AJO-DO

Three-dimensional modeling and finite element analysis in treatment planning for orthodontic tooth movement

Hussein H. Ammar,[a] Peter Ngan,[b] Richard J. Crout,[c] Victor H. Mucino,[a] and Osama M. Mukdadi[d]
Morgantown, WVa

Introduction: The objective of this study was to demonstrate the potential of 3-dimensional modeling and finite element analysis as clinical tools in treatment planning for orthodontic tooth movement. High stresses in bone and miniscrew implants under load can cause fractures and trauma for orthodontic patients, and treatments are typically planned by using clinical experience or simple 2-dimensional radiographs. **Methods:** Anatomically accurate 3-dimensional models reconstructed from cone-beam computed tomography scans were used to simulate the retraction of a single-rooted mandibular canine with a miniscrew placed as skeletal anchorage. Detailed stress distributions in the implant and peri-implant bone were found, in addition to the effect of the orthodontic bracket hook length and the angulation of retraction force on stress response in the periodontal ligament (PDL). **Results:** The numeric results showed that the equivalent von Mises stress on the miniscrew under a 200-cN tangential load reached 42 MPa at the first thread recession, whereas von Mises stress in the peri-implant bone only reached 11 MPa below the neck. High tightening loads of 200 N·mm of torsion and 460 cN of axial compression resulted in much greater bone and implant von Mises stresses than tangential loading, exceeding the yield strengths of the titanium alloy and the cortical bone. Increasing the hook length on the orthodontic bracket effectively reduced the canine PDL stress from 80 kPa with no hook to 22 kPa with a hook 7 mm long. Angulating the force apically downward from 0° to 30° had a less significant effect on the PDL stress profile and initial canine deflection. The results suggest that stresses on miniscrew implants under load are sensitive to changes in diameter. Overtightening a miniscrew after placement might be a more likely cause of fracture failure and bone trauma than application of tangential orthodontic force. The reduction of stress along the PDL as a result of increasing the bracket hook length might account for steadier tooth translation by force application closer to the center of resistance of a single-rooted canine. The relatively minor effect of force angulation on the PDL response suggests that the vertical placement of miniscrews in keratinized or nonkeratinized tissue might not significantly affect orthodontic tooth movement. **Conclusions:** This model can be adapted as a patient-specific clinical orthodontic tool for planning movement of 1 tooth or several teeth. (Am J Orthod Dentofacial Orthop 2011;139:e59-e71)

Anchorage is an important consideration for orthodontists and is often an essential component in treatment planning. Of particular clinical value is the situation in which absolute anchorage is required for retraction of anterior teeth or protraction of posterior teeth. Such anchorage can be provided extraorally with headgear or intraorally by using adjacent teeth or dental implants. The advantage of intraoral anchorage is reduced patient compliance for treatment.[1,2] This is an important factor, considering that 19% of orthodontic visits in 2004 were by children under 12 years of age, and nearly 77% were by minors less than 18.[3] Adults can also be averse to the use of headgear for esthetic or professional reasons.

Temporary skeletal anchorage devices such as miniscrew implants have become increasingly popular in orthodontic tooth movement because of their biocompatibility, small size, and placement versatility. Figure 1 shows the placement of miniscrews between the roots of the mandibular second premolars and first permanent

From West Virginia University, Morgantown.
[a]Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, College of Engineering and Mineral Resources.
[b]Professor and chair, Department of Orthodontics, College of Dentistry.
[c]Professor, Department of Periodontics, College of Dentistry.
[d]Assistant professor, Department of Mechanical and Aerospace Engineering, College of Engineering and Mineral Resources, Center for Cardiovascular and Respiratory Sciences, West Virginia School of Medcine.
The authors report no commercial, proprietary, or financial interest in the products or companies described in this article.
Supported by grants from NIDCR 1R21DE019561 and WV PSCoR.
Reprint requests to: Osama M. Mukdadi, Department of Mechanical and Aerospace Engineering, PO Box 6106, West Virginia University, Morgantown, WV 26506-6106; e-mail, sam.mukdadi@mail.wvu.edu.
Submitted, March 2010; revised and accepted, September 2010.
0889-5406/$36.00

doi:10.1016/j.ajodo.2010.09.020

molars to retract the anterior canines without forward movement of the posterior molars. Miniscrews provide the option of early or immediate loading without a lengthy initial latency period.[4] Other advantages include placement versatility because of the relatively small diameter of the endosseus body[1,5] and relatively simple procedures for placement and removal.[2] The smooth surface and minimal osseointegration reduce torsional resistance.[6] Miniscrews can be placed between teeth with sufficient bone density and root clearance, giving orthodontists a variety of placement options.[7] However, interference with the root or periodontal ligament (PDL) can cause significant anchorage loss and mobility or patient trauma.[8] Heightened stresses in peri-implant bone from orthodontic loading, miniscrew orientation, surrounding bone quality and quantity, or miniscrew design might result in soft-tissue inflammation, microfractures in the bone or implant, or bone resorption.[8,9] Such failures can compromise anchorage stability and increase the risk of pain or injury. Low stresses in bone at placement can also result in low primary stability of the implant or bone atrophy.[10] High torque might also cause bone damage or miniscrew fracture, requiring corrective surgery.[8]

Currently, the planning of miniscrew placement is limited to the use of clinical judgment in addition to 2-dimensional panoramic radiographs.[11] The use of digital radiography can overcome some problems of image distortions resulting from magnification or image noise and reflections, but stress and strain distributions under orthodontic force application cannot be determined.[11] Modern medical imaging, modeling, and finite element (FE) analysis solutions can provide powerful tools for optimizing 3-dimensional (3D) morphology from radiographic scans and determining stress and deflection distributions for complex anatomic geometries such as bone. Previous FE studies on miniscrews have used artificial, nonspecific bone-block geometries, finding critical stress areas and the effects of miniscrew length, diameter, and cortical bone thickness on stress response.[12] Motoyoshi et al[13] performed nonspecific simulations to test the effects of thread pitch and abutment attachment on miniscrew stresses. Pollei et al[14] conducted FE analyses of miniscrews on various commercial implant designs with patient-specific bone geometry, defining a rigidly bonded implant-bone contact for linear simulation. Gracco et al[15] performed nonspecific 2-dimensional FE simulations of a miniscrew with varying lengths and degrees of osseointegration, reporting that stresses decreased with greater osseointegration. Most FE studies focused solely on simulations with either miniscrews[12-15] or teeth[16-19] from different, isolated models. The objective of this study was to determine the stress profile on the miniscrew implant and peri-implant bone caused by both a tangential orthodontic force and tightening loads by using 3D modeling and FE analysis. In addition, the effects of orthodontic bracket hook length and force angulation on resulting stress response of the canine PDL were determined. The long-term goal was to determine the potential of 3D modeling and FE analysis in treatment planning for patient-specific tooth movements.

Fig 1. Clinical orthodontic example of canine retraction with miniscrew anchorage attached by elastics to the hook for space closure without forward movement of the posterior molars.

MATERIAL AND METHODS

Figure 2 shows the procedures for 3D modeling and FE analysis in planning for patient-specific tooth movement with a miniscrew. First, a cone-beam computed tomography (CBCT) scan of a patient's maxilla and mandible was acquired in vivo. Images with a square pixel size of 0.41 mm and a total size of 512 pixels per square were used. A total of 128 layered slices were saved in DICOM format with a 21-cm field of view and imported into Mimics software (version 12.1, Materialise, Plymouth, Mich). The voxel size was approximately 0.41 × 0.41 × 0.6 mm with a maximum smoothing error of half of this voxel volume. A global threshold was defined to isolate bone from soft tissues. Then automatic segmentation operations were performed on the morphology to reduce noise and artifacts. The mandibular left canine was isolated with its root for treatment by using local thresholding on the CBCT images. Scaling and Boolean operations were then carried out to model the PDL as a thin enclosure around the root with an average thickness of approximately 0.3 mm. Models were smoothed before the Boolean subtractions to ensure an even fit. One miniscrew implant design was chosen as anchorage for retraction of the mandibular canine