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Effects of the Geometric Parameters on the Interfacial Stresses Bone/Implant

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Abstract

Implantology is the fixation of an artificial root made of titanium in the mandibular bone, emerging from the gum and supporting a tooth or prosthetic element. In this work, the mechanical behavior of dental implants with different geometric shapes is analyzed numerically by the finite element method. The first objective of this study is to show the importance of the geometric parameters such as length on the variation of the equivalent stress in the close vicinity of the bone / implant interface. These interfacial stresses are evaluated on the outside and inside of the net. The results clearly show that the best model of the implant obtained is that of 10.43 mm in length. The second objective is focused on the distribution of von Mises stress in the bone and the dental implant in different loading cases. It is important to know the effects of this type of treatment to obtain a primary stabilization of the structure or at the interface bone/implant.

Keywords: bone, implant, thread, von Mises stress, interfacial stress, MEF.

1. Introduction

Dental implants are part of medical devices. Most dental implants used today are made of titanium, or titanium alloy with a modified surface. They are inserted into the bones of the maxilla to act as an "artificial root" [1] and emerge from the gum and will support a tooth or prosthetic element. It is reported that titanium is the best material that exhibits biocompatibility with soft tissue than other materials [2]. Dental implants are used to support and/or stabilize different types of fixed or removable dental prostheses intended to replace missing teeth, ranging from the single prosthesis to the complete bridge. The implant/prosthesis bond remains a factor in the lifetime of prosthetic treatments on the implant [3]. Most dental implants used today are cylindrical, conical or cylindrical-conical screws [4-5], have endo-osseous devices in the form of a cylinder or a cone, placed surgically in the bone of the bone Maxillary or mandible. For several decades, all forms of implants, materials and different operating procedures were tried. However, these technices are based on empirical methods than on rigorous scientific protocols which almost yielded unsatisfactory results with the loss of the implant in most cases. The first attempts to install dental implants were made in the 1950 by GOLBERT and DAHL [6]. Starting in the 1960, Suedios Per Ingvar BRANEMARK [7,8], an orthopedic surgeon, and a biologist, during his work on microcirculation in bone, described osseointegration. The choice of the implants is intimately linked to the available bone volume, bone quality and some aesthetic and prosthetic imperatives. This form ensures the stabilization of the various prosthetic parts, the fixation of which is made by means of an internal thread present on the implant. It's surface characteristics have a crucial effect on the management of osseointegration. The research has designed large diameter implants, and short ones, which have an implant anchoring surface and increased primary implant stabilization. The wide implants have diameters of 5 mm to 6 mm, and generally prosthetic rests are important. Moreover, the increased prosthetic seat allows the reduction of the tension forces on the abutment screw. For this, we have the plan described by the parts that make up this study:

- The first part is devoted to a three-dimensional analysis of the von Mises stress at the bone / implant interface at the inside and at the bottom of the net;

- The second part aims to analyze the constraints of von Mises in the bone and the implant chosen according to the type of loading (corono-apical, disto-mesial and lingual-buccal).

2. General morphology of implants

Dental implants are titanium structures most often, which function to replace one or more missing teeth. The anchoring is most often done by screwing in the bone mandibular or maxillary after bone drilling performed under irrigation.

The implant complex generally consists of two main parts:

- A part buried in the bone called implant;
- An emerging part of the bone and the gum attached to the implant by an attachment system: the prosthetic abutment.

The part of the implant that hosts and joins the prosthetic abutment is called the implant's neck. This part is the object of the morphology with which it is most often in intimate contact. The latter includes health and tissue tone. It is also at the level of the neck of the implant that the bacterial plaque is fixed preferentially. This zone is the most exposed to the saliva carrying elements that constitute the bacterial plaque at the origin of many phenomena soft tissue inflammations.

This plaque must therefore be carefully removed daily by careful brushing of the natural teeth. It is even more important for dental implants that do not benefit from the natural defenses of teeth against gingival inflammation caused by bacterial plaque and which facilitate bacterial progression by the presence of the turns along which the bacteria move and develop. Manufacturers have long felt that this pass must be polished in order not to allow of bacterial deposits on their surface and to preserve as much as possible the implant health, but it now appears that a certain roughness is tolerable, it is desirable to allow a better attachment of the hard tissues (the bone) and the soft tissues (the gum) and thus create a protective and sealed sleeve by contact with the neck of the implant [9-10].

3. Geometric model

The aim of this work is the three-dimensional analysis of the stresses and their level in the elements of the dental prosthesis and at the interface bone/implant under the effect of stresses. The bone is subdivided into two sections: the spongy bone which its size is representative of the section of the lower jaw. This living organ is composed of a spongy center surrounded by cortical bone. The implants are in the form of screws of different lengths L=10.43 mm, 12.00 mm, 14.00 mm and diameter D=5.4 mm. The geometric dimensions of the pillar are: L=08.88 mm, D1=02.80 mm, D2=03.60 mm.

3.1. Os mandibular

The purpose of tapping into the bone is to create room for the implant's turns before insertion into the stall. Tapping reduces friction and facilitates insertion of the implant, especially in dense bone. The geometry of the bone structure is made from radiological images using automatic 3D segmentation software. This model was built using tomographic scanning software (CT). Then, the software Rhinoceros 4.0® and Solidworks®, were used to generate the final model of the mandibular bone. The bone was modeled so that its core is the spongy bone (trabecular) surrounded by a layer of compact bone thickness 2.00 mm, the width and length of the model of the cortical bone are 12.43 mm and 36.00 mm respectively. These sizes are representative of the lower jaw (Figure 1).

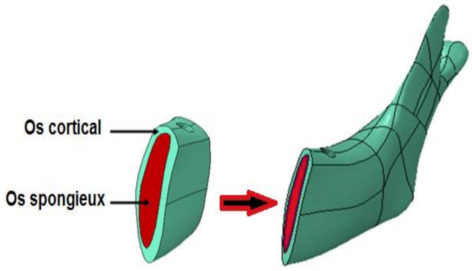

Figure 1: Components of the mandibular bone [11]

3.2. Implant system

The implant model, in a conical-cylindrical model in a titanium anchored to the lower jaw, in particular, the implant was placed on the Brånemark system (The Brånemark system is the most scientifically documented implant system in the world), its regular platform. The tooth model was chosen from several extracted teeth, so that its dimensions correspond as closely as possible to those mentioned in the dental anatomy manual [12]. The models of the crown and the crown door were designed on Rhinoceros® 4.0 and SolidWorks® 3D with 5 degrees of inclination in the bucco-lingual direction [13]. The implant model was placed in a vertical position in the region of the first molar of the mandible in identical shape of titanium screws with different geometry characteristic: length (Figure 2a). The implant system which consists mainly of the components:

a) "First molar" crown, crown gate, pillar, mandibular bone.
b) The global model with the first molar, implant, pillar and mandibular bone, was combined using the SolidWorks® (CAO/DAO) software [14], then was exported to the calculation program [15] (Figure 2b).

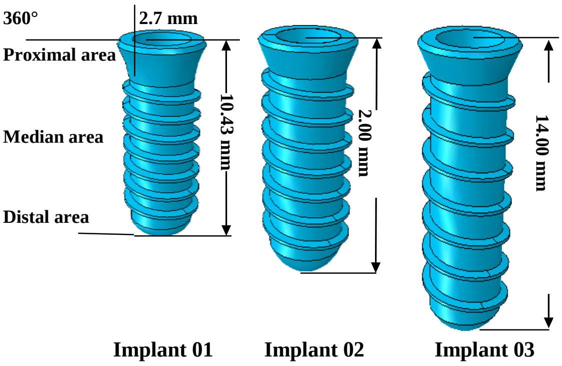

Figure 2a**:** Different geometries of the implant

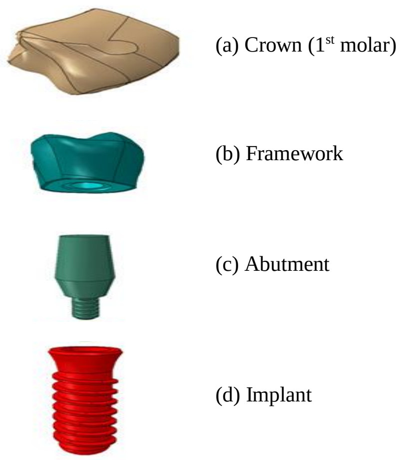

Figure 2b: Components of the dental prosthesis

The properties of the materials of the implant systems and the mandibular bone have been summarized in table 1:

Table 01
Mechanical properties of prosthesis and mandibular bone [16]

Components	Materials	Mechanical Properties	Young modulus [E] (GPa)	Poisson ratio	Breaking stress
Crown (1st molar)	Feldspar porcelain (ceramic)	Elastic	61.2	0.19	500
Framework	Alloy Cr – Co		220	0.30	720
Abutment Implant	Titanium alloy Ti-6Al-4V		110	0.32	800
Mandibular bone	Cortical bone		11.5	0.31	130
	Cancellous bone		2.13	0.30	130

4. Boundary conditions

The forces intensities, as well as their points of applications, were chosen as follows:

a) The occlusal surface of the crown is subjected simultaneously to three static forces: A normal force and two lateral forces along three respective directions: corono-apical, disto-mesial and linguo-buccal and define a 3D system have been applied.

b) The upper surface of the crown of the first molar is subjected to an applied stress of 6 MPa in the corono-apical direction (normal load), 1 MPa in the linguo-buccal direction and 1 MPa in the disto-mesial direction and the other surfaces are treated as free surfaces (Figure 2) [11].

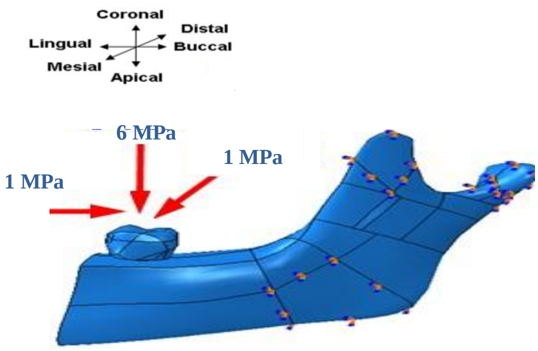

Figure 2: Boundary conditions and applied load type

4.1. Interface conditions

The interface between all components of the dental prosthesis is treated as an interface perfectly bonded [17, 18]. To simplify the analysis by finite elements, it has been assumed that the behavior of all the materials of this model is elastic, linear and homogeneous [17-19].

4.2. Meshing of bone structure and different implant models

As shown in figure 4, the bone and the different implants were meshed in linear four-node C3D4 and hexahedral linear tetrahedral elements at 8 nodes. It is the interface bone/implant subjected to maximum stresses under occlusal loading. It was considered fundamental to refine the mesh at this interface as shown in figure 5. The meshing of the components of this implant system is checked for a three-dimensional 3D analysis. Therefore, the dental implant system and the mandibular bone will have to be meshed with large elements when moving away from the interface.

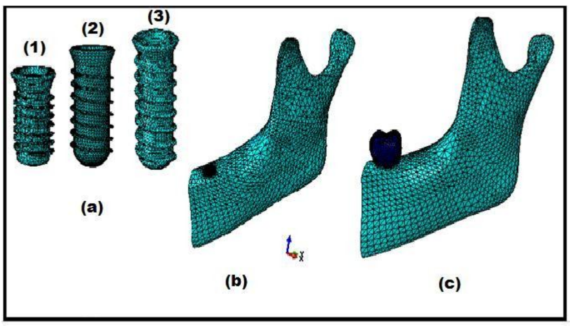

Figure 4- Meshing using linear tetrahedral elements
(a) Different implant models, (b) Mandibular bone, (c) Final model

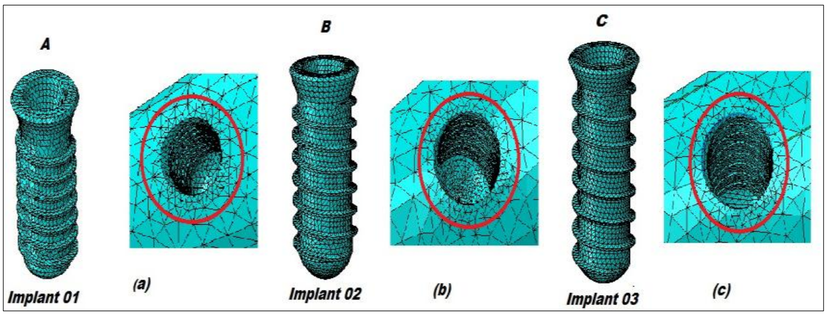

Figure 5 - Meshing of different implant models, Interface and bone

The mesh of the chosen implant, the interface and the bone showing that the elements in the bone increase in size as the distance from the interface increases.

The various components have been meshed into four-node tetrahedron elements. Since the bone-implant interface generates maximum stress, it was considered fundamental to refine the mesh at this interface.

The mesh of components is checked for use in a stress analysis and consequent deformations by finite element (Table 2).

Table 3
Mesh Results

Model	Element size (mm)	Number of elements	Number of nodes
The mandibular bone	0.25 ÷ 1.00	157 920	10 461
Selected implant	0.25	10 772	16 721

5. Results

5.1. Effect of the implant's length on the variation of the von Mises stress:

The simulation was carried out using a calculation manager. In this study, the distribution and intensity of the equivalent stress of von Mises in the part of the bone surrounding the implant were analyzed. This stress is a scalar variable defined as a function of a set of individual stresses and consequently constitutes a very good representative of the precise state of the set of stresses. It is widely used in biomechanical studies of bone [20, 21].

5.2. Equivalent stress inside and outside the implant thread

The figure below shows the interface bone/implant on the outside and inside the thread.

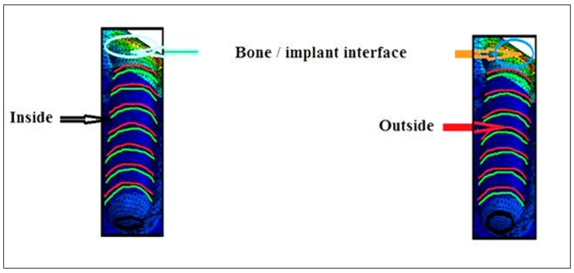

Figure 6: Representation of the bone-implant interface outside and inside three threaded dental implants

Figures 7 and 8 illustrate the variation of the interfacial stress respectively outside and inside three threaded implant's lengths under a corono-apical loading.

According to the curves, the distribution of the stress along the interface is not homogeneous and the most intense stresses are located at the beginning of the median zone for different lengths of the implant. The intensity of the equivalent stress diminishes as one moves away to the distal zone to reach a zero value. The intense stresses are recorded at the interface of implant 1 under the corono-apical loading.

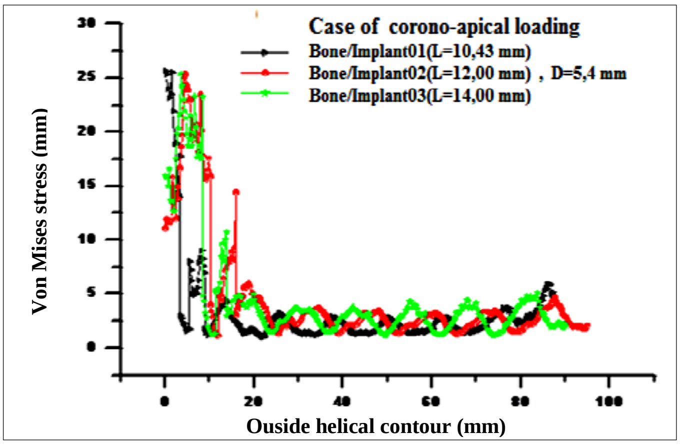

Figure 7: Variation of the interfacial stress outside of three threaded implants

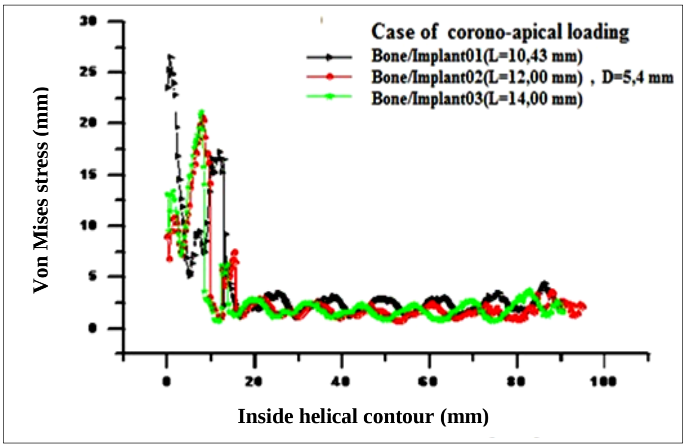

Figure 8: Variation of the interfacial stress inside of three threaded implants

Figures 9 and 10 show the variation of the interfacial stress for three implants under the distal-mesial loading. It is noted that the interfacial stress reaches a maximum value at the beginning of the median zone and more precisely at the level of the neck of the implant. The implant with the shortest length is subjected to a high interfacial stress field outside and inside the thread.

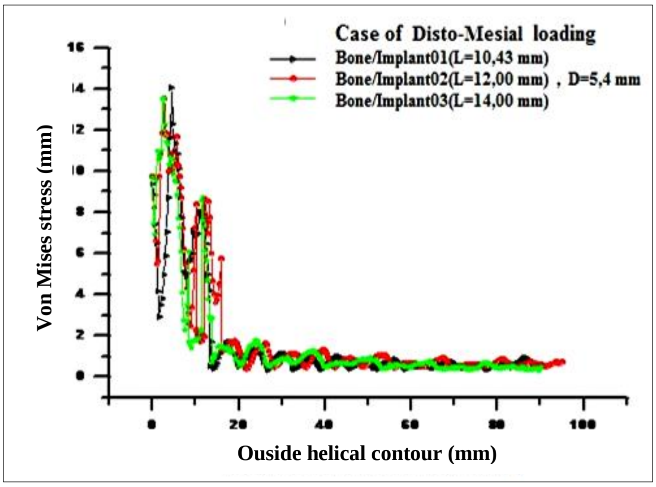

Figure 9: Variation of the interfacial stress outside of three threaded implants

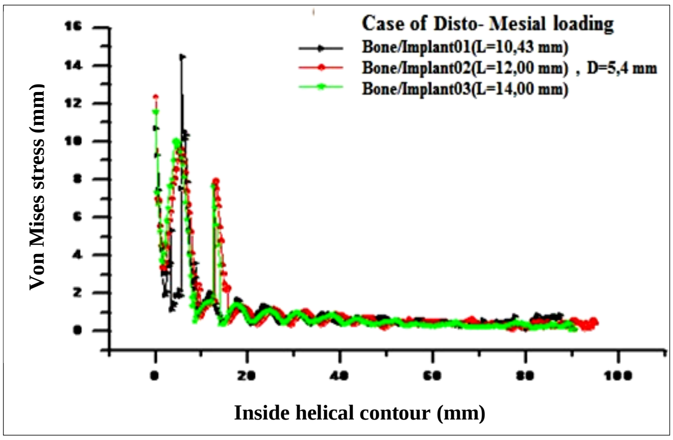

Figure 10: Variation of the interfacial stress inside of three threaded implants

Figures 11 and 12 show the variation of the interfacial stress outside and inside for three types of dental implant under a lingual-buccal loading. It should be noted that the most significant stresses are at the beginning of the thread and their intensities decrease progressively to reach a minimum value at the end of the threading. Beyond the implant, the equivalent stress tends towards an almost constant value in the alveolar bone. It is observed that the level of the interfacial stress in implant (1) is greater than those of the other two implants (2) and (3). The numerical results obtained by the finite element method show that a high concentration of interfacial stresses is recorded under the corono-apical stress applied to the crown. These interfacial stresses remain relatively low in the case of horizontal loadings. It is observed that the reduction in the length of the implant leads to a high concentration of stresses inside and outside the threads of three implants under the various loads.

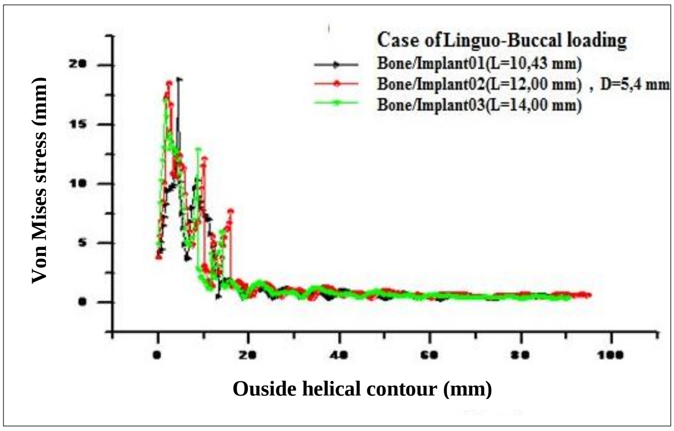

Figure 11: Variation of the interfacial stress outside of three threaded implants

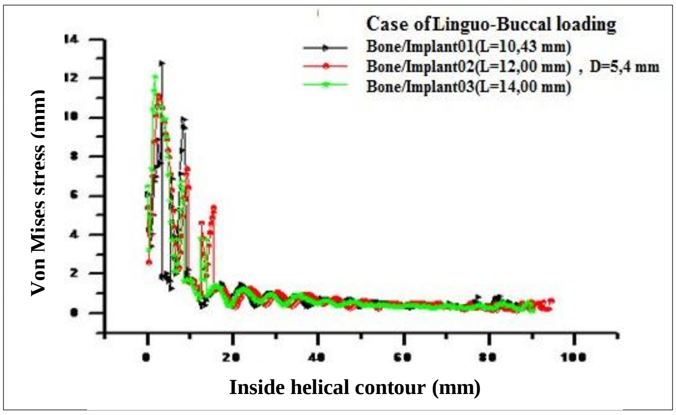

Figure 12: Variation of the interfacial stress inside of three threaded implants

5.3. Results and discussions

This section aims to determine by the finite element method the von Mises stress distribution in the mandible and four components of the dental prosthesis. A qualitative and quantitative analysis was carried out, based on a progressive visual color scale, predefined by the software used (Abaqus), ranging from dark blue to red. On the other hand, the intensity and distribution of the equivalent stress were evaluated in the cervical and apical area surrounding the dental implant and in the bone/implant interfacial area. This stress is a scalar variable defined as a function of a set of individual stresses. The latter shows that this stress is determined numerically for the vertical load (1) corono-apical and two horizontal loads distal-mesial (2) and lingual-buccal (3).

5.3.1. Mandibular bone

Figure 13 shows the von Mises stress distribution in the alveolar bone for three types of loading. It can be seen in all loading cases, the most intense stresses are localized in the cortical bone, whatever the type of loading. It is also noted that the level of stress is almost identical for the two loadings (disto-mesial and linguo-buccal). However, the level of stress induced by the corono-apical effort is almost double that of the other loads (2) and (3).

The cortical bone, cancellous bone and implant with abutment were presumed to be linearly elastic, homogeneous and isotropic [22, 23]. Although cortical bone has anisotropic [24]. There is a high concentration of stress in the upper part of the cortical bone, which shows that the vertical load applied to the crown is transmitted directly to the compact bone.

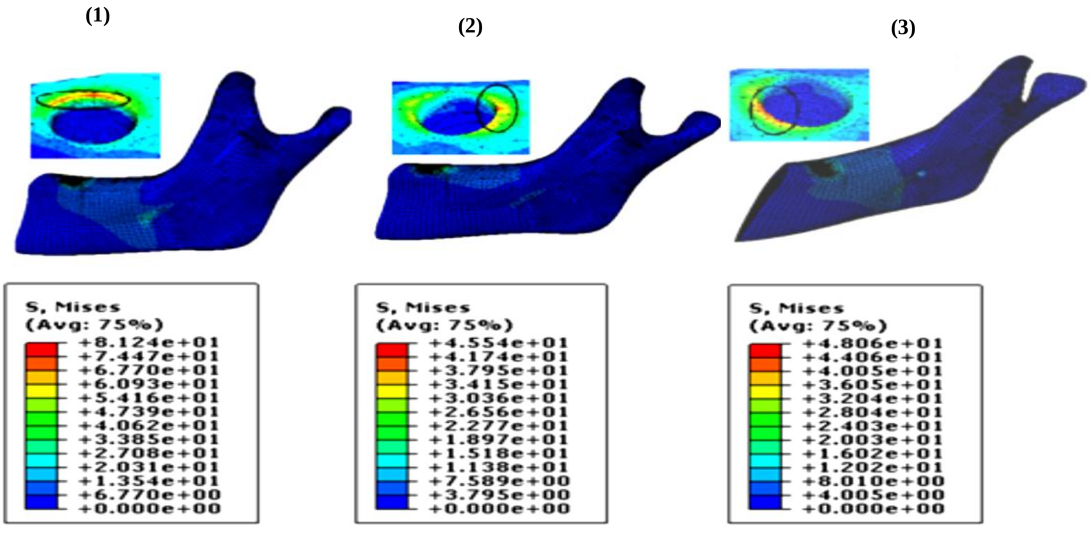

Figure 13: Stress distributions in the bone
(1), corono-apical load (2), distal-mesial load (3), lingual-buccal load

5.3.2. Implant choice

Figure 14, clearly shows the von Mises stress distribution in the implant for three types of loading. The upper part of the implant is the seat of stress concentration. In other words, the amplitude of the highest equivalent stress is observed on the lateral parts of this organ in its proximal zone. However, the other zones are subjected to stresses of low intensities and this whatever the type of loading. It is observed that the stresses created in the implant are almost the same for both loadings (disto-mesial and linguo-buccal). It should be noted that the stress level of the corono-apical loading (1) is almost double that of the other loads, (2) and (3), applied to the crown.

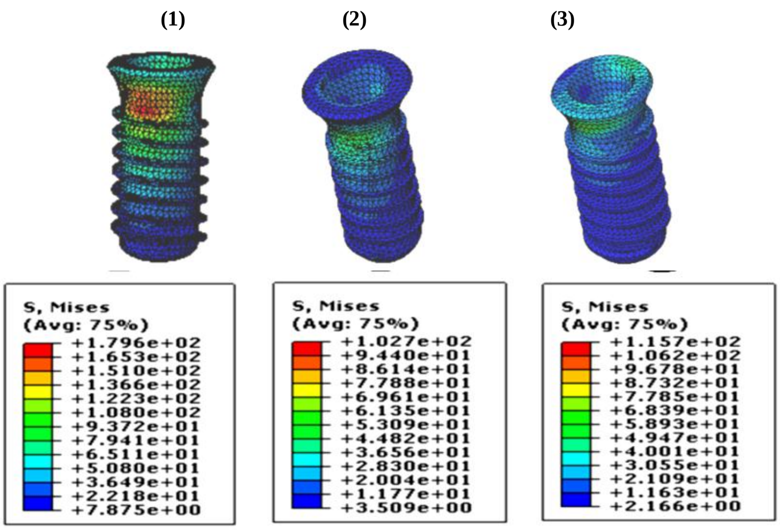

Figure 14: Stress distributions in the implant
(1), corono-apical load (2), distal-mesial load (3), lingual-buccal load

6. Conclusion

The distribution and intensity of the stresses in the mandibular bone and three dental implants with different lengths and the same diameter have been determined numerically by the finite element method. The interfacial stress bone/implant was evaluated both inside and outside the implant net and the results obtained allow us to draw the following conclusions:

- Regardless of the length of the implant, the upper part of the implant is the seat of high stress concentration and more particularly at the level of the implant's neck. This is probably due to the contact area implant/compact bone whose surface area is relatively small compared to that of the area implant/spongy bone. It is noted that the implant (2) is subjected to equivalent stresses of low intensity, which leads us to seek an optimal length to minimize the stress field and to ensure the long-term maintenance of the implant inside the implant alveolar bone;
- The amplitude of the equivalent stress in the dental implant, generated by the corono-apical effort, is almost twice that induced by the other loads (disto-mesial and linguo-buccal). The level of the von Mises stress depends essentially on the nature of the loading applied. The main factor in the success of a dental implant is the way in which the efforts are transferred to the surrounding bone;
- The shape of the stress curve along the thread is similar that of harmonic function’s graph, whose value is maximal at the beginning of the median zone and their amplitude will become very small beyond of 20 mm along the thread. It is observed that the curves of the stresses determined outside the thread of the implant are almost identical for two implants (2) and (3) and their intensity is relatively small compared to that of the implant (1).

The same behavior is observed for the equivalent stresses determined at inside the threaded implants. They concluded that the influence of the length of the implant, however, was not as pronounced as that of its diameter.

- The corono-apical loading leads to significant stresses in the cortical bone and the various components of the dental prosthesis. This loading puts the implant in compression;
- Two loadings (disto-mesial and linguo-buccal) give rise to stress of the same intensity in the mandibular bone and the other elements of the dental prosthesis. These two stresses cause the flexion of the implant.

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