Original Article

Evaluation of different force magnitude to orthodontic microimplants on various cortical bone thickness – Three-dimensional finite element analysis

ABSTRACT

Aims: The aim of this study was to determine appropriate range of cortical bone thickness (CBT) to adequately support microimplants and optimum force magnitude on microimplants for minimal stress distribution.

Settings and Design: Three-dimensional (3D) CAD models of the desired implant features and cylindrical bone piece of desired height and thickness were exported to FEA software, and variable load was applied on range of different CBT to determine the compressive radial stress and maximum failure load.

Subjects and Methods: it is clearly said that CBT of various thickness which will represent human maxilla and mandibular bone. The force magnitudes ranging from 15 g to 150 g (in range of 15 g, 50 g, 85 g, and 150 g) were taken to simulate typical orthodontic forces loaded onto microimplant.

Statistical Analysis Used: Statistical data were analyzed by IBM SPSS Statistics for windows Version 20.0 (IBM Corp., Armonk, NY, USA) software. For quantitative data analysis, ANOVA test was used.

Results: For CBTs of 0.5, 1.5, 2.5, and 3.0 mm, the maximum force magnitudes that could be applied safely were 533.7, 551.7, 552.3, and 552.9, respectively. Even though there was no difference statistically, the amount of displacement for CBT 1.5–3.0 mm is comparatively less than for 0.5 mm. CBT value of 1.5–3.0 mm might be appropriate for microimplant stability.

Conclusions: For the purpose of diminishing orthodontic microimplant failure, an optimal force that can be safely loaded onto a microimplant should not exceed a value of around 533–553 g. The CBT of 1.5–3.0 mm might be considered appropriate for the stability of microimplant.

Keywords: Cortical bone thickness, finite element analysis, force magnitude, microimplants

INTRODUCTION

A goal of any orthodontic treatment is to achieve desired tooth movement with minimum side effects, so introduction of microimplants was an evolutionary change for conventional treatment in orthodontics by simplifying the biomechanics. Most current microimplants are titanium (ti) or titanium alloy and are manufactured with a smooth, machined surface that is not designed to osteointegrate.[1] When an excessive load is applied, partly osseointegrated microimplants can become mobile and eventually fail. It is essential during treatment to set a maximal force magnitude that can be loaded safely onto the microimplants to fulfill the biomechanical requirements without affecting microimplant stability.[2] The use of FEA software (ANSYS Corp., USA) (finite element analysis) can simplify this

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task. Finite element analysis shows whether a product will break, wear out, or work the way it was designed; it is used to predict what is going to happen when the product is used. Using FEA, the orthodontic force applied can be simulated, and the results can be shown on a three-dimensional (3D) model that can be fabricated using a computed tomography scan. This method has become popular since it is completely noninvasive and very accurate because it is based on the mathematical properties of the structures. One can derive a precise and detailed description of the responses that the periodontal structures show in response to stress application.[3] Kuroda *et al*. (2007) experience that the thicker microimplants do not always guarantee higher success rate, even there is a report that microimplant of smaller diameter showed higher success rate than thicker ones; so, for different anatomical regions, different dimensions of micro-implants are used. Very few FEA studies are done to evaluate force magnitude of microimplant on different thickness of cortical bone. Therefore, the aim of this study is to determine appropriate range of cortical bone thickness (CBT) to adequately support microimplants and to determine optimum force magnitude that can be safely loaded to microimplants with minimal stress distribution.

SUBJECTS AND METHODS

The concept of this study was to relate different force magnitude loaded onto micro implant to different CBT. As of now, we know that CBT is considered important for microimplant stability and retention. 3D CAD models of titanium alloy-based orthodontic microimplant and a cylindrical bone piece 7.5 mm in height and 5.6 mm in diameter were used and exported to FE software ANSYS Version 14.5 (Bengaluru, Karnataka, India). The microimplant design of No. BH 1413-07, small head, 1.4-mm neck diameter, 1.3-mm tip diameter, and a 7 mm length (Absoanchor, Dentos Inc) was used. Many previous studies have stated that 1.3 × 6 mm dimension microimplants are recommended for use during anterior segment retraction. Thus, an approximately same dimension but bracket head design microimplant was considered in this study.

CBT of 0.5, 1.5, 2.5, and 3.0 mm was incorporated in this study which will represent the available data for human maxillary and mandibular bone with the remaining part being cancellous bone. The force magnitudes ranging from 15 g to 150 g (in range of 15 g, 50 g, 85 g, and 150 g) was taken to simulate typical orthodontic forces loaded onto microimplant.

A nonlinear FE analysis was used. The analysis began with meshing all the models as shown in Figure 1. Meshing was done using 3-dimensional tetrahedron elements with 4 nodes. To achieve mesh consistency among the models and thus prevent errors, the cortical and cancellous bone of all models was meshed with the same degree of density. Various force magnitudes (15, 50, 85, 105, and 150 g) were horizontally and separately applied to the oral micro-implant (OMI) head as inserted into the different bone assemblies with different CBTs to simulate typical orthodontic forces loaded onto microimplants.

Appropriate material properties for each assembly were adopted and depicted in Table 1 which is in accordance with previous studies.[4,5]

For each CBT assembly, different force magnitude was applied horizontally and resulting compressive radial stress and maximum load failure were derived. Simultaneously, the amount of displacement for each assembly was also evaluated to correlate the stability of implant with the thickness of cortical bone.

RESULTS

The maximum compressive stress (peak stress) at a point of intimate contact of microimplant and cortical bone was taken to be 54.8 MPa. The point at which cortical bone resorption might occur.[3]

For each CBT tested, the developing compressive radial stresses were found to be directly related to the forces applied. As the force magnitude increased, the compressive stress also increased. On the other hand, an increase in CBT can tolerate more forces applied as shown in Table 2. Compressive radial

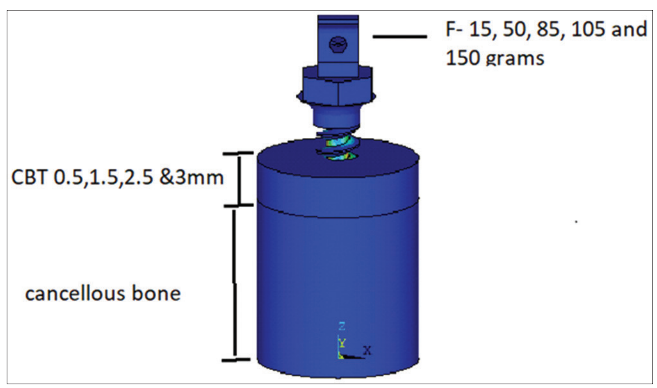

Figure 1: Geometric assembly of OMI and bone specimens used in the study after meshing step

Table 1: Material properties used in the study

Material	Young's modulus (GPa)	Poisson's ratio	Ultimate strength (MPa)
Cortical bone	13.7	0.3	198.2
Bone	1.37	0.3	
Titanium alloy	113.4	0.342	

stresses developed as a result of application of a certain force (150 grams is shown here) to the different CBTs used in the study [Figure 2]. Displacement of implant with application of 150gms force to 3mm thick cortical bone is shown in Figure 3 and stress distribution on implant is shown in Figure 4.

For 0.5 mm of CBT, the maximum force load is around 533 g. While that of CBT from 1.5 to 3.0 mm, the maximum force load ranges from 550 to 553. This implies that the CBT >0.5 mm to 3.0 mm has high value of maximum force load [Table 3].

Even though there was no difference statistically, the amount of displacement for CBT 1.5–3.0 mm is comparatively less than for 0.5 mm thickness. This implies that CBT more than 0.5 mm and up to 3.0 mm provides better stability for microimplant [Table 4].

For the purpose of diminishing orthodontic microimplant failure, an optimal force that can be safely loaded onto a microimplant should not exceed a value of around 533–553 gms. The CBT of 1.5–3.0 mm might be considered appropriate for the stability of microimplant.

DISCUSSION

Microimplants that are stable at insertion can occasionally loosen and fail. Although the etiology is multifactorial, overload (overload of cortical bone) could be one probable cause, especially when there is no apparent sign of inflammation. Bone is sensitive to mechanical stress, and strain higher than a certain threshold is known to cause pathologic bone resorption. It is thus a real possibility that overloaded microimplants lose osseous support and loosen.[6,7] According to recent reports on implant anchors in humans,[8,9] titanium screws have occasionally been removed because of their mobility before or during orthodontic force application. Thus, the orthodontist needs to understand which variables are related to this

Table 2: Correlation between various cortical bone thickness and compressive radial stress at different force levels

Thickness of cortical bone (mm)	Force (g)				
	15	50	85	105	150
	CRS (MPa)	CRS (MPa)	CRS (MPa)	CRS (MPa)	CRS (MPa)
0.5	1.54	5.13	8.73	10.79	15.41
1.5	1.49	4.97	8.46	10.45	14.93
2.5	1.48	4.96	8.429	10.41	14.88
3	1.45	4.95	8.426	10.40	14.87
Mean±SD	1.49±0.037	5.00±0.084	8.51±0.146	10.51±0.185	15.02±0.26
ANOVA test *P* and significance	F=405.43, P=0.000, very highly significant				

SD: Standard deviation, CRS: Compressive radial stress

Table 3: Comparison of maximum failure load with respect to force (g) and thickness of cortical bone (mm)

Force (g)	Thickness of cortical bone (mm)			
	0.5	1.5	2.5	3
15	533.9	551.87	552.77	553.0
50	534.29	551.46	552.77	552.99
85	533.74	550.77	552.77	552.99
105	533.44	553.74	550.77	552.77
150	533.6	550.75	552.77	552.97
Mean±SD	533.794±0.324	551.71±1.22	552.37±0.89	552.94±0.098
ANOVA test *P* value and significance	F=713.37, P=0.000, very highly significant			

SD: Standard deviation

Table 4: Comparison of displacement of implant with respect to force (g) and thickness of cortical bone (mm)

Force (g)	Thickness of cortical bone (mm)			
	0.5	1.5	2.5	3
50	0.003554	0.003112	0.003073	0.00307
85	0.006042	0.00529	0.005224	0.005219
105	0.007464	0.006535	0.006454	0.006446
150	0.010662	0.009336	0.009219	0.009209
Mean±SD	0.00693±0.0029	0.00606±0.0025	0.00599±0.0025	0.00598±0.0025
ANOVA test *P* value and significance	F=0.154, P=0.925, not significant			

SD: Standard deviation

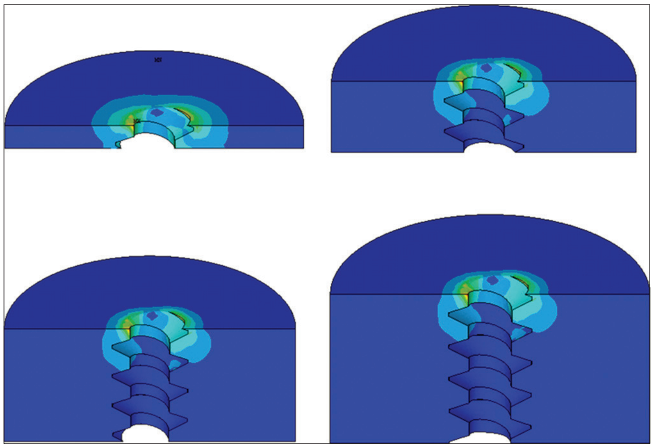

Figure 2: Compressive radial stresses developed as a result of the application of a certain force (150 g is shown here) to the different cortical bone thicknesses used in the study

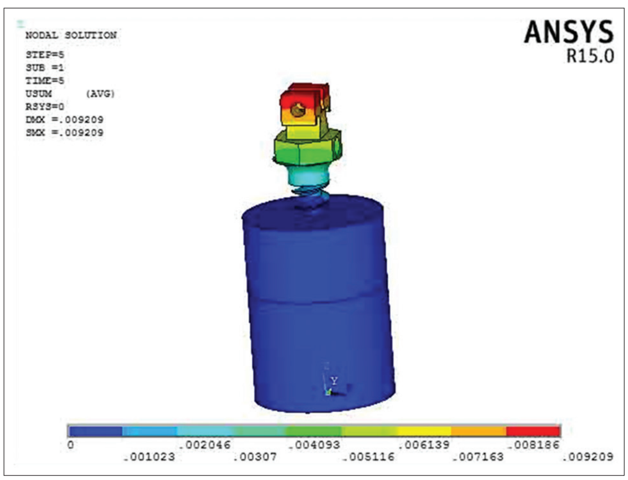

Figure 3: Displacement of implant with application of 150 g force to 3 mm thick cortical bone

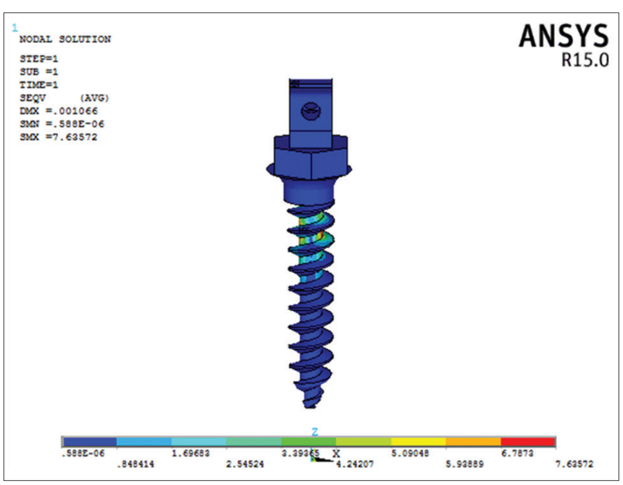

Figure 4: Stress generation on the implant for the given load of 150 g

mobility. To date, however, there have been few human studies that examined factors associated with the stability of titanium screws for orthodontic anchorage.

The purpose of this study was to determine optimum thickness of cortical bone and optimal range of load that can be safely loaded onto the microimplant to reduce the chances of implant failure. Variable force magnitudes (15, 50, 85, 105, and 150 g) were tested on thickness of cortical bone of 0.5, 1.5, 2.5, and 3 mm.

For each CBT, compressive radial stresses were found to be indirectly related to CBT. As the CBT increased, the compressive stress decreased which is explained from the tables [Tables 2 and 3]. Another important correlation found was that with increase in the CBT, the maximum failure load increases. This direct correlation states that more thickness of cortical bone in an individual will significantly increase the amount of load that can be safely loaded onto the microimplant.

Alrbata *et al*. also stated in their study that thick and dense cortical bone might appear to be an advantage because it increases the microimplant to bone contact area relative to the underlying trabecular bone.[10]

The results obtained in this study regarding the comparison between various CBT and compressive radial stress at different force levels also revealed that as the force magnitude increased, the compressive stress also increased. At the same time, an increase in CBT reduced the compressive radial stress developed and increased the maximum failure load. This indicates that with adequate thickness of cortical bone and increasing the load up to certain level can increase the stability of microimplant.

The threshold for triggering resorption of human cortical bone was set in this study at 24,000 microstrains, which is equivalent to a threshold compressive stress of 54.8 MPa. According to Frost's mechanostat,[7] the normal physiologic range of bone loading is around 200–2500 microstrains, and the ultimate strength of bone is around 25,000 microstrains. When the peak strain exceeds 2500 microstrains, subperiosteal hypertrophy builds bone mass to reduce surface strain. If bone is repetitively loaded at around 4000 microstrains, fatigue damage accumulates more rapidly than it can be repaired, and the bone is at risk for stress fracture. Accordingly, repetitive loading of large orthodontic forces on an microimplant beyond an optimum level that might result in stress level exceeding the above threshold may compromise the integrity of the surrounding bone and affect microimplant stability.

An attempt was made to obtain optimum force magnitude [Table 3] and found a linear correlation between maximum load failure and CBT.[11] But the values also suggested that by increasing the CBT beyond 1.5mm, although there was increase in the maximum failure load the value was not much significant. Thus, the optimum CBT required for stability of microimplant is above 1.5 mm to 3.0 mm.

Motoyoshi *et al*.[12,13] suggested that the thickness of cortical bone should be 1 mm or more to ensure the stability of miniimplants. Therefore, the primary stability of miniimplants is positively correlated with the quality and thickness of the cortical bone at the insertion site.

These results based on a quantitative FE analysis need to be validated by histological and clinical studies. Accordingly, we recommend starting microimplant loading with a minimal force of 0.5–1.0 N and after 3–4 months, as needed, increasing this level up to around 533–553 g, as found in this study, considering CBT.

CONCLUSIONS

Within the boundaries of this finite element study, the following conclusions were drawn:

1. The optimal force magnitude to be loaded onto an orthodontic bracket head microimplant to fulfill biomechanical demands and without diminishing microimplant stability should not exceed about 533–553 g, considering CBT. Beyond this magnitude, compressive stresses exceeding the normal capacity of bone might lead to failure of microimplant
2. The maximum load failure values did not vary much for CBT 1.5–3.0 mm as compared to 0.5 mm CBT. Thus, minimum CBT of 1.5 mm can ensure the stability of microimplants. This also indicated that increase in the CBT above certain limit did not affect the stress loaded onto the microimplant.

Thus, an overall conclusion that can be drawn from the study is the quality of bone and force magnitude; both play an equally important role in increasing the success rate of microimplant.

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Conflicts of interest

There are no conflicts of interest.

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