Original article

Biomechanical evaluation of anterior implants associated with titanium and zirconia abutments and monotype zirconia implants

Kelynn Alcântara Brandão de Holanda^a, Ricardo Armini Caldas^b, Marina Amaral^a, Lais Regiane da Silva Concilio^a, Rafael Pino Vitti^{a,c,*}

^aDepartment of Prosthodontics, Dental School, University of Taubaté, Taubaté, São Paulo, Brazil

^bDepartment of Prosthodontics, Piracicaba Dental School, University of Campinas, Piracicaba, São Paulo, Brazil

^cSchool of Dentistry, Herminio Ometto University Center, Araras, São Paulo, Brazil

Abstract

Purpose: The present in silico study evaluated the behavior of titanium dental implants associated with abutments in zirconia and monotype zirconia implant using finite element analysis (FEA).

Methods: A partial image of the anterior region of the maxilla was obtained by computed tomography. Three models of finite element were made using 3D modeling software (SolidWorks): Ti-Ti (control): implant morse cone (3.75 x 11mm; NobelActive) and titanium abutment (Esthetic Abutment); Ti-Zr: cone morse implant in titanium (3.75 x 11mm; NobelActive) and zirconia abutment (Procera Esthetic Abutment #9); Zr: monotype zirconia implant (4.1 x 12mm; Straumann Pure Ceramic). Computerized crowns of element 11 in lithium disilicate (IPS e.max Press, Ivoclar Vivadent) cemented in all groups were created. A load of 100N (45°) was applied simulating the excursion movement of the incisal guide. The von Mises, modified von Mises, maximum (tensile) and minimum (compression) principal stresses were obtained, compared and used for the quantitative and qualitative evaluation of the groups.

Results: The Zr presented the lowest values of maximum, minimum, and von Mises tensions than the two pieces systems (Ti-Ti and Ti-Zr). Ti-Zr group had the highest values of tensions evaluated in this study.

Conclusions: The type of material as well as the geometry of implant influenced the tension values evaluated.

Keywords: Ceramics, Dental prosthesis, Implant-supported, Tensile strength, Titanium

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1. Introduction

Titanium implants are widely used and their high success rate has been proven in several laboratory and clinical studies [1-3]. The main disadvantage of titanium is its coloration, which may appear through the soft tissues or may be visible in a gingival recession, compromising the esthetics of the restoration. Zirconia-based ceramics are aesthetic restorative materials that can be used as alternative materials to titanium [4]. Among the dental ceramics, zirconia presents high physical and chemical properties, such as high values of flexural strength (900-1200MPa) [5], fracture toughness (~4MPam^{1/2}) [6] and hardness (13-17GPa) [6,7], high Young's modulus (250 GPa) [7], as well as excellent dimensional stability and biocompatibility with the tissues of the oral cavity [5].

This ceramic exists in three forms: monoclinic, tetragonal and cubic. The zirconia has a monoclinic crystalline structure at room the zirconia has a tetragonal structure. Above 2370°C, the zirconia

temperature, and is stable up to 1170°C. Between 1170°C and 2370°C crystals have a cubic shape [8]. After its processing, during the cooling, the tetragonal phase again becomes monoclinic and this transformation leads to a volumetric expansion of 3-4%. However, yttrium oxide is added to zirconia in order to stabilize it in the tetragonal phase after cooling (yttria-stabilized tetragonal zirconia polycrystal - Y-TZP). This improves the mechanical strength of the zirconia, because when the Y-TZP is induced by tensions that initiate the propagation of a crack, the tetragonal crystals close to the crack become the stable monoclinic phase. The volumetric expansion occurred during this transformation causes stresses of compression that oppose the growth and propagation of the crack [9]. Because of this combination of factors, zirconia can be a material used to make ceramic implants and abutments [10,11]

Concurrently with the high utilization and success rate of dental implants, there is an increase in the incidence of mechanical complications of these restorations [9]. Important factors in maintaining osseointegration of implant-supported dentures are associated with the biomechanical behavior of dental implants, such as the transmission of stresses around the bone adjacent to the implant [12,13]. The occlusal forces induce tensions in the implants and prosthesis, influencing the bone remodeling around the dental implants [14].

Monotype implants tend to minimize bone resorption of bone tissue

* Corresponding author at: University of Taubaté, Rua dos Operários 09, Taubaté, SP, CEP: 12020-270, Brazil. Phone/Fax: 55-12-3629-2130
E-mail address: rafapvitti@gmail.com (R. P. Vitti).

adjacent to the implant by the absence of abutment/implant attachment and the surgical technique is simpler and less sensitive than the two-piece implant technique. The first monotype ceramic implant (alumina) appeared in Dentistry in the 1980s. However, despite having satisfactory osseointegration and aesthetics, these implants had a low survival rate because they had low fracture resistance and weak adhesion with the bone tissue [15,16]. The monotype implant in zirconia (monotype zirconia implant) has been recently developed and has the abutment integrated to the design of the implant, there being no gaps between the implant and the abutment. In addition, the good physicochemical and biological properties of zirconia relative to other types of ceramics justifying their use as components of dental implants [16].

The success of implant-supported prostheses is mainly due to the knowledge of how the tensions are transferred to implants and their components during prosthetic rehabilitation [17], since if these tensions are poorly distributed can lead to complications in the clinical prognosis, resulting in defects in prosthetic rehabilitation, such as: ceramic fracture, high bioperformance ratio, loosening of the screw as well as restorations and/or fracture of prosthetic components or even implant. [14,18,19]. Thus, the aim of this *in silico* study was to evaluate the tensions generated in titanium implant systems associated to titanium and zirconia abutments and monotype implants in zirconia and in the peri-implant bone structures of a single implant-supported prostheses in the anterior maxillary region submitted to functional occlusal loading.

2. Material and methods

2.1 Model construction

Three three-dimensional (3-D) models were developed reproducing a clinical situation with absence of an upper central incisor, implant replacement and crowns on implants in order to simulate functional occlusal loading on osseointegrable implants. For the construction of the 3-D bone model of the maxilla, images of dentate maxilla were obtained by computed tomography (i-CAT Cone Beam 3D Dental Imaging System, Imaging Sciences International, Hatfield, PA, USA). These images were used as a basis for the computational construction of the maxillary anterior region (18mm height x 19mm mesio-distal width x 15mm bucco-lingual depth). The constructed maxilla was type three (thin layer of cortical bone - 1.0mm - around a trabecular bone) with respect to its density.

The 3-D models were constructed using computer-aided design software (SolidWorks, SolidWorks Corporation, Concord, MA, USA). For all groups, a prosthetic crown of IPS emax Press lithium disilicate (Ivoclar Vivadent, Liechtenstein) was made using an image previously obtained by computerized microtomography and cemented onto abutments (Fig. 1). The models were distributed in the respective study groups: Ti-Ti (control): titanium cone morse implant (3.75 x 11mm; NobelActive, Nobel Biocare, Gothenburg, Västra Götaland, Sweden) and titanium abutment (Esthetic Abutment, Nobel Biocare), Ti-Zr: titanium cone morse implant (3.75 x 11mm; NobelActive, Nobel Biocare) and zirconia abutment (Procera Esthetic Abutment #9, Nobel Biocare); Zr: monotype zirconia implant (4.1 x 12mm implant; Straumann Pure Ceramic, Straumann, Basel, Switzerland).

2.2 Finite element analysis

The 3-D models were imported into computer-aided engineering software (ANSYS Workbench 14.0, Swanson Analysis Systems Inc., Houston, PA, USA) for performing the finite element analysis. The materials were considered isotropic, homogeneous and linearly elastic. The values of the Young's modulus and the Poisson's ratio are described in Table 1.

All contacts were considered in intimate contact (no friction), except

Fig. 1. 3-D model images: (A) Ti-Ti; (B) Ti-Zr; (C) Zr; (D) Red arrow indicating location and direction of applied load; (E) Regions in blue indicating the fixed support of the model.

for the abutment/implant attachment, where the coefficient of friction was set to 0.30 for the Ti-Ti group [22] and 0.19 for the Ti-Zr group [23]. The finite element analysis (FEA) meshes were generated and their integrity evaluated for the quality of the elements in the regions analyzed. The models presented a number of elements that varied between 391,959 and 532,624, and a number of nodes ranging from 581,165 to 794,119.

Then, the mechanical loading was simulated with a load of 100N at 45° to the implant axis, at the palatal portion of the prosthetic crowns, the initial position of the occlusion trajectory (Fig. 1.D). The trimmed regions of the maxilla were used as stabilizing points (zero degrees of freedom) (Fig. 1.C).

The results were obtained and evaluated by maximum principal stress (tensile), minimum principal stress (compressive), equivalent von Mises stress and modified von Mises stress, as described by Versluis et al. [24], being quantitatively and qualitatively compared.

3. Results

The Zr group provided lower values of maximum and minimum principal stresses and von Mises than the two-piece systems (Ti-Ti and Ti-Zr). However, comparing the same geometry (two-piece groups), it was noticed that the implant and abutment material also influenced the stress values, since the Ti-Ti group presented lower stress values in the implants and abutments than the Ti-Zr group (Fig. 2).

In the Ti-Ti and Ti-Zr groups, von Mises tensions were concentrated in the cervical third of the implants, in the micro-screw thread, extending to the screw in abutment. In the monotype zirconia implant (Zr), the stresses were concentrated in the cervical region extending to the last thread pitch of the implant (Fig. 3).

The maximum principal stress (tensile) was concentrated at implant connection. In the Ti-Ti group the tensions extended beyond the region of the abutment, except for Ti-Zr group, where the stresses were concentrated below the prosthetic abutment. In the Zr group, the tensions converged in the neck region of the implant in the palatine, distributing along the implant threads in the middle and cervical thirds of the abutment (Fig. 4).

The Zr group showed the lowest compressive values, and the tensions were converged in the implant neck region on the buccal surface, distributing along the implant threads and the cervical third of the abutment (Fig. 5).

The results show that the tensions induced in the bone tissue were also influenced by the type of material and geometry of the implants and abutments (Fig. 6)

Table 1. Mechanical properties.

Material	Young's Modulus (GPa)	Poisson's ratio
Cortical bone	13,7 ^a	0,30 ^a
Cancellous bone	1,37 ^a	0,30 ^a
Titanium	115 ^a	0,35 ^a
Zirconia	200 ^a	0,31 ^a
Lithium Disilicate	68 ^b	0,24 ^b

^aÇaglar et al. [20]; ^bEreifej et al. [21] **Fig. 2.** Tensile, compressive and von Mises tensions in implants and abutments (MPa). **Fig. 3.** Distribution of von Mises stress in the implants (A) Ti-Ti group; (B) Ti-Zr group; (C) Zr group; (D) Zr group with other color scale for better visualization. A, B and C have the standardized color scale.

The stress distribution in the bone tissue were concentrated in the cervical region of the cortical bone. In Ti-Zr and Ti-Ti groups the tension were uniformly distributed (Fig. 7, 8 and 9).

4. Discussion

The analysis of stress concentrations around implants, abutments and peri-implant bone structures is extremely important for a good clinical prognosis of dental implant rehabilitation, since bone loss/resorption and implant stability are directly associated with the tensions employed by the implants [14]. In the present study, it was observed that the different types of geometry and materials of the implants and abutments caused different tensions in the implant, abutment and bone tissue.

The results show that under occlusal loading of 100N at 45° along the implant axis, the implant geometry, as well as the different materials used in the implant and abutment influenced the distribution of tensions in the implant, abutment and bone tissue. The lower stress values (von Mises, tensile and compressive) for the Zr group may be associated with the application of the oblique load and macrogeometry of the monotype zirconia implant, which has advantages such as absence

Fig. 4. Maximum principal stress in implants and abutments. (A and B) Ti-Ti group; (C and D) Ti-Zr group; and (E and F) Zr group. **Fig. 5.** Minimal principal stress in implants and abutments. (A and B) Ti-Ti group; (C and D) Ti-Zr group; and (E and F) Zr group.

of gaps between abutment and implant, consequently there is no micromovements in the cervical region of the implant [25], besides the highest Young's Modulus for zirconia implants in relation to the titanium implants (Table 1). The Young's Modulus (elasticity) directly influences the bone-implant interface, since a larger Young's Modulus causes less bone resorption in the peri-implant region against occlusal forces [20,26]. Geng et al. [12] recommend that the Young's Modulus of the implants is at least 110 GPa, since a low modulus of elasticity leads to an increase in the concentration of these stresses in the bone tissue.

Analyzing the same geometry of the implants (Ti-Ti and Ti-Zr), it was verified that the Ti-Zr group obtained the highest values of

Fig. 6. Tensile, compressive and modified von Mises stress in the bone tissue (MPa).

Fig. 7. Modified von Mises tensions in the bone tissue (A) Ti-Ti group; (B) Ti-Zr group; and (C) Zr group.

Fig. 8. Maximum principal stress in bone tissue, (A) Ti-Ti group; (B) Ti-Zr group; and (C) Zr group.

Fig. 9. Minimum principal stress in bone tissue, (A) Ti-Ti group; (B) Ti-Zr group; and (C) Zr group.

tensions in implants and abutments. This result is in agreement with other studies [5,27] that observed a greater number of fractures in the region of connection with the implant for zirconia abutments compared to titanium. However, these higher stress values do not compromise the use of zirconia abutments in the anterior region of the oral cavity, since these abutments presented similar clinical performance to titanium abutments. In addition, this result shows that the abutment/implant interface also influences the stress distribution. In the Ti-Zr group there are materials with different physical properties in close contact: friction coefficients (0.30 for Ti-Ti group and 0.19 for Ti-Zr group), roughness and hardness ($Zr = 1800VHN$ $Ti \approx 260VHN$) [28]. These differences could promote

the different stresses at the abutment/implant interface, promoting a higher wear between the zirconia abutment with titanium (Ti-Zr) implant than the abutment and titanium (Ti-Ti) implant.

It should be noted that the tensile strength of the zirconia is approximately 710MPa [29]. Therefore, even the highest values found (abutments in the Ti-Zr group, Figure 4) are within this parameter set as a limit so that the fracture of this structure does not occur in zirconia. For titanium, these values vary according to the type of titanium used: 240–550MPa for commercially pure titanium (Ticp; grades 1 to 4) and 860MPa for Ti-6Al-4V alloy (grade 5) [30]. The implants evaluated in the present study are manufactured with Ticp (grade 4), and the abutments are made with Ti-6Al-4V (grade 5). Thus, all titanium implants and abutments used in this study also presented stress values below the tensile strength values.

Minimal principal stress (compressive) was also concentrated in the region of implant connection. In the Ti-Ti and Ti-Zr groups the tensions in the abutments were concentrated in the posterior base and in the anterior region of the cone-morse. In the implants of these same groups the highest values were found in the internal region, in the hexagonal part of the connection. Although they have similar distribution, the highest compressive values were found in the Ti-Zr group. The Zr group showed the lowest compressive values converged in the implant neck region on the buccal surface.

The regions where the different stresses were concentrated also varied among the groups tested. In groups with two-piece implants (Ti-Ti and Ti-Zr) the stress distributions were similar. Compressive and tensile stresses were concentrated at the implant connection region, below the prosthetic abutment and at the anterior face of the cone-morse. Zr group presented the lowest values of stresses, which were concentrated in the implant collar surface, distributing along the threads of the implant and the cervical third of the abutment, corroborating with other studies [31,32]. This accumulation of stresses in the fulcrum region (Zr group) could be explained by the oblique load applied in the methodology and because these implants present the fulcrum of the lever arm near bone crest [25,33]. Although the axial load is preferable to minimize variables in the results, making the results easier to interpret, implants are subject to oblique loads in the oral cavity during chewing movements, in addition to the presence of cusps of prosthetic crowns. Thus, tensions accumulate at the crest of the alveolar bone, rotational fulcrum region of the implant/prosthetic component assembly, since, because of its single-body configuration, the abutment/implant attachment creates a larger lever arm during the application of a force [33].

The monotype zirconia implant (Zr) induced lower values for modified von Mises in bone tissue when compared to two-piece implants (Ti-Ti and Ti-Zr groups). Comparing the two two-piece systems, titanium (Ti-Ti) promoted lower modified von Mises stresses than zirconia (Ti-Zr) (Fig. 6)

The stress distribution in the bone tissue were concentrated in the cervical region of the cortical bone, especially in Zr group, where tensions (modified von Mises and tensile) accumulated in the alveolar region, while Ti-Zr and Ti-Ti groups the tension were uniformly distributed (Fig. 7, 8 and 9). In addition, the cervical geometry of the titanium implants (Ti-Ti and Ti-Zr) causes high stresses in the bone tissue and near the neck of the implant [34], corroborating with the results of the present study.

In the bone tissue, tensions accumulated in the posterior region of the alveolus in the single-body implant (Zr), being more evenly distributed to the two-piece implants (Ti-Zr and Ti-Ti). This result is due to the shape of the implant in this region of contact with the bone. The macrogeometry of monotype zirconia implant provides at the same time a more uniform distribution of stress in its body and more concentrated in the alveolar region of the bone tissue. This is a characteristic of single-body implants, which minimize the concentration of stress in their body, concentrating these stresses in the alveolar region [35].

Just as the present study, Kohal et al. [36] showed that monotype implants in zirconia is a practicable mechanical and esthetic option

for maxillary anterior rehabilitation. Furthermore, Kniha et al. [37] showed that the monotype zirconia implant showed good results after three years in function, presented satisfactory bone resorption and good survival and success rates. This result corroborates our study, since the long-term success of implant treatment is closely related to the low values of tensions caused in the peri-implantal bone structures and, consequently, the lower bone resorption in this region. All groups presented adequate bioperformance indexes, since they promoted modified von Mises stress values below the maximum stress limit (167MPa) that the cortical bone can receive without damage, such as plastic deformations (beginning of the process of bone resorption) or fracture [38,39].

5. Conclusion

In maxillary anterior rehabilitation, the monotype zirconia implant is the system that presents and transmits to the peri-implantal bone structures lower stress values when compared to titanium implants of cone-morse type with titanium or zirconia abutments.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

- [1] Borgonovo AE, Censi R, Vavassori V, Dolci M, Calvo-Guirado JL, Ruiz RAD, et al. Evaluation of the success criteria for zirconia dental implants: a four-year clinical and radiological study. *Int J Dent* 2013;8:1-7.
- [2] Spies BC, Balmer M, Patzelt SBM, Vach K, Kohal RJ. Patient-reported outcomes of a zirconia oral implant: Three year results of a prospective cohort investigation. *J Dent Res* 2015;94:1385-91.
- [3] Galvão GH, Grossi JA, Zielak JC, Giovanini AF, Furuse AY, Gonzaga CC. Influence of metal and ceramic abutments on the stress distribution around narrow implants: a photoelastic stress analysis. *Implant Dent* 2016;25:499-503.
- [4] Hashim D, Cionca N, Courvoisier DS, Mombelli A. A systematic review of the clinical survival of zirconia implants. *Clin Oral Invest* 2016;20:1403-17.
- [5] Nakamura K, Kanno T, Milleding P, Ortengren U. Zirconia as a dental implant abutment material: a systematic review. *Int J Prosthodont* 2010;23:299-309.
- [6] Turon-Vinas M, Anglada M. Strength and fracture toughness of zirconia dental ceramics. *Dent Mater* 2018;34:365-75.
- [7] Roitero E, Anglada M, Mücklich F, Jiménez-Piqué E. Mechanical reliability of dental grade zirconia after laser patterning. *J Mech Behav Biomed Mater* 2018;86:257-63.
- [8] Chevalier J, Gremillard L, Virkar AV, Clarke DR. The tetragonal-monoclinic transformation in zirconia: lessons learned and future trends. *J Am Ceram Soc* 2009;92:1901-20.
- [9] Hannink RHJ, Kelly PM, Muddle BC. Transformation toughening in zirconia-containing ceramics. *J Am Ceram Soc* 2000;83:461-87.
- [10] Passos SP, Linke B, Larjava H, French D. Performance of zirconia abutments for implant-supported single-tooth crowns in esthetic areas: a retrospective study up to 12-year follow-up. *Clin Oral Implants Res* 2016;27:47-54.
- [11] Gungor MV, Yılmaz H. Evaluation of stress distributions occurring on zirconia and titanium implant-supported prostheses: A three dimensional finite element analysis. *J Prosthet Dent* 2016;116:346-55.
- [12] Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: a review of the literature. *J Prosthet Dent* 2001;85:585-98.
- [13] Torcato LB, Pellizzer EP, Verri FR, Falcón-Antenucci RM, Santiago Junior JF, Almeida DAF. Influence of parafunctional loading and prosthetic connection on stress distribution: A 3D finite element analysis. *J Prosthet Dent* 2015;114:644-51.
- [14] Sahin S, Çehrel MC, Yalçın E. The influence of functional forces on the biomechanics of implant-supported prostheses - a review. *J Dent* 2003;30:271-82.
- [15] Andreietelli M, Wenz HJ, Kohal RJ. Are ceramic implants a viable alternative to titanium implants? A systematic literature review. *Clin Oral Impl Res* 2009;20:32-47.
- [16] M Gahlert M, Kniha H, Weingart D, Schild S, Gellrich N-C, Borman K-H. A prospective clinical study to evaluate the performance of zirconium dioxide dental implants in single-tooth gaps. *Clin Oral Implants Res* 2016;27:e176-84.
- [17] Nedir R, Bischof M, Szmukler-Moncler S, Belser UC, Samson J. Prosthetic complications with dental implants: from an up-to-8-year experience in private practice. *Int J Oral Maxillofac Implants* 2006;21:919-28.
- [18] Manfredini D, Poggio CE, Lobbezoo F. Is bruxism a risk factor for dental implants? A systematic review of the literature. *Clin Implant Dent Relat Res* 2014;16:460-9.
- [19] Dos Santos Marsico V, Lehmann RB, de Assis Claro CA, Amaral M, Vitti RP, Neves ACC, et al. Three-dimensional finite element analysis of occlusal splint and implant connection on stress distribution in implant-supported fixed dental prosthesis and peri-implantal bone. *Mater Sci Eng C Mater Biol Appl* 2017;80:141-8.
- [20] Caglar A, Bal BT, Karakoca S, Aydın C, Yılmaz H, Sarisoy S. Three dimensional finite element analysis of titanium and yttrium-stabilized zirconium dioxide abutments and implants. *Int J Oral Maxillofac Implants* 2011;26:961-9.
- [21] Ereifeh N, Rodrigues FP, Silikas N, Watts DC. Experimental and FE shear bonding strength at core/veneer interfaces in bilayered ceramics. *Dent Mater* 2011;27:590-7.
- [22] Bhering CLB, Mesquita MF, Kemmukub DT, Noritomi PY, Consani RLX, et al. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: A prototyping guided 3D-FEA study. *Mater Sci Eng C Mater Biol Appl* 2016;69:715-25.
- [23] Macdonald W, Aspenberg A, Jacobsson CM, Carlsson LV. Friction in orthopaedic zirconia taper assemblies. *Proc Instn Mech Engrs* 2000;214:685-92.
- [24] Versluis A, Tantbirojn D, Douglas WH. Why do shear bond tests pull out dentin? *J Dent Res* 1997;76:1298-307.
- [25] Çehrel, Duyck J, De Cooman M, Puers R, Naert I. Implant design and interface force transfer. A photoelastic and strain-gauge analysis. *Clin Oral Implants Res* 2004;15:249-57.
- [26] Jung RE, Grohmann P, Sailer I, Steinhart YN, Fehér A, Hämmerle C, et al. Evaluation of a one-piece ceramic implant used for single-tooth replacement and three-unit fixed partial dentures: a prospective cohort clinical trial. *Clin Oral Implants Res* 2016;27:751-61.
- [27] Kim JS, Raigrodski AJ, Flinn BD, Rubenstein JE, Chung KH, Mancil LA. In vitro assessment of three types of zirconia implant abutments under static load. *J Prosthet Dent* 2013;109:255-63.
- [28] Klotz MW, Taylor TD, Goldberg AJ. Wear at the titanium-zirconia implant-abutment interface: a pilot study. *Int J Oral Maxillofac Implants* 2011;26:970-75.
- [29] White SN, Miklus VG, McLaren EA, Lang LA, Caputo AA. Flexural strength of a layered zirconia and porcelain dental all-ceramic system. *J Prosthet Dent* 2005;94:125-31.
- [30] Fernandes DJ, Elias CN, Valiev RZ. Properties and performance of ultrafine grained titanium for biomedical applications. *Mat Res* 2015;18:1163-75.
- [31] Moris ICM, Faria ACL, de Mattos MGC, Ribeiro RF, Rodrigues RCS. Mechanical analysis of conventional and small diameter conical implant abutments. *J Adv Prosthodont* 2012;4:158-61.
- [32] Pesqueira AA, Goiato MC, Filho HG, Monteiro DR, Santos DM, Haddad MF, et al. Use of stress analysis methods to evaluate the biomechanics of oral rehabilitation with implants. *J Oral Implantol* 2014;40:217-28.
- [33] Misch CE, Bidez MW, Sharawy M. A bioengineered implant for a predetermined bone cellular response to loading forces. A literature review and case report. *J Periodontol* 2001;72:1276-86.
- [34] Rieger MR, Fareed K, Adams WK, Tanquist RA. Bone stress distribution for three endosseous implants. *J Prosthet Dent* 1989;61:223-8.
- [35] Kong L, Hu K, Li D, Song Y, Yang J, Wu Z, et al. Evaluation of the cylinder implant thread height and width: A 3-dimensional finite element analysis. *Int J Oral Maxillofac Implants* 2008;23:65-74.
- [36] Kohal RJ, Papavasiliou G, Kamposiora P, Tripodakis A, Strub JR. Three-dimensional computerized stress analysis of commercially pure titanium and yttrium-partially stabilized zirconia implants. *Int J Prosthodont* 2002;15:189-94.
- [37] Kniha K, Schlegel KA, Kniha H, Modabber A, Hölzle F, Kniha K. Evaluation of peri-implant bone levels and soft tissue dimensions around zirconia implants-a three-year follow-up study. *Int J Oral Maxillofac Surg* 2018;47:492-8.
- [38] Ciftçi Y, Canay S. The effect of veneering materials on stress distribution in implant-supported fixed prosthetic restorations. *Int J Oral Maxillofac Implants* 2000;15:571-82.
- [39] Teixeira MF, Ramalho SA, de Mattias Sartori IA, Lehmann RB. Finite element analysis of 2 immediate loading systems in edentulous mandible: rigid and semirigid splinting of implants. *Implant Dent* 2010;19:39-49.