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Comparative study of the influence of dental implant design on the stress and strain distribution using the finite element method

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Abstract. The aim of this study is to evaluate and compare the response of the anisotropic maxilla bone, in the peri-implant region, when osseointegrated implants are placed in different angles, based on the stress and strain distribution obtained by finite element analysis. Models were created to represent a portion of a maxilla bone (upper first molar region) with two types of implants which have different thread geometry (squared and V-shaped) and material (Ti-6AL-4V ELI and grade IV Titanium). Compressive axial load was applied to anisotropic models of the bone tissues, assuming complete osseointegration. Results show that the increase of the implant angle leads to a more critical state, especially for strain distribution which cannot exceed the limit of 4000 microstrain. Squared thread implants are a better option for osseointegrated dental implant treatments when inclined positions are required. More detailed models should be created to represent the use of bone allografts in a patient after bone resorption happened.

1. Introduction

In the field of odontology, engineering developments have generated alternatives to improve oral health. The use of dental implants, that are inserted into the maxilla or mandible bone, is one of the most implemented alternatives as a replacement for lost teeth, with an efficacy rate of 94% [1] and a wide variety of models to adjust to the different patients.

In Colombia, a report from the Ministry of Health & Social Protection exposed the problematic situation of teeth loss in the population. According to the statistics, more than 80% of the population has already lost one tooth [2]. Dental implants have been used as a rehabilitation treatment for edentulous patients, counteracting the resorption of the maxilla or mandible [3]. When a dental implant is placed, it initiates the process of osseointegration, where a direct connection between the bone and the implant is created, without the presence of gingival tissue, obtaining stiffness. The osseointegration of dental implants offers plenty of benefits to the patient compared to removable prostheses dentures, it gives greater support to the denture [3] and improves the aesthetics. However, making the decision of using dental implants demands a careful analysis of the biological conditions of the patient, due to complications that may occur. Some of the criteria include the state of the lip support, related to the undesired resorption of the alveolar bone, facial profile, smile line and amplitude, upper lip length, intermaxillary relationship, bone density and soft tissue thickness [4]. More research is required to give insight on the effectivity of the implants most commonly used in the region [5].



Finite element analysis (FEA), widely used for engineering applications [6–8], was first used in implant dentistry in 1976 [9]. Since then, it has been used extensively to predict biomechanical performance on the implant-bone interface, due to a large number of variations in patients studied [10–14]. The progress of dental implant design has allowed the wide variety found in the market. However, there are still complications due to factors such as the location of the implant, the surgical procedure and bone composition (quantity and density) [15], high loading conditions which lead to weakening and loss of bone tissues [16], translating into implant failure, and requiring it to be removed. Machtei *et al.* [17] indicated that the location of the implant it is a key factor in achieving a satisfactory occlusion and peri-implant health. The implant placement is not always as desired because of anatomical limitations of the patient which lead to an angular placement of it and the use of angular abutments as a solution [18,19].

The aim of this work is to evaluate and compare the response of the maxilla bone in the peri-implant region, considering an anisotropic model of the bone, when osseointegrated implants are placed in different angles, based on the stress and strain distributions obtained by FEA. We focus on two implant models commonly used by practitioners. These results will provide information on the implant stability when forces are applied to osseointegrated angular placed implants. The paper is organized as follows: in the next section, the experimental design is defined and the conditions are established, then, the two models of dental implants are described. Later, the FEA conditions are presented, the data of the maxilla bone properties, the values of the loads, the characteristics of the mesh designed and a description of the models. In the results section, we show the stress and strain distributions for each model, critical points, and discuss the mechanical performance. Finally, the conclusions are presented.

2. Materials and methods

Several studies indicate that the failure rate of implants used in the maxilla bone is higher than in the jawbone [20]. Thus, we perform the analysis in the maxilla for the implants under consideration, assuming a complete osseointegration between implants and bone tissues [16,21]. The portion of maxilla bone selected from the computed axial tomography (CAT) of the patient was modelled as an anisotropic material, based on the density provided by the CAT scan. We considered 3D models with multiple angular placements of the dental implants and variations on the material and mechanical design, for axial loading conditions. The response variables were the stress and strain produced by the loads on the peri-implant bone, in the region of the upper first molar.

2.1. Segmentation of the bone

For the FEA, we considered a female patient around fifty years old, who suffered a fracture in an upper first molar and went under surgery to remove the tooth (Figure 1). The quality and quantity of the bone around the missing tooth were acceptable to pursue a dental implant treatment. Furthermore, the case was analysed with help provided by the dentist, following the Lekholm and Zarb [22] bone classification, obtaining a Type II bone. The bone quality classification system based on Hounsfield scale is as follows: Type I bone is homogeneous compact bone (>1250 HU), Type II bone is when a thick layer of compact bone is surrounding a dense trabecular bone core (750-1250 HU), Type III bone is when a thin layer of cortical bone is surrounding a dense trabecular bone core (375-750 HU) and Type IV bone is when a thin layer of cortical bone is surrounding a low-density spongy bone core (<375 HU) [23]. The segmentation of the maxilla was done using the Materialise Mimics v19 software, selected the area of the affected tooth.

2.2. Dental implants

There are different brands available in the market for dental implants, e.g., Zimmer Biomet, BioHorizons, GMI-Ilerimplants Group and Straumann. We selected, with the help of practitioners, two implants from BioHorizons [24] and GMI-Ilerimplants Group [25]. The model TLX3409 from BioHorizons is a mount-free tapered internal implant, which is made from a Titanium Alloy (Ti-6AL-

4V ELI), which the company claims is more resistant to fractures and fatigue. The model KDA0F3602 from GMI-Ilerimplants Group is a GMI frontier internal connection hexagonal implant, machined in CP grade IV Titanium, one of the most common materials employed for dental implants, see **Table 1**.

Table 1. Material properties of the dental implants.

Brand	Reference	Material	Modulus of Elasticity (GPa)	Poisson's ratio
BioHorizons	TLX3409	Ti-6AL-4V ELI	120	0.31
GMI	KDA0F3602	CP grade IV Titanium	110	0.35

The TLX3409 has an external square thread which provides higher functional surface area translating into higher bone-implant contact, this is desired to dissipate compressive and tensile load to the bone for stability, Figure 2(a). Square threads have demonstrated greater bone contact compared with standard V-shape and reverse buttress threads [26]. The thread design of the KDA0F3602 implant is a V-shape, Figure 2(b). Both designs have self-threading millings and are slightly tapered which facilitate the insertion and reduce the tension at the bone-implant interface [25].

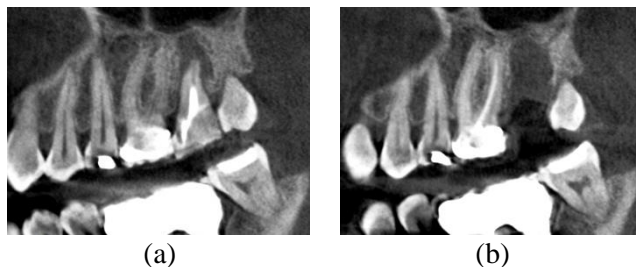


Figure 1. (a) Upper first molar fracture of the patient selected, and (b) maxilla condition after its removal.

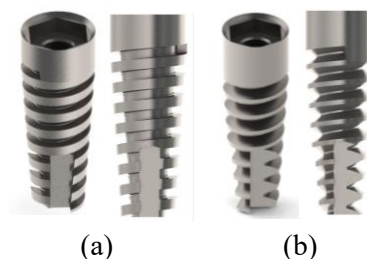


Figure 2. Isometric and lateral view of the (a) TLX3409, and (b) KDA0F3602 models.

The dimensions of the implant required by the patient, recommended by the professional, are 3.5mm diameter and 9.5mm. Hence, based on the previous assessment, the dimensions selected for the two implant references are 3.4mm diameter and 9.0mm in length for the TLX3409, and 3.3mm diameter and 10.0mm in length for the KDA0F3602.

2.3. Load application

The implants support occlusal forces during its functional phase, the axial force represents the masticatory force. The values of axial loads employed in the literature show that the most used values are in the range between 50N and 150N [13,18,27,28]. Thus, in this study, we apply an axial load of 150N. We do not consider the effect of forces appearing during the procedure of inserting the implant as we assume osseointegration.

Figure 3 shows the forces applied to the abutments of the implants, which have the same material properties as them, notice that the oblique load is applied in the direction of the implant inclination. As boundary conditions, fixed supports were applied to the lateral faces of the models which are restricted by the rest of the maxilla.

2.4. Finite element models

Two types of models are considered, as shown in Figure 4. Type 1 models are anisotropic bone with a low-density cortical bone cylinder that represents the new bone, created after filling the empty space produced by teeth loss with bone allografts, Figure 4(a). This model reproduces real conditions when the gap on the bone is filled before proceeding with the implant treatment. The complete model includes the abutment, the cylinder, the implant, and the maxilla. Figure 4(b) is the model without allografts and anisotropic properties. Notice that most dental implants studies with FEA are developed

under isotropic and ideal conditions, which may not relate to real cases because bone composition is patient specific. The proposed anisotropic models are defined considering a range of 10 different materials properties, from 500MPa for the elastic modulus of trabecular bone, to 15000MPa for cortical [19]. Cortical bone starts with an elastic modulus of 1370MPa, hence, material with a lower value corresponds to trabecular bone. The distribution was based on the Hounsfield scale of the CAT scan which relates to the density of the maxilla. The two selected implants are placed in the bone structures in three positions (0° , 15° and 20°) with axial loading conditions. New bone tissue, represented as the cylinder in Type 1 models, has an elastic modulus of 6000MPa. All bone tissues have a Poisson's ratio of 0.3.

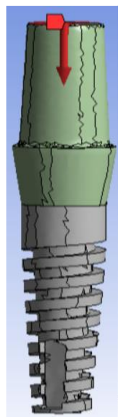
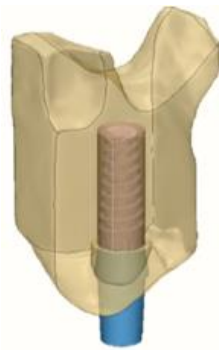


Figure 3. Model indicating the direction of the forces applied to the implants.



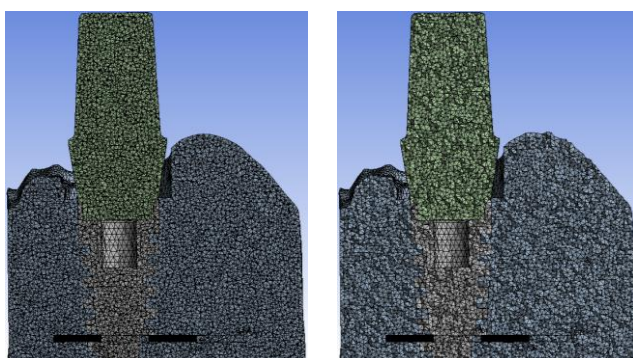
(a)



(b)

Figure 4. FE models developed: (a) Type 1, anisotropic model taken from the CAT SCAN with cortical bone allograft, (b) Type 2, anisotropic/isotropic model taken from the CAT SCAN without allografts.

The meshing was done in the 3 Matic and Ansys software, using linear tetrahedrons with 8 nodes (SOLID185). We made mesh independence analyses for the different models, to obtain, e.g., a final mesh with a characteristic length of 0.3mm and 1696314 elements, see Figure 5. Table 2 shows the average number of nodes and elements for each group.



(a)

(b)

Figure 5. Detailed view of the (a) superficial and (b) volumetric mesh of the models.

Table 2. Average number of nodes and elements of the meshes according to the implant and type of bone.

Implant Reference	Type of Bone	Nodes	Elements
TLX3409	CAT scan Bone	283132	1695533
	CAD Bone	386446	2282128
KDA0F3602	CAT scan Bone	284616	1700050
	CAD Bone	389208	2292754

3. Results

We obtained the stress and strain fields caused by the applied loads. The physiologic strain limit is fixed to 4000 microstrain, more than this is considered to be pathologic [19]. Regarding the compressive stress [16], the maximum value in the cortical bone should not exceed 190MPa, while for the trabecular bone is 5MPa. Overloads may cause bone resorption or fatigue failure of the implant [9].

3.1. TLX3409 implant

The firsts results correspond to the Type 1 models with the squared thread implants. Table 3 shows the maximum values of equivalent stress and strain, for the complete model and the maxilla only, for different angular positions. None of the models (0° , 15° and 20°) exceeds the limit of stress for cortical bone (190MPa) and the maximum is located at the cylinder surface. The maximum value of strain for the maxilla (1420 microstrain) is lower than the limit for the bone of 4000 microstrain.

Table 3. Maximum von Mises stress and strain, indicating location for Type 1 models with TLX3409 implants. Abutment (A), Cylinder (C), Implant (I), Maxilla (M).

Location		0°	15°	20°
Max. stress (Pa)	Model	4.91E7 (C)	1.19E8 (C)	1.59E8 (C)
	Maxilla	4.91E7	1.18E8	1.59E8
Max. strain (m/m)	Model	1.43E-2 (A)	1.51E-2 (A)	1.83E-2 (A)
	Maxilla	9.42E-3	5.58E-4	1.42E-3

As Figure 6 shows, for the angle positions, strain values are under the physiologic limit for the 15° and 20° models, while the model at 0° exceeds it. The model at 0° was not expected to exceed the limit of the strain because it is the ideal position of the implant. The strain distribution in the 0° model is symmetrical as shown in the previous Figure 6(a), and concentrated near to the apex of the implant, while the inclined models show a lateral and wider distribution of the strain to the left middle side. The peri-implant region tends to have cortical bone with higher elastic modulus, which explains the concentrated strain at 0° , while the inclination produces a lateral distribution to the middle region with lower elastic modulus without reaching the limit.

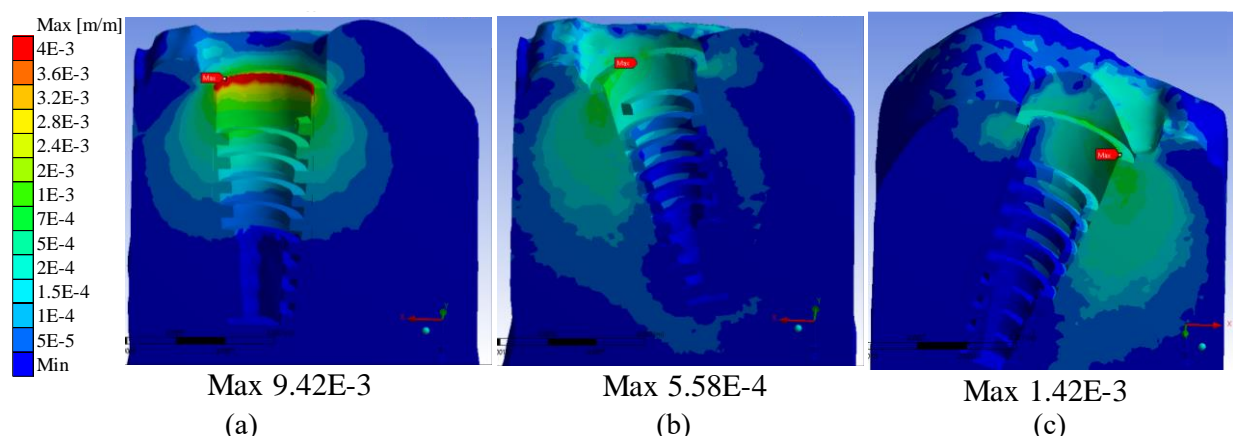


Figure 6. Von Mises strain results on the maxilla with a TLX3409 implant for (a) 0° , (b) 15° and (c) 20° inclination under axial load in Type 1 models.

The next type of models analysed are the Type 2 with squared thread implants, **Table 4** presents the maximum stress and strain values. The maximum stresses do not exceed the admissible value for the bone. In contrast to Type 1, the highest strain is for the model at 20° , which yields a microstrain of 2810, below the admissible limit.

Table 4. Maximum von Mises stress and strain, indicating location for Type 2 models with TLX3409 implants. Abutment (A), Cylinder (C), Implant (I), Maxilla (M).

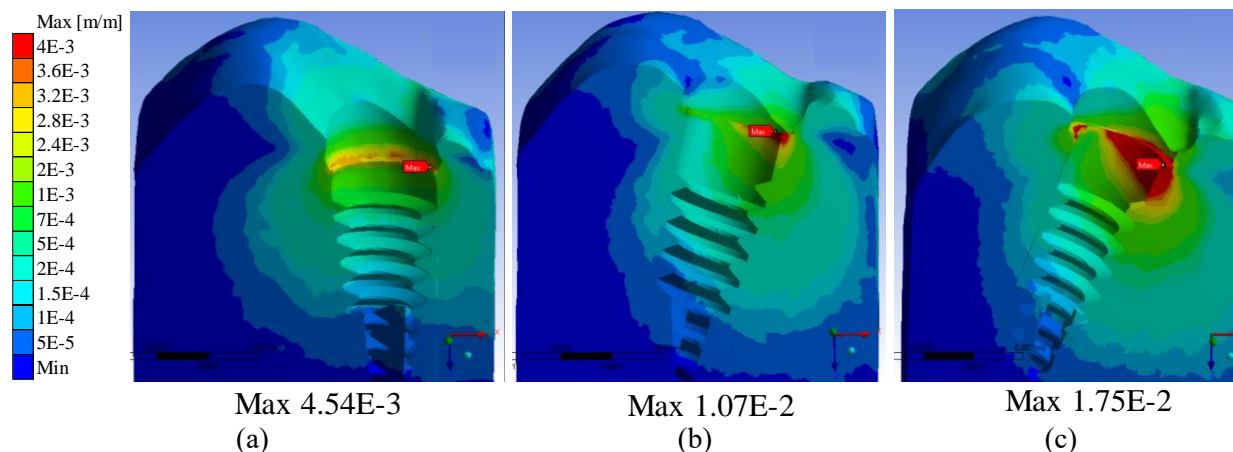
Location		0°	15°	20°
Max. stress (Pa)	Model	5.92E7 (I)	6.90E7 (M)	9.49E7 (M)
	Maxilla	3.67E7	6.89E7	9.44E7
Max. strain (m/m)	Model	7.35E-3 (A)	1.24E-2 (A)	1.13E-2 (A)
	Maxilla	9.29E-4	1.32E-3	2.81E-3

3.2. KDA0F3602 implant

The results presented in Table 5 correspond to the maximum values of equivalent stress and strain for the Type 1 model with V-shaped thread implants. None of the models exceeds the stress limit for cortical bone. However, all the models exceed the maximum strain limit for the maxilla bone. Figure 7 shows the strain distributions for the three models, showing high gradients affecting bone tissue.

Table 5. Maximum von Mises stress and strain, indicating location for Type 1 models with KDA0F3602 implants. Abutment (A), Cylinder (C), Implant (I), Maxilla (M).

Location		0°	15°	20°
Max. stress (Pa)	Model	3.01E7 (C)	7.97E7 (C)	9.99E7 (C)
	Maxilla	3.01E7	7.97E7	9.99E7
Max. strain (m/m)	Model	4.98E-3 (A)	1.07E-2 (C)	3.16E-2 (A)
	Maxilla	4.54E-3	1.07E-2	1.75E-2

**Figure 7.** Von Mises strain results on the maxilla with a KDA0F3602 implant for (a) 0°, (b) 15° and (c) 20° inclination under axial load in Type 1 models.

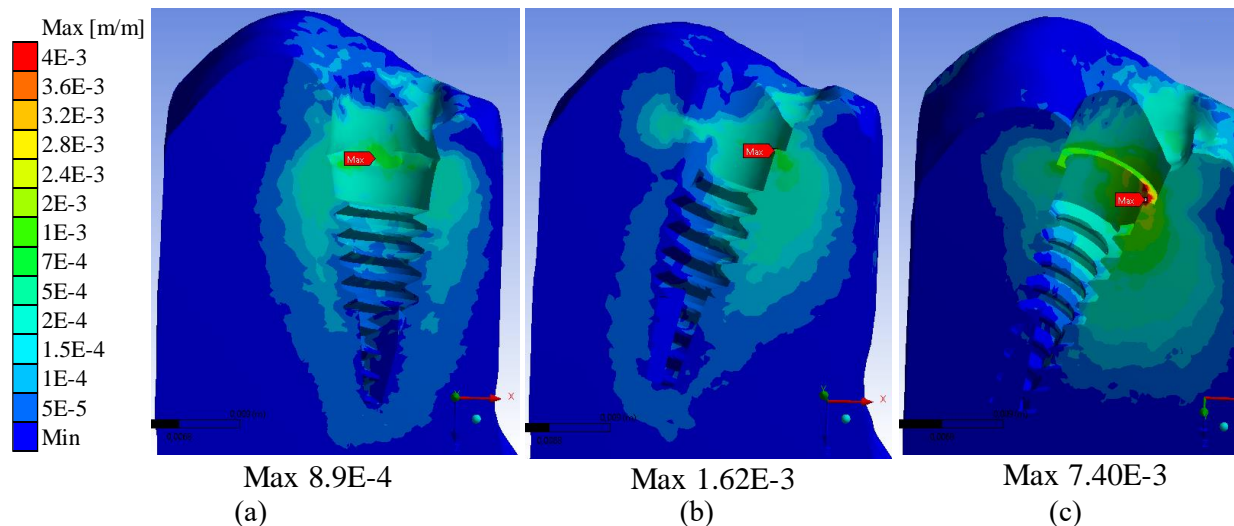
Comparing both implants for Type 1 models, the TLX3409 only presents an unexpected strain concentration in the vertical model, but for the KDA0F3602, all angles exceed the limit and show problematic regions. The diameter and length variation between the implants are not considered as a cause for their behaviour. The difference in the response is associated with the lower elastic modulus of the KDA0F3602 and the geometry of the thread.

Table 6 shows the values for to the model Type 2 results for maximum von Mises stress and strain values likewise its location. The maximum admissible stress is not exceeded, but for strain distribution, the model at 20° presents a maximum value above the 4000 microstrain.

Figure 8 presents the strain distribution for Type 2 in each inclination. In this case, the 20° inclined implant exceeds the limit in the peri-implant region.

Table 6. Maximum von Mises stress and strain, indicating location for Type 2 models with KDA0F3602 implants. Abutment (A), Cylinder (C), Implant (I), Maxilla (M).

Location		0°	15°	20°
Max. stress (Pa)	Model	7.65E7 (M)	1.09E8 (A)	1.41E8 (I)
	Maxilla	7.65E7	9.57E7	1.36E8
Max. strain (m/m)	Model	1.29E-2 (I)	4.25E-3 (A)	1.12E-2 (I)
	Maxilla	8.9E-4	1.62E-3	7.4E-3

**Figure 8.** Von Mises strain results on the maxilla with a KDA0F3602 implant for (a) 0° (b) 15° and (c) 20° inclination under axial load in Type 2 models.

4. Conclusions

Anisotropic models with squared thread implants behave properly and do not fail by stress or strain even at inclined positions. V-shaped thread implants tend to present strain failure, increasing with the angle of inclination. Uneven distributions of von Mises stress and strain in models with inclined implants is due to the direction of the force producing high bending moments, which yield higher stress values.

The differences between the von Mises stress and strain response for the 15° and 20° inclined implant models are not conclusive regarding the 5° angle variation. Some of the models with KDA0F3602 implant present a more noticeable zone of failure despite their similar maximum values, while, in for the TLX3409 implant, the size of the critical zone and maximum values are similar.

The length of the implant is not important in the stress distribution, as other studies have corroborated, while thread design has an important impact on the mechanical response.

Anisotropic models without bone allografts resist better than models with new bone tissues, due to the denser cortical bone in the peri-implant region. Thus, it is recommended to avoid too much time before seeking dental implant treatment. After a long time exposure without teeth, the bone reabsorbs and it would be necessary to use bone allografts which may end in failure.

For dental implant treatments where is not possible to locate the implant in a vertical way, thus, an inclined position is needed, squared thread implants are better than V-shaped ones due to the load distribution, minimizing strain concentration on the bone.

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