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Stresses around a miniscrew. 3-D analysis with the finite element method (FEM)

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Background: Miniscrews used for absolute anchorage may induce stresses in the surrounding tissues that are dependent on their proximity to the miniscrew.
Aims: To determine the stresses in the buccal walls of the sockets of lower molars adjacent to a miniscrew under load when the position and angulation of the miniscrew are changed.
Methods: Five 3-D FEM models containing the first and second lower molars, their periodontal ligaments and the surrounding spongy and cortical bone, were modelled in SolidWorks 2006 (SolidWorks, Concord, MA, USA) and transferred to the ANSYS Workbench (ANSYS Inc., Southpointe, Canonsburg, PA, USA). A tensile force of 2 N, decomposed in 3-D space, was applied to a miniscrew inserted between the lower first and second molars. The von Mises (equivalent) stresses along the buccal walls of the sockets of the first and second molars were derived following changes in miniscrew position and angulation. No direct force was applied to the molars.
Results: When the miniscrew was inserted at right angles to the bone and midway between the molars the stress in the crestal area was 0.093 MPa. This stress increased proportionally in the first molar socket as the miniscrew was moved towards the first molar and declined when the miniscrew was tipped towards the second molar. Stresses also decreased in the crestal area of the second molar as the miniscrew was moved towards the first molar, but increased when it was tipped towards the second molar. A 30–55 per cent increase in crestal stress in the first molar socket was detected.
Conclusion: Stress occurred in the tissues surrounding a miniscrew subjected to a force vector. Changes in the position or angulation of a miniscrew can affect the stress in the socket walls of adjacent teeth.
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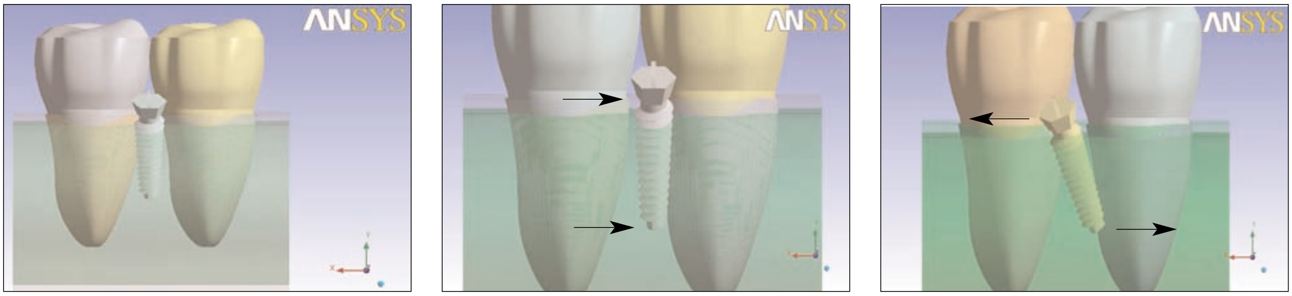
Introduction

Orthodontic treatment relies on forces and moments to move teeth into predetermined positions. Unfortunately, the reaction to many orthodontic forces can result in unwanted movement of the anchor teeth or 'loss of anchorage'. As a result, orthodontists have developed new intra-oral sources of anchorage that do not rely on the teeth. These new methods use plates and/or screws inserted into the bone(s) of the facial skeleton. These devices are claimed to provide so-called absolute anchorage: in other words, they remain stationary when subjected to an orthodontic load.

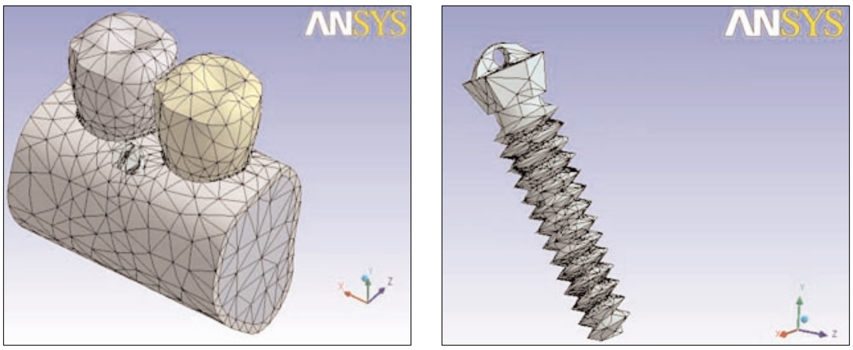
The first attempt at so-called absolute anchorage was carried out over 60 years ago by Gainsforth and Higley, who used the anchorage provided by vitallium screws in the ascending rami of six dogs to retract the lower canines.[1] It was almost 20 years before the anchorage provided by screws inserted in skeletal structures was used to treat an actual malocclusion.[1,2] Since then a variety of methods has been developed to provide absolute anchorage.[3–11] The newer methods use small titanium-alloy screws or miniscrews that have acceptable stability under orthodontic loads.[12–14]

At present there is a lack of information on the importance of miniscrew location and angulation to anchorage resistance and stability, and of the stresses in the tissues surrounding a miniscrew under load.[14,15] The FEM is an effective method of investigating stresses in the tissues surrounding a miniscrew because it enables the investigator to 'model' a system made up of different tissues/structures (e.g. tooth, periodontal ligament, surrounding bone, miniscrew), assign properties to the components or elements in



(a) (b) (c)

Figure 1. (a) Model 1, miniscrew midway between the lower first and second molars. (b) Model 3, miniscrew 1.0 mm closer to first molar on the right. (c) Model 5, miniscrew tilted 20 degrees towards second molar on the left.



(a) (b)

Figure 2. (a) The meshed 3-D computer model. (b) The meshed 3-D computer model of the miniscrew.

the system and study the behaviour of the system under defined loads and conditions.[16–22] The objective of the present study was to investigate the hypothesis that a miniscrew under load induces stresses in the surrounding tissues that vary according to the position and angulation of the miniscrew.

Materials and methods

Five 3-D computer models of the first and second lower molars were designed in SolidWorks 2006 (SolidWorks, Concord, MA, USA) to simulate situations when a force is applied to a miniscrew inserted perpendicular to the surface of the bone and midway between the first and second molars, displaced bodily to one side or tipped to one side of the point of insertion. The 3-D models contained compact and cancellous alveolar bone, the first and second lower molars and their periodontal ligaments, and a 10 mm miniscrew inserted between the molars. The teeth were modelled according to Ash's dental anatomy.[23]

The head of the miniscrew (i.e. the part protruding from the bone), which plays no part in the resistance offered by the screw, was omitted from the model.

In Model 1 the miniscrew was inserted perpendicular to the surface of the bone and 2.6 mm from each molar (Figure 1). In Model 2 the miniscrew was inserted perpendicular to the surface of the bone, but moved 0.5 mm mesially from the position in Model 1. In Model 3 the miniscrew was inserted perpendicular to the surface of the bone, but moved 1.0 mm mesially from the position in Model 1. In Model 4 the miniscrew was inserted with a 10-degree tilt towards the second molar with the axis of rotation through the point of insertion in Model 1. In Model 5 the miniscrew was inserted with a 20-degree tilt towards the second molar with the axis of rotation through the point of insertion in Model 1.

The roots of the molars were given a periodontal ligament with a uniform thickness of 0.25 mm. The

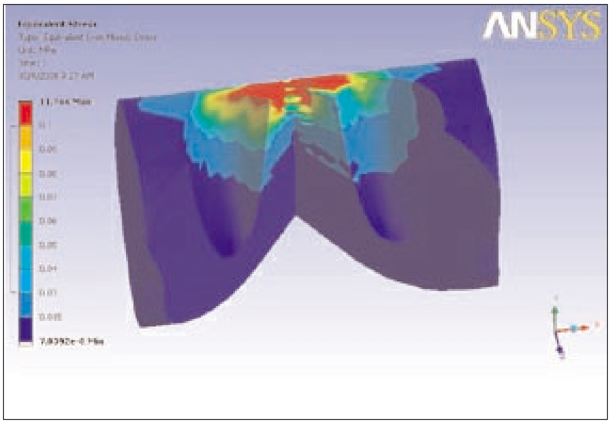


Figure 3. The slices defined and the von Mises stresses in the sockets of both molars.

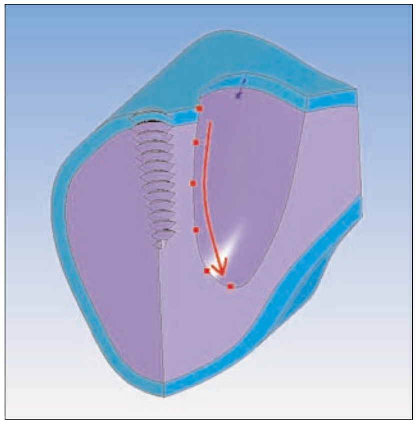


Figure 4. The von Mises stresses were determined at six points along the crestal-apical path in the buccal walls of both lower molars, only one socket is shown.

Table I. Mechanical properties of the materials used in the models.

	Young's modulus (MPa)	Poisson's ratio
Tooth	20300	0.26
PDL	0.667	0.49
Spongy bone	13400	0.38
Cortical bone	34000	0.26
Titanium	96000	0.36

3-D models were designed to be as realistic as possible, without using any symmetry in modelling. Each model was transferred to the ANSYS Workbench Version 10 (ANSYS Inc., Southpointe, Canonsburg, PA, USA). Boundary conditions restricted displacements of the nodes at the mesial and distal parts of the models. Solid bodies are free to move in 3-D space while under load in FEM. This rigid body motion was restricted by preventing definite nodes from moving along the 3-D space axes. The manner of restriction was based on the anatomy of mandible. All nodes at the mesial and distal surfaces of the model were prevented from being displaced bucco-lingually, mesio-distally and occluso-apically. Mechanical properties were then applied and the models were meshed (Table I, Figure 2).

A 3-D force system was then applied to the miniscrew and each molar in turn in each model, based on decomposition of a 2.0 N force at 20 degrees to sagittal plane. The force, applied between the miniscrew and lower canine, resulted in a vertical component of 0.685 N and a horizontal component of 1.879 N. This component, in turn, decomposed to a mesial vector (i.e. along the dental arch) of 1.85 N and a medial force vector (i.e. towards the mid-sagittal plane) of 0.326 N. No direct force was applied to either the first or second lower molars. The 3-D model was 'sliced' along two planes: the first passed through the disto-lingual line angle of the model and the centre of the miniscrew and the second slice through the mesio-lingual line angle of the model and the centre of the miniscrew. The first slice showed the inner wall of the second molar and the second slice the inner wall of the first molar (Figure 3). The von Mises stress, which is defined as $\sigma_e=(0.5[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2])^{0.5})$ where σ_1 is the maximum principal stress; σ_2 is the intermediate principal stress; and σ_3 is the minimum principal stress produced by the applied force system, was then assessed along the inner walls of the tooth sockets in each sectioned model. The forces were assessed at six equally-spaced points between the crestal and apical areas of each molar (Figure 4).

Results

Numeric findings of the von Mises stress at locations indicated in Figure 4 are given in Table II. The stress contours are shown in Figures 3, 5 and 6.

First molar

In Model 1, the miniscrew was inserted perpendicular to the surface of the bone and 2.6 mm from each molar. The stress findings along the defined path are

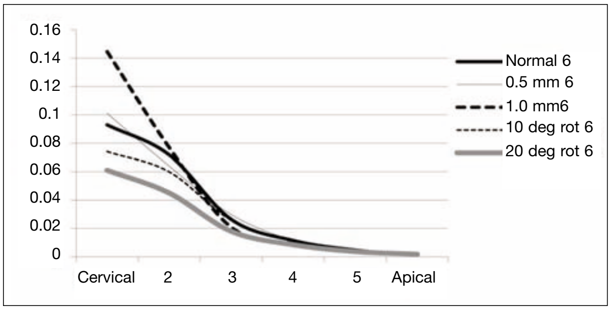


Figure 5.The von Mises stress along the crestal-apical path in the buccal wall of the lower first molar socket.

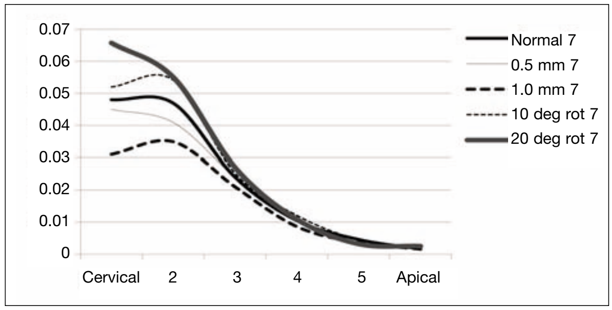


Figure 6. The von Mises stress along the crestal-apical path in the buccal wall of the lower second molar socket.

Table II. Stress findings (MPa) for different positions and angulations of the miniscrew.

	Normal	Normal	0.5 mm mesial displace-ment	0.5 mm mesial displace-ment	1.0 mm mesial displace-ment	1.0 mm mesial displace-ment	10 degree distal tip	10 degree distal tip	20 degree distal tip	20 degree distal tip
Tooth	6	7	6	7	6	7	6	7	6	7
Crestal 1	0.093	0.048	0.101	0.045	0.144	0.031	0.074	0.052	0.061	0.066
2	0.072	0.047	0.064	0.041	0.077	0.035	0.060	0.054	0.045	0.055
3	0.026	0.024	0.030	0.024	0.021	0.021	0.026	0.025	0.018	0.027
4	0.011	0.010	0.012	0.010	0.009	0.009	0.011	0.012	0.008	0.011
5	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.003
Apical 6	0.001	0.002	0.001	0.002	0.002	0.002	0.001	0.002	0.002	0.002

Normal, miniscrew inserted perpendicular to the bone surface
Mesial displacement, miniscrew moved towards the first molar
Distal tip, miniscrew tipped towards the second molar

0.093 MPa at the crestal point and 0.001 MPa at the apical point. When the miniscrew was moved 0.5 and 1.0 mm towards the first molar without any change in the angulation, the stress at the crestal point increased to 0.101 and 0.144 MPa, respectively. Stress at the apical point increased from 0.001 MPa (0.5 mm) to 0.002 MPa (1.0 mm).

A 10-degree change in angulation of the miniscrew away from the first molar reduced the stress at the crestal point to 0.074 MPa. At the apical point, the stress (0.001 MPa) was similar to the 0.001 MPa stress at the apical point in Model 1. When the miniscrew was inclined 20 degrees toward the second molar the stress at the crestal point was 0.061 MPa and at the apical point 0.002 MPa.

Second molar

Stress at the crestal point started at 0.048 MPa and fell to 0.045 MPa and 0.031 MPa when the miniscrew was moved mesially 0.5 mm and 1.0 mm, respectively. Stress at the apical point started and remained at 0.002 MPa.

A 10-degree tilt of the miniscrew towards the second molar increased the stress at the crestal point to 0.052 MPa and the stress at the apical point increased slightly to 0.002 MPa. Increasing the angulation of the miniscrew to 20 degrees resulted in 0.066 MPa stress at the crestal point and 0.002 MPa at the apical point.

Discussion

FEM analysis is seldom used to analyse the stress induced on teeth and anchor structures by orthodontic forces, but it has been shown to be a cost-effective and valid method of determining the behaviour of structures under load. When a miniscrew is the anchor structure the distribution of loads to the surrounding tissues need to be considered from a stress point of view. The force on a tooth with a healthy periodontal ligament (PDL) results in tooth movement, which is a PDL-based phenomenon, but force on a miniscrew, which lacks a PDL, is transferred directly from the miniscrew to the surrounding tissues. Relatively small variations in the placement and/or orientation of a miniscrew can increase the stress in the surrounding tissues, which may include teeth and PDL. In the present study the main issue was to determine if small changes in the position and angulation of a miniscrew relieved the PDL from external effects or introduced new stresses on the PDL.

The present study is the first to assess stress in the tissues surrounding a miniscrew. It would be fair to say that most clinicians regard a miniscrew inserted in sound bone as stable anchorage, and give little consideration to the stress transferred from a loaded miniscrew to the surrounding tissues. The findings show that the stress on the PDL of the first and second lower molars changed as the miniscrew was shifted bodily towards the first molar or tipped toward the second molar. When the miniscrew was moved mesially stress increased in the tissues surrounding the first molar and reduced in the tissues surrounding the second molar. The reverse occurred when the angulation of the miniscrew was changed. Moving the head of the miniscrew closer to the second molar increased stress in the tissues surrounding the second molar.

If small changes in the position of a miniscrew can alter stress in the tissues surrounding a tooth, the consequences of the loads affecting the PDL should be considered. The PDL of a tooth close to a miniscrew is not completely isolated from the stresses induced by loads on the miniscrew. The health of the tissues surrounding a miniscrew is an important consideration just as the health of the PDL is important in orthodontic treatment. High loads on a miniscrew could result in high stresses in the surrounding tissues, which may initiate unwanted tooth movement or, in an extreme case, unseen pathological changes. Stress in the tissues surrounding a miniscrew can be controlled by ensuring that the miniscrew is not subjected to a high load, that it does not perforate the PDL and that it is inserted in thick, healthy bone. In situations where it is necessary to insert a miniscrew close to the PDL, a light load to the miniscrew should be employed.

As we have seen, increases in stress can affect the PDL of an adjacent tooth. For example, stress in the crestal area of the lower first molar increased up to 55 per cent by moving the miniscrew 1.0 mm towards the first molar, and increased by 37 per cent in the second molar socket adjacent to the PDL by inclining the miniscrew 20 degrees towards the second molar. Changes in the location or angulation of a miniscrew are followed by changes in the von Mises stresses in one location or another. Examination of the stress curves revealed that if the position of a miniscrew is to be changed, moving a miniscrew toward a tooth will increase the stresses more uniformly than inclining the miniscrew towards the tooth. The study also showed the apical half of the roots of both molars were free of the effects of the miniscrew, suggesting that an apically-placed miniscrew with a cervical extension/attachment would leave the critical crestal area stress-free (Figures 5 and 6).

Conclusion

As a rule, miniscrews are reliable and safe sources of intra-oral anchorage. The von Mises stresses in the sockets of teeth adjacent to the miniscrew are influenced by the proximity and angulation of the loaded miniscrew to the teeth.

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