ISSN : 1001-1781

Journal of Clinical Otorhinolaryngology, Head, and Neck Surgery

EVALUATION OF STRESS DISTRIBUTION PATTERNS IN BONE AT VARYING LENGTHS, DIAMETERS, FORCE MAGNITUDES AND ANGULATIONS OF MINI-IMPLANTS USING FINITE ELEMENT MODELLING

Dr. Sushma Sonawane [a], Dr. Sameer Narkhede [b] & Dr. Neha Mahajan[c]

[a] Professor, MDS, Department of Orthodontics, DY Patil School of Dentistry, Navi Mumbai, Maharashtra, India

[b] Head of Department, MDS, Department of Orthodontics, DY Patil School of Dentistry, Navi Mumbai, Maharashtra, India

[c] *Corresponding Author, MDS, Post Graduate Student, Department of Orthodontics, DY Patil School of Dentistry, Navi Mumbai, Maharashtra, India.

Abstract

Objectives: Evaluation and comparison of the stress distribution patterns in bone at various lengths, diameters, force magnitudes and angulations of mini- implants using Finite Element Modelling.

Methods: FEM model of mini implant and bone model. MI is meshed in diameters of 1.2 mm, 1.4 mm, 1.6 mm, 1.8 mm and 2 mm and in lengths of 6 mm, 7 mm, 8 mm and 9 mm. The optimum implant size of the mini implant with the least resultant stress is evaluated. This implant size is compared with angulation of insertions- 50^0, 60^0, 70^0, 80^0 and 90^0 and compared with different force magnitudes of 8 oz, 9 oz, 10 oz, 11 oz and 12 oz. Von Mises stresses in the surrounding bone were measured.

Results: As the diameter increased, the stress decreased. As the angle of insertion increased, the stress decreased. As the force applied increased, the stress increased. Length has no significant relation with stress formation in bone.

Conclusion: Increasing of the diameter and the angulation of insertion of mini-implant increases the primary stability of the mini-implant.

KEYWORDS: Bone, Finite Element Analysis, Finite Element Modelling, Mini-implant, Stress Distribution.

INTRODUCTION

The field of Orthodontics is slowly switching from a practice build on opinions to a practice build on evidence[1]. While treating malocclusions, it is necessary and very important to achieve anchorage to achieve the results desired by the clinician. Therefore, orthodontists are concerned about methods to control anchorage in various clinical circumstances.

With the development of anchorage using mini-implants by Kanomi in the year 1997, the methods to reinforce anchorage and control significantly improved. Mini-implants allowed absolute anchorage, cheaper treatment and different options in various situations clinically. They also enabled immediate loading after insertion[2].

Temporary anchorage devices have gained widespread popularity in orthodontics during the past decade. Popularity of mini-implants has increased due to their ease of use, minimal invasiveness and inexpensiveness. The angle of insertion plays a trivial role for maintaining anchorage, avoiding risking damage to adjoining teeth and to create an optimal contact between the mini implant and the surrounding bone[3]. There are various applications of mini-implant insertion at different sites such as intrusion, retraction, extrusion and protraction of dentition. They also help in movement of impacted teeth.

However, there are many Mini implant failures reported. Loosening of implants and failure was reported my various authors during routine orthodontic treatment. It is believed that certain factors influence the retention or stability of mini-implants such as – characteristics of surface of implant, type of implant, magnitude of force applied, location where placed, angle of insertion, proximity to the root, dimensions of implant and insertion torque. The implants are loaded immediately and therefore their primary stability is very important as this will reduce any minute motions and give a beneficial response from bone by increase in the remodelling rate[4].

The stress patterns cannot be calculated easily in clinical settings in the patients oral cavity which makes it difficult to study the stress patterns that are created. When limitations of experimental methods exceed the benefit they can provide, or are unable to measure the variable in question, investigators are driven toward alternative mathematical predictive approaches through analytical and numerical techniques.

To overcome these limitations, researchers have tried to use a procedure called the Finite Element Modelling (FEM) which was developed by Richard Courant in 1943. It is a means where a structure is discretized into elements also called as sub domains which forms the basis for finite element analysis (FEA). This analysis was used in 1973 in dental biomedical field of research and it has been used and applied for analysing the alveolar bone and periodontal ligament for stress and strain patterns. This study method was established in 1980's in the field of orthodontics. It helps in accurately studying the stress and strain patterns in living assemblies using Finite Element Analysis method. Non-invasive geometric modelling of complex areas can be done using FEM. To know whether the materials fractures or yields under tough loading circumstances, FEM can be used non-invasively. By careful evaluation of stress patterns along bone and mini-implant, the exact position and configuration of the mini implant can be decided which in turn would help in reducing failures.

The implants are influenced by the direction and quantity of the force applied to them which causes bone deformation. Analysis of stress is important for investigating the alveolar tissue turnover and the method in which maximum anchorage can be applied. The success or failure of the mini implant is governed by the method of stress transfer to the adjacent bone. FEA predicts the stress patterns on the implant neck where it contacts the surrounding bone, the apex of mini implant and the adjoining cancellous bone.

This study of the analysis for stress will allow the clinician to optimize the method of placement of mini implants in order to achieve primary stability with least amount of stress transferred to the surrounding bone[5].

MATERIALS AND METHODS-

This study was conducted using a three dimensional scan of SK surgical cylindrical mini-implant for creating a three dimensional study model of bone consisting of cortical bone and cancellous bone using CAD 2017 software- to convert the files into STL format, Inventor 2017 software- to construct geometric model, Hypermesh software- to create mesh models and ANSYS 2019 R3 software was used to read finite element results, generate result images and extract stress data from simulation. The results were represented using tables, charts, graphs, Microsoft excel and statistics.

-This study is approved by ethical committee of DY Patil Deemed to be University, School of Dentistry, Navi Mumbai number**: IREB/ 2022/ ORTHO / 05**, dated 04.5.2023.

-the recognized standards have been followed (Declaration of Helsinki; US Federal Policy for the Protection of Human Subjects; or European Medicines Agency Guidelines for Good Clinical Practice).

-This is to confirm that all persons involved had provided their informed consent prior to inclusion in the study.

TABLE 1- Physical properties allotted to the implant and surrounding bone

Material	**Youngs Modulus (MPa)**	**Poisson's Ratio**	**Thickness**
Implant	1.14×10^5	0.34	NA
Cortical Bone	13700	0.3	1.5mm
Trabacular / Cancellous Bone	7900	0.3	7-12 mm

This study was done in 2 phases.

1st Phase-

Various lengths and diameters of the implant were compared using constant force application and degree of insertion throughout.

1. The different diameters used were1.2mm,1.4mm,1.6mm,1.8mm and 2 mm.
2. The different lengths that were compared were 6 mm, 7 mm, 8 mm and 9 mm.

The constants- degree of insertion was considered to be 90^0 which is the commonly used angulation in routine placement of mini-implants while the force applied to the mini-implant was 10 oz (1 ounce= 28.3495 grams)

2nd Phase-

The optimum implant size and diameter was found out to be 2 mm in diameter and 7 mm in length. This size was compared with different angulations of insertion and forces.

3. Different angulations used were- 50^0, 60^0, 70^0, 80^0 and 90^0
4. Different forces applied during mini-implant insertion were- 8 oz, 9 oz, 10 oz, 11 oz and 12 oz

A total number of 50 models were created through finite element modelling to evaluate the stress distribution by calculating the Von Mises stresses and the total deformation in the surrounding bone.

RESULTS-

Results conclude that as the diameter increased, the stress decreased. As the angle of insertion increased, the stress decreased. As the force applied increased, the stress increased. Length has no significant relation with stress formation in bone.

PHASE 1 –

Figure 1- showing implant size of 1.2 mm diameter with length of 6 mm inserted in the bone.

PHASE 2-

Figures 2-6 show the resultant stress distribution when 2x7 mm implant is inserted at an angle of 90^0 with 5 different magnitudes of force that is 8 oz, 9 oz, 10 oz, 11 oz and 12 oz.

2x7 inserted at an angle of 90 degrees with different forces.

Fig 2- showing Stress Distribution and Deformation of 2 x 7 mm implant when inserted at 90^0 and 8 oz of force applied.

Fig 3- showing Stress Distribution and Deformation of 2 x 7 mm implant when inserted at 90^0 and 9 oz of force applied.

Fig 4- showing Stress Distribution and Deformation of 2 x 7 mm implant when inserted at 90^0 and 10 oz of force applied.

Fig 5- showing Stress Distribution and Deformation of 2 x 7 mm implant when inserted at 90^0 and 11 oz of force applied.

Fig 6- showing Stress Distribution and Deformation of 2 x 7 mm implant when inserted at 90^0 and 12 oz of force applied.

PHASE 1 RESULTS-

Table 2-6 shows the resultant stress values and total deformation when different diameters of 1.2 mm, 1.4 mm, 1.6 mm and 2 mm are compared with 4 different lengths of 6 mm, 7 mm, 8 mm and 9 mm.

TABLE 2- showing equivalent stress values and total deformation when diameter of 1.2 mm was compared with 4 different lengths

TABLE 3- shows equivalent stress values and total deformation when diameter of 1.4 mm was compared with 4 different lengths.

TABLE 4- shows equivalent stress values and total deformation when diameter of 1.6 mm was compared with 4 different lengths.

TABLE 5- shows equivalent stress values and total deformation when diameter of 1.8 mm was compared with 4 different lengths.

TABLE 6- shows equivalent stress values and total deformation when diameter of 2 mm was compared with 4 different lengths.

PHASE 2 RESULTS-

Table 7-11 shows the resultant stress distribution when the optimum size implant of 2 x 7 mm is inserted at angles of 50^0, 60^0, 70^0, 80^0 and 90^0. The least stress values is found when the implant is inserted at an angle of 90^0.

TABLE 7- shows equivalent stress and total deformation for 2 x 7 mm implant inserted at 50^0 angle and compared with 5 force values.

TABLE 8- shows equivalent stress and total deformation for 2 x 7 mm implant inserted at 60^0 angle and compared with 5 force values.

TABLE 9- shows equivalent stress and total deformation for 2 x 7 mm implant inserted at 70^0 angle and compared with 5 force values.

TABLE 10- shows equivalent stress and total deformation for 2 x 7 mm implant inserted at 80^0 angle and compared with 5 force values.

TABLE 11- shows equivalent stress and total deformation for 2 x 7 mm implant inserted at 90^0 angle and compared with 5 force values.

GRAPH 1- Resultant Stress distribution on Y axis as the degree of insertion increases on the X axis.

Graph 2- Resultant Stress distribution on X axis as the magnitude of force increases on X axis

DISCUSSION-

TADS- Temporary devices used for anchorage have led to a new aspect to treatments in orthodontics, which allows movements of teeth which were initially thought to be impossible and difficult[6]. Mini implants provide managing complicated malocclusions which are rather difficult to treat with traditional mechanics. With their help, the application of force is done directly in the alveolar bone. Hence, orthodontic implants are helping eliminate the anchorage concerns and also enabling the tooth movement in all three dimensions. A few other indications of orthodontic treatment also include the treatment of teeth that are impacted in adults.[7]

There are two types of stability observed with orthodontic implants- Primary stability or initial stability is resultant immediately after inserting the implant. This stability is important for healing. The factors that are responsible for the primary stability are- Implant diameter, the length of implant, and the number of flutes and design of threads, cortical bone thickness and also the bone density. The technique of placement and location of placement also play an important role in primary stability. Secondary stability is observed after the healing occurs during the time of regeneration and remodelling of bone[8]. Osseointegration is not a factor for stability of the implants because the tight contact between the implant and the bone surface matters to give primary stability. The health of the surrounding bone is also of utmost importance[9].

In this study 50 models were created. Phase 1 consisted of 25 models and Phase 2 consisted of 25 models. This study was done to evaluate- -Role of implant diameter, length, angulation of insertion and force applied in the primary stability of the implant by studying the stress distributions.

Role of Diameter of mini-implant-

From Table 2, When different lengths (6 mm, 7 mm, 8 mm, 9 mm) of 1.2 mm diameter mini-implant were compared, the least amount of stress was generated from implant of 1.2 x 7 mm with the stress value of 11.616 MPa and the maximum stress was generated with the implant of 1.2 x 8 mm with the stress value of 27.676. In Table 3, When compared with 1.4 mm diameter, 1.4 x 9 mm mini-implant generated the least stress with the stress value of 18.264

MPa and 1.4 x 6 mm implant caused the maximum stress of 37.616 mm which was the highest stress value generated out of all the diameters.

From Table 4 and 5 it is observed that when different lengths (6 mm, 7 mm, 8 mm, 9 mm) of 1.6 mm diameter mini-implant were compared, the least value was generated by 1.6 x 8 mm implant and the maximum stress was generated by 1.6 x 9 mm with stress values- 10.405 MPa and 17.21 MPa respectively. With 1.8 mm diameter, 1.8 x 8 mm implant generating a stress of 7.16 and 1.8 x 9 mm generating 30.31 MPa stress showed the least and maximum amount of stress respectively.

From Table 6 it is evident that when the implant of 2 mm diameter with 4 different lengths were compared, the overall stress values decreased with 2 x 8 mm mini-implant generating a stress of 3.81 MPa and 2 x 9 mm mini-implant showing the maximum stress of 9.383 MPa. It was also observed from the Finite element models that the stress gradually decreased from the cortical bone to the cancellous bone where it was maximum adjacent to the neck of the implant. This concludes that as the diameter of the implant increases, the equivalent stress in the surrounding bone decreases.

Poggio et al[10] observed that thinner the implants, more the risk to fracture to the implant while with thicker implants, there is a possibility of contacting the root. There was a strong relation of diameter more than length to decrease the stress and displacement.[11] The present study results were in conformance with the study of Dr. Munish C Reddy et al[12] which also concluded that as the diameter of the TAD was increased, the mean stress was significantly reduced.

Role of length of mini-implant-

In the current study the least amount of Von Mises stress was observed in the mini-implant size combination of 2 mm diameter and 7 mm length and the maximum for implant with 1.4 mm diameter and 6 mm length. There is as such no remarkable difference between the stress values with changing of length.

With average total deformation for all the diameters and lengths, 2 x 7 mm implant caused the least amount of equivalent stress and total deformation. This tendency for increasing deflection with increase in mini-implant length is congruous for all bone densities[13].

This study is in accordance with the study done by Duaibis et al.[14] On the contrary, Deguchi et al[15] found safest length of the TAD as 6 mm. As the length increased the total deformation also increased.

Role of angle of insertion of mini-implant-

Studies have shown that the angle of the insertion of mini-implant placement has an effect on the stress transmitted and the anchorage value. In the Phase 2 of the study, when the mini-implant of 2 x 7 mm was inserted at an angle of 50^0 , from table 7 its observed that the maximum stress was generated with 12 oz of force generating a stress of 15.932 MPa and the least stress was generated with 8 oz of force generating stress of 10.23. Tables 8 to Table 10 compare the stress distribution in the bone when mini implant of 2 x 7 mm is inserted an angle of 60^0 , 70^0 , 80^0 respectively. From Table 11 it is inferred that when the mini-implant was inserted at 90^0 to the cortical bone 8 oz of force generated the least amount of stress that is 3.015 MPa whereas 12 oz of force generated the maximum amount of stress of 4.536 MPa. This shows a drastic decrease in the stress values as the angle of insertion decreases. The maximum stress was generated when the implant was inserted at an angle of 50^0 and the least amount was stresses were generated when the mini-implant was inserted at 90^0. The relation between angle and equivalent stress was statistically significant with all values <0.05.

Insertion of mini-implant perpendicular to the bone reduces the concentration of stress and increases stability to loading. The placement of mini-implant at an angle of 90^0 to the bone is recommended so that mini-screw is stable biomechanically[14,15].

Role of force applied to the mini-implant-

With loading of the MI with increasing the force, there was generation of higher values of stress in the cancellous as well as the cortical bone. From figures 2 to 6, the maximum stress was observed with application of 12 oz of force while the minimum stress was observed at 8 oz. There was maximum stress in the bone in the vicinity of mini-implant threads. Within the spongy/ cancellous bone, stress was transferred to a limited extent. It was observed that when the magnitude of force increased, there was a linear increase in the stress without regarding the angle of insertion. There was minimal stress observed in the cancellous bone which proved that cortical bone can tolerate high stress gain.

In the current study, as the force increases the stress distribution in the surrounding bone increases. Although as the angle of insertion increases, the stress distribution in the surrounding bone gradually decreases being the least for 8 oz of force when implant is inserted at 90^0 and the maximum for 12 oz of force applied when implant is inserted at 60^0.

Biomechanical impact or changes play a vital role in the durability of bone surrounding the implants. There is responsive remodelling of Bone tissue when stress is applied. Low stresses can cause poor relation of implant with surrounding bone. However, pressure necrosis and consequently implant failure is the result of abnormally high stresses[5].

Hence all factors perform a principal role in the primary stability of the MI. This study included some technical constraints regarding the construction of precise models that are ubiquitous for FEM analyses. It was assumed that both cortical and cancellous bone were linearly elastic, homogeneous, and isotropic. But they are not either. These speculations were formed as it was convenient and also for compensating for the scarcity of bone tissue behaviour. Additionally, bone block geometry was simplified and soft tissue stimulation was not conducted. With the present understanding, it is not easy to foretell the exact changes which can occur when similar conditions of loading are applied.

Transfer of stress to the neighbouring areas, such as the teeth roots, should be investigated in ensuing studies in the future. Therefore, this analysis study is predictive and should be used to refer in other clinical situations for facilitating better judgment. Future clinical studies planning can be done by using the same protocol of insertion of mini-implant in multi-centric sample. Supplemental research with improved analysis from finite element software can help the clinicians in creating 3D models with more accuracy that will help in simulation of clinical aspects and help in rugged clinical evidence for placing of mini-implant[2].

CONCLUSION-

This study provides important information regarding the method of placement of mini implants in order to obtain primary stability. The observations of this study are as under-

1. As the mini implant diameter is increased, the stress distribution in the surrounding bone decreases.
2. The stress distribution in the surrounding bone increases as the force applied to the mini-implant increases.
3. As the angle of insertion of the mini-implant to the cortical bone increases, the stress distribution in the surrounding bone decreases.
4. Changing the length of the mini implant did not have a considerable effect on the maximum von Mises stress generated in bone at mini implant site.
5. The mini implant that resulted in the least stress in the surrounding bone was found to be 2 mm in diameter and 7 mm in length.
6. When different angulations of insertion were compared with force applied- the least stress was resultant when the mini implant was inserted at an angle of 90^0 with 8 oz of force applied.

There are some clinical challenges that are faced to evaluate stress levels in bone and mini implant in the patients, which make it difficult for the interpretation of generated stress patterns. In order to remedy these limits, researchers used the engineering tool of finite element analysis. It is possible to accurately study the Stress/stress models of the living structure using the finite element analysis**.** Modelling of Complex structures is possible in a non-invasive manner with FEM for analysing stress and the strain. Stresses evaluated on the simulation models will determine if that material yields or fractures when subjected to complex conditions of loading. Optimization of position and configuration of the mini-implant is possible with careful evaluation of the patterns of stress in the bone and the mini-implant, which will help in reducing failures[2].

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DECLARATIONS

1. **Ethics Approval and Consent to Participate**:

   This is to confirm that all persons involved had provided their informed consent prior to inclusion in the study.

   The research/study approved by the Institutional Review Board at DY PATIL DEEMED TO BE UNIVERSITY, SCHOOL OF DENTISTRY, NAVI MUMBAI, number**: IREB/ 2022/ ORTHO / 05**, dated 04.5.2023.
2. **Consent for Publication:**

   We, the undersigned give our consent for the publication of identifiable details, which can include photographs or details within the text to be published in the above journal.
3. **Availability of Data and Materials:**

   The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.
4. **Funding Acquisition:**

   No funding from external sources.
5. **Acknowledgements:**

I would sincerely like to acknowledge Mr. Amit from Milestone PLM solutions Pvt Ltd for carrying out the simulations and creating FEM models required for the research study.

Conflicts of interest

The authors declare no conflict of interest concerning the authorship and/or publication of this article.

Author Contribution Statement-

Dr. Sushma Sonawane: conceptualization, methodology, validation, visualization.

Dr. Sameer Narkhede: conceptualization, methodology, validation, visualization.

Dr. Neha Mahajan: Data curation, investigation, resources, writing original draft, writing-reviewing and editing, software, funding acquisition.

SUMMARY BOX

What is known on the topic-

1. Ideal angulation for insertion of an Orthodontic mini Implant is between 45^0 to 90^0 .
2. The technique of placement and location of placement also play an important role in primary stability.
3. Thinner the size of the mini implant, more the risk to fracture.

WHAT THE SUBMITTED STUDY ADDS-

1. This study will help clinicians to achieve **optimum primary stability** of the mini implants and **reduced risk of failure**.
2. Study will help determine ideal angulation, force magnitude and size of mini implant for insertion and in turn avoid failure.