Influence of the thickness of cortical bone on the stability of orthodontic miniscrews

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ABSTRACT

Three 10-mm-long miniscrews commonly employed in orthodontic treatment were compared in four different situations involving diverse thicknesses of cortical bone. The finite element method (FEM) was used in the study, in which a force of 250 g was applied in two directions: perpendicular and parallel to the bone surface. As the parameter under study was the thickness of cortical bone, simulations were performed in four different bone loss situations: 2.5, 2, 1.5 and 1 mm. Our aim was also to quantify the stresses and displacements generated when applying a force of 250 g perpendicular and parallel to the bone surface under the same skeletal conditions. The results reveal similar performance in the three analysed samples, with increased stresses and displacements in the surrounding bone in relation to similar variations in the thickness of cortical bone.

KEY WORDS

Miniscrews

cortical bone

skeletal anchorage

trabecular bone

INTRODUCTION

Skeletal anchorage systems (mini orthodontic implants [MOI], miniplates, palatal implants, onplants, etc.) have opened up a whole new field, enabling the limitations of

traditional anchorage systems to be overcome. MOI are perhaps the most versatile and most widely used of these devices, providing 'absolute anchorage' in three

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dimensional space in most cases. Furthermore, the ideal skeletal conditions for their placement (1-3), potential locations (4) and biomechanical properties (5) have been studied. Miniscrews may be made of type 5 titanium alloy (the most common), steel or lactic-glycolic. Their diameters range between 1 and 2.5 mm, and their length, although variable, generally ranges between 6 and 12 mm. The choice of the type of miniscrew depends on its placement location, the anatomy of the site and biomechanical requirements. Although the success rate of miniscrews is high (6-8), an appropriate choice of the anatomical site for placement is crucial for a good result (9, 10). The main cause of failure is the lack of primary stability due to insufficient thickness of cortical bone (11). However, other factors, such as

inflammation of the peri-implant tissue, incorrect placement, miniscrew design (thread depth, shape and length of its profile), applied force and direction thereof, among others, may also contribute to their failure (12-14).

This study aims to evaluate the performance of three types of miniscrews widely used in orthodontic treatment, employing finite element analysis in different situations of thickness of cortical bone. We also aim to quantify the stresses and displacements generated when applying a force of 250 g in two directions, perpendicular and parallel to the bone surface, under the same skeletal conditions.

MATERIAL AND METHODS

Three miniscrews measuring 10 mm in length and 1.6 mm in diameter were chosen to carry out the comparative study.

These were: Dual top anchor system [Jeil Medical Corporation], IMTEC OrthoImplant [3M Unitek] and Tomas® [Dentaurum].

The stress values generated around a miniscrew when applying a force were studied using the FEM. This method enables a more manageable approximation to the underlying biomechanics than an experimental study.

The miniscrews were first measured using a PERTHOMETER S5P profile projector (Model VB-400, sigma. Madrid [Spain]), subsequently

generating a 3D model of the MOI. The profile projector allows measurements where normal instruments cannot be used. This means that most of the measurements are of small parts, although the image to project may be 50, 100 or 200 times its original size. Qualitative and quantitative chemical analysis of the elements present was also performed on the MOI using a CAMECA SX-100 (Electron Probe Micro Analyzer) equipped with five WDS spectrometers.

The results showed that all three miniscrews are made of 90% titanium, a fact that was taken into ac-

Figure 1
Solidworks design of the Jeil, 3M and Dentaurem miniscrews.

count when assigning physical properties to the MOI.

A previous simulation was performed using finite element analysis (FEA) by means of a simplified MOI model in two different situations (model 1 [Fig. 2] and model 2 [Fig. 3]). A 1 mm diameter by 5 mm length cylinder was used for model 1. A force of 100 g was applied at the top of the model at a distance of 4 mm from the cortical bone surface, varying the direction of this force between 0° (perpendicular to the miniscrew axis), 45° and 90° (in the same direction as the axis).

Using the profile projector and microscope data, we generated a 3D model for each miniscrew as similar as possible to the real models (Fig. 1).

Additionally, a geometrically perfect matrix was generated to simulate the cortical and trabecular bone layers measuring 10 mm x 10 mm in the plane perpendicular to the miniscrew axis, with a thickness of

20 mm (in the direction of miniscrew axis). The dimensions of the matrix were kept constant for all studies. Varying the thickness of the cortical bone thickness thus resulted in changes in the thickness of the trabecular bone in order for the same final dimensions of the matrix to be maintained. The simulated thicknesses of cortical bone were 1 mm, 1.5 mm, 2 mm and 2.5 mm.

All the materials in the model were considered homogeneous, isotropic and linearly elastic. The miniscrew was likewise considered to be made of pure titanium due to its high content in this material (90%), Table I.

Trials were conducted by applying a force of 250 g parallel and perpendicular to the cortical bone surface.

Twenty-four simulations were performed in all involving 3 miniscrews, 4 thicknesses of cortical bone and 2 directions of applied force.

With the aim of comparing the performance of the miniscrews, the distance between the area where force

	Young's modulus	Poisson's coefficient
Titanium alloy	114 GPa	0,30
Cortical bone	14 GPa	0,30
Trabecular bone	50 MPa	0,30

Table I
Physical properties of the materials.

Figure 2
Distribution of displacement and stress values. Model 1.

was applied and the outer layer of cortical bone was similar for all three cases. The 3M miniscrew was taken as the reference measurement, see-

ing as it presents the greatest distance between the cylindrical face where force is applied and the end of the thread.

RESULTS

The following results (Tab. II) were obtained in the simulations

carried out using simplified MOI models:

	Force applied at 0°	Force applied at 45°	Force applied at 90°
Maximum stress (MPa)	42,5	29,1	7,55
Maximum deformation (mm)	0,05	0,035	0,0007

Table II
Results for simplified MOI model 1.

Figure 3
Distribution of displacement and stress values (2-4 mm). Model 2.

A scale composed of 9 colours was used for the miniscrew as well as for the cortical and trabecular bone in order to evaluate the distribution of the displacement and stress values quantitatively. This scale ranges from blue, indicating the lowest displacement and stress values, to red, indicating the highest.

In model 1 (Fig. 2; 1 mm diameter by 5 mm length cylinder), it was observed that both the maximum stress and maximum deformation in the miniscrew increase as the force approaches 0° , as can be seen in Table II.

In model 2 (Fig. 3; 2 mm diameter by 15 mm length cylinder), three loading conditions are once again proposed, respectively fixing the distance from the point of application of the load at 4 mm, 2 mm and 1 mm (the distance between the top of the screw and the outer layer of cortical bone). As regards the orientation of the force, 0° was employed for all three cases, as shown in Table III.

After generating the simplified models, finite elements were used to study the performance of the three micro-implants. The studies consisted in applying a force of 250 g in

	Force applied at 4 mm	Force applied at 2 mm	Force applied at 1 mm
Maximum stress (MPa)	4,38	2,37	2,278
Maximum deformation (mm)	0,0037	0,0008	0,00028

*Table III
Results for simplified MOI
model 2.*

parallel to the direction of the cortical bone surface (perpendicular to the axis of the implant). As the key parameter under study in this paper is the influence of the thickness of cortical bone, simulations were performed with 4 different cortical bone thicknesses ranging from 1 mm to 2.5 mm.

The results, shown in Table 4, include the stress state and the displacement in the miniscrew and in both the cortical and trabecular bone in the direction of the applied force, as well as the different thicknesses of cortical bone. The von Mises equivalent stress was taken as the stress state.

			Implant		Cortical bone		Trabecular bone	
			Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
Jeil miniscrew	2,5mm	Fx	31,29	4,30E-03	11,92	3,57E-04	0,03	1,60 E-04
		Fz	32,04	4,26E-03	12,75	3,94E-04	0,03	1,59 E-04
	2mm	Fx	31,30	4,45E-03	12,08	3,85 E-04	0,05	2,79 E-04
		Fz	32,06	4,41E-03	12,93	4,23 E-04	0,05	2,77 E-04
	1,5mm	Fx	31,31	4,84E-03	12,50	4,56 E-04	0,08	5,06 E-04
		Fz	32,10	4,80E-03	13,43	4,94 E-04	0,09	5,06 E-04
	1mm	Fx	31,33	5,96E-03	13,52	6,36 E-04	0,16	1,01 E-03
		Fz	32,21	5,90E-03	14,57	6,94 E-04	0,17	1,01 E-03
3M miniscrew	2,5mm	Fx	19,34	2,38E-03	7,77	2,72E-04	0,04	2,64E-04
		Fz	19,00	2,39E-03	8,11	2,78E-04	0,03	2,65E-04
	2mm	Fx	19,36	2,57E-03	7,91	3,10E-04	0,07	4,27E-04
		Fz	18,90	2,58E-03	8,31	3,16E-04	0,06	4,28E-04
	1,5mm	Fx	19,40	2,97E-03	8,17	3,84E-04	0,11	7,20E-04
		Fz	18,84	2,98E-03	8,66	3,93E-04	0,09	7,20E-04
	1mm	Fx	19,38	3,81E-03	8,36	5,29E-04	0,19	1,24E-03
		Fz	18,85	3,82E-03	8,90	5,42E-04	0,16	1,24E-03
Dentaurum miniscrew	2,5mm	Fx	22,20	3,13E-03	13,83	3,83E-04	0,05	1,31E-04
		Fz	20,05	2,90E-03	8,43	3,83E-04	0,05	1,31E-04
	2mm	Fx	22,20	3,34E-03	13,99	4,22E-04	0,08	2,38E-04
		Fz	20,05	3,11E-03	8,59	4,22E-04	0,08	2,34E-04
	1,5mm	Fx	22,19	3,87E-03	14,40	5,13E-04	0,14	4,61E-04
		Fz	20,04	3,64E-03	9,06	5,17E-04	0,14	4,55E-04
	1mm	Fx	22,20	5,34E-03	15,22	7,54E-04	0,27	9,81E-04
		Fz	20,01	5,09E-03	9,91	7,46E-04	0,25	9,66E-04

*Table IV
Comparison of results for the three miniscrews.*

To evaluate the results, we represent the sequence graph of the most significant images of the finite element analysis representing the stresses and displacements in the

miniscrew (Fig. 4), in the cortical bone (Fig. 5) and in the trabecular bone (Fig. 6) at different thicknesses of cortical bone.

DISCUSSION

A comparison of the performance of three MOI is made in this study, quantifying and analysing stresses and displacements. In MOI model 1, Figure 2, when applying a force of 100 g to the same screw and changing its orientation, both the maximum stress and maximum deformation increased as the force approaches 0°. The stresses were

lower when the force was applied at 90° along the main axis of the miniscrew. These results are in line with those obtained by Pickard¹⁹, who showed that when force is applied along the main axis of the miniscrew, it had greater stability and resistance to failure than in any other situation, resisting maximum forces of up to 342 N. Under these circumstances,

Figure 4
Miniscrew stresses and displacements, 1 mm thickness cortical bone.

Figure 5
Miniscrew stresses and displacements, 1 mm thickness cortical bone.

Figure 6
Miniscrew stresses and displacements.

the thread of the miniscrew is perpendicular to the load, *i.e.* it is in the optimum position to withstand the applied force. However, if the miniscrew is placed at 45° in the same direction as the applied force, it has greater stability and resistance to failure than another miniscrew placed at the same angle, but facing in the opposite direction to the application of force. Jasmine *et al.*⁹ likewise concur that the miniscrew should be placed as perpendicular to the bone as possible to achieve greater stability. However, it is not always possible to place the miniscrew perpendicular to the surface of the bone. The arrangement of the tooth roots or the special anatomy of the chosen area sometimes forces us to modify the main axis of the MOI. Addressing the risk of root injury that placement of a MOI perpendicular to the bone in the posterior interradicular spaces subsequently involves, Park *et al.*¹⁷ suggests placing miniscrews with a distal inclination of 10° to 20°. Melsen¹⁴ recommends placing the miniscrews obliquely in the maxilla, in an apical direction, but advocates placing them as parallel as possible to the roots in the interdental spaces in the mandible. Kyung *et al.*¹¹ propose placing them at an angle of 30° to 40° to the axis of the tooth in the maxilla and of 10° to 20° in the mandible. Carano *et al.*² suggest an angle of 30° to 45° in the maxilla, although they recommend placing the miniscrew in a perpendicular position in areas near the maxillary sinus to prevent damaging it. In our study, the performance of the three screws was very similar. Although the differences between the 3 MOI are minimal, the area of maximum

stress is located at the site supporting the base of the head of the 3 miniscrews (Fig. 4A), while the displacement of all three (Fig. 4B) is practically zero at the base. As for load stresses at the cortical bone level (Fig. 5A) and displacements (Fig. 5B), these are very similar, in the order of $2.2 - 2.9 \times 10^{-4}$. Greater stresses appear in the trabecular bone in the Jeil screw (Fig. 6) under the same load conditions. Therefore, despite the low value of the stresses, this MOI design would be the one in which the cortical bone supports the highest load (Fig. 6A). As regards displacements, however, the Jeil MOI shows around 30% less displacement than the other two designs (Dentaurum and 3M) (Figure 6B).

Chazigianni *et al.*⁴ concluded that length and diameter are significant parameters in miniscrew stability only when high levels of force are applied. However, Liu *et al.*¹³ state that the diameter is the dominant factor in the mechanical response of miniscrews. As in the present study, they found that both stress and displacement decrease with increasing thickness of cortical bone. In our results, displacement increases with decreasing thickness of the cortical bone. This may be due to the fact that the miniscrew tends to move more as the thickness of the most rigid layer decreases. The 3M miniscrew, which showed the lowest displacement values in cortical bone, presented the greatest displacements in trabecular bone. This may have been the result of the effect of the miniscrew rotating in the direction of the applied force. The structural differences between cortical bone and trabecular

bone lead to lower stress in trabecular bone than in cortical bone.

Miniscrew design also varies between different manufacturers and it is difficult to discern which offers the best mechanical properties. In this study, we chose three miniscrews with similar insertion features. We found a higher concentration of stress at the neck of the miniscrew. This is consistent with findings by Singh *et al.*²¹, who also found, as in this study, that the stress in trabecular bone was minimal. Furthermore, these authors showed that when a lateral force is applied, miniscrews with a smaller neck diameter are more likely to bend or break than those with a larger diameter. This breakage tends to occur in the neck of the miniscrew, where it joins the cortical bone.

In simplified MOI model 2 employed in this study, it can be seen that both the maximum stress and deformation increase as the point of application of force moves further away. Our results agree with those of Choi *et al.*⁵, who used a lateral force of 2 N, also reporting that the stress in the adjacent bone increases with the increasing height of the miniscrew head and the point of application of force.

As regards the analysis by means of the finite element model, the variations in the thickness of cortical bone do not affect the maximum stresses recorded on each miniscrew, the Jeil miniscrew being the one showing the highest load, while the 3M and Dentaurem miniscrews had the lowest values. However,

increased stress was observed in both cortical and trabecular bone. Reducing the thickness of the cortical bone layer leads to an increase in the recorded stresses in cortical bone. This increase, which is relatively constant, is due to the fact that the effective cross-section of embedment of the most rigid implant decreases with decreasing thickness of the layer of cortical bone. Reducing the thickness of the cortical bone layer leads to an increase in the recorded stresses in the trabecular area. By decreasing the cross-section of embedment in the most rigid area (cortical bone), the influence of the less rigid area becomes greater, thereby leading to increased stress in trabecular bone.

The 3M miniscrew showed significantly lower maximum stress in cortical bone than the Dentaurem and Jeil miniscrews. The increased stress in trabecular bone increased with decreasing thickness of cortical bone. The 3M miniscrew, which had showed the lowest values of displacement in cortical bone, had the greatest displacements in trabecular bone.

Although the load conditions are very similar, the Jeil screw supports the load better, whereas the 3M screw withstands displacements better.

The stress in trabecular bone is much lower than that in cortical bone due to differential features of each type of bone.

The design of the MOI threads influences both the conditions of displacements and stresses. This structure accordingly withstands stresses

better in some cases (Jeil) while avoiding displacements better in others (3M).

Nonetheless, our study has certain limitations. First, the geometry of the bone block was simplified to that of

a rectangular block and the material properties were considered homogeneous. The possible influence of soft peri-implant tissue was not taken into account either.

CONCLUSION

The three miniscrews studied were perform similarly in this study.

Reduced thickness of cortical bone does not produce an increase in stress in the miniscrews, the stress values remaining constant for different thicknesses.

A reduction in cortical bone leads to increased displacement in the direction of the force vector of the

miniscrew, increasing significantly for low cortical bone thicknesses. It also leads to a small increase in maximum stresses in cortical bone and a more significant increase in trabecular bone. Finally, the reduction in cortical bone thickness leads to increased directional displacements into both cortical and trabecular bone.

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