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Carbon Fiber-reinforced PEEK for dental implant and abutment: A scoping review on the finite element method.

Sofia dos Santos Pinho

Dissertação conducente ao Grau de Mestre em
Medicina Dentária (Ciclo Integrado)

Gandra, 26 de Setembro de 2020

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Trabalho realizado sob a Orientação do Prof. Doutor Júlio C. M. Souza e Prof. Doutora Maria do Pranto Braz

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Gandra, 28 de Julho de 2020

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O Orientador

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RESUMO

O objetivo do presente estudo foi efetuar uma revisão sistemática integrativa sobre a distribuição de tensões através da análise de elementos finitos em implantes e pilares dentários compostos por PEEK. Uma pesquisa eletrónica foi realizada nas bases de dados PUBMED e ScienceDirect com os seguintes termos de pesquisa: PEEK, Polyetheretherketone, Finite element, Stress, Dental implant, abutment. Os resultados revelaram as propriedades mecânicas e a distribuição de tensão dos implantes e pilares compostos por PEEK e os seus compósitos reforçados com fibras. Puro PEEK revelou baixos valores de módulo elástico e de força que afetam negativamente a distribuição de tensão através do pilar e do implante no tecido ósseo. A incorporação de 30% de fibras de carbono aumentou o módulo elástico e a resistência, embora alguns estudos não refiram diferenças significativas na magnitude da tensão quando comparada com o PEEK puro. No entanto, um aumento das fibras curtas de carbono para 60% revelaram uma melhoria na distribuição de tensão dos implantes no tecido ósseo. A utilização de PEEK laminados em estruturas de núcleo de titânio também podem ser uma estratégia para controlar a distribuição de tensões na interface implante-osso. Assim, a rigidez e resistência dos implantes e pilares compostos por compósitos PEEK podem ser aumentadas através da incorporação de fibras curtas de carbono. Assim, o conteúdo, forma, dimensões e composição química das fibras são fatores chave para melhorar a distribuição de tensões através de pilares e implantes compostos por compósitos PEEK.

PALAVRAS-CHAVE

PEEK; Polyetheretherketone; Finite element; Stress; Dental implant; abutment.

ABSTRACT

The aim of the present study was to perform an integrative systematic review on the stress distribution assessed by finite element analysis on dental implants and abutments composed of PEEK-composites. An electronic and structural search was performed on PUBMED and ScienceDirect using a combination with the following search terms: PEEK, Polyetheretherketone, FEA, FEM, Finite element, Stress, Dental implant and Dental abutment. The findings reported mechanical properties and the stress distribution implant and abutment structure composed by PEEK and its fiber-reinforced composites. Unfilled PEEK reveals low values elastic modulus and strength that negatively affect the stress distribution through the abutment and implant to the bone tissue. The incorporation of 30% carbon fibers increases the elastic modulus and strength although some studies report no statistic differences in stress magnitude when compared to unfilled PEEK. However, an increase in short carbon fibers to 60% revealed an enhancement on the stress distribution through abutment and implants to the bone tissue. The use PEEK laminates onto titanium core structures can also be a strategy to control the stress distribution at the implant-to-bone interface.

The stiffness and strength of implant and abutment composed of PEEK-matrix composites can be increased by the incorporation of short carbon fibers. Thus, the content, shape, dimensions, and chemical composition of fibers are key factors to improve the stress distribution through abutment and implants composed of PEEK-matrix composites.

KEYWORDS

PEEK; Polyetheretherketone; Finite element; Stress; Dental implant; abutment.

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1. INTRODUTION

The selection of materials for dental implants and abutments is dependent on the mechanical properties of materials such as strength, elastic modulus, corrosion resistance, and biocompatibility. Commercially pure titanium (cp Ti) is commonly used to manufacturer dental implants while abutment can be produced from titanium alloys (e.g. Ti6Al4V) (1–8) . Zirconia also has gathered attention in the manufacturing of dental implants and prosthetics (9,10). The major reason to use titanium and its alloys is determined by their physicochemical properties and biocompatibility(4,6). Nevertheless, the elastic modulus of titanium- and zirconia-based materials is significantly higher than those of bone tissues.(9,10) That leads to a mismatch of mechanical properties among the materials leading to stress concentrations at the implant connections and the implant-to-bone interface(11,12). Regardless the type of connection, micro-gaps can occur at implant-abutment connections that are susceptible to the accumulation of oral fluids, glycoproteins, and microorganisms (11-13). Additionally, the implant system shows micro movements during occlusal loading that can lead to friction and wear of the implant-abutment surfaces(12,13).

The mismatch in elastic modulus values between zirconia (E~240 GPa) or cp Ti (E~110 GPa) and bone tissue (E~10-20 GPa) can also result in stress shielding at the peri-implant bone(9-10). Consequently, the soft and hard tissue biological dimensions are altered since the tissue arrangements naturally denote hard tissue remodeling around the implant(9-10). Also, the mechanical behavior the over-all implant-supported prostheses and aesthetic outcomes are affected by the bone volume loss(11-13). In this way, oblique and lateral loading take place since the bone support was decreased that leads to an increase in stresses on the structural materials and surrounding bone tissue(11-12). Thus, the stress-shielding effect have been reported by previous studies regarding the use of titanium o zirconia implant materials and therefore alternative materials has been studied such as poly-ether-ether-ketone (PEEK) and its composites(2-9,14,18,24). PEEK is a thermoplastic polymer with excellent mechanical properties, biocompatibility, and low density (1.31 g/cm) resembling human bone(15-17,19-22). PEEK has a low Young's elastic modulus (~3-4 GPa), which is closer to that recorded on bone tissue, in combination with a flexural strength of around

90-100 MPa(2-9,15-22). In fact, such mechanical properties are not enough to guarantee a long-term mechanical performance as a dental implant or abutment (15-17). Notwithstanding, the incorporation of fillers into the PEEK matrix has resulted in PEEK-matrix composites with enhanced mechanical properties.(16-17). Carbon fiber-reinforced PEEK (CFR-PEEK) is a promising candidate to replace metallic materials because of the inherited advantages of PEEK and carbon short fibers.(15-17) .PEEK reinforced with 30% carbon fibers has an elastic modulus close to the cortical bone (16-18 GPa)(15-17). Therefore, the mechanical properties of PEEK-matrix composites can be controlled by the content, dimensions, and orientation of the fillers (1-8,14-18,24).

The development of novel implant, abutment, and prosthetic materials follows the standard *in vitro* and *in vivo* assays prior to the industrial manufacturing(12,23).

The *in vivo* assessment of a high number of samples in this field might be time-consuming with further discomfort to animals or patients (12,23). In addition, the *bias* related to the *in vivo* assessment could bring inconclusive findings in the case of failures in manufacturing materials as well as on the experimental achievements(12,23). In this way, the use of finite element analysis (FEM) can predict mechanical issues via theoretical models in association with experimental assays(12,23). The dental implant design, bone tissue, and prosthetic structures can be successful modeled by FEM for analysis (FEA) of their mechanical behavior by mimicking clinical conditions(1-4,6-8,14,18,24).FEA predict the magnitude of stress distribution through implants, abutment, prosthetics, and surrounding bone under mastication loading(12,23). Alternative *in vivo* study in this field would be time-consuming with further discomfort to animals or patients (12,23).

The aim of this study was to perform an integrative systematic review on the stress distribution through dental implants and abutments composed of PEEK-composites by finite element method studies. It was hypothesized that the implants and abutments composed of CFR-PEEK can improve the stress distribution through the prosthetic and implant structures towards to the bone.

2. METHODS

A literature search on PUBMED and ScienceDirect was conducted using the following search terms: “PEEK” OR “Polyetheretherketone” AND“FEA” OR “FEM” OR “Finite element” OR “Stress” AND “Dental implant” OR “abutment”. The inclusion criteria encompassed articles published in English language from 2009 up to 2020. The eligibility inclusion criteria used for article searches also involved meta-analyses, randomized controlled trials and prospective cohort studies.

The selection of articles was dependent on the data regarding the biomechanical analyses of dental implant or abutment composed of unfilled PEEK and carbon fiber-reinforced PEEK. The total of articles was compiled for each combination of key terms and therefore the duplicates were removed using Mendeley citation manager. Two of the authors (JCMS, SP) independently analyzed the titles and abstracts of potentially relevant articles. A preliminary evaluation of the abstracts was carried out to establish whether the articles met the purpose of the study. Selected articles were then independently read and analyzed concerning the purpose of this study. The following variables were retrieved for this review: author name, journal, publication year, purpose, finite element modeling (FEM), finite element Analysis (FEA), materials properties, implant and abutment type and outcomes.

3. RESULTS

The literature search identified a total of 74 articles on PubMed and 127 articles on ScienceDirect. After reading the titles and abstracts of the articles, four were excluded because they did not meet the inclusion criteria. The remaining 13 potentially relevant studies were then evaluated. Of those studies, two were excluded because they did not provide comprehensive data for the outcomes criteria. Resulting in 11 selected articles, as shown in Figure 1.

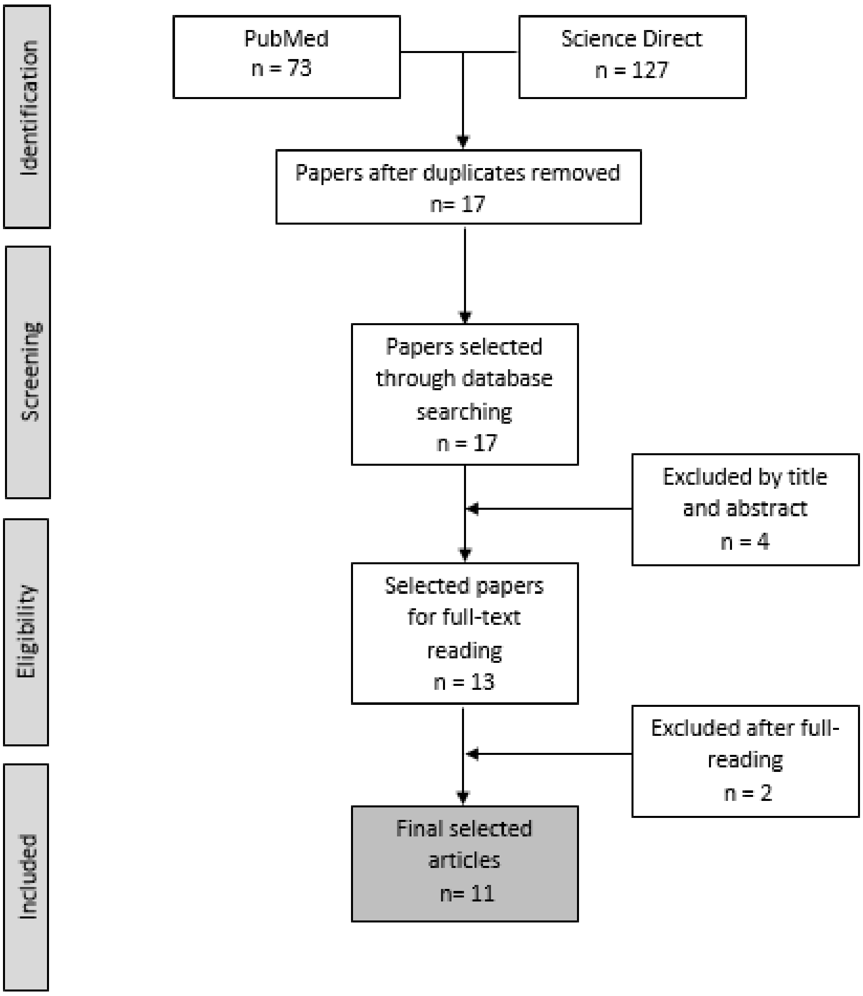

Figure 1. Flow diagram of the search strategy used in this study.

The eleven articles selected for this review were published between the years 2009 and 2019(1-8,14,18,24). Of the 11 studies selected, nine studies assessed the mechanical behavior of implants or abutments by using a tree-dimensional finite element method (1-4,6-8,14,18,24), while 1 study applied aging/loading procedure and scanning electron microscopy (SEM) (5).

The mechanical effect of implant and abutments properties was evaluated by building different model types concerning clinical situations (1-4,6-8,14,18,24). The tree-dimensional section of bone was constructed from a computer tomography scan (CT), and then imported into a software, namely, Rhionoceros, Ansys, Abaqus, Solid Works, CAD/CAM and Creo Parametric (1-4,6-8,14,18,24). Most of finite element analyses (FEA) was reported in the selected studies by using ANSYS software (1-3,6,8,24). Data from FEA was recorded on von Mises stresses, contact stress and shear stress (1-4,6-8,14,18,24).

The main outcomes from the selected are given in Table 1 and briefly described as follows:

- Regarding the Young's modulus of the different materials, pure PEEK ranged from 3 to 4 GPa, the 30% carbon fiber reinforced PEEK was 18 GPa, 60% parallel oriented endless CFR-PEEK was 150 GPa, Glass Fiber Reinforced-PEEK between 12 to 13 GPa, cortical bone ranged from 13 to 18 GPa, Ti6Al4V was equal to 110-115 GPa, a poly-methyl methacrylate with solid surface PMMA was 3 GPa and the FRC with solid surface was equal to 15 GPa(1-8,14,18,24).
- Concerning the peri-implant region, stresses were concentrated in the cortical bone decreasing towards to the cancellous bone on axial or oblique loading (1,3,4,6,8). However, higher stresses were recorded on both cortical and cancellous bone on oblique loading (1,3,4,6,8).
- Von Mises stresses decreased in 50 to 70% at the peri-implant bone by adding a micro thread onto the implant (3). In this case, the titanium implant with micro threads showed the lowest stress values of about 10 MPa at the cortical bone in comparison with 30% CFR-PEEK implant. Standard implants distributed significantly higher stresses at around 100 MPa on cortical bone (3).
- The PEEK abutments provided less stress on the abutment by transmitting the stress to implant and screw. Using PEEK as a crown material decreased the stress on the abutment made of titanium and increased the stress concentration in restorative crowns (2,4). On axial and oblique loading, von Mises stresses were observed to be much higher on PEEK abutments than those recorded on titanium abutments (2,4).

- Coating dental implants and abutments with PEEK reduced the stress shielding effects (7). However, PEEK veneering thickness play a key role on the stress distribution and strength of hybrid abutments or implants (24).
- On axial and oblique loading, von Mises stresses were higher on PEEK abutments than those recorded on titanium abutments (2,4). PEEK reinforced with 30% carbon fiber implants and abutment showed a higher stiffness than unfilled PEEK that improves stress distribution through the abutment and implant structures (8). Studies reported controversial von Mises stresses and deformation when comparing PEEK-matrix composites and titanium structures (1,6).
- In the case of glass-fiber reinforced composite implant with porous surface (FRC) distributed the shear stress over the bone-implant more uniformly than poly-methyl methacrylate with solid surface (PMMA) implants. The shear force of the FRC-bone interface was higher than the shear forces of the PMMA solid interface (18).

Author (year)	Purpose	Finite element modeling (FEM)	Implant and abutment type and properties	Finite element Analysis (FEA)	Main outcomes
Bataineh et al., (2019)[1]	Evaluation of the effect of carbon fiber-reinforced PEEK composite for implant /abutment on stress distribution in peri- implant bone.	*Modeling software*: SolidWorks *3D model:* of first mandibular molar segment and crown by computer tomography (CT).	*5 model:* A) Ti 6Al4V implant and abutment B) Ti 6Al4V implant and 30% CFR-PEEK abutment C) 30% CFR-PEEK implant and ti6Al4V abutment D) 30% CRF-PEEK implant and abutment E) Ti 6Al4V implant and LD abutment *Young Modulus (GPa):* Ti- 110; 30% CFR-PEEK- 18; Zinc phosphatase cement- 14; LD- 96; Cortical bone- 17.8; Cancellous bone- 1.148;	*Computer Simulation:* ANSYS *Mesh resolution:* 3.875.423 tetrahedral elements *Forces:* 13.45 N, 100 N, and -36.5 N in a lingual, an axial, oblique direction	*von Mises stress (MPa) at implant/ abutment / cortical bone:* A)178.3 / 184.5 / 33.63; B) 159.73 / 192.61 / 33.66; C) 67.26 / 261.05 /33.5; D) 99.78 / 168.09 / 33.49; E) 64.46 / 131.67 / 33.59.

Tekin et al., (2019)[2]	Comparison of stress occurring in the peri-implant bones, implants, crowns, abutments, and screws after loading through finite element analysis by using the PEEK materials.	*Modeling software:* Rhionoceros *3D model:* of maxilla by computer tomography (CT);	4 models (Implants / abutment / screws): A) Titanium / Titanium / Metal substructure (Cr-Co), Porcelain B) Titanium/ Titanium / PEEK C) Titanium / PEEK /Metal substructure, (Cr-Co) Porcelain D) Titanium / PEEK / PEEK *Elastic modulus (GPa*): Cortical bone - 13,7 PEEK - 4,10 Ti - 110 Porcelain - 82,8	*Computer simulation:* ANSYS *Mesh resolution:* 48,900 nodes and 224,145 tetrahedral elements; *Forces:* 178 N at 45° oblique direction.	*von Mises stress (MPa) at implant/ abutment /cortical bone/ crown / screws:* A) 210.64 / 284.12 / 61.162 / 33.663 / 63.259 B) 210.46 / 279.23 / 62.196 / 10.867 / 60.953 C) 233.07/ 249.38 / 61.154 / 81.544 / 380.74 D) 233.96 / 248.38 / 61.51 / 45.876 / 393.59
Wazeh et al., (2018)[3]	Evaluation of the effect of dental implant threading and material selection on the mandibular bone under two different prosthetic materials.	*Modeling software.* CAD-CAM *3D model:* implant with micro thread BTICV3 and implant Zimmer	*Models:* 2 crown materials: Translucent zirconia and Porcelain fused to metal, combined with 3 implant materials: Titanium, 50% GFR-PEEK, and 30% CFR-PEEK *Elastic modulus (GPa):* Translucent Zirconia crown (TZI) - 210 Porcelain fused to metal crown-149.5 PEKK implant (50% GFR-PEKK) -14.0 PEEK implant (30% CFR-PEEK) -18.3 Titanium Implant -110 Cortical bone -13.7	*Computer Simulation:* ANSYS *Mesh resolution:* total of 505.373 tetrahedral elements *Forces:* Axial on 100 N and 50N at 45° oblique direction	*von Mises Stress (MPa) at BTCV3 and Zimmer - axial force:* Ti implant- 13 to 14 (average) / 68 to 75 (max); 30% CFR-PEEK implant - 16 to 14 (max) / 55 to 53 (average); 50% GFR-PEKK implant - 14 to 15 (average) / 52 to 54 (max). *von Mises stress (MPa) at BTCV3 and Zimmer – oblique force:* Ti implant- 70 to 75 (average) / 130 to 155 (max);

					30% CFR-PEEK implant - 80 to 90 (average) / 190 to 200 (max); 50% GFR-PEKK implant - 70 to 75 (max) / 180 to 190 (average).
Kaleli et al., (2018)[4]	Evaluation of biomechanical behaviors of resin-matrix ceramics and PEEK customized abutments in terms of stress distribution in implant-bone.	*Modeling software:* Rhionoceros *3D model:* of 15 tooth;	*6 Models*:* A) IPS-PEEK B) IPS-Zirconia C) TZI-PEEK D) TZI-Zirconia E) VTE-PEEK F) VTE-Zirconia *Elastic modulus (GPa):* Cortical bone - 13.7; Cancellous bone - 1.37; Titanium implant - 110; Titanium base abutment - 110; Zirconia customized abutment- 210; PEEK customized abutment - 3.5; Polymer infiltrated hybrid ceramic- 30; Zirconia - 210.	*Computer simulation:* ALGOR *Mesh resolution:* 52.451 nodes and 207.931 tetrahedral elements *Forces:* 200N axial direction and 100 N oblique direction (30°)	*von Mises stress (MPa) under axial force at costum-abutment/ titanium abutment / Implant:* A) 20 / 107 / 105 B) 40 / 85 / 110 C) 25 / 105 / 104 D) 40 / 85 / 105 E) 20 / 106 / 105 F) 95 / 85 / 106 *von Mises stress (MPa) under oblique force at costum-abutment/ titanium abutment / Implant:* *A) 25 / 320 / 405* *B) 100 / 318 / 410* *C) 25 / 320 / 405* *D) 100 / 318 / 410* *E) 24 / 320 / 405* *F) 100 / 318 / 410*

Gallagher et al., (2018)[14]	Evaluation of mechanical behavior and failure of a unidirectional carbon fibre reinforced PEEK material, PEEK-OPTIMA™ Ultra-Reinforced.	*Modeling software:* ABAQUS; *3D model:* Femur.	*Models:* PEEK-OPTIMA Ultra (CFR-PEEK) laminates; 0° and 90° laminates; Modulus (GPa) / Strength (MPa)- 0°: 183 / 1625 90°: 11 / 108	*Computer simulation:* ABAQUS Tensile tests are performed on 0° and 90° laminates;	*Tensile failure of 0° laminates:* Longitudinal tensile strength of 2765.14 ± 274.98 MPa; *Tensile failure of 90° laminates:* Transverse tensile strength of 49.60 ± 3.95 MPa;
Spies et al., (2018)[5]	Investigated the long-term stability of a metal-free zirconia two-piece implant assembled with a carbon fiber-reinforced (CRF) screw for implant-abutment connection.	*Modeling software:* NR *3D model: NR*	*Models:* 3 different two-piece implants: A) Zirconia (Zr); B) Titanium grade 4 (Ti); C) Titanium grade 4 and titanium-zirconium alloy (TiZr); All models had CFR PEEK abutment screws; Elastic modulus (GPa): NR	*Computer simulation:* NR *Mesh resolution:* NR *Forces: NR*	*Dynamic loading test:* *Force* - 98N *Fracture analysis:* A) 838 N B) 986 N C) 963 N None of CRF abutment screws fractured.
Sampaio et al., (2016)[24]	Investigated the influence of PEEK thickness on the friction	*Modeling software:* ANSYS; *3D model:* Ti6Al4V and PEEK cylinders;	*Models:* PEEK veneer thicknesses (0.1; 0.2; 0,3; 0,6; 1 or 2mm), Ti6Al4V substrate (8mm diameter and 4 mm thick) and alumina ball.	*Computer simulation:* ANSYS *Mesh resolution:* 98,996 elements and 387,826 nodes; *Force:* 50 N axial.	*Maximum contact stress (MPa):* PEEK thickness 0.1mm - 300 (max);

	and wear behavior of veneering of PEEK and Ti6Al4V.		*Elastic modulus (GPa):* PEEK OPTIMA 450 – 3; Ti6Al4V – 115; Alumina ball (5mm radius) - 300		PEEK thickness 2mm - 170 (min); *Von Mises stress (MPa):* PEEK thickness 0.2mm - 101 (max); PEEK thickness 2mm - 98.2 (min).
Schwitall et al., (2015)[6]	Compared the differences in the biomechanical behavior of a dental implant of Endolign and a commercial powder-filled PEEK.	*Modeling software:* Creo Parametric 2.0 *Bone geometry*. 3D section of a left mandible bone.	*3 models (implant/screw/abutment):* A) Ti6A14V / Ti6A14V / Ti6A14V B) PEEK MC4420 / PEEK MC4420 / PEEK MC4420 C) PEEK MC4420 / Endolign / Endolign *Elastic modulus (GPa)-* Ti: 110; PEEK: 4,1; 60 % CFR-PEEK (Endolign): 150; cortical bone: 12,4; cancellous bone 1,37;	*Computer simulation:* ANSYS *Mesh resolution:* 498,543 nodes 137,425 hexahedral elements; *Force:* 100N at axial direction and 100 at oblique Load (30°).	*Von Mises stress (MPa) at axial/oblique forces:* *A) 17, 59;* *B) 24, 98;* *C) 17, 59.*
Lee et al., (2012)[7]	Evaluation of the fatigue limits of PEEK and the effects of the low elastic modulus PEEK in relation to existing dental implants.	*Modelling program:* CAD-CAM *3D model:* NR	*10 models (diameter/ materials/ PEEK coating):* A) ø4.1 / PEEK / None B) ø4.1/ Titanium / None C) ø4.1/ Zirconia / None D) ø4.1/ Titanium/ 5 x 0.5 mm^2 PEEK E) ø4.1 / Zirconia/ 5 x 0.5 mm^2 PEEK F) ø4.8 / PEEK/ None G) ø4.8 / Titanium / None H) ø4.8 / Zirconia / None I) ø4.8 / Titanium/ 5 x 0.5 mm^2 PEEK J) ø4.8 / Zirconia / 5 x 0.5 mm^2 PEEK Ø-diameter *Elastic Modulus (GPa):*	*Computer simulation:* PAM-IMPLICIT; *Mesh resolution*. 428,466 tetrahedral elements and 79,067 nodes; *Forces:* 100N, 30N at axial direction.	*Von Mises stress (MPa):* Ø4.1-mm under horizontal force- a) 24, b) 18, c) 10, d) 17, e) 15; Ø4.1-mm under axial force- a) 18, b) 14, c) 13, d) 16, e) 15; Ø4.8-mm under horizontal force- f) 18 g) 10, h) 8, I) 16, j) 14; Ø4.8-mm under axial force- f) 16, g) 12, h) 11, I) 15, j) 14;

			Cortical bone - 15 Ti - 110 GFR-PEEK - 12 Zirconia - 210		
Sarot et al., (2010)[8]	Compared the stress distribution in the peri-implant bone of distinct models composed of reinforced PEEK.	*Modeling software:* ANSYS *3D model:* Tooth 35 of a CT image of the jaw;	*4 models:* A) Titanium implant and abutment B) Titanium implant, 30% CFR-PEEK abutment C) 30% CFR-PEEK implant, Titanium Abutment D) 30% CFR-PEEK implant and abutment *Elastic modulus (GPa):* 30% CFR PEEK-18; Ti-110; Cortical bone-17400;	*Computer simulation:* ANSYS *Meshes resolution:* 1,402,615 nodes and 894,630 tetrahedral elements. *Forces:* 100N at axial load and 100N at oblique load (30°);	*Von Mises Stress (MPa) implant/abutment/cortical bone/ medullar bone:* A) 76.46/41.76/ 32.70/2.48; B) 74.70/ 33.82/ 32.70/2.47; C) 85.54/41.32/ 27.77/4.22; D) 86.61/33.96/ 27.90/4.2.
Mattila et al., (2009)[18]	Compared three different implant materials, glass-reinforced PMMA composite with a porous surface, titanium and PMMA with a solid surface.	*Modeling software:* OOF program*; *3D model:* Femur and tibia of rabbits;	*3 cylindrical models:* A) PMMA*-based E-glass-fibre-reinforced composite (FRC) with porous surface; B) PMMA with a solid surface; B) Titanium. *Young modulus (GPA):* PPMA - 3 FRC - 15 Ti - 110 Cancellous bone - 6	*Computer simulation:* ABAQUS *Meshes resolution:* 19,628 nodes *Force:* 66 N axial direction.	*Stress distributions were tested post in vivo push-out after 12 weeks healing.* PMMA implants: <66 N Ti implants: >66 N FRC: >66N. The shear force: PMMA solid (14.4 ± 11.0 N) Ti (130.6 ± 22.2 N FRC (283.3 ± 55.3 N) .

*

(NR), not reported.

(LD), Lithium disilicate.

(CFR-PEEK), carbon-reinforced PEEK.

(Ti), Titanium.

(CT), Computerized tomography.

(TZI), translucent zirconia, (VTE): polymer-infiltrated hybrid ceramic.

(PPMA), Poly-methyl methacrylate, OOF program: developed at National Institute of Standard and Technology, USA.

4. DISCUSSION

4.1. Dental implant and abutment

Commercially dental implant systems involve an endosseous implant and the implant abutment component, as seen in Figure 2. The geometric configuration of the endosseous implant should be designed to achieve an extensive implant-bone contact area allowing a fast and predictable osseointegration while the abutments are positioned in a transition zone where they are in contact with the surrounding peri-implant tissues (11, 12,13,25). Therefore, structural components can be manufactured from titanium-based materials or zirconia (4,5,7,9,10). Also, commercially available temporary abutments can be produced from PEEK-based materials (1, 24).

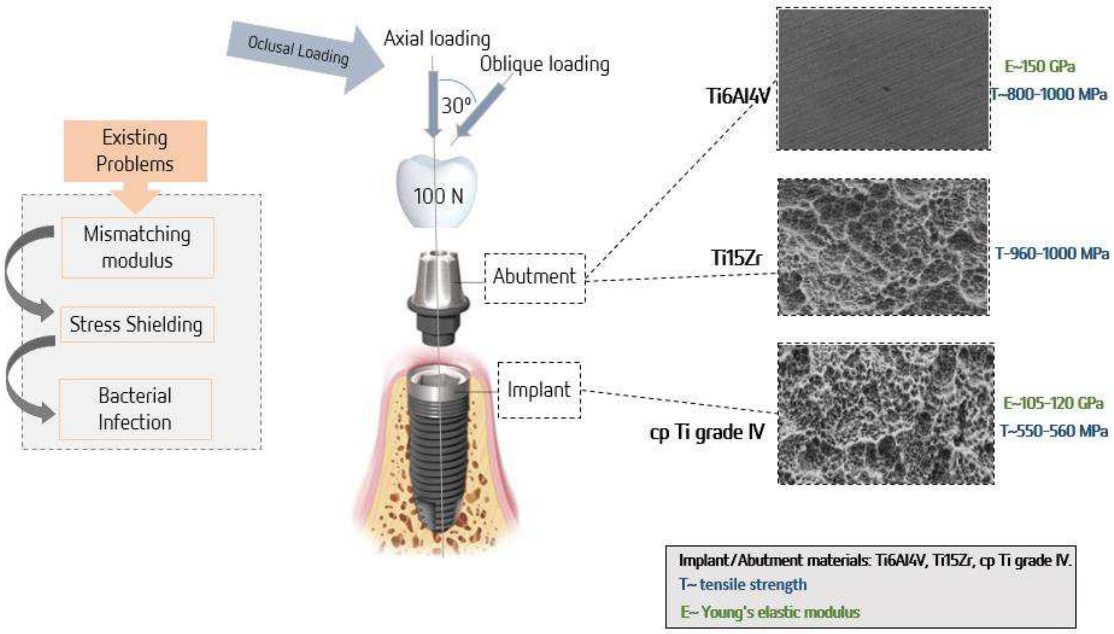

Figure 2. Schematic of implant/abutment metal materials.

Dental implant systems are currently available within single- or multiple pieces depending on the materials and clinical applications (11,12,13,25). A screw component can be an extension from the titanium abutment for connection into the endosseous implant (two-pieces) or a third component to connect abutment (post through bolt) and the endosseous implant. The implant-abutment connection has been developed as external hexagonal, internal hexagonal, or Morse taper (11,12,25). Among the current implant-abutment connections, Morse taper exhibit proper stress distribution from occlusal loading through the endosseous implant and surrounding bone (1,11,12,25). The selection of the implant abutment is of major importance concerning aesthetics outcomes, corrosion resistance, elastic modulus, strength, biocompatibility, and peri-implant healthy state maintenance (1-8,13). Abutments can be manufactured as standard (straight or angled) or custom-made design(11-13). Custom-made and angled abutments are indicated in cases to balance the positioning of the implant systems regarding the maxillofacial relationship (11-13). Custom-made abutments provide accurate positioning and optimization of stress distribution(11-13).

Commercially pure titanium (cp Ti) grade IV or Ti15Zr alloy has been used to manufacture the endosseous implant while titanium alloys such as Ti6Al4V are used to produce abutments, as seen in Figure 2(9,10). Cp Ti grade IV has a high biocompatibility followed by successful osseointegration rates and an elastic modulus of around 105-120 GPa associated with a tensile strength at approximately 550-560 MPa (5,9). Those properties are proper for standard endosseous implants. Recently, Ti15Zr alloy (Roxolid®) has been used to manufacture standard and narrow implants due to the higher tensile strength (around 960-1000 MPa) when compared to the cpTi grade IV maintaining a high biocompatibility and osseointegration rate (5,9). Concerning the occlusal loading, abutment must be produced from titanium alloys such as Ti15Zr or Ti6Al4V (elastic modulus at 150 GPa and tensile strength at around 800-1000 MPa), as shown in Table 1 (1,2,4-6,8). Regarding zirconia, one-single implant systems involving the endosseous implant and abutment part is recommended to decrease failures at the connections(4,9,10). However, zirconia can be used to produce hybrid abutments in which the core is produced from titanium alloy and then veneered with a zirconia layer (4, 10). Yttria-stabilized tetragonal zirconia polycrystals (YTZP) are the first choice considering a high osseointegration rate and chemical stability associated with the flexural strength at around 1000-1200 MPa and elastic modulus at around 240-270 GPa (4,10). However, the high elastic modulus can induce a stress shielding effect leading to bone resorption at the peri-implant region (9,10). Stress shielding occurs due to the large difference in elastic modulus of zirconia and bone tissues (20-30 GPa) that inhibit a physiologic stress stimulus to the peri-implant bone(9,10). In this way, alternative materials with a lower elastic modulus could avoid undesirable bone resorption and therefore polymer-matrix composites or hybrid materials have been developed (1-8,14,18,24).

Although dental implant systems have been the first choice for teeth replacement, there are still clinical limitations concerning materials, stress distribution, and peri-implant health maintenance(1-8,14,18,24). A high stress concentration through the implant system and at the joints can induce the abutment screw loosening leading an increase in the joint micro gaps or micro-cracks and fractures of structural materials (13,17). Micro-movements between the screw, abutment, and inner implant surfaces result in degradation of the implant-abutment connections (13,17). Additionally, the stress distribution to the bone vary depending on the materials and implant design that regulates the bone resorption(13,17). The peri-implant region is also susceptible to biofilm accumulation with risks of bone resorption due to peri-implant inflammations (13,17,26). The progressive bone loss negatively affect the stress distribution through the implant and mechanical stability of the implant and implant-supported prosthetics (13,17,26). For this reason, the mismatch in elastic modulus and stress distribution at the implant-bone interface are still been discussed(1-8,14,18,24).

4.2. Stress distribution through PEEK-based implant and abutment

Poly-ether-ether ketone (PEEK) is a thermoplastic polymer that has been used in orthopedic and dental applications (19-22,27). PEEK has an elastic modulus of around 3-4 GPa which is lower than that recorded on titanium and its alloys(1-8,14,18,19-22,,24). Such elastic modulus closer to that recorded for bone tissues leading to the distribution of stresses from occlusal loading to the bone (2,4,6,7). In addition, PEEK has a lower tensile strength (90-100 MPa) when compared to those measured for cp Ti grade IV (550-600 MPa) and titanium alloys (900-1000 MPa)(19-22). Furthermore, PEEK have getting attention with the incorporation of glass or carbon fibers resulting in a fiber-reinforced PEEK-matrix composite with improved mechanical properties (1,2,8,18). The tensile strength of PEEK reinforced with 30% carbon fibers (30CFR-PEEK) is recorded at around 200-215 MPa and the elastic modulus can reach values of approximately 18 GPa, which is at range as that recorded for the cortical bone (10-18 GPa)(1-8,15,16). Then, a proper stress distribution is expected through CFR-PEEK abutments on occlusal loading(1,8) as inspected by Finite element analysis (FEA)(7) . The elastic modulus of cancellous bone is around 1 to 4 GPA and moreover the highest stresses are concentrated around the neck of the implant in the cortical bone (1-4,6,8). For this reason, the authors stated that implant materials should have a moderately high modulus of elasticity although the properties should be balanced at the implant neck (1-4,7-8,24). Thus, the mechanical properties of abutment, implant, and prosthetics influences the stress distribution and mechanical behavior at the implant-to-bone interface (1-4,6-8,14,18,24).

On the biomechanical analysis of biomedical materials, finite element method (FEM) uses digital models to simulate and test progressive the stress distribution through structural materials and human body tissues considering different design, loading, and properties (1-4,6-8-14,23). FEM studies enables the study of mechanical problems, by using a 3D digital mesh of elements linked to mathematical functions (1-4,6-8-14,23). After modeling, stress distribution of isotropic or anisotropic materials can be evaluated by FEA regarding different loading and materials' parameters (1-4,6-8-14,23). Most selected studies assumed materials are isotropic and have a linear elastic behavior (1-4,6-8,24) except for carbon fiber-reinforced PEEK laminates which are anisotropic(14).

A previous FEA study compared the distribution of von Mises stresses through titanium or PEEK implants and abutment to the surrounding cortical bone (2). Results showed that unfilled PEEK abutment did not provide any mechanical advantage when compared with titanium abutments(2). In fact, unfilled PEEK abutment increased the stress concentration on the implants, prosthetic crown, and the abutment screw. (2). In another study, unfilled PEEK custom-made abutment demonstrated lower stress values when compared to zirconia custom-made abutments(4). In spite of that, stress concentration was higher through the prosthetic crowns when unfilled PEEK was assessed as abutment(4). Also, lower stressed were recorded by FEA on the cervical region of 30CFR-PEEK implants when compared to the same region of titanium implants(8). However, a recent study revealed no differences in von Mises stresses distribution to the cortical bone when 30CFR-PEEK or titanium abutment was assessed on oblique loading(1). Findings for both materials revealed similar stress distribution and the load transferring to the surrounding bone tissue was at the same magnitude(1,3,8). Studies corroborate taking into consideration that 30CFR-PEEK implant or abutments did not provide any mechanical advantages regarding the stress distribution to the peri-implant bone when compared to titanium structures(1,3,8). In the case of implants, the strength of cp Ti grade IV or Ti15Zr guarantee the low risks of fractures on complex stresses from occlusal loading(5). On abutments, cp Ti or 30CFR-PEEK revealed lower strength values than those for titanium alloys for maintenance of the long-term mechanical performance (1,6,8). The incorporation of glass fibers into the PEEK matrix (GFR-PEEK) showed similar mechanical outcomes taking into account the elastic modulus of the GFR-PEEK composite at around 12 GPa (4,7). Additionally, the optical properties of GFR- PEEK composites are proper for abutment applications to mimic the color and translucence of dentin structures (4,7). Lee et al., assessed The fatigue limits of implants (4 or 5 mm in diameter) composed of GFR-PEEK, 30CFR-PEEK, or Ti grade IV was also assessed(7). GFR-PEEK implants with standard diameter for teeth replacement (4 mm) was capable of supporting cyclic loading at around 250 N that is above the threshold in the anterior (1401-170N) or pre-molar (200-250 N) regions(7).

The assumption that an increase in the proportion of carbon fibers into the PEEK matrix could reduce the stresses at the implant-to-bone was validated by a few recent studies (6,7,14). PEEK reinforced with 60% parallel-oriented endless carbon fibers (60CFR-PEEK) implants reveals an increased elastic modulus around 150 GPa and tensile strength at 2000 MPa (6). That is statistically higher when compared with unfilled PEEK and cp Ti (6). Results demonstrated that unfilled PEEK implants showed higher stresses within the surrounding cortical bone when compared with 60CFR-PEEK or Ti6Al4V implants(6).

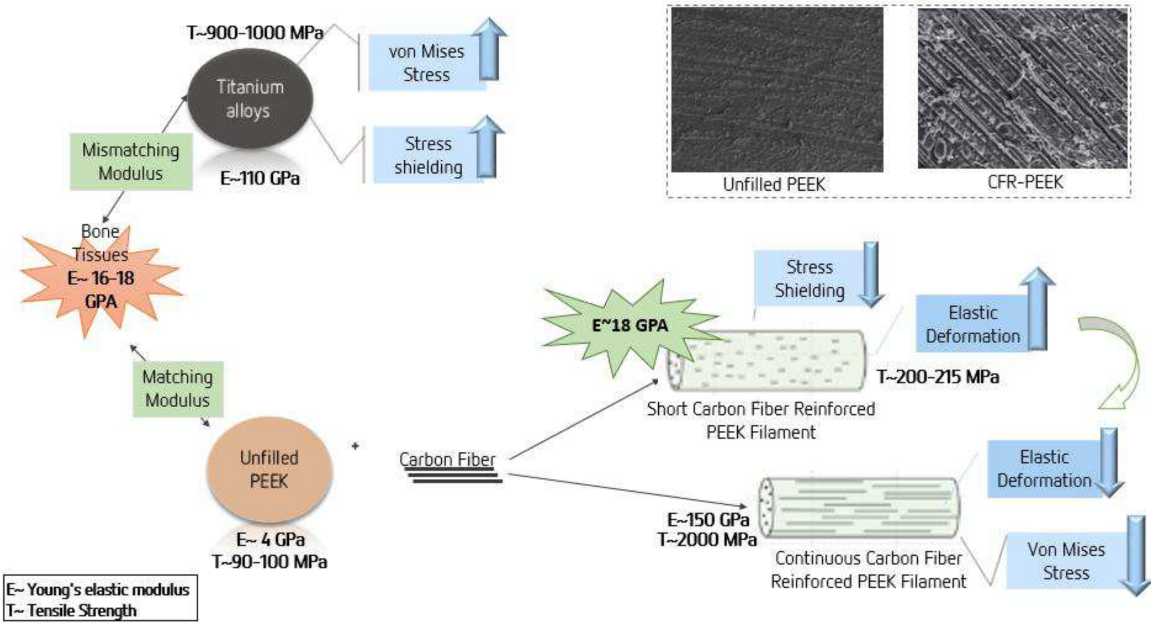

Figure 3. Schematic of PEEK and CF-reinforced PEEK.

However, FEA assumed that the PEEK composite had isotropic properties and linear elasticity and therefore further studies are required to validate the mechanical behavior of PEEK-matrix composites (1,6). In addition, the influence of different content of fibers into the PEEK should be assessed to determine the optimum amount regarding mechanical properties for implant or abutment applications (6). Unidirectional long carbon reinforced PEEK laminates (PEEK-OPTIMA Ultra reinforced) provided increased stiffness and high specific strength along with anisotropic material properties decreasing the stress shielding effect at the peri-implant bone, as illustrated in Figure 3 (14).That was the first experimental study on the mechanical behavior and failure performed in a medical grade unidirectional 62% carbon fiber reinforced PEEK (60CFR-PEEK) (14). The current study performed fracture testing of 0, 45 and 90° laminates (14). The multi-axial experiment showed that CFR-PEEK had different yield strength in different loading direction (14). The plastic yielding and strain hardening occurred during axial loading of 45 or 90° laminates (14). Veneering titanium structures with PEEK layers can also be a strategy to enhance the mechanical behavior in some clinical cases (2,24). Sampaio et al., investigated the influence of the PEEK layer thickness on the wear and mechanical behavior of the veneering PEEK to Ti6Al4V assembly (24). Results showed that PEEK veneer thickness above 0.2 mm decreased the stresses at the PEEK to Ti6Al4V interfaces on loading (24). Then, PEEK thickness below 0.2 mm must be avoided to maintain the mechanical performance of the veneering PEEK to Ti6Al4V structure (24).

5. CONCLUSIONS

The present literature review provided a critical analysis of previous studies on the stress distribution through dental implants and abutments composed of PEEK-matrix composites by finite element method. Even though the limitations of the theoretical analyses, the previous studies revealed significant data on the biomechanical behaviour of PEEK-matrix composites that corroborate with experimental studies. The major findings are drawn as follow:

- The elastic modulus of PEEK range from 3 to 4 GPa, which is closer than that of metals and ceramics to the modulus of human bone, but is relative low. Reinforcement with carbon and glass fiber to PEEK are the most effective choice to solve this problem. The stress shielding can be prevented by selecting proper PEEK-matrix composites in function of the content, shape, and dimensions of fillers.
- Regarding the stress distribution through the implant and abutment, PEEK reinforced with 30% carbon fibers (30CFR-PEEK) did not exhibit any advantage when compared to titanium implant or abutments. Thus, 30CFR-PEEK showed higher stress concentration and deformation at the bone-implant interface whereas the titanium implants distributed gradually the stress at the interface. This finding lead to the assumption that an endless carbon fiber (60CFR-PEEK) dental show reduced stress due to a reduced elastic deformation at the bone-implant interface.
- PEEK reinforced with 60% carbon fibers (60CFR-PEEK) provided a gradual stress distribution through the implant to the bone interface due to the elastic modulus (~150 GPa) and deformation. However, the optimum amount and dimensions of carbon fibers can still be adjusted to promote a compatible mechanical behaviour with the bone and abutment.
- Although experimental tests are limited, CFR-PEEK composite revealed great potential to be used as a dental implant or abutment. Further experimental studies are required on different content, shape, and dimensions of fibers to reinforce PEEK-based materials. Additionally, the oral conditions should be mimicked regarding loading, acidic environment, pH, temperature, and presence of biofilms.

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