https://jap.or.kr | J Adv Prosthodont 2020;12:67-74 | https://doi.org/10.4047/jap.2020.12.2.67

Does the prosthesis weight matter? 3D finite element analysis of a fixed implant-supported prosthesis at different weights and implant numbers

João Paulo Mendes Tribst[1]*, Amanda Maria de Oliveira Dal Piva[1], Alexandre Luiz Souto Borges[1], Vinicius Anéas Rodrigues[2], Marco Antonio Bottino[1], Cornelis Johannes Kleverlaan[3]

[1]Department of Dental Materials and Prosthodontics, São Paulo State University (UNESP), Institute of Science and Technology, São José dos Campos, SP, Brazil

[2]Department of Dentistry, Faculty of Pindamonhangaba (FUNVIC), Pindamonhangaba, SP, Brazil

[3]Department of Dental Materials Science, Academic Centre for Dentistry Amsterdam (ACTA), The University of Amsterdam and Free University Amsterdam, Amsterdam, Netherlands

PURPOSE. This study evaluated the influence of prosthesis weight and number of implants on the bone tissue microstrain. **MATERIALS AND METHODS.** Fifteen (15) fixed full-arch implant-supported prosthesis designs were created using a modeling software with different numbers of implants (4, 6, or 8) and prosthesis weights (10, 15, 20, 40, or 60 g). Each solid was imported to the computer aided engineering software and tetrahedral elements formed the mesh. The material properties were assigned to each solid with isotropic and homogeneous behavior. The friction coefficient was set as 0.3 between all the metallic interfaces, 0.65 for the cortical bone-implant interface, and 0.77 for the cancellous bone-implant interface. The standard earth gravity was defined along the Z-axis and the bone was fixed. The resulting equivalent strain was assumed as failure criteria. **RESULTS.** The prosthesis weight was related to the bone strain. The more implants installed, the less the amount of strain generated in the bone. The most critical situation was the use of a 60 g prosthesis supported by 4 implants with the largest calculated magnitude of 39.9 mm/mm, thereby suggesting that there was no group able to induce bone remodeling simply due to the prosthesis weight. **CONCLUSION.** Heavier prostheses under the effect of gravity force are related to more strain being generated around the implants. Installing more implants to support the prosthesis enables attenuating the effects observed in the bone. The simulated prostheses were not able to generate harmful values of peri-implant bone strain. ***[J Adv Prosthodont 2020;12:67-74]***

KEYWORDS: Dental implants; Finite element analysis; Prosthodontics; Bone tissue; Biomechanics

INTRODUCTION

Several studies evaluating prosthetic materials report that a light restorative material is advantageous.[1-3] A previous study[4] asserted that reinforced composite frameworks seem to be a viable alternative to traditional metal frameworks in implant prosthodontics. The authors also described the lighter framework as an advantage for the treatment. However, there is no mechanical justification in the literature demonstrating the effect of the prosthesis weight on a patient's rehabilitation. One of the most extensive restorations in dentistry is a full arch implant retained prosthesis. This prosthesis can have a large part of their structure made in metal and ceramics, leading to a higher volume of synthetic and dense material.[5-9] A full arch implant retained prosthesis can rehabilitate the patient and promote patient satisfaction[10] in cases in which the supporting tissue loss and tooth loss occur simultaneously.

Corresponding author:
João Paulo Mendes Tribst
Department of Dental Materials and Prosthodontics, São Paulo State University (Unesp), Institute of Science and Technology, Av. Eng. Fco. José Longo, 777, São José dos Campos, SP, 12245-000, Brazil
Tel. +55123947-9032: e-mail, joao.tribst@gmail.com
Received November 6, 2019 / Last Revision February 27, 2020 / Accepted February 28, 2020

The advantage of a lighter structure is indicated for obturator prostheses for maxillary defect patients, but there is no information regarding the influence of prosthesis weight for implant-retained prostheses.[11] Thus, some authors consider the all-ceramic zirconia design as an evolution from metal frameworks with acrylic or porcelain full-arch implant-supported prostheses[12] regarding the strength and load distribution during chewing. This design is the opposite from the lighter design suggested by other authors since it can be heavier than the conventional cast-metal framework, but a comparison of its mechanical effect in the maxillary bone has never been performed.

As bone strain around osseointegrated implants can induce unwanted bone remodeling with consequent loss of osseointegration,[13] it is necessary that all the choices during the surgical and prosthetic planning should be considered to optimize the biomechanical response to occlusal loads.[14] What is unknown is whether the prosthesis weight itself is already capable of causing some damage or benefit to the bone tissue around the implants. According to Wolff's law, the bone tissue may be encouraged to stay in position, depending on the magnitude of the generated strain.[13]

Another important point for the biomechanics of implant-supported prostheses is the number of implants that support the prosthesis, since it will be through them that the masticatory load will be transmitted from the outer face of the synthetic teeth to the bone tissue.[15] Thus, the literature is quite concise in stating that a larger number of implants are better for the mechanical response during mastication.[11] For example, the survival rate and patient satisfaction for implant-supported overdentures is not substantially influenced by the number of implants.[15,16] However, there are no reports on the influence of the number of implants to support the prosthesis weight.

The force acting on the synthetic teeth during chewing is the compressive force generated from the occlusal faces of the teeth making contact with the food bolus.[17] However, the gravitational force of a prosthesis in the maxilla can act in the same direction, pulling the prosthesis from the implants.

Therefore, the goal of this study was to evaluate the effect of prosthesis weight and the number of implants on the mechanical response of the bone tissue. The null hypotheses were that neither 1) the prosthesis weight, nor 2) the number of implants would influence the generated bone strain.

MATERIALS AND METHODS

A full skull model was selected from the database[18] and exported in STEP format to a computer-aided-design software (Rhinoceros Version 5.0 SR8, McNeel North America, Seattle, WA, USA). The maxilla was isolated with a transversal plane in the region of the anterior nasal spine. Next, an edentulous maxilla was constructed following the main anatomical characteristics of a healthy bone (size, shape, and absence of pathology). The bone structure was mirrored from the midline for complete construction of the virtual maxilla model, thus allowing symmetry between the antimeres. The cortical bone contained 1 mm thickness in juxtaposition with cancellous bone. A 3D volumetric model of the bone was then created based on the surface created by the curve network automatically generated with a reverse engineering tool.

External hexagon implants (10 mm × 4.1 mm) were subsequently modeled. The external thread diameter was established according to the dimensions provided by the manufacturer (as technology Titanium Fix, São José dos Campos, Brazil), and the platform showed 4.1 mm in diameter such as a conventional regular implant. The external hexagon was extruded 0.7 mm high and attached to the previously created cylindrical body.[14]

One of the evaluated factors was the number of implants (3 levels) used on the simulated surgical approach: 4, 6, or 8 equidistant implants. A mini conical abutment indicated for the screw retained prosthesis was modeled for each implant. The abutments presented centralized insertion with 2.5 × 4 mm. A three-dimensional abutment screw was modeled for each abutment, with a prosthetic screw on top of it.

Based on a generic maxillary arch, a full arch implant retained prosthesis was constructed in two different designs:

Model 1: Internal framework with a 2 mm cross-section and a 4.1 mm coping screw for each abutment. An acrylic resin model was constructed around the framework from the right second molar until the left second molar.

Model 2: Machinable framework with palatal face of all teeth made from same material of the framework and a 4.1 mm coping screw for each abutment. The veneering aesthetics presented 1 mm of thickness and was limited to the buccal face of the teeth for this prosthesis.[8]

Both prosthesis designs were associated with the simulated surgical approaches (3 levels) totaling six models with different geometries. Fig. 1 shows the 3D models.

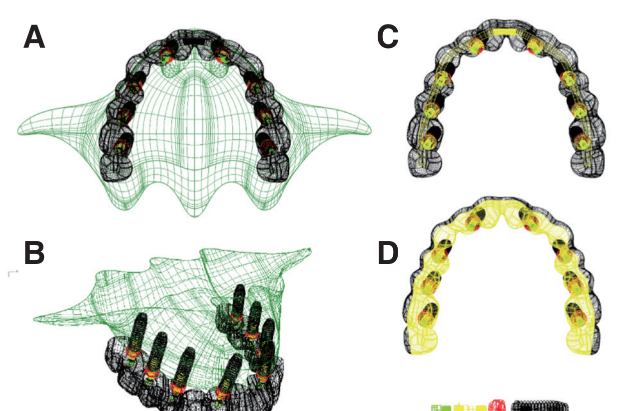

Fig. 1. Three-dimensional modeling of full arch prosthesis in occlusal and perspective view. Two designs of prosthesis and implant/abutment geometries. (A) Occlusal view of the 3D model wireframe; (B) 3D model demonstrating the implants position; (C) Prosthesis model 1, the infrastructure is completely covered by the artificial teeth; and (D) Prosthesis model 2, the infrastructure compose part of the artificial teeth.

Each solid geometry was imported to the analysis software (ANSYS 17.2, ANSYS Inc., Houston, TX, USA) in STEP format and tetrahedral elements formed the mesh. A convergence test of 10%[18] determined the total number of tetrahedral elements and nodes. Any difference in value higher than 10% during the result analysis is to be assumed as a significant difference. The mesh for the first model was composed by 644244 nodes and 368362 tetrahedral elements, with the maximum element size of 0.2 mm and an aspect ratio of 1.76. The mesh for the second model was composed by 743712 nodes and 424264 tetrahedral elements, with the maximum element size of 0.2 mm and an aspect ratio of 1.63.

The Young's modulus and Poisson's ratio of the materials were assigned to each solid component with isotropic and homogeneous behavior. The friction coefficient (μ) was set as 0.3 between all the metallic interfaces,[19] 0.65 for the cortical bone-implant interface,[20] and 0.77 for the cancellous bone-implant interface.[21] The mechanical properties of the materials and structures are summarized in Table 1.[22-34]

The standard earth gravity direction for this study was defined along the Z-axis (negative direction) of the coordinate system with 9.8065 m/s^2 of acceleration. A restriction only occurred on the bone for the Z-axis, allowing lateral strain of the peri-implant bone.[35] Thus, 15 different groups were simulated based on the geometries and prosthetic materials available for manufacturing full arch implant retained prostheses. The weight (P) of each prosthesis was estimated based on the formula: $P = m * g$, in which g is the gravitational acceleration at the point of space where the object of mass m is located. The following formula was used to calculate the mass of each material in each model: $m = v * \mu$, in which v is the volume in cm^3 and μ corresponds to the density in g/cm^3. The density of the materials was informed based on the literature, and the volume was automatically calculated through the 3D-modeling software. The prosthesis weight was then calculated after determining the material mass. The groups' distribution according to the factors of prosthesis weight (5 levels) and number of implants (3 levels) are summarized in Table 2.

Based on Wolff's law,[13] the bone strain is able to generate bone remodelling. Thus, the resulting Equivalent Strain was assumed as analysis criteria and selected for each simulation.

Table 1. Mechanical properties of each material/structure used in this study

Material/Structure	Elastic Modulus (GPa)	Poisson ratio	μ (g/cm^3)
Titanium[17,18]	110	0.35	4.50
CoCr[19,20]	220	0.30	8.00
Acrylic Resin[21,22]	2.7	0.35	1.20
Zirconia[23,24]	200	0.31	5.68
PEEK[25,26]	3.70	0.40	1.32
Feldspathic[27,28]	48.7	0.23	2.50
Cancellous bone[29]	1.37	0.30	-
Cortical bone[29]	13.7	0.30	-

Table 2. Group distribution according to prosthesis weight (5 levels) and number of implants (3 levels)

Group	Number of implants	Prosthesis weight (in g)	Prosthesis design	Volume (in cm^3)		Peak of microstrain in the peri-implant bone tissue
				Framework	Esthetic material	
4i10	4	$\cong$ 10 g	PEEK framework with acrylic resin tooth	6.53	1.56	6.29
6i10	6					3.89
8i10	8					1.29
4i15	4	$\cong$ 15 g	Titanium framework with acrylic resin tooth	6.53	1.56	7.64
6i15	6					4.61
8i15	8					1.89
4i20	4	$\cong$ 20 g	CoCr framework with acrylic resin tooth	6.53	1.56	10.01
6i20	6					5.79
8i20	8					4.60
4i40	4	$\cong$ 40 g	Zirconia framework with ceramic veneer	1.22	6.94	2.23
6i40	6					13.73
8i40	8					4.67
4i60	4	$\cong$ 60 g	CoCr framework with ceramic veneer	1.22	6.94	39.99
6i60	6					18.88
8i60	8					7.86

RESULTS

The generated strain values in the maxilla as a function of the weight of each prosthesis were plotted in colorimetric graphs in Fig. 2. It was possible to observe that the heavier the prosthesis, the more strain concentrated in the bone tissue. Moreover, the more implants used to support the prostheses, the better the distribution of peri-implant strain. It was possible to observe that the strain was homogeneously concentrated in the main support zone in the peri-implant region between all the implants.

The peak value of each group was exported from the

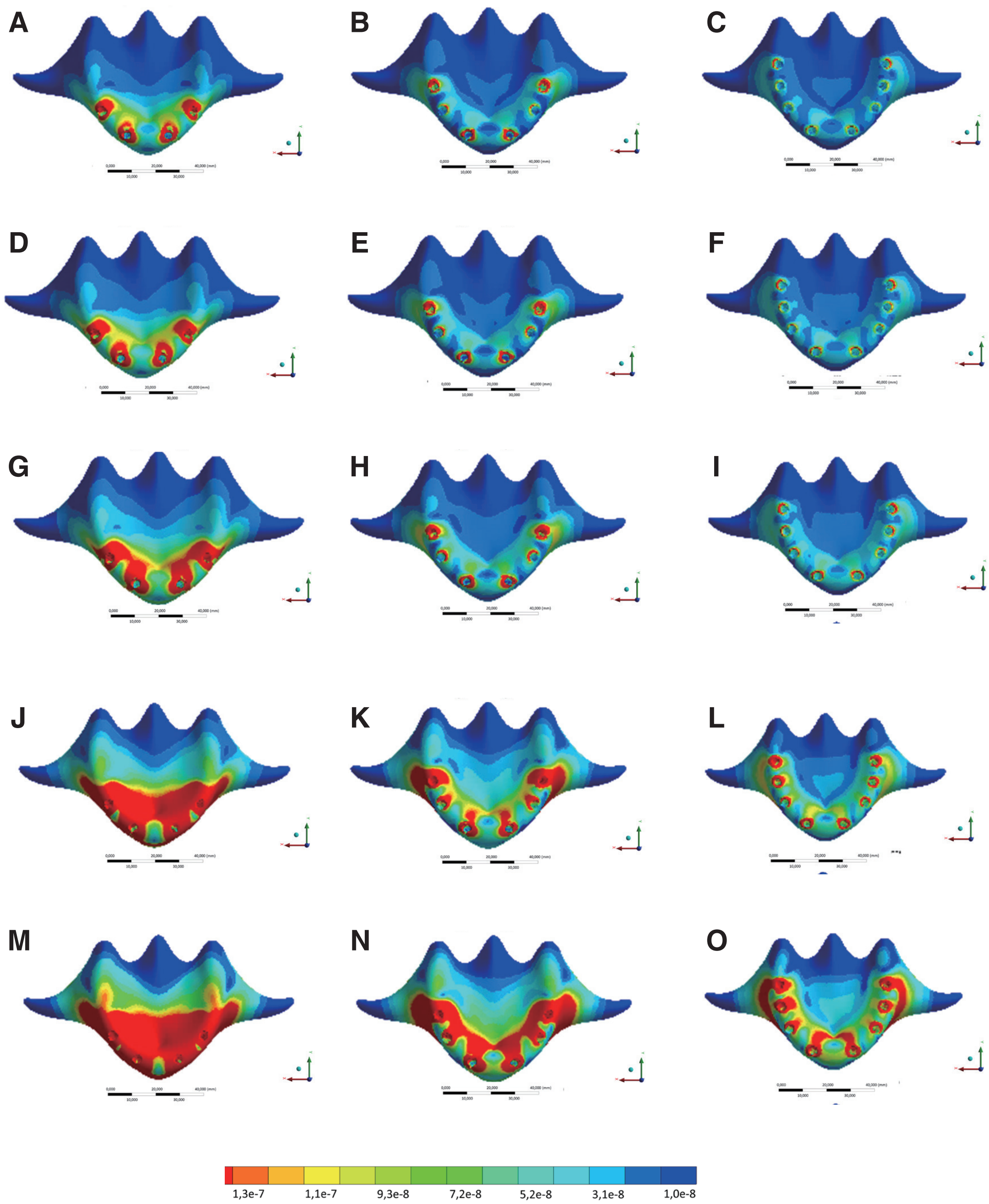

Fig. 2. Equivalent strain in the bone according to implant number (Rows) and weight (Lines). (A) 4i10, (B) 6i10, (C) 8i10, (D) 4i15, (E) 6i15, (F) 8i15, (G) 4i20, (H) 6i20, (I) 8i20, (J) 4i40, (K) 6i40, (L) 8i40, (M) 4i60, (N) 6i60, (O) 8i60.

analysis software to quantify the strain (Table 2). The values were also plotted in line graphs to project the generated strain trend as a function of the prosthesis weight according to the number of implants.

Based on the proposed linear regression between the prosthesis weight and the strain generated around the implants, the coefficient of determination (R^2) was 98% for the situation with 4 implants, 98% for 6 implants, and 86% for 8 implants (Fig. 3). Thus, the prosthesis weight was strongly related to the bone strain, regardless of the surgical approach. In addition, considering the inclination of the plotted lines, it was possible to affirm that the more implants installed, the less the amount of strain generated in the bone considering a prosthesis of the same weight.

According to Wolff's law,[13] strain values below 50 mm/mm are able to promote bone remodeling by disuse, and that values above 3000 mm/mm are able to promote bone remodeling by micro-damage. The most critical situation herein was the use of a 60 g prosthesis supported by 4 implants (group 4i85), showing the largest calculated strain magnitude of 39.9 mm/mm. However, there was no simulated group which could prevent or promote bone remodeling simply due to the prosthesis weight (up to 60 g).

DISCUSSION

This study evaluated the influence of the weight of full arch implant retained prosthesis and the number of implants on the bone strain in maxilla. The results showed that there was a direct trend between the prosthesis weight and the calculated strain. Therefore, the first hypothesis was rejected. It was also possible to observe that the more implants installed, the less magnitude calculated around the implants, thus also rejecting the second hypothesis.

Several studies report that light restorative materials are advantageous,[2] but without exactly explaining the classification parameter between a light and heavy material and without explaining the advantage for the restorative treatment. Thus, based on the results herein, a light prosthesis is advantageous to decrease the strain generated around the supporting tissue as a function of the material weight. There are few reports in medicine evaluating the prosthesis weight.[36] There are no studies in dentistry which have evaluated the influence of the prosthesis weight on the biomechanical response of the supporting tissues.

There is a general concern that the prosthesis is too heavy to impair the mechanical performance of rehabilitation.[3] Thus, seeking designs and light materials can facilitate creating a prosthesis that more accurately mimics the missing part of the body. However, a concern seems to be different for intraoral prostheses. An indirect rehabilitation of 14 adult teeth supported by implants was simulated herein, and no microstrain values which could be harmful for any of the bone tissue were calculated.[13,14] Thus, dentists and technicians can choose the design and material which are advantageous for dissipating the masticatory load, not simply considering light or heavy materials.

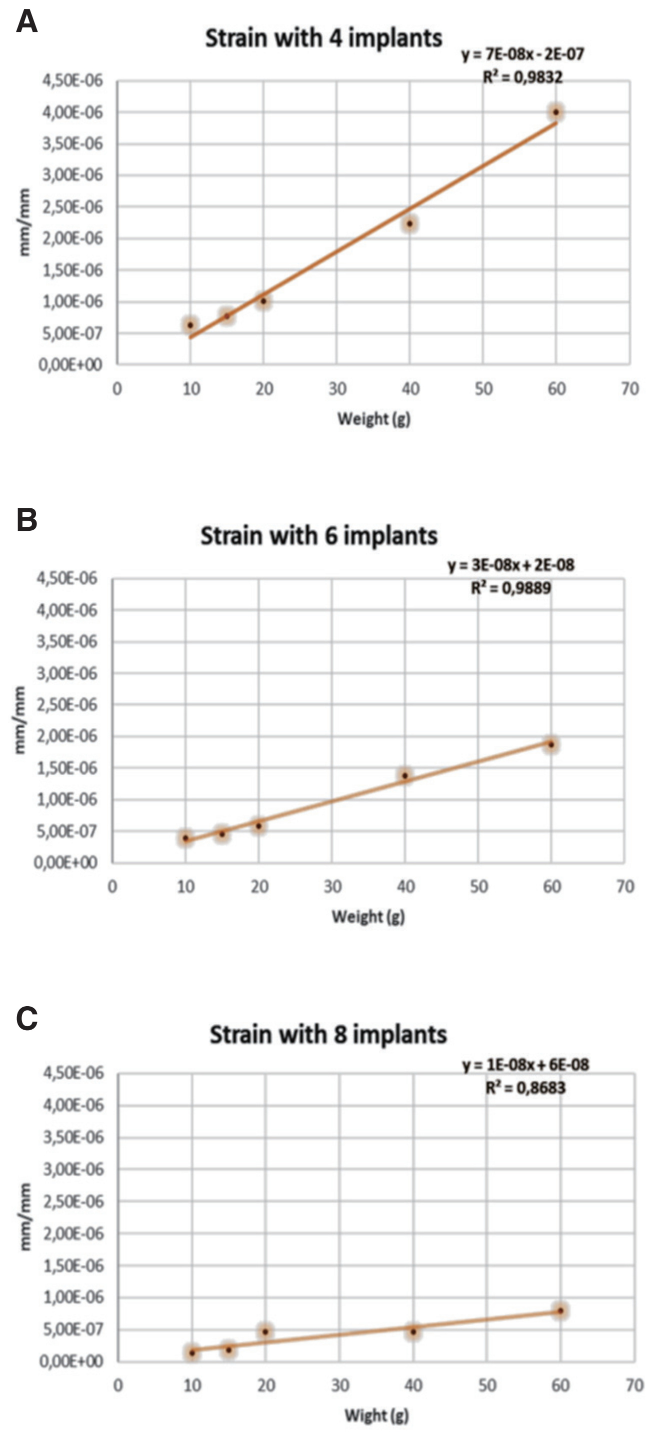

Fig. 3. Linear regression between the prosthesis weight and the strain. (A) Linear trend between the weight of the prosthesis and mirostrain in the bone tissue for situations with four implants; (B) Linear trend between the weight of the prosthesis and mirostrain in the bone tissue for situations with six implants; and (C) Linear trend between the weight of the prosthesis and mirostrain in the bone tissue for situations with eight implants.

It is important to note that the simulated situation in all models consists of a total prosthesis supported by implants. Thus, clinical situations with dentures supported by teeth with the presence of the periodontal ligament may modify the generated biomechanical response due to the exerted forces, thus presenting different bone deformation values for the application of Wolff's law.[13] This is because the periodontal ligament enables micro movements between each of the dental abutments, in addition to containing a layer of hard lamina composed of cortical bone around the connective tissue of the ligament fibers.[37,38] All of these structures are different from the bone/implant interface simulated herein. Therefore, a dental abutment under the same compressive force applied presents lower bone deformation values compared to a dental implant.[37] However, the dynamics generated by the compression of the periodontal ligament enable orthodontic movements with variable forces and are time dependent.[38] Thus, it is not recommended to extrapolate these results for natural teeth supported prostheses, and further studies evaluating the effect of tensile forces on the biomechanics of these prostheses should be conducted.

The lightest simulated prosthesis presented infrastructure in PolyEtherEtherKetone (PEEK) coated with acrylic resin.[5] This design had an approximate weight of 14 g and the lowest bone strain values. However, there are no longitudinal studies which demonstrate the success of this rehabilitation modality. The second lighter prosthesis presented a titanium infrastructure and was fully coated with acrylic resin.[7] This restorative modality has proven clinical success of approximately 15 years, observing chipping and synthetic dentition wear as the main defects.[7] However, this treatment is not commonly used because of the difficulty of casting titanium alloys, since titanium is much more reactive to oxygen than conventional dental casting alloys.[39] The use of titanium-machined infrastructure could solve these difficulties[8,40] and optimize the use of this metal which presents proven longitudinal results[35] and less bone strain due to a lighter prosthesis. Another option instead of titanium is the use of an infrastructure in CoCr (Cobalt-chromium). CoCr alloys are widely used in dentistry due to their casting ease, low cost and adequate strength, but they are high density alloys which are difficult to polish and finish.[41] In the strain results generated by the prosthesis weight, a CoCr infrastructure with similar geometry to the titanium infrastructure was able to increase the prosthesis weight by 55% and increase the strain around the implants. However, Bhering *et al.*[42] evaluated the strain generated around implants during the incidence of masticatory loading and argued that the use of CoCr as an infrastructure material was more appropriate than titanium infrastructures by minimizing strain around the peri-implant tissue.

All the previously reported prostheses were constructed containing an acrylic resin-coated infrastructure.[40] Thus, a second design used for manufacturing prostheses with machined infrastructures[43] was simulated in order to simulate the possibly heavier designs of intraoral prostheses. This infrastructure design extends to the palate of the upper teeth and its use is directly related to the use of zirconia in dentistry.[43] There are reports on the success of full arch prostheses with infrastructure in zirconia of more than 3 years.[4] Its use is justified by the high resistance of this material, eliminating the application of a layer of opaque material in the infrastructure due to the white color of the material and wear resistance.[43] It was one of the most heavily simulated prostheses in the present study, and generated the second most microstrain around the implants. In addition, zirconia may exhibit wear on juxtaposed metal structures.[44] Moreover, there are studies which define that a zirconia infrastructure presents a similar biomechanical response to a titanium infrastructure,[34] while other reports define that more rigid materials are less damaging to the bone tissue.[45] These studies which compare implant infrastructures generally use the mechanical properties of the elastic modulus and the Poisson's coefficient of the simulated materials.[34,45]

The elastic modulus and the Poisson's coefficient are properties related to the elasticity and plasticity of each material, allowing more or less displacement depending on the applied force. In addition to the elastic modulus, the density of each simulated structure in the present study was inserted to observe the effect of gravity as a function of weight. Thus, a CoCr infrastructure presents an elastic modulus which is very close to the elastic modulus of zirconia, and often materials with quite similar mechanical response are assumed in many simulations.[12] However, the density of CoCr is greater than that of zirconia, which causes the use of this metal to increase the final prosthesis weight. Thus, a prosthetic piece machined in CoCr will be subjecting the supporting tissue to higher peri-implant strain values than if the prosthetic piece was machined in zirconia.

Another factor evaluated herein was the simulation of different surgical approaches by installing 4, 6, or 8 implants to support the full arch prosthesis. Previous studies have reported that the more implants installed (respecting the minimum space between each implant), the better the mechanical response of bone tissue to masticatory loads.[15,16] Likewise, the use of 8 implants softened the bone strain generated as a function of the prosthesis weight.

In observing the linear distribution of the generated strain (Fig. 3), it is possible to note that the strain peak magnitude decreases as a function of the prosthesis weight in using 8 implants in comparison with the prosthesis with 4 implants. However, the relationship between the number of implants and the generated strain is not a direct proportion, since twice as many implants (8 instead of 4) did not generate twice as much bone strain. This probably occurs because of the shape of the maxillary arch, which has a thinner anterior region than the posterior region, and also because the distribution of 4 implants is not exactly equidistant from the distribution of 8 implants. This theory reinforces the need to use three-dimensional anatomical models in numerical simulations of implant prosthesis, since simplified geometric models such as blocks[14] or cylinders[17] may propagate a symmetry force distribution in the bone tissue.

The main novelty of this study over other reports in the literature is the simulation of tensile forces in the prosthesis, representing the effect generated by the structural weight in the bone tissue. Although the load exerted during mastication is simulated in several previous studies,[5,7,14,16,19,35,37,45] which seek to study the instant of maximum average force capable to generate mechanical problems in the prosthesis/bone, this simulation included a momentary load. The effect of gravity on the prosthesis is present throughout the patient's life, especially during the rest position where there is no contact between the antagonist tooth.[46] The option of simulating a maxillary prosthesis occurred due to gravity acting against the masticatory forces, and there were no reports of this in the scientific literature.

It is worth noting that the implemented methodology was a numerical computational simulation, and that simplifications of the method do not enable direct extrapolation of the results found for dental clinicians.[17] This is due to the simulated materials being homogeneous with no internal defects such as bubbles or pores. Maximum Principal Stress, Minimum Principal Stress or von-Misses stress would not assist in achieving the aim of the present study, but these analysis criteria can be helpful for chewing and overloading simulations. Considering the final density, it is possible to understand that the simulated prostheses present a close final weight to the real prostheses. However, they were overestimated due to the homogeneity of the simulated structures. The limitation of the FEA model was that all implants present an ideal position, there are no defects or gaps between the mini-conical abutment and the prostheses, there is a perfectly symmetric maxilla, and there is no saucerization of the peri-implant bone of any implant. Despite these limitations arising from an idealized situation, the results presented herein can serve as a basis for new hypotheses, clinical studies and even assist dental laboratory decisions in conjunction with the literature data.

Therefore, the following could be concluded from this study:

There is a directly proportional relationship between the prosthesis weight and the strain generated around the osseointegrated implants. Therefore, the installation of more implants to support the prosthesis enables attenuating the effects observed in the bone considering the prosthesis weight. Prosthetic weights of 10 to 60 g were not able to generate harmful values of peri-implant bone strain in situations with at least four implants.

ORCID

João Paulo Mendes Tribst *https://orcid.org/0000-0002-5412-3546*
Amanda Maria de Oliveira Dal Piva *https://orcid.org/0000-0002-3844-2053*
Alexandre Luiz Souto Borges *https://orcid.org/0000-0002-5707-7565*
Vinicius Anéas Rodrigues *https://orcid.org/0000-0002-7209-868X*
Marco Antonio Bottino *https://orcid.org/0000-0003-0077-3161*
Cornelis Johannes Kleverlaan *https://orcid.org/0000-0002-3218-8031*

REFERENCES

1. Skirbutis G, Dzingutė A, Masiliūnaitė V, Šulcaitė G, Žilinskas J. A review of PEEK polymer's properties and its use in prosthodontics. Stomatologija 2017;19:19-23.
2. Ohkubo C, Sato Y, Nishiyama Y, Suzuki Y. Titanium removable denture based on a one-metal rehabilitation concept. Dent Mater J 2017;36:517-23.
3. Tran L, Caldwell R, Quigley M, Fatone S. Stakeholder perspectives for possible residual limb monitoring system for persons with lower-limb amputation. Disabil Rehabil 2018;42:1-8.
4. Pera F, Pesce P, Solimano F, Tealdo T, Pera P, Menini M. Carbon fibre versus metal framework in full-arch immediate loading rehabilitations of the maxilla - a cohort clinical study. J Oral Rehabil 2017;44:392-7.
5. Larsson C, Vult von Steyern P, Nilner K. A prospective study of implant-supported full-arch yttria-stabilized tetragonal zirconia polycrystal mandibular fixed dental prostheses: three-year results. Int J Prosthodont 2010;23:364-9.
6. Sereno N, Rosentritt M, Jarman-Smith M, Lang R, Kolbeck C. In-vitro performance evaluation of polyetheretherketone (PEEK) implant prosthetics with a cantilever design. Clin Oral Implants Res 2015;26:296.
7. Tiossi R, Gomes ÉA, Faria ACL, Rodrigues RCS, Ribeiro RF. Biomechanical behavior of titanium and zirconia frameworks for implant-supported full-arch fixed dental prosthesis. Clin Implant Dent Relat Res 2017;19:860-6.
8. Ravald N, Dahlgren S, Teiwik A, Gröndahl K. Long-term evaluation of Astra Tech and Brånemark implants in patients treated with full-arch bridges. Results after 12-15 years. Clin Oral Implants Res 2013;24:1144-51.
9. Belur D, Nagy WW. An alternative digital workflow for fabricating a mandibular implant-supported complete fixed dental prosthesis with limited restorative space: A clinical report. J Prosthet Dent 2018;120:1-4.
10. Huh YH, Shin HJ, Kim DG, Park CJ, Cho LR. Full mouth fixed implant rehabilitation in a patient with generalized aggressive periodontitis. J Adv Prosthodont 2010;2:154-9.
11. Ramsey WO. Comparison of weight reduction in different designs of solid and hollow obturator prostheses. J Prosthet Dent 1990;63:602.
12. Ouzer A. The evolution and fabrication of implant-supported full-arch hybrid prostheses. From conventional casted metal to an all-ceramic zirconia. N Y State Dent J 2015;81:44-9.
13. Frost HM. Wolff's Law and bone's structural adaptations to mechanical usage: an overview for clinicians. Angle Orthod 1994;64:175-88.
14. Tribst JP, Rodrigues VA, Dal Piva AO, Borges AL, Nishioka RS. The importance of correct implants positioning and masticatory load direction on a fixed prosthesis. J Clin Exp Dent 2018;10:e81-7.
15. Lee JY, Kim HY, Shin SW, Bryant SR. Number of implants for mandibular implant overdentures: a systematic review. J Adv Prosthodont 2012;4:204-9.
16. Ogawa T, Dhaliwal S, Naert I, Mine A, Kronstrom M, Sasaki K, Duyck J. Impact of implant number, distribution and

prosthesis material on loading on implants supporting fixed prostheses. J Oral Rehabil 2010;37:525-31.
17. Dal Piva AMO, Tribst JPM, Borges ALS, Souza ROAE, Bottino MA. CAD-FEA modeling and analysis of different full crown monolithic restorations. Dent Mater 2018;34:1342-50.
18. Tribst JPM, de Oliveira Dal Piva AM, Borges ALS, Bottino MA. Influence of custom-made and stock mouthguard thickness on biomechanical response to a simulated impact. Dent Traumatol 2018;34:429-37.
19. Alkan I, Sertgöz A, Ekici B. Influence of occlusal forces on stress distribution in preloaded dental implant screws. J Prosthet Dent 2004;91:319-25.
20. Yu HY, Cai ZB, Zhou ZR, Zhu MH. Fretting behavior of cortical bone against titanium and its alloy. Wear 2005;259:910-8.
21. Grant JA, Bishop N, Götzen N, Sprecher C, Honl M, Morlock M. Artificial composite bone as a model of human trabecular bone: The implant-bone interface. J Biomech 2007;40:1158-64.
22. Danza M, Palmieri A, Farinella F, Brunelli G, Carinci F, Girardi A, Spinelli G. Three dimensional finite element analysis to detect stress distribution in spiral implants and surrounding bone. Dent Res J (Isfahan) 2009;6:59-64.
23. Opalinska A, Malka I, Dzwolak W, Chudoba T, Presz A, Lojkowski W. Size-dependent density of zirconia nanoparticles. Beilstein J Nanotechnol 2015;6:27-35.
24. Oğuz K, Emir Y, Fehmi E. Static, dynamic and fatigue behaviors of dental implant using finite element method. Adv Eng Softw 2006;37:649-58.
25. Hyslop DJS, Abdelkader AM, Cox A, Fray DJ. Electrochemical synthesis of a biomedically important Co-Cr alloy. Acta Materialia 2010;58:3124-30.
26. Nagai E, Otani K, Satoh Y, Suzuki S. Repair of denture base resin using woven metal and glass fiber: effect of methylene chloride pretreatment. J Prosthet Dent 2001;85:496-500.
27. Polymethylmethacrylate (PMMA, Acrylic): https://www.makeitfrom.com/material-properties/Polymethylmethacrylate-PMMA-Acrylic/. Accessed 22/7/19
28. Çaglar A, Bal BT, Karakoca S, Aydın C, Yılmaz H, Sarısoy 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.
29. Nielsen R, Wilfing G. Zirconium and zirconium compounds. Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co. KGaA, 2000.
30. Anguiano-Sanchez J, Romero OM, Siller HR, Díaz-Elizondo JA, Flores-Villalba E, Rodríguez CA. Influence of PEEK coating on hip implant stress shielding: a finite element analysis. Comp Math Method Med 2016;2016:6183679.
31. Why PEEK: http://www.hmp.com.tw/peek/. Accessed 22/7/19
32. Ramos Nde C, Campos TM, Paz IS, Machado JP, Bottino MA, Cesar PF, Melo RM. Microstructure characterization and SCG of newly engineered dental ceramics. Dent Mater 2016;32:870-8.
33. Coldea A, Swain MV, Thiel N. Mechanical properties of polymer-infiltrated-ceramic-network materials. Dent Mater 2013;29:419-26.
34. Madfa AA, Kadir MR, Kashani J, Saidin S, Sulaiman E, Marhazlinda J, Rahbari R, Abdullah BJ, Abdullah H, Abu Kasim NH. Stress distributions in maxillary central incisors restored with various types of post materials and designs. Med Eng Phys 2014;36:962-7.
35. Tribst JPM, de Morais DC, Alonso AA, Piva AMOD, Borges ALS. Comparative three-dimensional finite element analysis of implant-supported fixed complete arch mandibular prostheses in two materials. J Indian Prosthodont Soc 2017;17:255-60.
36. Battaglia S, Taddei P, Tozzi S, Sudanese A, Affatato S. Toward the interpretation of the combined effect of size and body weight on the tribological performance of total knee prostheses. Int Orthop 2014;38:1183-90.
37. Kumar GA, Kovoor LC, Oommen VM. Three-dimensional finite element analysis of the stress distribution around the implant and tooth in tooth implant-supported fixed prosthesis designs. J Dent Implants 2011;1:75-9.
38. Li Y, Jacox LA, Little SH, Ko CC. Orthodontic tooth movement: The biology and clinical implications. Kaohsiung J Med Sci 2018;34:207-14.
39. Koizumi H, Ishii T, Okazaki T, Kaketani M, Matsumura H, Yoneyama T. Castability and mechanical properties of Ti-15Mo-5Zr-3Al alloy in dental casting. J Oral Sci 2018;60:285-92.
40. Meloni SM, De Riu G, Pisano M, Lolli FM, Deledda A, Campus G, Tullio A. Implant restoration of edentulous jaws with 3D software planning, guided surgery, immediate loading, and CAD-CAM full arch frameworks. Int J Dent 2013;2013:683423.
41. Hjalmarsson L. On cobalt-chrome frameworks in implant dentistry. Swed Dent J Suppl 2009;201:3-83.
42. Bhering CL, Mesquita MF, Kemmoku DT, Noritomi PY, Consani RL, Barão VA. 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.
43. Papaspyridakos P, Kang K, DeFuria C, Amin S, Kudara Y, Weber HP. Digital workflow in full-arch implant rehabilitation with segmented minimally veneered monolithic zirconia fixed dental prostheses: 2-year clinical follow-up. J Esthet Restor Dent 2018;30:5-13.
44. Stimmelmayr M, Edelhoff D, Güth JF, Erdelt K, Happe A, Beuer F. Wear at the titanium-titanium and the titanium-zirconia implant-abutment interface: a comparative in vitro study. Dent Mater 2012;28:1215-20.
45. Menini M, Pesce P, Bevilacqua M, Pera F, Tealdo T, Barberis F, Pera P. Effect of framework in an implant-supported full-arch fixed prosthesis: 3D finite element analysis. Int J Prosthodont 2015;28:627-30.
46. Yilmaz G, Uginčius P, Sebik O, Türker KS. Tonic activity of the human temporalis muscle at mandibular rest position. Arch Oral Biol 2015;60:1645-9.