J. Comput. Appl. Res. Mech. Eng. Vol. 11. No. 1, pp. 1-11, 2021 *DOI: 10.22061/JCARME.2021.7542.2001*

SRTTU
Journal of Computational and Applied Research in Mechanical Engineering
jcarme.sru.ac.ir
JCARME
ISSN: 2228-7922

Research paper

Numerical analysis of the mechanical stimuli transferred from a dental implant to the bone

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Article info:

Article history:

Received: 21/11/2020
Revised: 16/05/2021
Accepted: 19/05/2021
Online: 22/05/2021

Keywords:

Stiffness,
Numerical model,
Thread,
Dental implant.

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Abstract

This work presents a numerical approach to predict the influence of material stiffness in a dental implant using different thread profile shapes, always with a constant number of threads, thread width and thread pitch. Dental implant affects bone tissue, in response to various mechanical stimuli where the biomechanical behavior plays a significant role in the study of stress and strain calculation. In this work, four different thread profile shapes were considered (Model1 - Plateau typeA, Model2 - Plateau typeB, Model3 - Triangular, Model4 - Rectangular) with two different inner diameters equal to 4 and 6 mm, using three different implant materials (titanium, an iso-elastic titanium and zirconium alloys). Two dimensional computational axisymmetric models of a bone-implant were constructed using the finite element method. This study presents the numerical results about the mechanical stimuli on dental implant according to the chosen material and profile shape. The main contribution of this work is giving additional information about the stability and implant loosening with the application on surgical techniques in dental science.

1. Introduction

In dental medicine, osseointegration is described to be affected by many factors, i.e., dental implant, screw design, surface treatment, bone quality, surgical technique, and post-operative care [1, 2].
Osseointegration refers to the progress of bone growing right up to the outward implant and where it is no progressive movement between the bone interface and the implant [2, 3].

According to different investigations, the thread profile design and the configuration of a dental implant are dominant problems that affect the developed stress levels into the bone resorption [1, 4-9].
There are many thread profile shapes used in dental implants, and different researchers have reported different conclusions. Threads are used to maximize initial contact and stability and increase the implant surface area [5, 10].
The implants vary in diameter from 3 to 7mm, depending on surgical and prosthetic prerequisites [11]. This dimension is designed to

gain the maximum stability between bone-implant. From a biomechanical point of view of, wider implants permit engagement of a maximal measure of bone; and stress distribution is improved in theory [11]. The stress distribution varies with respect to the implant design. The success of implants depends on the way stresses are transferred to the surrounding bone-implant [12-15].

For improvement, the osteointegration, a low elastic modulus in the implant, is important to mimick the bone substitutes and allow a balanced stress distribution between bone-implant [12].

The titanium alloy is a metallic material widely used in implants [5]; but the elastic modulus is still significantly higher than the bone tissue. The difference in the metallic biomaterials and the bone causes the stress shielding that affect the bone resorption and bone loss. This study [16] investigates the properties of zirconium metallic alloys (with alloy elements Cu and Sn), to obtain a low elastic modulus (14-18 GPa). Zirconium alloys have excellent biocompatibility and combining it with a low elastic modulus is such an advantage to implants application which probably minimizes the bone loss.

The thread profile is one of the major contributors to initial implant stability. Implant stability will promote successful osseointegration and will lead to stress distribution over a wide area at a low level [17].

Many publications present studies about the design of the implant including the study of various parameters: geometry of thread shape, types of threads, thread pitch, dimensions, material properties, that promote uniform distributed stress around the implant surface [14, 17]. There is different thread shape available including V shape, square shape, buttress shape, and reverse buttress shape [14, 18]. The implants vary in the standard-length that ranges from 8 to 16 mm [17]. Other implants like zygomatic can reach 52.5mm [19]. The zygomatic implant has an increased tendency to bend, due to the increased length (30-52.5 mm) and the fixation bone support [19]. Some authors refer that Zygomatic implants provide an alternative to conventional implants; they have been developed for compromised maxillary situations [20, 21].

Many publications present different numerical simulations used to test different geometries combined with different materials [1, 4, 11-12]. But the number of the involved variables is considerable, for instance material properties, dimensions, analysis type, applied boundary conditions, etc. All these findings have a great significance in biomechanical behavior of transferred loads between bone-implant and always, and will give more information about the better performance, dependent on the chosen thread profile shape. The success of the implants depend on the way stresses are transferred to the surrounding bone-implant [12].

The present work gives additional information about the developed stress and strain level on the implant, using less expensive computational models (two dimensional (2D) axisymmetric planes). Four different thread profile shapes (Model1 - Plateau typeA, Model2 - Plateau typeB, Model3 - Triangular, Model4 - Rectangular) with two different inner diameters equal to 4 and 6 mm, outer diameters of 6 and 8mm respectively, in three different implant materials (titanium, an iso-elastic titanium and a zirconium alloy) will be numerically tested.

In the studied models, the following parameters are considered constant: the length of the implant equal to 11 mm, the number of threads equal to 4, the thread width 1 mm and the thread pitch length of 3 mm. Recently, analytical, numerical, and experimental methodologies have been introduced by the authors of this work to analyze the bone mass density and measure the cortical bone thickness in different structural parts [22-26].

According to this, the goal of this work is to study the von Mises stress and elastic strain along the implant axis and trabecular bone using ANSYS® program; and to explore the mechanical stimuli between the bone-implant interface, according to the use of different materials, profile implant shape and size diameter.

The results allowed to conclude about the effect on mechanical stimulus when the inner diameter, material and implant profile are changed.

The mechanical stimuli transferred from a dental implant to bone is calculated, as an essential parameter for bone remodeling, stability, and implant loosening.

The studied model produces relevant conclusions that it is important to pay attention to. Namely, around the dental implant the combination between the materials and the shape profile played a significant role that allows the understanding the mechanical stimuli parameters.

2. Materials and methods

2.1. Numerical model

2D axisymmetric computational models of a bone-implant were constructed using finite elements with ANSYS® program. The numerical model is structural and linear, using 2D axisymmetric plane finite element with 8 nodes, PLANE183. The linear 2D axisymmetric computational model correctly predicts the stress and the strain concentration locations, that can be used for qualitative and quantitative analyses. The finite element analysis was assumed as a state of ideal osseointegration, where the contact between all parts (cortical, trabecular and implant) is perfectly bonded. Bone is usually modelled with isotropic material properties, although the bone seems to be more appropriate using orthotropic material.

Therefore, all materials were assumed linearly elastic, homogeneous, and isotropic.

The corresponding elastic properties such as Young's modulus (E) and Poisson ratio (υ) were determined from the literature, [4, 16]. The model consists of a homogeneous cortical bone (E=20 GPa) and a trabecular bone (E=1 GPa) with a Poisson ratio of 0.35 [4]. Dental implants were modelled as an iso-elastic titanium alloy (E=40G Pa) [4], titanium alloy (Ti-6Al-4V) with E=105 GPa [4] and zirconium alloy (Zr-7Cu-5Sn) with E=14.4 GPa [16]. The Poisson ratio was considered equal to 0.35 in all materials, with an exception in zirconium material that is equal to 0.30 [4, 16].

Fig. 1 shows all 2D computational models of the study. Different geometries were studied, i.e., implant with two different inner diameters equal to 4 and 6 mm, and outer diameters of 6 and 8 mm respectively [11]. From the literature [17], in all models some parameters were selected and considered constant. These assumptions are the implant length of 11 mm, 4 threads, the thread width equal to 1 mm and the thread pitch 3 mm.

The boundary conditions include the bottom edge of the model on Y-axis as fixed and an average masticatory axial vertical force of 80N imposed in the implant head, determined from the literature and [4].

According to Nickolay et al. [27], the maximum bite force is greater in males as compared to females. In men the maximum bite force has a mean value of 138N (with a minimum value of 33 N and a maximum value of 228 N) [27]. In women the mean value is 97 N (minimum value of -37 N and a maximum of 198 N) [27].

The represented points (t, b, t_i=2, 4 and b_i=2, 4) through the models in Fig. 1, allow the calculations of the stress and strain level between the implant and in the neighboring bone. The variables are t in the thread profile implant and b in bone tissue.

The finite element analysis was carried out to calculate the von Mises stress and the elastic strain in all studied models. A regular mesh was considered with a size finite element equal to 0.25 mm, ensuring that the smallest edges of the model have at least 4 elements. In the model, the cortical bone has a violet mesh, the trabecular bone is red, and the implant is blue.

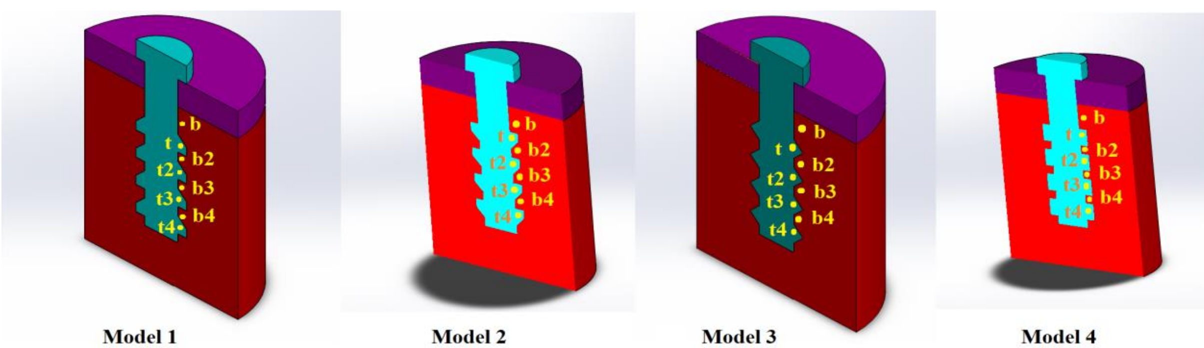


Fig. 1. Computational models: Model1 - Plateau typeA, Model2 - Plateau typeB, Model3 - Triangular, Model4 – Rectangular.

All 2D axisymmetric models have the same regular mesh to allow a better comparison, represented in Fig. 2.
The numerical results will be presented in the implant material and in the trabecular bone.

2.2. Mechanical stimuli between bone-implant

To quantify the level of mechanical stimuli transferred between the dental implant and in the neighbouring bone, two parameters will be calculated, as proposed by Haase and Rouhi [4] in their work.
These parameters, that allow to compare stimuli transfer to the bone, are resulting from changes in implant parameters: the stress transfer parameters (*STPs*) according to Eq. (1) and the strain energy density transfer parameters (*SEDTPs*) according to Eq. (2).

$$STPs = \frac{\sigma_b}{\sigma_t} + \sum_{i=j=2}^{i=j=4} \frac{\sigma_{bi}}{\sigma_{tj}} \quad (1)$$

where σ_{bi} is the von Mises stress within bone and σ_{tj} is the von Mises stress in the adjacent implant thread.

$$SEDTPs = \frac{\sigma_b \, \varepsilon_b}{\sigma_t \, \varepsilon_t} + \sum_{i=j=2}^{i=j=4} \frac{\sigma_{bi} \, \varepsilon_{bi}}{\sigma_{tj} \, \varepsilon_{tj}} \quad (2)$$

In addition, in Eq. (2), ε_{bi} is the elastic strain within the bone and ε_{tj} is the elastic strain in the adjacent implant thread.
The values were measured along a path as represented in Fig. 1, at the defined points (t, b, t_i=2, 4 and b_i=2, 4).

3. Results and discussion

3.1. The von Mises stress along the implant axis

The obtained numerical results, using finite element analysis, allow to determine the stress and the strain level in all models, to determine better mechanical stimuli for predicting less bone loss due to the chosen implant.
The results were obtained for all four different thread profile shapes (Model1 - Plateau typeA, Model2 - Plateau typeB, Model3 - Triangular, Model4 - Rectangular) according to the variables definition for the used internal implant diameter and the material. The internal implant diameters 4 mm is represented by d4 and 6 mm with d6. The dental implant material is modelled as an iso-elastic titanium alloy (with the denomination isoTi), titanium alloy (represented by Ti) and zirconium alloy (as Zr). All these denominations were introduced in the presented results.
Fig. 3 shows the von Mises stress in different positions along the implant axis in all models, according to the path represented in each sketch.

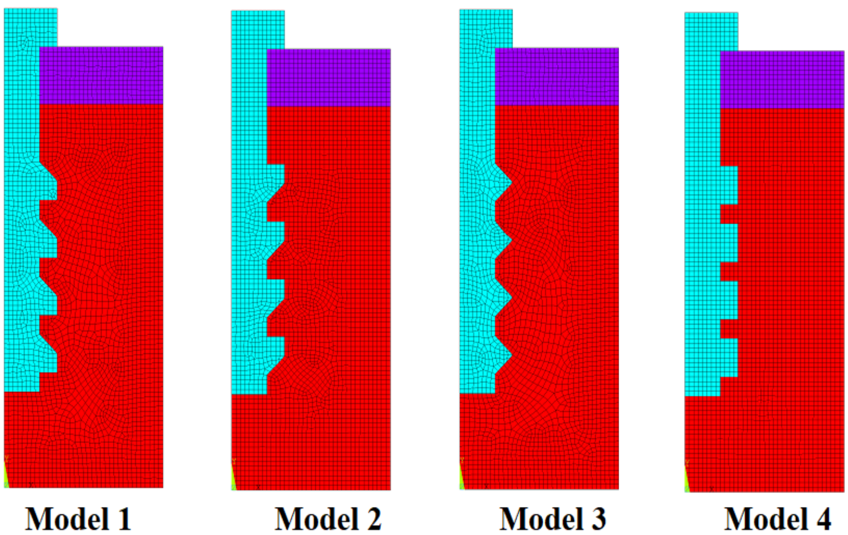
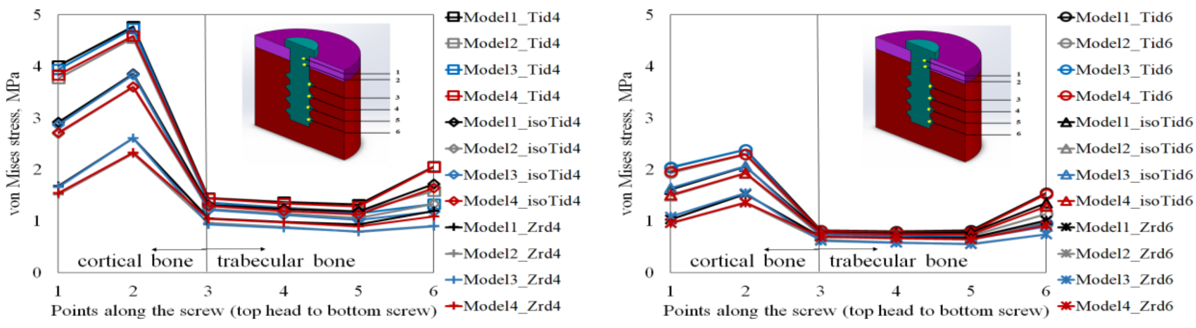
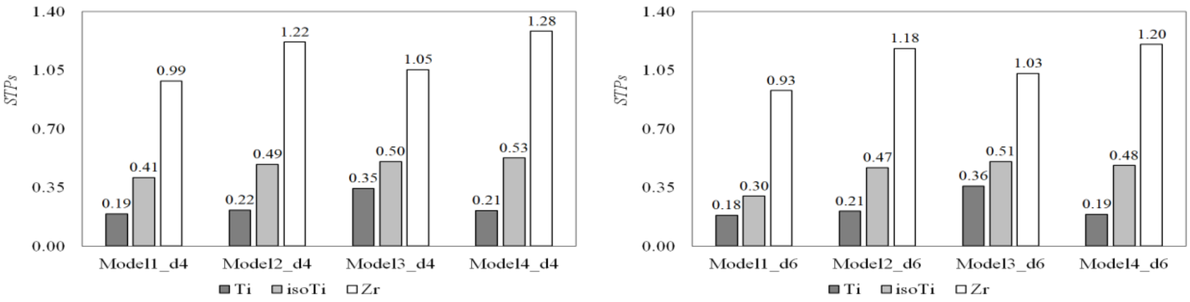


Fig. 2. 2D computational models and respectively meshes: Model1 - Plateau typeA, Model2 - Plateau typeB, Model3 - Triangular, Model4 – Rectangular.



(a) (b)

Fig. 3. The von-Mises stress in all 6 points along the axis, function of material and inner implant diameter: (a) implant diameter d4 and (b) implant diameter d6.



(a) (b)

Fig. 4. *STPs* calculation in all Models, function of material stiffness and inner diameter implant: (a) implant diameter d4 and (b) implant diameter d6.

The obtained results were compared using two different inner implant diameters. The obtained results in implant with higher size diameter allow higher values for the stress level. In all models, point 2 has the highest value of stress, located neighbouring to the cortical bone. Point 3, in the first thread, represents the least value of stress, very close among all models.

In comparison, in all four implant threads, the von Mises stress decreases along the implant and increases at the last thread.

In the last thread, the inner diameter effect is not so great, and the highest value occurs in Model4 (Rectangular), titanium alloy and inner diameter equal 6 mm. Models3 (Triangular) and 4 (Rectangular) in zirconium material have the lowest stress along the 6 points in study.

3.2. Stress transfer parameters (STPs) and strain energy density transfer parameters (SEDTPs)

The results to quantify the level of mechanical stimuli transferred between the implant and in the neighboring bone are obtained using Eqs. (1-2). The results are represented in Figs. 4-6, where the effect of the implant geometry (thread profile shape and inner diameter size) and material stiffness can be compared.

Fig. 4 represents the obtained stress transfer parameters (*STPs*) using Eq. (1) and all numerical calculations. *STPs* measure the total ratio of stresses transferred to the bone versus the adjacent implant. Maximized values indicate high stress transferred to the bone [4].

According to the results, the stress transfer parameters *STPs* values increase by decreasing the inner diameter implant and material stiffness, as reported by Haase and Rouhi [4].

The maximized values of *STPs* were obtained when the models are in zirconium.

The minimum values were obtained with titanium alloy. Comparing all different models, according to the thread profile shape, Model4 (Rectangular) in zirconium material represents the highest *STPs* values in comparison with other models.

Model2 (Plateau typeB) has a behaviour close to Model4. Implants with a reduced elastic modulus probably result in less bone loss due to higher stress transferred to the bone.

This conclusion agrees with in vitro work wherein implants with a reduced elastic modulus result in less stress shielding and consequently bone loss [4, 28].

Fig. 5 shows the results for strain energy density transfer parameters (*SEDTPs*), according to Eq. (2).

The strain energy density transfer parameters *SEDTPs* values quantify the transfer strain energy density between the implant and in the neighbouring bone [4]; and they have the same behaviour as *STPs*.

According to the obtained results, *SEDTPs* increase by decreasing the inner diameter implant and material stiffness, as reported by Haase and Rouhi [4]. However, in Model3, titanium alloy (Ti-6Al-4V) allows a higher *SEDTPs* value, comparing with the iso-elastic titanium for both diameters.

Furthermore, using an inner diameter of 6 mm, *SEDTPs* of titanium alloy (Ti-6Al-4V) and zirconium alloy (Zr-7Cu-5Sn) have the same value. It was not expected, but probably that is particularity related to the thread geometry of Model3. The lesser inner diameter implant exhibited higher strain energy density in comparison to a higher inner diameter implant.

Model4 (Rectangular) in zirconium material represents the higher *SEDTPs* values in comparison with other models. Model2 (Plateau typeB) has the same behaviour close to Model4.

The bone strain relates to the stimulus which leads to bone remodelling.

High strain stimuli cause bone mass increases or changes in the architecture, such as the increase in bone strength [29], as shown in Model4_d4 in zirconium dental implant material.

Low strain stimuli (due to reduced activity) can cause bone loss or changes in the architecture that reduce bone strength [29], as reported in our Model1_d6 in titanium alloy.

The average values of ratio *STPs*/*SEDTPs* are represented in Fig. 6.

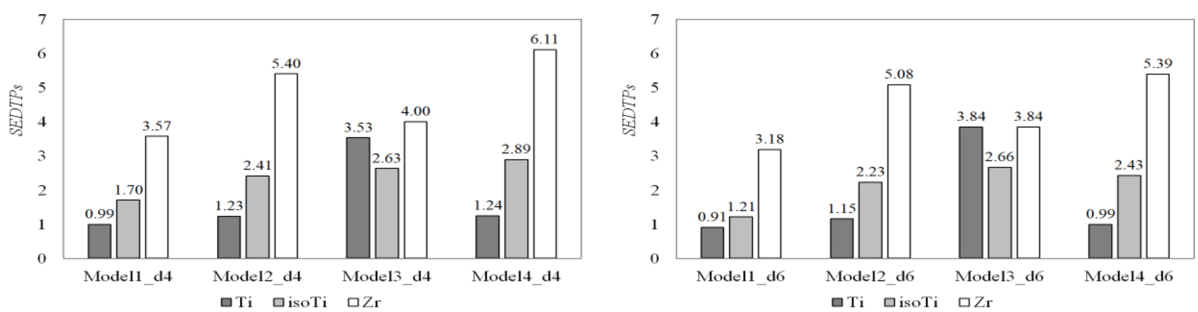
The average values of ratio *STPs*/*SEDTPs* with changing material stiffness and inner diameter implant show that Model4 (Rectangular) is the thread implant profile that allow similar behaviour in relation to different implant diameter or used material.

A higher ratio is obtained in Model1 for zirconium implant. The inner diameter does not have a great significant effect on the ratio between the stress and strain. The major effect is produced by the implant material and implant thread profile shape.

3.3. The von Mises stress in trabecular bone

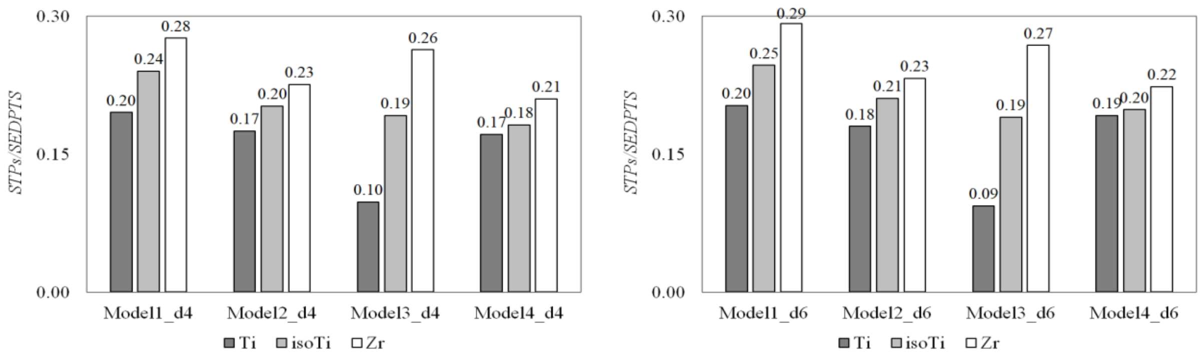
Fig. 7 represents the von Mises stress in all models with different materials and different size diameter. The results are represented in the trabecular bone and the maximum obtained value of stress in each model was included.

A comparison between all four Models, with different thread profile shape with inner diameter of 4 mm and 6 mm, revealed that lower and constant stress distribution in trabecular bone appears when zirconium material is used. In titanium dental implant, the peaks of stress concentration located on distal thread profile corner of Models 2 and 3 are notable.



(a) (b)

Fig. 5. *SEDTPs* calculation in all Models, function of material stiffness and inner diameter implant: a) implant diameter d4 and b) implant diameter d6.



(a) (b)

Fig. 6. *STPs/SEDTPs* calculation in all Models (Model1 - Plateau typeA, Model2 - Plateau typeB, Model3 – Triangular, Model4 – Rectangular), function of material stiffness and inner diameter implant: a) implant diameter d4 and b) implant diameter d6.

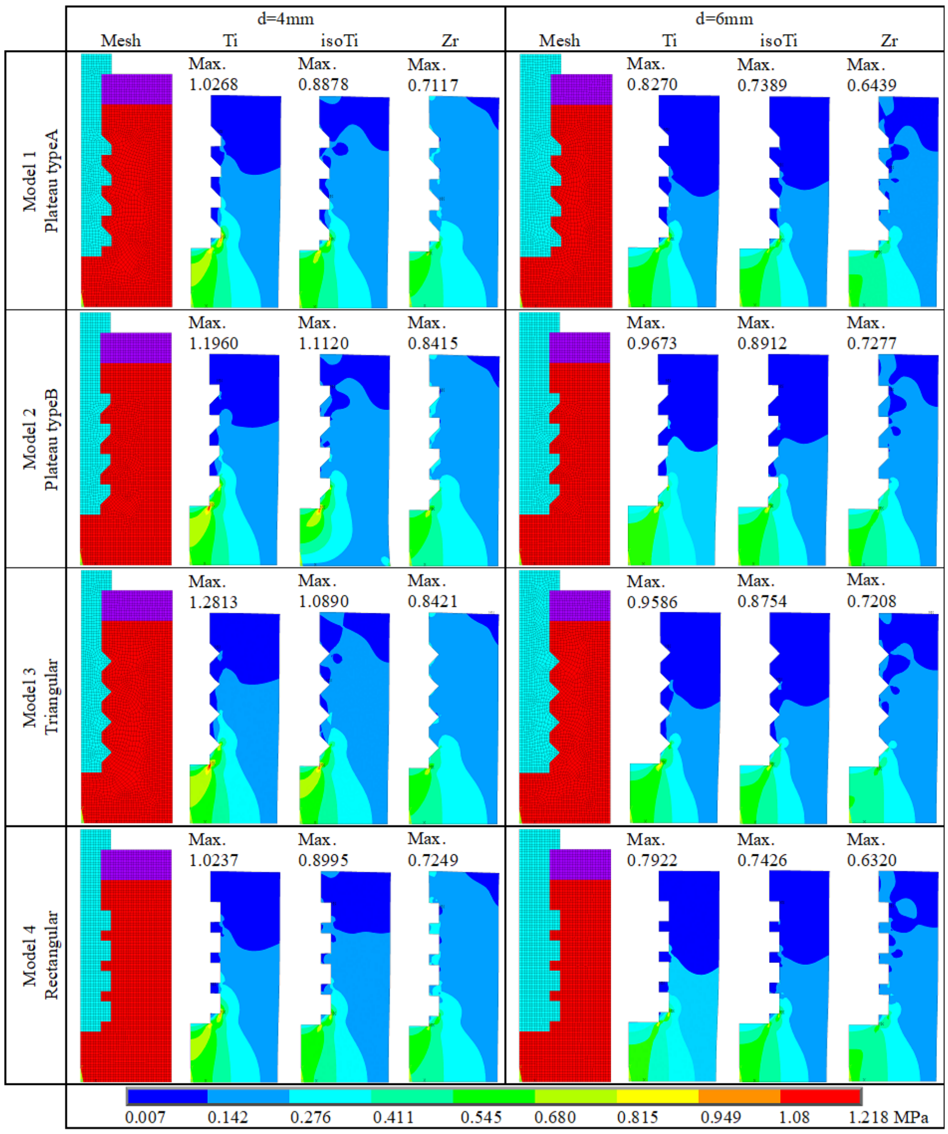


Fig. 7. Meshes and von Mises stresses, all Models (d=4 mm and 6 mm, Ti, isoTi and Zr).

The stress around the implant tip in the vicinity of bone was reduced with high inner diameter. High concentration of the stress may cause damage and subsequent bone absorption around the implant.

When the maximum stress concentration is in trabecular bone, it is around the apex of the implant, as referred by Aunmeungtong, et al. [30] and investigated in our study. In general, in trabecular bone, the stress distribution is over a broader area. In small implant diameter, stress occurring in the surrounding bone is higher and wider in distribution in comparison to in higher implant diameter, as mentioned by Aunmeungtong, et al. [30].

A comparison between all materials revealed that the lower stress distribution in trabecular bone appears when the implant is zirconium material due to the calculated high stress transfer parameter, Model4 (rectangular) with an implant inner diameter of 6mm. Beyond the thread profile, the implant diameter also induces different levels of stress throughout the bone, in general with higher diameter the stress decreases into the bone, as mentioned in [11].

As in conclusion, the stress declines to increased implant inner diameter and decreased stiffness material. Nevertheless, using the largest inner diameter implant may not be the best choice. The stimuli parameters need to be specified accordingly to guarantee less bone loss.

4. Limitations

There are some points to discuss the limitation of our study. The major limitation is that some of our data were based on published articles, where our dental implant was assumed as specific for our study.

Some assumptions were considered:

- Our studied implant, as a numerical model, may not reproduce a similar condition in another model. The finite element method is a mathematical in vitro study and may not accurately characterise the clinical situation.
- The use of patient and implant geometry is mandatory for a detailed clinical explanation.
- The bone mechanical properties were assumed to be linear and isotropic, independent of gender and age.
- The density and porosity of the bone were not considered.
- Also, the possible thermal damage to the vasculature, cells and matrix was not considered due to the used simplified finite element model.

However, the studied Models produce relevant conclusions that is important to give attention to. Namely, around the implant, the materials and the thread profile combination played a significant role that allows the understanding of the mechanical stimuli parameters, which need to be validated by further in vivo clinical studies.

5. Conclusions

This study presents numerical results about the mechanical stimuli transferred from a dental implant to the bone, according to different chosen materials for the dental implant with various thread profile shape. Following, the summary of the present research is presented to fulfill the main motivation of the study:

- The load transferred to the bone increases with lesser implant inner diameter and the lower stiff material. Implants with a reduced elastic modulus and also reduced inner diameter probably minimize the bone loss.
- In all models, stress dissipates along the implant length, but culminates in the most distal implant thread and passes to the adjacent trabecular bone. The same conclusions were observed in our models, where Models2 and 3 were the most critical ones with visible high stress concentration at distal near the thread profile corner.
- The implant with rectangular (Model4) or square profile obtains less stresses and shows better performance as compared with other profiles in trabecular bone, as demonstrated in Hasan Karaman, et al. [31]. In both cases of stimuli, for *STPs* and *SEDTPs*, the rectangular and plateau typeB shaped threads resulted in increased stimuli transferred to the bone, in comparison to triangular and plateau typeA threads.
- High mechanical stimuli cause bone mass and strength increased, as shown in our

Model4_d4 (Rectangular) in zirconium implant material. In opposite, low mechanical stimuli can cause bone loss that reduces bone strength, as verified in our Model1_d6 (Plateau typeA) in titanium alloy.

- The majority of the results were found to correlate well with other studies. Some conclusions were new and will further help in the appropriate choice of dental implant, according to different materials or thread profile, using a constant number of threads.

In future works it is intended to study the effect of different implant lengths with different number of threads, different thread width and thread pitch. Anisotropic material properties for bone (cortical and trabecular) should be considered. Also, a more complex geometry and contact mechanics between all parts of the model need to be included. This drawback seems unavoidable to extend our contribution.

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How to cite this paper:

Diana Martins, Rui Couto, Elza M. M. Fonseca and Ana Rita Carreirasa, "Numerical analysis of the mechanical stimuli transferred from a dental implant to the bone," *J. Comput. Appl. Res. Mech. Eng.*, Vol. 11, No. 1, pp. 1-11, (2021).

DOI: 10.22061/JCARME.2021.7542.2001

URL: https://jcarme.sru.ac.ir/?_action=showPDF&article=1552