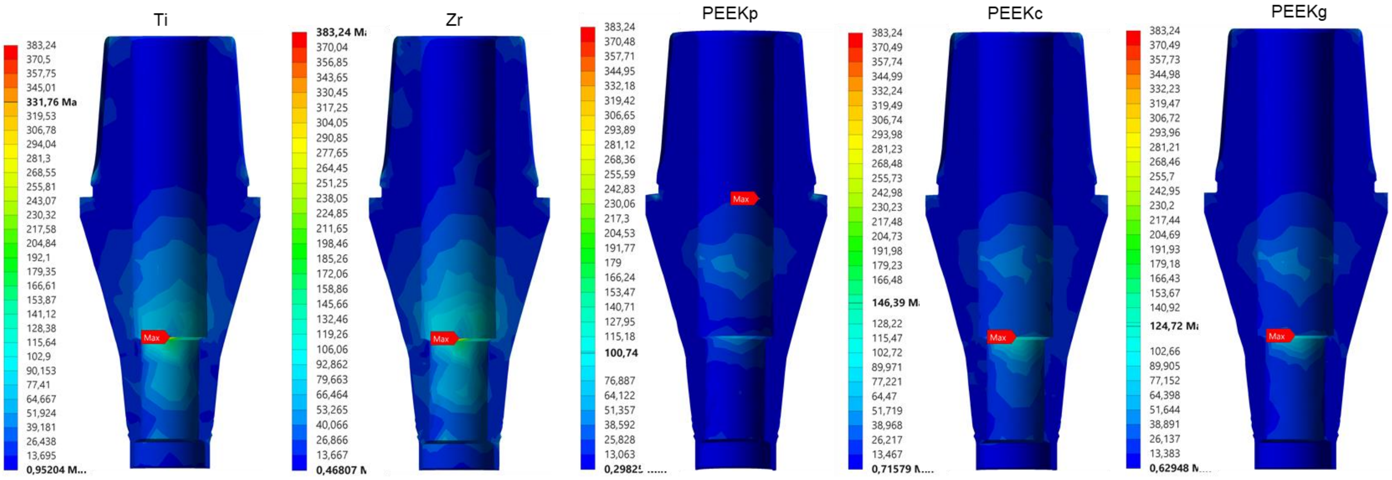

Figure 4. Von-Mises stress (MPa) peak concentration for abutments for all groups**.** Blue to red color represents stress values from lower to higher, respectively. The red flag indicates the stress peak localization.

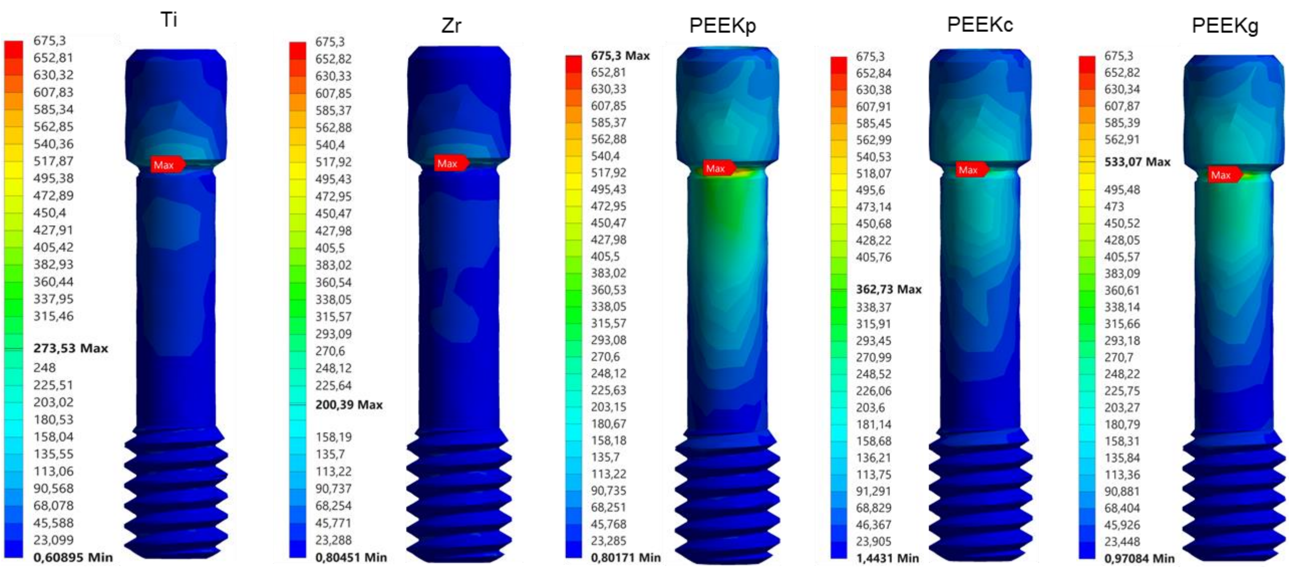

Figure 5. Von-Mises stress (MPa) peak concentration for abutment screws for all groups**.** Blue to red color represents stress values from lower to higher, respectively. The red flag indicates the stress peak localization.

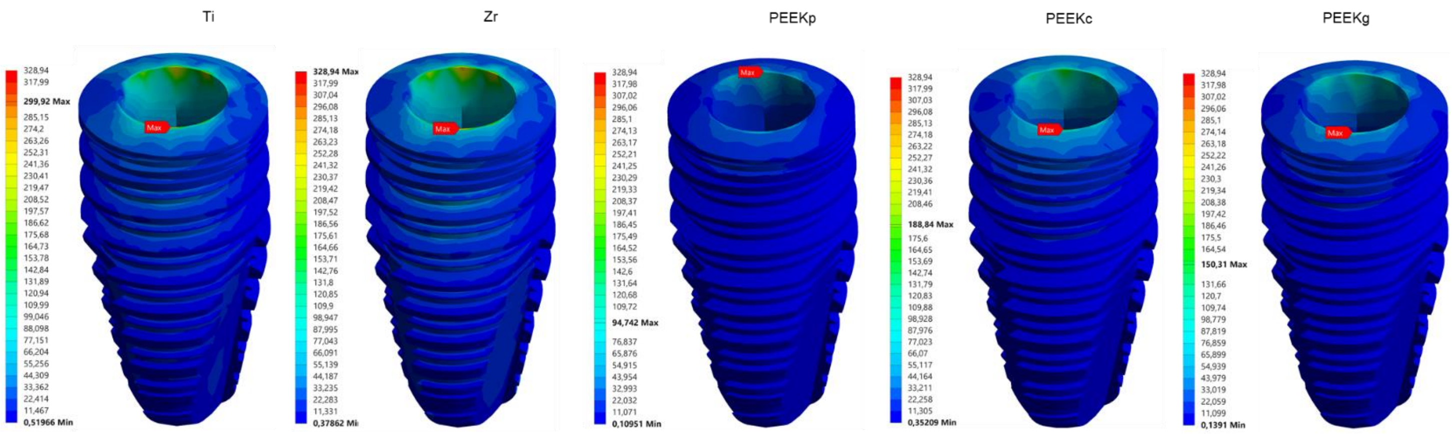

Figure 6. Von-Mises stress (MPa) peak concentration for implants for all groups**.** Blue to red color represents stress values from lower to higher, respectively. The red flag indicates the stress peak localization.

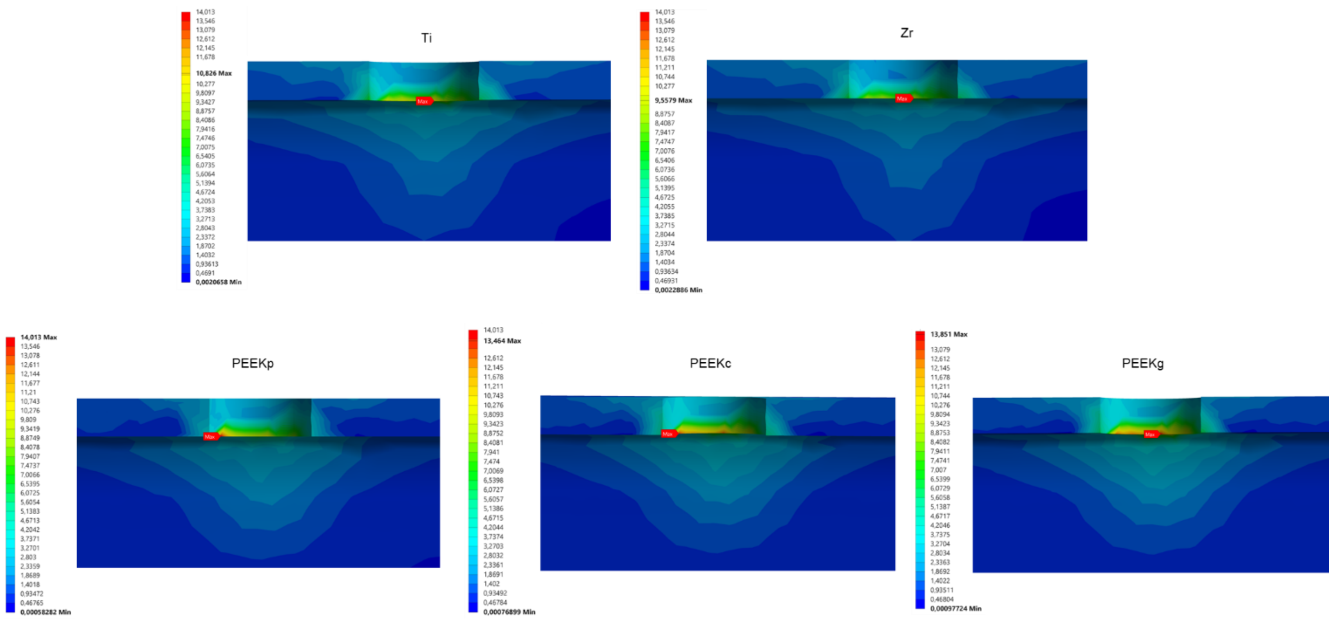

Figure 7. Maximum shear stress (MPa) peak concentration for cortical bone for all groups. Blue to red color represents stress values from lower to higher, respectively. The red flag indicates the stress peak localization.

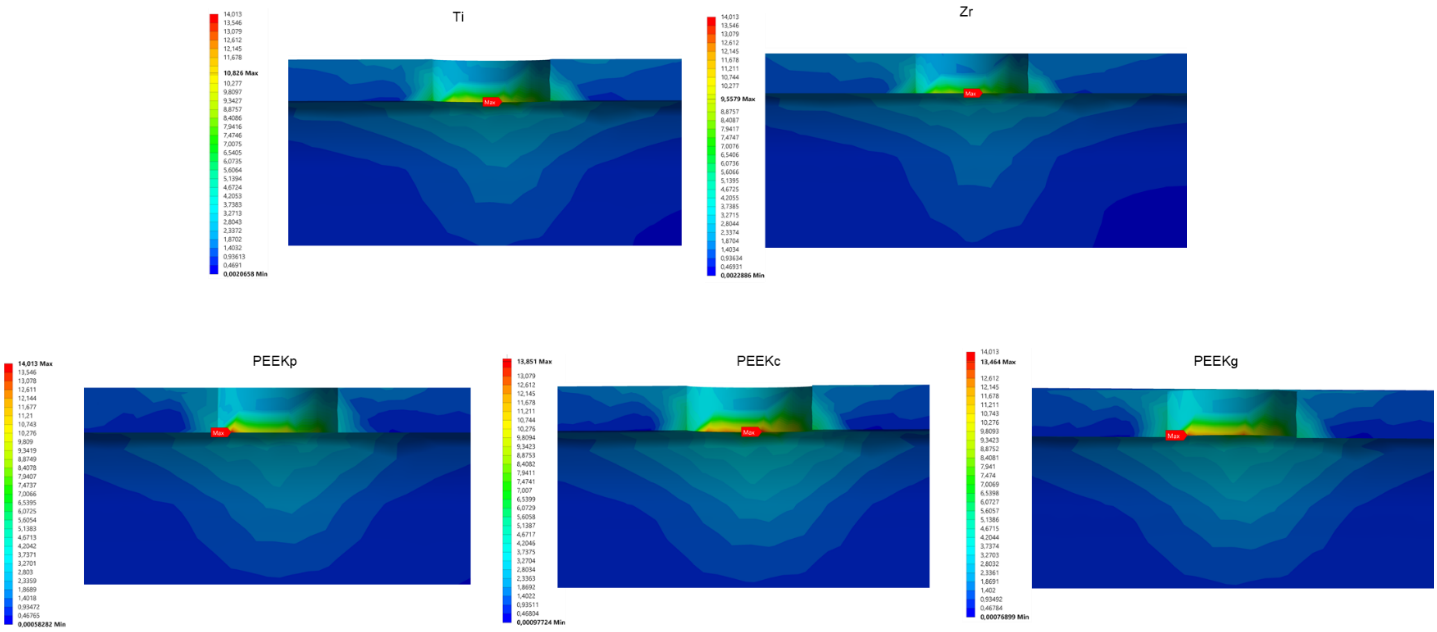

Figure 8. Minimum principal (MPa) peak stress concentration for cortical bone for all groups. Blue to red color represents stress values from higher to lower, respectively. The red flag indicates the stress peak localization.

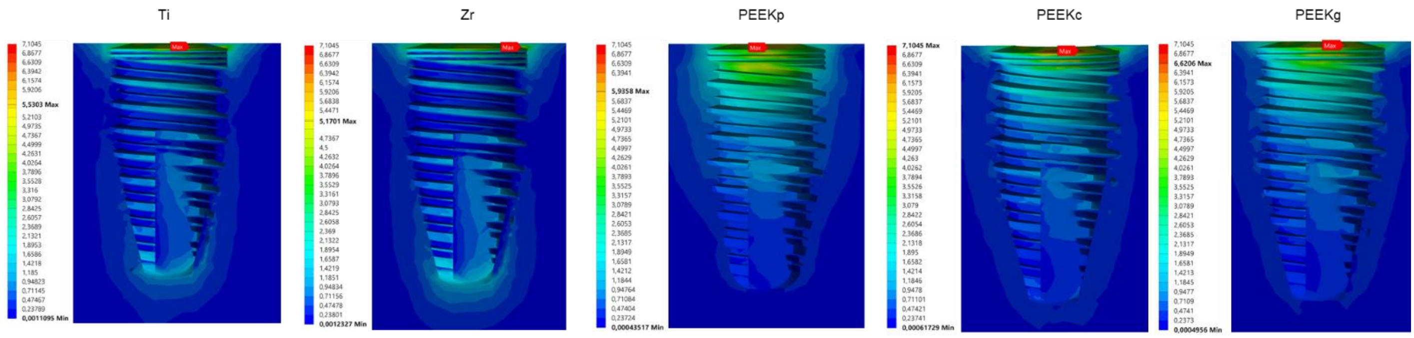

Figure 9. Maximum principal stress (MPa) peak concentration for cortical bone for all groups. Blue to red color represents stress values from lower to higher, respectively. The red flag indicates the stress peak localization.

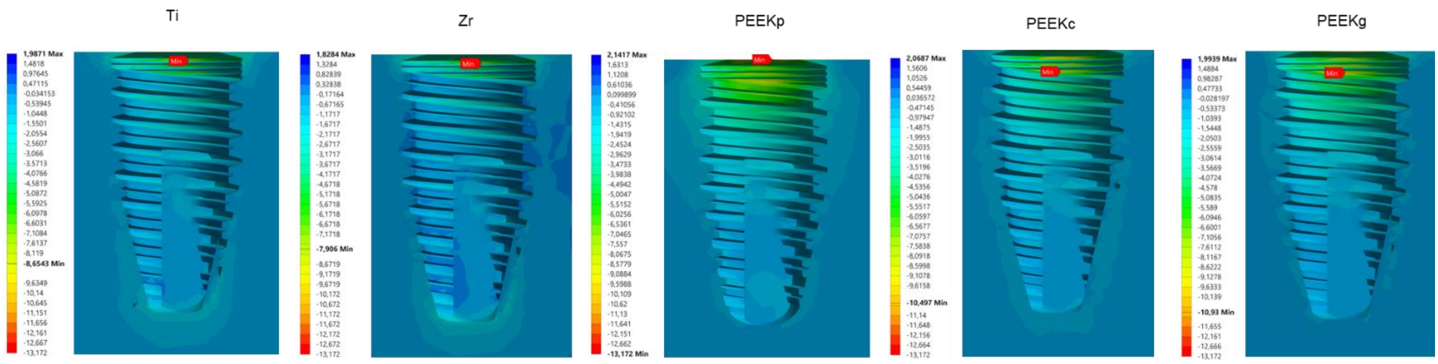

Figure 10. Minimum principal stress (MPa) peak concentration for cancellous bone for all groups. Blue to red color represents stress values from higher to lower, respectively.

4.0 Discussion

PEEK is a potential polymer for implant material manufacturing due to its biological and mechanical properties[21,22]. Thus, this study assessed stress distribution by FEA in PEEK implant systems and its modifications and observed that all PEEK groups showed a stress reduction in abutment and implant, with PEEKc suggesting a better biomechanical behavior. These results demonstrate a promising behavior of PEEK when used for implant-supported rehabilitations, thus demonstrating that it is a potential alternative material for implants and abutments.

All PEEK groups showed a stress reduction in the abutment. The stress location was observed primarily in the screw joint portion for all groups. A previous study evaluating PEEKc implant and solid abutment in the posterior region submitted to oblique (30º) 100N load also found better stress distribution in PEEK abutments (69.41 MPa)[23]. However, the present study is a novelty because it assessed PEEK implants in a specific load and direction in the anterior region with a universal abutment with an abutment screw. This condition simulates a clinical situation, offering various prosthetic options for reversible rehabilitation instead of a one-piece implant[26, 27].

On the other hand, another previous study that evaluated an 100N axial load in the upper incisor, found an extremely high-stress peak (927 MPa) in one-piece implant made in PEEKc[9]. However, in the present study a balanced stress peak reduction in this component was found. This difference may be explained due to presence of the screw abutment, being a critical component to improving the stress distribution. It provides clamping forces between the components and consequently improve stress distribution in the complex[33]. Finally, regarding localization of the stress peaks observed between cervical internal portion of the abutment and in the coronal portion of the abutment screw, even changing abutment manufacturing material, the results agree with previous studies that found the same site[14,25]. Thus, in front of a significant stress decrease, it can mean a reduction in abutment/abutment screw loosening/fracture, the most common complaint [24]. In addition, the peaks found in this study were below their failure limit (especially PEEKc – 217MPa)[33].

Among all components in the PEEK groups, the highest peak stress was concentrated on the collar level of the abutment screw, which is manufactured in Ti. The stress peaks were higher (at least 80%) than the Ti control except for the PEEKc group, which was only 33% higher than this. In addition, the latter was the only group that fell below the Ti failure limit, representing 75% of this limit. A systematic review shows that 75% is the limit maximum to avoid deformation/fracture[26]. Thus, it is possible to affirm that the abutment screw manufactured in PEEKp and PEEKg can suffer fracture or deformation. The most common mechanical failure is pre-load loss or fracture in these components, as related to current studies[24,27], as it is one of the items responsible for creating clamping force, which keeps the complex tightened together[24]. When solid abutments or one-piece implant are used all components should be replaced in case of fracture. To solve these problems and take advantage of PEEKc strategies like different materials from crowns to make a better stress distribution in implant prosthetic components[25] or also screw design modification[28] can be used to improve stress relationships in the complex. A systematic review categorized yet type of connection, use of friction abutments or anti-vibration components in the threads as ways of reducing screw abutment problems[26]. Therefore, the PEEKc presents better results, enabling more *in vitro* and *in silico* studies with this reinforced as an alternative to implant system manufacture.

Meanwhile, this study's findings demonstrated a stress reduction in the PEEK implant groups compared to the control groups. According to recent studies, materials with low EM commonly show less deformation than those with high EM, representing a risk of fracture reduction[1]. Especially in PEEKc, which reduced stress by 37% compared to Ti, peak stress is 87% below its failure limit (217 MPa). In addition, as highlighted by Tretto et. al. (2020), only internal conical connections (morse taper) can support the stress from masticatory load[1]. In this view, the association between conical connections and a manufacturing material with low EM can result in proper stress distribution in the abutment complex, avoiding fracture.

Regarding cortical bone, all test groups demonstrate a slight τmax stress increase. In recent studies, high stress was observed in this region using PEEK as implant material, even in different designs, abutment materials, or load conditions, than in the present study[1,23]. In one of them, PEEKc implants showed τmax 57.53 and σmin 177.58 MPa on cortical bone[23]. Another one assessed PEEK abutments in Ti implants and found τmax 483 MPa[1]. The authors considered these results higher than bone limit (34.72 MPa) meaning bone loss by overload[1]. None of the test groups in the present study exceeded the cortical bone limit, even increasing peak stress. The effects of excessive or absence of peri-implant bone stress stimulus are not entirely clear in the literature. According to some authors, the lack of stress stimulus caused by rigid material (high EM) can lead to resorption by the stress-shielding phenomenon[7]. On the other hand, overload caused by less rigid material (low EM) can lead to marginal bone loss by excessive stress concentration[29]. The increase observed in the results may represent a balanced stress stimulus, as Fabris et al. (2019) concluded. They found that PEEKc can concentrate a balanced stimulus in one-piece implant and can maintain bone crestal peri-implant[9].

Previous studies showed that materials with high EM suffer more deformation and transfer more stress to adjacent structures[29]. On the other hand, low EM can create a mechanical environment that can form bone on a suitable load[30]. Recent studies found high-stress concentration on peri-implant bone using PEEK implant[1,23,31]. The direction or magnitude of the load (100N and axial) used by these authors is the main point of such high values. In this study, on 30º oblique 50N load, the stress peak achieved 7% of σmin reduction on PEEKg. In addition, especially in the PEEKc group, τmax and σmin increase was less than 30% in both cortical and cancellous bone. Considering this sensible difference, our results can base future *in vitro* and *in vivo* studies to confirm PEEK as an implant manufacturing material, in agreement with Carpenter et al (2018)[30].

The FEA method enables the assessment of stress distribution patterns in oral structures, which can be used to preview in vitro and clinical stages[9,25]. However, there are limitations regarding elastic linearity, isotropism, and homogeneity of biological structures or limited boundary conditions, and should be interpreted with caution since it is a preliminary research [10,16]. Despite that, this study's results highlight the innovative properties of PEEK materials and their potential impact on implant research. The stress values found in all PEEKc components were within their failure limit and lower than the ones found in the control groups. Thus, it suggests PEEKc is a potential candidate for manufacturing implant systems, but since is a dark-colored material, it is still a question to be solved. Hence, this study is valuable for guiding future *in vitro* and *in vivo* research to confirm its use as a material for implant systems.

5.0 Conclusion

Our findings suggest that abutments and implants made by PEEKc may generate the best stress distribution to each other and the cortical bone, enabling future *in vitro* and *in vivo* research with this material. However, its dark color remains an aesthetic limitation.

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3.0 CONCLUSÃO GERAL

Com base nos achados desse estudo, é possível concluir que pilares e implantes confeccionados em PEEKc geram a melhor distribuição de tensões entre si e com o osso cortical. Entretanto, a cor preta permanece sendo uma limitação estética.

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ANEXO 1 - COMPROVANTE DE SUBMISSÃO

Clinical Oral Investigations - Receipt of Manuscript 'Dental implant and...' Caixa de entrada ×

Clinical Oral Investigations <boygeorge.miranda@springernature.com> qua., 21 de fev., 13:58 (há 12 dias)

para mim

Ref: Submission ID b233da94-7e35-4a94-adc5-75322525eb54

Dear Dr Rocha de Almeida,

Please note that you are listed as a co-author on the manuscript "Dental implant and abutment in PEEK: stress assessment in single crown retainers on anterior region", which was submitted to Clinical Oral Investigations on 21 February 2024 UTC.

If you have any queries related to this manuscript please contact the corresponding author, who is solely responsible for communicating with the journal.

Kind regards,

Editorial Assistant
Clinical Oral Investigations

Responder Encaminhar

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