Finite Element Analysis of Stress & Strain Distribution in The Bone Around The Mini - Implants Used For Orthodontic Anchorage at Different Sites as Per Different Bone Density & Thickness : A FEM Study

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Abstract

Aim: To evaluate stress and strain distribution in the bone around the mini-implants used for orthodontic anchorage at different sites as per different bone density and thickness by performing a FEM study.Materials and Methods:Computer aided design(CAD) model of mini-implants of different dimensions were generated by laser scanning of the mini-implants and also CAD model to represent bone were generated using material properties of the bone.FEA was carried out using different loading variables at 7 different mini-implant sites having different thickness and density at those respective sites.

Results: Result showed that all the FE models showed the area with the highest stress and strain to be around the neck of the micro-implant and the cortical bone and least were seen at the tip of the micro-implants around the trabecular bone. Comparision of all the FE models showed on application of orthopaedic load more stress and deformation were seen as compared to orthodontic load. Also comparision of the FE models showed more stress and deformation on application oblique load as compared to the vertical load.Conclusion: To obtain an optimal biomechanical response, the implant should preferably be placed entirely in the cortical bone (however, this may not always be feasible clinically). The neck of the implant should be sturdy enough, and the head of the implant should not produce any kind of irritation to the overlying mucosa.

Keywords: Mini-Implant, Trabecular Bone, Cortical Plate, Finite Element Analysis.

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Introduction

Anchorage control is one of the most important to accomplish effectual orthodontic and dentofacial orthopaedic treatment. Implants are excellent substitute to traditional orthodontic anchorage techniques in the circumstances when patients compliance during treatment is doubtful and using extraoral devices is avertable .Every orthodontic device, which exercises a force onto the tooth, generates an opposite force which then affects the anchorage.

In recent years use of TAD's(Temporary Anchorage Device) for anchorage has gained popularity due to easy technique of placement and retrieval and also being economical[3].TAD's have been used as anchorage for tooth movements that could not otherwise have been performed. Mini-implant researchers and manufacturers have developed mini-implant's of smaller dimensions for orthodontic anchorage which can be effectively used at any surfaces of the alveolar process also in the interdental areas. mini-implant's are easy to implant and remove. In addition, orthodontic force application can begin almost immediately after implantation.

It's important to comprehend the stress and strain distribution around the load bearing TAD's in the bone as the biomechanical influences on the bone structure plays an essential role in the longevity of the bone around the mini-implant's. The quality and direction of the applied force affects the mini-implant's resulting in bone deformation around them. The bone density around the implant site also plays a cruicial role of longevity of the mini-implant's. Also one of the factors affecting the success is the different angulation of loading of mini-implant's, Different loading forces which can be orthodontic as well as orthopaedic can have an effective impact on the mini-implant's longetivity. Different dimensions of the mini-implant's at different implants sites plays a major role for the longetivity of the mini-implant's.

Clinical evaluation of stress and strain distribution in the bone is unattainable so the stress analysis of these endosseous implants is necessitous for examination of bone turnover and to attain maximum orthodontic anchorage[4].

In the field of engineering finite element method (FEM) has been successfully applied for the mechanical study of stress and strain. So its attainable to explain stress and strain distribution in living structures as a result of different internal and external forces. Crucial element for the success or faliure of mini-implant's is the manner stress are transferred to the surrounding bone. Finite element analysis (FEA) has been used extensively to predict the biomechanical performance of various dental implant designs as well as the effect of clinical factors on implant success. Finite element analysis(FEA) is the most popular tool to estimate the effects of stress and strain distribution on the mini-implant's and the surrounding bone. FEA allows us to anticipate stress distribution in the contact area of the mini- implant's with the cortical bone as well as contact of the apex of the mini-implant in the trabecular bone.

Materials & Methods

a) Source of data: This FEM study will be carried out at a specialised center for the same, named FEA Solutions, located in Thane.

- **Generation of CAD Model**

Computer Aided Design(CAD) Models will be generated with avaiable specific Mini-implant screw dimensions. Laser scanning of actual mini-implant will be done to get exact CAD Model for FE Analysis. CAD Model to represent the bone will be modelled as a simple cylinder around the mini-implant.

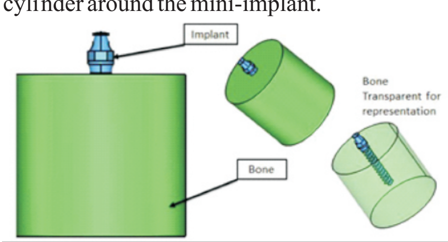

Fig: CAD Model of bone generated with the TAD

a) FEM Analysis:FE Simulation for Stress-Strain Analysis of:

1. Implant (TAD) at different sites o Bone around the mini-implant
2. Orthodontic & orthopaedic force By varying:

- **Different Types of Bone Density depending on implant site– the bone densities at 7 implant sites are as follows** :

I. Site 1 – 1.65 mg/cm³ (Vertical Insertion).
II. Site 2 – 1.75 mg/cm³ (Vertical Insertion).
III. Site 3 – 1.75 mg/cm³ (Oblique Insertion).
IV. Site 4 -- 1.70 mg/cm³ (Oblique Insertion).
V. Site 5 -- 1.65 mg/cm³ (Oblique Insertion).
VI. Site 6 -- 1.64 mg/cm³ (Oblique Insertion).
VII. Site 7 -- 1.72 mg/cm³ (Oblique Insertion).

- **Different angulation of insertion : 60°to Occlusal plane at Buccal sites. 90°at Palatal sites**.

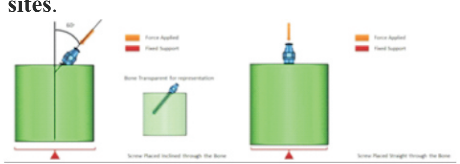

Fig: Placement of TAD at 60°in the CAD Model& Placement of TAD at 90°in the CAD Model

- **Implant loading**

I. Orthodontic loading -- Forces applied for Oblique direction 150gm ,Vertical force 75gm
II. Orthopaedic loading -- 500gm

Sites	Density (mg/cm³)	Insertion	Dimensions (mm)		
			A	B	C
1.Anterior Palatal Paramedian	1.65	Vertical	1.8	1	7
2.Posterior Palatal Paramedian	1.75	Vertical	1.8	3	9
3.Anterior palatal alveolar	1.75	Oblique	1.6	2	8
4.Posterior palatal alveolar	1.70	Oblique	1.6	2	8
5.Anterior Alveolar	1.65	Oblique	1.4	1	6
6.Anterior buccal alveolar	1.64	Oblique	1.8	1	7
7.Posterior buccal alveolar	1.72	Oblique	1.8	1	7

Table: Different bone densities at 7 different TAD sites

Results

Post processing is done to analyze the results in FEM. Stress and strain calculation around the Mini-implant and the bone at the 7 different sites as per different vertical oblique and orthopaedic load. Based on objectives of the study. Results were presented under following headings.

- **Implant loading at Site 1 :** Mini-implants is placed at anterior palatal paramedian site on which the vertical load of 75gm , and orthopaedic load of 500gm was applied. When vertical load of 75gm was applied the maximum stress is seen on the body of the mini-implant of 0.64MPa.The deformation due to the stress is maximum seen around the body of the mini-implant 1.5mm from the surface of the cortical bone(0.0000283mm). Least deformation is seen in the trabecular bone around the tip of mini-implant. When Orthopaedic load of 500gm is applied the maximum stress is seen on the body of the mini-implant of 31.95MPa.The deformation due to the stress is maximum seen in the cortical bone 1.5mm fron the surface of bone around the body of the mini-implant(0.0044mm).Least deformation is seen in the bone around the tip of the mini-implant in the trabecular bone.
- **Implant loading at Site 2 :** Mini-implant is placed at posterior palatal paramedian site on which the vertical load of 75gm , and orthopaedic load of 500gm was applied. When vertical load of 75gm applied the maximum stress is seen on the head of the TAD of 0.59MPa. The deformation due to the stress is maximum seen around the body of the mini-implant 1.5mm from the surface of the cortical bone (0.0000253mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone. When Orthopaedic load of 500gm was applied the maximum stress is seen on the head of the mini-implant of 29.22MPa. The deformation due to the stress is maximum seen in the cortical bone 1.5mm from the surface of the bone around the body of the mini-implant(0.0029).Least deformation is seen in the bone around the tip of the mini- implant in the trabecular bone.
- **Implant loading at Site 3 :** Mini-implants is placed at anterior palatal alveolar site on which the oblique load of 150gm , and orthopaedic load of 500gm was applied.When oblique load of 150gm was applied the maximum stress is seen on the body of the mini-implant of 3.23MPa. The deformation due to the stress is maximum seen around the body of the mini-implant 0.5mm from the surface of the cortical bone (0.0005mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone.When Orthopaedic load of 500gm was applied the maximum stress is seen on the body of the mini-implant of 42.38MPa. More deformation is seen around the body of mini-implant in the cortical bone(0.0073mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone.
- **Implant loading at Site 4 :** Mini-implants is placed at Posterior palatal paramedian site on which the oblique load of 150gm , and orthopaedic load of 500gm was applied. When oblique load of 150gm was applied the maximum stress is seen on the body of the mini-implant of 3.18MPa. The deformation due to the stress is maximum seen around the body of the mini-implant 0.5mm from the surface of the cortical bone(0.0005mm) whereas least deformation is seen around the tip of the mini-implant in the trabecular bone. When Orthopaedic load of 500gm was applied the maximum stress is seen on the body of the mini-implant of 12.89MPa. More deformation is seen around the body of mini-implant(0.002mm) whereas least deformation is seen around the tip of mini- implant in the trabecular bone.
- **Implant loading at Site 5 :** Mini-implants is placed at anterior alveolar site on which the oblique load of 150gm , and orthopaedic load of 500gm was applied. When oblique load of 150gm was applied the maximum stress is seen on the body of the mini-implant of 4.24MPa. The deformation due to the stress is maximum seen around the body of the mini-implant 1mm from the surface of the cortical bone (0.0004mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone. When Orthopaedic load of 500gm was applied the maximum stress is seen on the body of the mini-implant of 17.04MPa. More deformation is seen around the body of mini-implant in cortical bone(0.002mm) whereas least deformation is seen around the tip of mini-implant in the trabecular bone.
- **Implant loading at Site 6 :** Mini-implants is placed at anterior buccal alveolar site on which the oblique load of 150gm , and orthopaedic load of 500gm was applied. When oblique load of 150gm was applied the maximum stress is seen on the body of the mini-implant of 2.2MPa. The deformation due to the stress is maximum seen around the body of the mini-implant 4mm from the surface of the cortical bone(0.0002mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone. When Orthopaedic load of 500gm was applied the maximum stress is seen on the body of the mini-implant of 8.14MPa. More deformation is seen around the body of the mini-implant in the cortical bone (0.001). Least deformation is seen around the tip of the mini-implant in the trabecular bone.
- **Implant loading at Site 7 :** Mini-implants is placed at posterior buccal alveolar site on which the oblique load of 150gm , and orthopaedic load of 500gm was applied. When oblique load of 150gm was applied the maximum stress is seen on the body of the mini-implant of 2.28MPa. The deformation due to the stress is maximum seen around the body of the mini-implant 4mm from the surface of the cortical bone(0.0002mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone. When Orthopaedic load of 500gm was applied the maximum stress is seen on the body of the mini-implant of 8.14MPa. More deformation is seen in the bone around the body of the mini-implant 1mm in the cortical bone from the surface of the bone (0.001mm). Least deformation is seen around the tip of the mini-implant in the trabecular bone.

Discussion

Biomechanical influences on bone structure play an important role in the longevity of bone around implants. Bone tissue is known to remodel its structure in response to mechanical stress. Low stress levels around an implant may result in poor connection with bone or bone atrophy. On the other hand, abnormally high stress concentrations in the supporting tissues can result in pressure necrosis and subsequently in implant failure.

Most of the clinical reports on orthodontic endosseous implants have been in the form of case reports or focused mainly on technical description Wehrbein and coworkers[10] reinforced orthodontic anchorage with palatal titanium screws (Orthosystem; Straumann, Waldenburg, Switzerland) in 9 patients. All 9 implants remained stable throughout the treatment period, with only a minimal loss of anchorage. Bernhart and associates[16] used short epithetic implants (Nobel Biocare, Go□teborg, Sweden) in the paramedian region of the palate for augmentation of orthodontic anchorage, and a survival rate of 84.8% (18/21) was obtained.

As for orthodontic mini-implants, Ohmae and colleagues[17] showed that miniscrews 1 mm in diameter were able to sustain an intrusive force of 150gm for 12 to 18 weeks in beagle dogs. However, only preliminary studies can be found concerning the clinical applications of mini- implants as orthodontic anchorage. Costa and coworkers[11] used 2-mm titanium mini-screws as anchorage for various types of tooth movement, and a failure rate of 12.5% (2/16) was found. They noted that a force system that generated a moment to the screw in the unscrewing direction condemned an implant to failure. Freudenthaler and associates[18] placed 2mm bi-cortical titanium screws in the interdental alveoli of mandibles for the protraction of posterior teeth, and 3 of the 12 screws (25%) were considered failures. Risk factors associated with implant failure were not mentioned in the report.

Seven micro-implant sites were considered out of which two sites which were Site 1 (anterior palatal paramedian) and Site 2 (posterior palatal paramedian) on which vertical load of 75gms were applied and orthopaedic load of 500gms were applied whereas on Site 3 (Anterior palatal alveolar), Site 4(Posterior palatal alveolar), Site 5 (Anterior alveolar), Site 6 (Anterior buccal alveolar) & Site 7 (Posterior buccal alveolar) on which oblique load of 150gms and orthopaedic load of 500gms were applied. It was noted that at Site 1 & Site 2 on application of vertical load more deformation was seen in the cortical bone around the micro-implant and least were seen around the tip of micro-implant in the trabecular bone. Similar result were seen at the sites 3,4,5,6,&7 on application of oblique load more deformation was seen in the cortical bone around the micro-implant and least were seen around the tip of micro-implant in the trabecular bone. This may be due to variation in density and thickness of the cortical & trabecular bone .

On conducting the study on application of orthopaedic load of 500gms more stress and deformation were seen as compared to application of vertical load of 75gms and oblique load of 150gms as shown in Tab 2. Oblique insertion of micro-implants at sites 3,4,5,6 & 7 showed more stress as compared to vertical insertion at sites 1 & 2. This could be because when the micro- implants is placed at an angle in the cortical bone ,then the magnitude of the forces were more therefore the stresses as well as the deformation in the surrounding bone is more. Also the bone density at the various sites in the maxilla can play crucial role in the stress and deformation at those sites.

On comparision of stresses at oblique site 3(anterior palatal alveolar) site 4(posterior palatal alveolar) site 5(anterior alveolar), site 6(anterior buccal alveolar)& site 7(posterior buccal alveolar) most stress is seen at site 5 followed by site 3 ,4 ,7 and least stress were seen at site 6 this maybe due to combined factor of cortical bone thickness and bone density. On comparision of deformation at oblique site 3(anterior palatal alveolar) site 4(posterior palatal alveolar) site 5(anterior alveolar), site 6(anterior buccal alveolar)& site 7(posterior buccal alveolar) most deformation is seen at site 3 & 4 followed by site 5 and least stress were seen at site 6 & 7 this maybe due to combined factor of cortical bone thickness and bone density.

After evaluating the stresses in the micro-implant and the bone around the micro implant it was noted that orthopaedic loading produced more stress and deformation around the bone compared to orthodontic loading this could be because of higher force magnitude (500gm)compared to orthodontic loading(75-150gm). It was also seen that stress was highlyconcentrated in the head and neck of the micro-implant, the contact point between the implant thread and cortical bone, and the cortical bone surrounding the implant. The stress concentration was greater at the micro-implant neck. This was because greater resistance is exerted at the micro- implant entrance into the cancellous and cortical bones. This result is consistent with the study of Van Staden et al.[30]

The results showed that the stresses decreased in the micro-implant and the cortical & trabecular bone with increase in insertion angulations from $60^0$to 90^0Similar results were seen in the study by Zhang et al[24]who analyzed the influence of different tilted angles including 30^0, 40^0, 50^0, 60^0, 70^0, 80^0, and 90^0on the biomechanical characteristics of orthodontic anchorage at the implant-bone interface.

Noble et al[29]found that removal of a temporary anchorage device that had been inserted at an angle exerted greater stress on the bone than when the mini-screw was placed perpendicular to the bone. This indicates that stress levels decrease as the insertion angle increases from $30^0$to 90^0. Moon et al[27]reported that mini-screws should be inserted at $70^0$to $80^0$to the long axis of the teeth for better stability and success of the micro-implant in the posterior buccal region of the maxilla and the mandible. These 2 studies agree that he micro-implant should be inserted as perpendicular to the bone possible; this is also evident from the results of our study. The thickness of the cortical bone is a decisive parameter for the stability of mini-implants. Our results showed that stress was highly absorbed in the cortical bone, and very little stress was transmitted to the trabecular bone. This agrees with the findings of Byoun et al.[26] They reported that the maximum von Mises stress in cortical bone was more significantly related to the contact point of the mini- implant in the cortical bone surface than the insertion angle to the bone surface and the maintenance of the mini-implant is more closely related with its diameter and contact point into the cortical bone surface than the insertion angle. The finding of significantly more stress on bone with micro-implant insertion at 60^0than at 90^0supports this hypothesis. Clinically increased stress might draw more cytokines, macrophages, and inflammatory mediators to the site, possibly resulting in a higher risk of micro-implant failure through loss of primary stability. Most dental implant failures have been attributed to biomechanical stresses and strains at the bone-implant inter- face, resulting in peri-implant inflammation that can lead to bone loss.

From the results of the present study, following clinical implications could be derived:

- The micro-implants would efficiently resist oblique loading, simulating anterior intrusion and retraction. The loads of 150 gm produced strain in the optimal range of bone maintenance. These devices would serve as a reliable means of 'absolute anchorage' as per the initial stress pattern.
- The use of these micro-implants for the purpose of orthopaedic loading is questionable, since the stress values experienced by the implant are quite high. Even though the strain values experienced by the bone were in the range of optimal maintenance, the site of placement of the micro-implants and the timing become crucial factors in deciding the usage of these micro-implants for orthopaedic loading. The ideal time for orthopaedic protraction of maxilla is during the mixed dentition phase. The mini-screw can loosen, even after having been initially fixed, if an adjacent deciduous tooth is exfoliating. There can also be a risk of injuring the underlying permanent tooth bud.
- In the implant, the most critical area is itsneck, where there is maximum stress concentration, and the marginal bone (cervical margin) which surrounds it. Thus, this area should be preserved clinically in order to maintain the bone-implant interface structurally and functionally.
- Based on the experience from our study, the following suggestions can be made for optimization of the implant design The neck of the implant must be long enough to project away from the soft tissues, so that any attachments placed on the implants do not impinge the mucosa. The inflammation of the overlying soft tissue and/or the marginal bone resorption can jeopardize the stability of the implant. The neck of the implant must be sturdy enough, since the maximum stress concentration occurs at the neck of the implant.

If the implant is not strong in this region, it may affect the integrity of the implant. When using these mini-implants for orthodontic loading, it is advisable to take all the necessary precautions to place the implant as much in the cortical bone as possible. The reason is that the stress and strain values in the trabecular bone were very low, which would result in atrophy of the surrounding bone (as postulated in Frost's mechanostat principle).

Conclusion

The following conclusions can be drawn from this study:

1. The comparison of the maximum von Mises stress in the micro-implant showed that, as the insertion angle increased from $60^0$to 90^0, stress decreased. The comparison of the maximum von Mises stress in the cortical bone showed that, as the insertion angle increased from $30^0$to 90^0, stress decreased. The comparison of the maximum von Mises stress in the trabecular bone showed that, as the insertion angle increased from $30^0$to 90^0, little stress was transmitted to the trabecular bone. Micro-implants should be placed as perpendicular to the bone as possible for better stability. However as we want more cortical placement of micro-implants for better anchorage, the micro-implants are inserted at an angle.
2. All the FE models showed the area with the highest stress and strain to be around the neck of the micro-implant and the cortical bone and least were seen at the tip of the micro-implants around the trabecular bone. This finding is clinically important in order to preserve the bone-implant interface.
3. Evaluation of the FE model showed on application of orthopaedic load more stress and deformation were seen as compared to orthodontic load.
4. Evaluation of the FE model showed more stress and deformation on application oblique load as compared to the vertical load.
5. To obtain an optimal biomechanical response, the implant should preferably be placed entirely in the cortical bone (however, this may not always be feasible clinically). The neck of the implant should be sturdy enough, and the head of the implant should not produce any kind of irritation to the overlying mucosa.

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