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Can the modeling for simplification of a dental implant surface affect the accuracy of 3D finite element analysis?

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ABSTRACT

The aim of this study was to assess stress/strain of different implant modeling simplifications by 3D-FEA. Three variation of external hexagon implant ($\varnothing 3.75 \times 10$ mm) supporting one molar crown were simulated: A (no threads); B (slightly threads simplification); C (original design). 200 N (axial) and 100 N (oblique) were applied. Cortical bone was evaluated by maximum principal stress and microstrain qualitatively and quantitatively (ANOVA and Tukey *post hoc* ($p < 0.05$)). Higher stress levels ($p < 0.05$) were observed in model A. Models B and C presented similar stress transmission. It was possible to conclude that slightly simplification should be used for studies evaluating stress transferring for bone tissue.

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Dental implants; finite element analysis; biomechanics

Introduction

The process of osseointegration can be affected by the interaction between biological and mechanical factors varying from bone quality to the treatment of the implant surface. Therefore, the understanding of the influence of these factors in implant-supported rehabilitation must be improved in order to obtain better clinical results (Chung et al. 2008).

In this context, biomechanical studies have been used in different areas of dentistry to improve understanding of the relationship between dental restorative materials and buccal tissues (Choi et al. 2014). Nowadays, different methodologies are used to assess the biomechanics – under static loads – in the implantology, such as photoelasticity (Pellizzer et al. 2014), digital image correlation (Tiossi et al. 2013), strain gauge (Sallam et al. 2012), and finite element analysis, or FEA (Dayrell et al. 2015).

Several scientific works use FEA in implantology (Liang et al. 2015; Lofaj et al. 2015; Ramos Verri et al. 2015; Sotto-Maior et al. 2016). These works describe different methodological steps to obtain the 3D model. Consequently, each work might generate different results when the same situation is tested. The accuracy of FEA can be influenced

by factors such as the geometric detail of the object to be modeled and analyzed (i.e. surface simplification), the applied boundary conditions, the functional loading, and the mechanical properties of materials (Choi et al. 2014). On the issue of surface simplification in implantology, different techniques are used to simulate the surface of an implant using the computer-aided design (CAD) provided by the implant company. These include total elimination of the threads (smoothed surface) (Barão et al. 2013), slight simplification of the implant but sustaining the threads (Ramos Verri et al. 2015), and no simplification of the implants or threads (Pessoa et al. 2014). However, the literature does not describe how much of this simplification can be performed without losing the accuracy of the analysis.

Based on the topics above, the aim of this study was to use FEA 3D to assess the different types of modeling used in the literature for simplification of an implant surface and the influences these modeling types have on the stress/strain distributions on the bone tissue around implant. The present study tests the hypothesis that the modeling technique for simplifying an implant surface can modify the stress/strain distribution on the cortical bone.

Material and methods

Experimental design

This research follows the methodology of previous studies (de Faria Almeida et al. 2014; Moraes et al. 2015; Ramos Verri et al. 2015). Three 3D models varying the simplification of the implant surface were simulated with two load variations (Table 1).

Three-dimensional modeling

Each 3D model was composed of a mandibular bone section relative to the second molar region and an external hexagon implant of $\varnothing 3.75 \times 10$ mm (Conexão[®] Sistemas de Prótese Ltda., Aruja, SP, Brazil), supporting a screw-retained single crown.

The bone tissue was composed of trabecular bone in the center, surrounded by a 1 mm layer of cortical bone. The bone tissue was obtained using decomposition of the computerized tomography with InVesalius[®] software (CTI, Campinas, SP, Brazil) and surface simplification with Rhinoceros 4.0[®] software (NURBS Modeling for Windows, Seattle, WA, USA).

The modeling of the implant was performed with three variations: model A, a total elimination of the threads in

the CAD (smoothed surface); model B, a slight simplification of the implant sustaining the threads in the CAD; and model C, no simplification of the implant or threads in the CAD (Figure 1). The abutment (UCLA, Conexão[®] Sistemas de Prótese Ltda., Aruja, SP, Brazil) and feldspathic porcelain simulated were the same for all situations compatible to the implant type.

Implants, abutments, crowns, and fixation screws were simplified using SolidWorks[®] 2010 (SolidWorks Corp[®], Waltham, MA, USA) and Rhinoceros 4.0[®]. The software was the same for all models. Finally, all geometries were exported for discretization in the finite element software FEMAP 11.1.2[®] (Siemens PLM Software Inc., Santa Ana, CA, USA).

Three-dimensional FE configuration

The FEMAP 11.1.2[®] software was used to do the finite element models in pre- and post-processing steps. In the pre-processing step, meshes using tetrahedral parabolic solid elements were generated (Figure 1). The number of nodes and elements for each model is illustrated in the Table 2. All mechanical properties of each simulated material were attributed to the meshes using values from the literature (Table 3). All materials were considered isotropic,

Table 1. Specifications of the models.

Model	Loading	Description	Nodes/Elements
1	Axial	Dental implant (3.75 × 10 mm), external hexagon, simplification with total elimination of the threads	461.677/308.917
2		Dental implant (3.75 × 10 mm), external hexagon, slight simplification of the implant sustaining the threads	462.059/305.609
3		Dental implant (3.75 × 10 mm), external hexagon, no simplification in the thread	597.768/364.982
4	Oblique	Dental implant (3.75 × 10 mm), external hexagon, simplification with total elimination of the threads	461.677/308.917
5		Dental implant (3.75 × 10 mm), external hexagon, slight simplification of the implant sustaining the threads	462.059/305.609
6		Dental implant (3.75 × 10 mm), external hexagon, no simplification in the thread	597.768/364.982

Figure 1. Mesh of generated models simulating a real clinical situation, mesial view: (A) simplification with total elimination of the threads in the CAD; (B) slight simplification of the threads in the CAD, arrows illustrating the axial load of 200 N, 50 N at each cusp tip; (C) no simplification of the threads in the CAD, arrows illustrating the oblique load of 100 N, 50 N at each lingual cusp tip.

Table 2. Mechanical properties of materials used in model.

Structures	Elastic modulus (λ) (GPa)	Poisson ratio (ν)	References
Trabecular bone	1.37	0.3	(Ramos Verri et al. 2015)
Cortical bone	13.7	0.3	(Ramos Verri et al. 2015)
Titanium (implant)	110.0	0.35	(Ramos Verri et al. 2015)
NiCr alloy	206.0	0.33	(Eraslan et al. 2005)
Feldspathic porcelain	82.8	0.35	(Ramos Verri et al. 2015)

Table 3. Values of the mean and standard deviation of the maximum principal stress and microstrain on bone tissue.

Models	Loading	Mean/ Standard deviation	
		Maximum principal stress	Microstrain*
A – simplification with total elimination of the threads	Axial	-0.435 ± 0.263	0.000337 ± 0.0000670
B – slight simplification of the implant sustaining the threads	Axial	-0.244 ± 0.168	0.000149 ± 0.0000394
C – no simplification in the thread	Axial	-0.235 ± 0.180	0.000151 ± 0.0000310
A – simplification with total elimination of the threads	Oblique	6.577 ± 9.971	0.00112 ± 0.000773
B – slight simplification of the implant sustaining the threads	Oblique	2.747 ± 2.731	0.000574 ± 0.000460
C – no simplification in the thread	Oblique	2.645 ± 2.846	0.000510 ± 0.000353

*Values $\times 10^{-6}$.

homogeneous, and linearly elastic. In the post-processing step, the FEMAP software was utilized for reading and plotting of stress and strain maps obtained by the mathematical calculations using the NEi Nastran 11.1[®] software (Noran Engineering, Inc., Westminster, CA, USA), which will be described in more detail in the FE analysis section.

Interface conditions, boundary conditions, and loading

The interface conditions were also simulated in the pre-processing step. Thus, abutment/implant penetration types were assumed as symmetric contact (by NeiNastran[®] analysis) and all other contacts (cortical bone/trabecular bone; cortical bone/implant; trabecular bone/implant; internal implant threads/screw threads; screw seating surface/abutment seating surface; abutment/feldspathic ceramic) were assumed as symmetric welded (by NeiNastran[®] analysis). The boundary conditions were fixed in all axes (x , y , and z) at both bone block sections (anterior and posterior faces) (Ramos Verri et al. 2015). To simulate a real clinical situation, the applied force was 200 N axially, with 50 N at each cusp tip, and 100 N obliquely, with 50 N at each lingual cusp tip (Ramos Verri et al. 2015) (Figure 1(c)).

FE analysis

To obtain the results, all analyses were processed using NEi Nastran 11.1[®] software. The processing analysis of the models was performed on a workstation (HP Workstation[®] Z200, São Paulo, Brazil) with the following characteristics: Intel[®] Xeon[®] processor x3470, 16 GB of RAM, and 2 TB of HD. After the analyses, the results were transferred to the FEMAP 11.1.2[®] software for graphic visualization of the stress and strain maps of the cortical bone tissue.

Maximum principal stress maps and microstrain maps (μ -strain or strain $\times 10^{-6}$) were used to evaluate the cortical bone tissue surrounding the dental implant. The unit of measurement in this study was the megapascal (MPa) to maximum principal stress.

Statistical analysis

Analysis of variance (ANOVA) and the Tukey *post hoc* test were performed to verify the influence of different modeling types on stress/strain distributions for the cortical bone tissue. Sigma Plot 12.3[®] (Systat Software Inc., San Jose, CA, USA) performed all statistical analyses and values of $p < 0.05$ were considered statistically significant, according to studies in the literature (de Faria Almeida et al. 2014; Ramos Verri et al. 2015).

Results

Maximum principal stress on cortical bone

The modeling modified the stress distribution on the cortical bone tissue ($p < 0.001$; Figure 2). Under axial loading, models B and C showed similar compressive stress distribution ($p = 0.974$), but model A showed a different pattern of stress distribution (A vs. B, $p < 0.001$; A vs. C, $p < 0.001$; Figure 3).

The oblique load statistically increased the stress for all models ($p < 0.001$; Figure 2). Furthermore, of the three models, model A showed the highest stress values on the cortical bone tissue surrounding the dental implant (A vs. B, $p = 0.004$; A vs. C, $p = 0.004$; Figure 4), particularly the traction stress ($p < 0.001$; Figure 5). Nevertheless, models B and C showed similar biomechanical behavior ($p = 0.996$; Figures 4 and 5). The mean and standard deviation values can be seen in Table 3.

Figure 2. Mean and standard error values for the maximum principal stress on the cortical bone.

Notes: Differences between uppercase and lowercase letters indicate statistically significant results (A,a; B,b). Equal letters indicate no statistically significant results (b,b; B,B).

Figure 3. Maximum principal stress for axial loading, occlusal view. (A) simplification with total elimination of the threads in the CAD; (B) slight simplification of the threads in the CAD; (C) no simplification of the threads in the CAD.

Figure 4. Maximum principal stress maps for oblique loading, occlusal view. (A) simplification with total elimination of the threads in the CAD; (B) slight simplification of the threads in the CAD; (C) no simplification of the threads in the CAD.

Microstrain on cortical bone

Compared to the other models, model A statistically increased the microstrain on the cortical bone tissue surrounding the dental implant under axial loading (A vs. B, $p = 0.038$; A vs. C, $p = 0.039$, Figure 6), but models B and C showed no statistically significant difference ($p = 1.000$).

For all models, the oblique loading increased the microstrain on the cortical bone tissue compared to axial loading ($p < 0.001$; Figure 7). Furthermore, the microstrain increase in model A was statistically significant compared with that of models B ($p < 0.001$) and C ($p < 0.001$). However, there was no statistically significant

Figure 5. Mean and standard error values for the maximum principal stress on the cortical bone, analysis of traction stress and compressive stress under oblique loading.

Notes: Different uppercase letters indicate statistically significant results (A,B). Equal uppercase letters indicate no statistically significant results (B,B). Equal lowercase letters indicate no statistically significant results (b,b).

Figure 6. Mean and standard error values for microstrain on the cortical bone.

Notes: Differences between uppercase and lowercase letters indicate statistically significant results (A,a; B,b). Equal letters indicate no statistically significant results (b,b; B,B).

Figure 7. Microstrain maps for axial loading, occlusal view. (A) simplification with total elimination of the threads in the CAD; (B) slight simplification of the threads in the CAD; (C) no simplification of the threads in the CAD.

Figure 8. Microstrain maps for oblique loading, occlusal view. (A) simplification with total elimination of the threads in the CAD; (B) slight simplification of the threads in the CAD; (C) no simplification of the threads in the CAD.

difference between models B and C ($p = 0.703$; Figure 8). The mean and standard deviation values can be seen in Table 3.

Discussion

The modeling technique modified the stress and strain values on the cortical bone tissue around the implant when a major alteration – the total elimination of the threads – was performed (model A), but a slight simplification in the thread (model B) showed no statistically significant difference compared to no simplification in the thread (model C). Thus, the hypothesis of study was partially accepted. This can be justified because the threads increase the contact area between the implant and bone, helping dissipate interfacial stresses (Huang et al. 2007, 2008). Another factor is the major shear force in model A, since the threads offer stouter resistance to the shear force by increasing surface friction (Huang et al. 2008); this alters the stress and strain distribution on the bone/implant interface (Matsunaga et al. 2013).

Our results showed similar stress and strain distribution on cortical bone tissue between models B and C even though there was a slight difference between the mean values obtained (Table 4). It is probably due to changes in the threads of the implant. The difference between the mean values obtained is justified by the simplification of the apical area of the implant. In this context, the literature has shown differences in the stress distribution among different thread shapes; however, the studies performed macro alteration in the thread shapes (e.g. square and triangular threads) in addition to alteration in the body implant (e.g. stepped and tapered bodies) (Huang et al. 2007; Chowdhary et al. 2013; Fuh et al. 2013).

Oblique loading increased the stress and strain on the cortical bone tissue, mainly in model A (with total elimination of the threads). In this context, studies that used FEA to evaluate the biomechanical behavior of dental implants have related that oblique loading is more harmful (de Faria Almeida et al. 2014; Moraes et al. 2015; Ramos Verri et al. 2015). We believe increased stress and strain from oblique loading in model A is due to the decrease of bone/implant contact area (Huang et al. 2007, 2008), as well as the major shear force (Huang et al. 2008) previously described. Additionally, the implant format (smoothed) leads to a higher shear friction than threaded surfaces.

However, analyzing the stress and strain maps can be observed that the major difference between models is always constricted around the implant neck. It was reported that marginal bone loss might be partially caused by a high stress concentration in this region (Hoshaw et al. 1994; Kitamura et al. 2004). In this way, considering results of our study mathematical analysis of implant/bone interface should not to use totally simplified implant surface. However, if the focus of biomechanical study is not the bone/implant interface it is possible the use of a simplified implant surface since stress and strain distribution far from implant were similar for all models.

Experiments can be replicated with a good level of accuracy using 3D FEA, consequently, this method is potentially useful as a preclinical assessment (Limbert et al. 2010). In our study, the materials were considered isotropic, homogeneous, and linearly elastic, as in previous studies (Moraes et al. 2015; Ramos Verri et al. 2015); however, it is known that bone tissue is inhomogeneous and anisotropic (Limbert et al. 2010; de Faria Almeida et al. 2014). Recent studies report the registration procedure between the microtomography scan-based Stereolithography descriptions of the peri-implant

mandibular bone, thus improving the accuracy of the analysis by simulating more realistic bone tissue (Limbert et al. 2010; Kinoshita et al. 2013). However, further studies are necessary to disseminate and improve this technique. Furthermore, this technique demands higher computational capacity as well as a nonlinear analysis. Thus, as the purpose of this study was to assess the viability of simplifications that do not tend to change the result of biomechanical studies performed by this methodology, the use of linear analysis appears to be effective for this purpose.

A limitation of the study is the analysis of different threads simplification techniques in only one implant design and one bone type. The literature reports that internal connection and external connection showed different patterns of stress distribution (de Faria Almeida et al. 2014). Moreover, different types of bone can modify stress distribution patterns (Xiao et al. 2011). Thus, these variables should be evaluated in future studies for a better understanding of thread simplification on 3D FEA results.

Indeed, the option of modeling the simplification or total elimination of the threads facilitates the execution of study from modeling in simplification programs (e.g. SolidWorks® and Rhinoceros®) to processing the data (Barão et al. 2013). Therefore, the literature contains several studies using this modeling option (Huang et al. 2006; Abu-Hammad et al. 2007; Barão et al. 2013). In future, with technological advances, it is probably that this modeling will not be performed since these changes affect the stress/strain distribution patterns near from implants, which can act as a potential methodological bias when the bone tissue is the focus of the analysis. Thereby, the results of studies that use this modeling option should be carefully analyzed, in particular those studies that evaluate the stress and strain distribution in the bone tissue and draw conclusions based in the using the simplification with total elimination of the threads.

Conclusion

Within the limitations of this study, the following conclusions can be drawn:

The modeling for simplification of the implant surface was able to alter the stress and strain distribution on the cortical bone.

The total elimination of the threads in the CAD provided by the implant company should be avoided when the aim of study is to evaluate the stress transferred to the cortical bone.

Slightly simplification of the implant sustaining the threads in the CAD provided by the implant company can be performed, as this does not influence the stress and strain distribution on the cortical bone tissue.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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