ORTHODONTIC WAVES XXX (2016) XXX–XXX

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/odw

Original article

Evaluation of long-term orthodontic tooth movement considering bone remodeling process and in the presence of alveolar bone loss using finite element method

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ARTICLE INFO

Article history:
Received 28 May 2016
Received in revised form
14 August 2016
Accepted 3 September 2016
Available online xxx

Keywords:
Alveolar bone loss
Bone remodeling theory
Finite element method
Tipping tooth movement

ABSTRACT

Purpose: In the presence of alveolar bone loss, magnitudes of orthodontic forces should be modified, so that the desired tooth movement could be achieved without further bone loss. The main scope of this research was to investigate the effects of force magnitudes on the long-term tipping movements of the teeth with different degrees of bone loss.

Materials and methods: Five finite element models of an incisor with different degrees of bone loss were developed. The long-term tooth movements were simulated in a 4-week period based on a bone remodeling theory. Under a 1.00N force, the tooth displacements of models were evaluated. Under forces of 0.25–1.00N, teeth rotations were also evaluated.

Results: As the height of the bone decreased, for a constant magnitude of force, the amount of tooth movement increased and reached to the maximum amount of 2.60mm in the model with 6.00mm of bone loss. By increasing the applied force from 0.25N to 1.00N, the degree of teeth rotations in the models with 6.00mm of bone loss and normal bone height increased 9% and 81% respectively.

Conclusion: Though the amount of tooth movement increased by increasing the force magnitude in all models with different bone heights, this increase was only pronounced in milder degrees of bone loss. This study suggests that applied force magnitude can be remarkably reduced in the patients with reduced bone height, particularly in the cases with extreme bone loss.

1. Introduction

Orthodontic treatment planning of patients with alveolar bone loss has consistently been a concern for dental researchers [1,2]. The most frequent type of alveolar bone loss is called horizontal bone loss (HBL) that is characterized by an even reduction in the bone height around one or more teeth [3]. It can be induced by periodontal diseases [4], or can be an age-related phenomenon [5]. Despite the reduction of bone height

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http://dx.doi.org/10.1016/j.odw.2016.09.001

in patients with the HBL, orthodontic tooth movements are possible [6], though the orthodontic treatment will require changes due to the different degrees of bone loss [7]. When the alveolar bone support is reduced, the same orthodontic force system induces greater pressure in periodontal tissues compared to those with normal alveolar bone support [8]. Accordingly, the resulting final tooth displacement would be altered [1,9,10]. Also, patients with the alveolar bone loss are more susceptible to further bone loss and subsequent tooth loss during the orthodontic treatment [11]. In addition, in the presence of alveolar bone loss, there is a greater chance of apical root resorption as a consequence of applying excessive orthodontic forces [12]. Therefore, in order to achieve the desired tooth movement without causing damage to the tooth and periodontal tissues, the proper modification of applied force system in the treatment of the tooth with alveolar bone loss is of great importance. The lack of sufficient investigation in this field necessitates the performance of additional studies to determine appropriate level of forces and moments that are required to attain the required tooth movement without further bone loss. For this purpose, the finite element method (FEM) is a useful tool for analyzing periodontal tissues under varying forces [13]. The FEM has been widely used to study different problems in orthodontics, such as the estimation of stress and strain distribution in periodontal tissues under different orthodontic loading conditions [14,15] and tooth movements [16,17]. So far, several studies have used the FEM to investigate the effects of reduced alveolar bone height on orthodontic tooth movements [2,9–11]. Moreover, a few researchers analyzed the stress and strain in the tooth, periodontal ligament (PDL), and alveolar bone with different alveolar bone heights under orthodontic forces [10]. In addition, in some of the previous studies, the effects of reduced alveolar bone height on the initial tooth displacement, location of center of resistance (CRes) and location of center of rotation (CRot) were also analyzed [1,2].

All of the previous numerical studies on HBL biomechanics have exclusively investigated initial periodontal tissues' reactions to orthodontic forces [2,9–11]. The initial tooth movement, which is produced by the deformation of the periodontal tissues under applied orthodontic forces, is followed by the long-term orthodontic tooth movement in a therapy period [18]. During the period of orthodontic treatment, tooth position and geometry of the periodontal support are changed, altering the applied force system. Therefore, estimates based on stress/strain analysis and initial tooth displacement alone might be inadequate to precisely assess the optimal force system in the orthodontic treatment of patients with different degrees of bone loss. To the best of our knowledge, the effect of HBL on biomechanical aspects of the long-term orthodontic tooth movement has not yet been tackled by other investigators. The long-term orthodontic tooth movement is a result of the alveolar bone adaptation in response to the mechanical stimuli that are applied to periodontal tissues by orthodontic appliances [19]. The ability of bone to adapt its shape and density to changes in the mechanical loading environment, which is called bone remodeling, first described by Wolff in 1892 [20]. Many researchers have tried to develop mathematical models to simulate and predict bone remodeling based on Wolff's law. Different expressions of the mechanical stimuli have been proposed as the bone remodeling triggers including strain [21,22], stress [23], strain energy density [24–26], and tissue damage [27,28]. Throughout the orthodontic treatment, both internal bone remodeling (which results in changes in internal architecture and density of the bone), and external or surface bone remodeling (which results in changes in shape and size of the bone) occur. Since the rate of the orthodontic tooth movement is mainly affected by the external bone remodeling [29], in this study, external bone remodeling was mathematically modeled to evaluate the rate of tooth movement in the presence of HBL. Thus, the word "bone remodeling" in this study will be used for the external bone remodeling. In recent years, a few researches have employed bone remodeling theories to simulate long-term orthodontic tooth movements [30–33]. It was suggested that the strains in the PDL are the key stimulus of the alveolar bone remodeling rather than stresses or strains in the bone itself [30].

In this study, we hypothesized that the height of alveolar bone may have a significance influence on the magnitude of force needed for a desired tooth movement, to test our hypothesis, a numerical model that calculates the alveolar bone remodeling process, on the basis of PDL strain magnitudes was developed to simulate long-term orthodontic tooth movements. The developed model was then used to study the biomechanical effects of the reduced alveolar bone height in the presence of HBL, on the long-term orthodontic tooth movement. Center of resistance (CRes) and center of rotation (CRot) of the teeth with different bone heights were also calculated in the developed model when a labio-lingual tipping force of 1.00N was applied. CRes and CRot are two useful parameters to study the behavior of tooth movements and can be used for determining the type of tooth movement in the orthodontic treatment planning [34]. Assessment of the impact of bone loss on the positions of CRes and CRot can facilitate the design of orthodontic appliances and treatment sequences for patients with deficient alveolar bone support. The objectives of this work were: (1) to evaluate and compare the long-term orthodontic displacements of 5 maxillary incisors with different alveolar bone heights subjected to a tipping force; (2) to determine and compare the positions of centers of resistance and rotation of the incisor teeth with different alveolar bone heights when a tipping force was applied; and (3) to study the effects of different magnitudes of tipping force on long-term orthodontic displacements of the incisor teeth with different alveolar bone heights.

2. Materials and methods

In this study, FEM was used to simulate the long-term orthodontic tooth movement. The numerical simulation was an iterative process and each iteration was divided into two stages: (1) analysis of the model under orthodontic force by means of the FEM analysis; and (2) investigation of bone remodeling and the tooth movement.

2.1. *Establishing the finite element models*

Five three-dimensional (3D) models of a maxillary lateral incisor were constructed, in which each model consisted of the