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Angulated Dental Implants in Posterior Maxilla FEA and Experimental Verification

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Abstract

AIM: This study aimed to evaluate the effect of different implant angulations in posterior maxilla on stress distribution by finite element analysis and verify its results experimentally.

METHODS: Two simplified models were prepared for an implant placed vertically and tilted 25° piercing the maxillary sinus. Geometric models' components were prepared by Autodesk Inventor then assembled in ANSYS for finite element analysis. The results of finite element analysis were verified against experimental trials results which were statistically analysed using student t-test (level of significance $p < 0.05$).

RESULTS: Implant - abutment complex absorbed the load energy in case of vertical implant better than the case of angulated one. That was reflected on cortical bone stress, while both cases showed stress levels within the physiological limits. Comparing results between FEA and experiment trials showed full agreement.

CONCLUSION: It was found that the tilted implant by 25° can be utilised in the posterior region maxilla for replacing maxillary first molar avoiding sinus penetration. The implant-bone interface and peri-implant bones received the highest Von Mises stress. Implant - bone interface with angulated implant received about 66% more stresses than the straight one.

Introduction

Trials for replacing missing teeth with root form implants back to thousands of years. Antiquities from ancient China and ancient Egypt show bamboo pegs and similarly shaped pegs from precious metals tapped into the bone for replacing lost teeth [1]. This way of thinking is translated into what we called dental implant. Dental implants support prosthesis like a crown, bridge, denture as a primary use for it. This support based on osseointegration, the process in which bone unite firmly with the surface of certain materials such as titanium or some ceramics biologically. The integration between bone and implant can bear the physical load for several years [1].

Although dental implants are considered as ideal manner for replacing missing teeth, the bone height from the alveolar crest to the sinus floor at the posterior maxillary region is usually insufficient due to sinus pneumatization, as well as to the lack of stability caused by maxillary bone loss at the edentulous sites required for osseointegrated implantation [2].

Tilting implants are an effective and safe substitute for surgery of augmentation of maxillary sinus floor and to maxillary sinus which is pneumatized. It can usually be conducted in patients with different systemic conditions which often have limitations for grafting of the bone. The angulated implants permit insertion that avoids anatomical structures like maxillary sinus [3].

High risks will be involved when restored prostheses are subject to non - axial loading. It is recommended to direct occlusal loads as close to the long axis of the fixture as possible. However, it is known that the loading on angled abutments is mostly off - axis, which raises the concern of how angled abutments perform with such an unfavourable loading regimen [4].

The way in which loads are transmitted to the surrounding bone is the key factor for success or failure of the dental implant. Between different mathematical methods which can evaluate stress distribution within bone supporting dental implants, finite element analysis (FEA) is usually used in dentistry to evaluate the influence of clinical agents on the survival of implant placement, and also to predict the biomechanical status correlated with the different dental implant and alveolar bone conditions [5]. FEA allows the prediction of the stress distribution in the contact area of the implants with cortical bone, and around the apex of the implants in the surrounding bone. This method is advantageous for solving complex structural problems as it divides them into smaller and simpler interrelated sections through the use of mathematical techniques [6].

This study aimed to evaluate the effect of different implant angulations in posterior maxilla on stress distribution by finite element analysis and verify its results experimentally.

Materials and Methods

Two finite element models were specially prepared for simulating the clinical situation where a dental implant was placed into posterior maxilla in two different ways. The implant to be placed vertically (case study #1) and tilted by 25° inside the bone to avoid sinus penetration (case study #2).

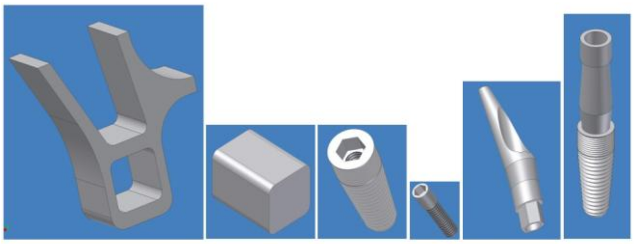

Figure 1: Screenshots of the two models' components on Inventor GUI

The finite element models' components (prescribed in the in - vitro study) as the abutments, screw, implant, cortical and cancellous bones were created on “Autodesk Inventor” Version 8 (Autodesk Inc., San Rafael, CA, USA) as presented in Figure 1. These components were exported as SAT files [7]. These components were assembled in ANSYS environment (ANSYS Inc., Canonsburg, PA, USA), where all used materials were assumed to be isotropic, homogenous and linearly elastic and its properties are listed in Table 1.

Table 1: Material properties used in the finite element model(s)

Material	Young's modules [GPa]	Poisson's ratio
Implant abutment complex	110.0	0.34
Cortical bone	13.7	0.30
Cancellaus bone	1.37	0.30

Set of Boolean operations between the modelled components were performed before obtaining the complete model(s) assembled. The meshing of these components was done by 3D brick solid element “187” which has three degrees of freedom (translation in main axes directions) [8]. The resulted numbers of nodes and elements are listed in Table 2, and cut sections in the meshed models are presented as screenshots from ANSYS in Figure 2.

Table 2: Number of nodes and elements in all meshed components

Volume	Vertical Implant Model (case #1)		Angulated Implant Model (case #2)	
	Number of Nodes	Number of Elements	Number of Nodes	Number of Elements
Cortical bone	18,738	18,549	20,345	21,555
Cancellous bone	14,928	14,465	27,663	25,303
Implant	49,958	45,193	32,353	29,282
Screw	364,884	283,868	1,857	1,876
Abutment	9,591	11,341	1,358	1,840

The extreme areas of the cortical bone were set to be fixed in place as a boundary condition. While the applied compressive load were set to be 200N, distributed equally on the abutment top area nodes. Solid modelling and finite element linear static analyses were performed on Workstation HP ProLiant ML150, with Intel Xeon 3.2 GHz processor (with 1MB L2 cache), 10GB RAM, using ANSYS version 14.5. The finite element analysis results were verified against experimental trials.

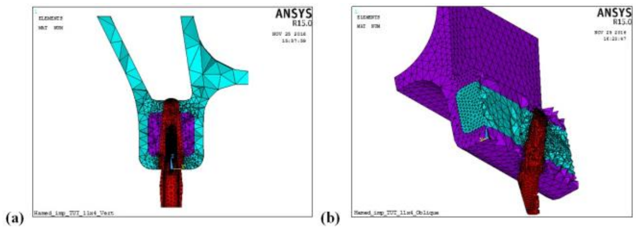

Figure 2: Screenshots of cut sections in the two models

The in - vitro study utilised six segments of bovine bone ribs. The samples were cleaned and removed of all soft tissue residues, then immersed in a saline and ethanol solution (1:1). Each rib received one implant, where vertically drilled to show the 11 mm depth of the implant site. The specific implant, rib and site to receive the implant preparation were chosen randomly. Accurate and atraumatic preparation of the bone at the implant site was done using the instrument set for 11mm length, 4mm diameter TUT - II implant system (TUT Dental Implant Co., Egypt). The six segments were divided into two groups; Group A (three bovine ribs received three straight implants) and Group B (three bovine ribs received three tilted implants). Fracture resistance test conducted using INSTRON® universal testing machine (model 3345). All specimens were individually mounted in a jig then secured to the lower grips. While a load cell of 5 kN was used for force measurements that results were acquired using BlueHill software version 3.3 (by INSTRON®). A special stainless steel rod with a round end of 5 mm diameter was fixed in the upper moving grips to apply compressive load over the top of the abutment of each specimen till failure occurred in any component.

Results

The concentration of Von Mises stress was found on the surface of the crestal cortical bone around the implant neck except that for the bicortical implantation. Finite element results showed that implant-abutment complex absorbed the load energy in case of vertical implant better than the case of angulated one. That was reflected in cortical bone stress. Vertical implant transferred less - load to cortical bone (of order 22 MPa) by about 66% in comparison to angulated one (of order 67 MPa), while both cases showed stress levels within the physiological limits [9][10].

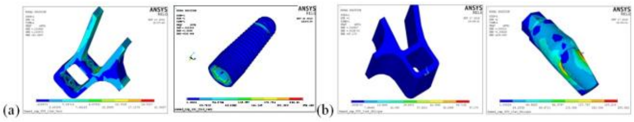

Figure 3: Sample of Von Mises stress distributions on both case studies (a) vertical implant; (b) angulated implant

Implant abutment connection received most of the load energy in both cases, where maximum Von Mises stress on implant appeared on this section. On the other hand, the maximum Von Mises stress appeared on abutment at different locations; at the connection with the implant in vertical implant case, and at thin walls around screw way to the implant in case of the angulated implant. Figure 3 demonstrates a sample of Von Mises stress distributions, while Figure 4 compares all components maximum, Von Mises, stress.

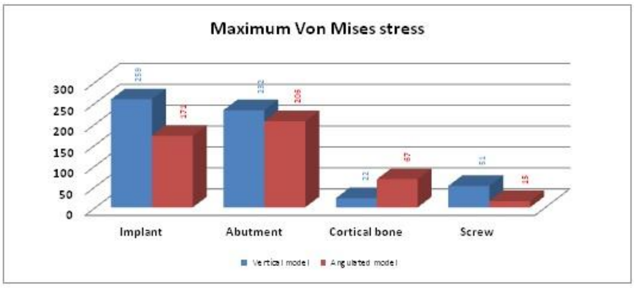

Figure 4: Maximum Von Mises stress comparison between the two cases

Applying the student t-test to the experimental trials' results of the fracture resistance for the two studied groups showed that there was a highly significant difference between the mean compressive loads of them, as shown in Table 3.

Table 3: Fracture load comparison between the two studied groups

Fracture Load	Vertical (control) (n = 3)	Angulated (n = 3)	T	P
Min. – Max.	449.1 – 524.4	381.4 – 421.4		
Mean ± SD.	496.3 ± 41.1	399.7 ± 20.2	3.651*	0.022*
Median	515.3	396.4		

t, p: t and p values for Student t-test for comparing between the two groups; *: Statistically significant at $p \leq 0.05$.

Comparing results between FEA and experiment trials showed full agreement. The bone was strongly affected by the implant angulation because it was the first component to be fractured through the experimental verification. But in case of an angulated implant, the complex had endured less vertically applied forces to generate the similar level of stress on the cortical bone. This may be referred to abutment design, and its level of stress appeared on it. The more the abutment stress, the more the energy it absorbs, which reduce the energy or load transferred to the following parts of the system (implant and bone).

Discussion

The finite element analysis resulted in huge graphical representations (screenshots/pictures), each one present a type of deflection, strain, or stress. Commonly when Von Mises stress reaches critical values, all other types of stresses and deflections would be discussed to indicate the dominant effect from loading or system materials. In this study, the von Mises stress distribution on the bone away from the implant-bone interface was considered. This is because it was difficult to estimate the effect of stress distribution solely based on the stress pattern at the localised implant-bone interface in case of a severely atrophied bone. Also, stress on the implant/abutment complex was analyzed to estimate the risk of fracture in an angulated implant case.

The posterior maxillary area contains cancellous bones with low bone density and thin cortical bones, the quantity and quality of which are lower than those of the mandibular bone. Therefore, it is difficult for implants installed in this region to be stable. This is due to the small implant-to-bone contact area and the inferior bone quality [11].

Maminskas et al. [12] found out risks of mechanical impacts of peri-implant bone loss and prosthetic influence on bone stability. They concluded that peri-implant strain could be generated by nonaxial loading, cantilever prosthetic elements, crown/implant ratio, type of implant-abutment connection, misfits, properties of restoration materials and antagonistic tooth.

The experimental trials where the implant was placed vertically was used as the control group. All tested samples showed the same mode of failure in cortical bone (where the implant was pushed into the bone) under different values of the applied load. Applying the student t-test to the experimental results of the fracture resistance test of the two studied groups showed that there was a highly significant difference between the mean compressive loads of them. Bone was mostly affected by the implant angulation as demonstrated through FEA stresses results too. Also, the angulated implant complex may endure more force to collapse in comparison to straight implant complex. Finally, comparing results between FEA (maximum Von Mises stress) and experiment trials (maximum load at failure) proved that the tilted implant 25° could be utilized in the posterior region maxilla for replacing maxillary first molar to avoid sinus penetration.

In previous studies [9][10][13] influence of implant - abutment angulations on stress distribution on central incisor were investigated. The conclusion of these studies was; cortical and spongy bone were insensitive to the crown material, and increasing abutment angulation from 15° to 25°, increases stress on cortical bone by about 20% and reduces it by about 12% on spongy bone.

Also, the cervical areas are the most critical on the abutments due to the force concentration that may be a reason for failures, i.e. increasing the abutment angulation had a negative influence on the fracture load.

Majority of finite element models in dental researchers [9][14] assumed perfect bond between assembled model components to simulate natural condition, in addition to assuming linear, static and isotropic material properties. The trend of the presence of higher Von Mises stresses in the bone around the angulated implant than bone around the straight implant did not differ by the bone levels [9][14]. Prominently, the highest level of stress was exhibited in the stepped area of the bones. In clinical situations, however, these phenomena are not likely to occur as the bone loss occurs continuously. In preliminary modelling, the maxillary bone was reconstructed from the data of other researchers [15][16] according to the anatomical area of the sinus.

For immediate loading, when the implant apex broke into or through the sinus cortical bone, the maximum displacements of the implant, particularly at the implant apex, were smaller than those did not reach sinus floor. Yan et al. [16] FE study on the association between implant apex and sinus floor showed that having the implant apex in contact with, piercing or breaking through the sinus floor cortical bone benefited the implant stability, particularly for immediate loading.

Finally, the results of this study were in agreement with the literature [9, 10, 13, 17] when abutments with 0, 15°, and 25° angulations were evaluated in the maxilla by 3D FEA, that the implants were recommended to be vertically aligned with axial loads.

Comparing results between FEA and experiment trials showed full agreement and found that the tilted implant by 25° can be utilised in the posterior region maxilla for replacing maxillary first molar avoiding sinus penetration.

Within the limitations of this study, it can be concluded that the highest bone stress was observed on the implant-bone interface and peri-implant bones, while the case of angulated implant showed higher Von Mises stress by about 66%. On the other hand, angulated implant complex components received more Von Mises stress by about 15 to 70% in comparison to the straight one's components.

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