SHORT COMMUNICATION

An analytic technique to simulate bone remodeling during orthodontic tooth movement

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Introduction

In clinical orthodontics, various treatments with orthodontic appliances are used in the correction of malocclusions. In such treatments, orthodontic force in the only external stimulus, therefore, bone remodeling should be considered in association with such mechanical products of the force as strain or stress¹⁾.

For elucidating the mechanism of bone remodeling, histological, biochemical and biomechanical approaches have been used. Experimental studies have demonstrated site specific resorption and new bone deposition at the periodontal ligament (PDL)-alveolar bone interfaces²⁻⁴⁾. Biochemical studies have revealed an important role of cellular changes in bone remodeling⁵⁻⁷⁾. Further, biomechanical studies have demonstrated the nature of stress distributions in the periodontal tissue produced by various force systems^{8,9)}. However, an exact interaction between these variable factors has not yet been elucidated. For investigating the sequence of bone remodeling, an analytic approach has recently been employed in the field of biology and dental and medical sciences^{5,9-13)}. This technique is based on simulating biological phenomena in a computer system which can not be represented in any experimental model^{9,13)}.

The purpose of this study was twofold, 1) to intro-

duce an analytic approach or a numerical simulation technique based on the finite element method (FEM), and 2) to investigate the association between stresses in the PDL and bone remodeling during orthodontic tooth movement.

Materials and Methods

A two-dimensional finite element model was developed for the upper canine from the average anatomical data in Japanese. The model consists of 315 nodes and 571 triangular elements, comprising the tooth, PDL and compact and cancellous bones (Fig. 1). Mechanical properties of these structures were defined according to previous experimental data^{8,14)}, as shown in Table 1.

Stress distributions in the PDL were first analyzed under various force systems with different moment-to-force (M/F) values^{1,15)}. Distally-directed horizontal force and anti-tipping moment (couple) were applied simultaneously at the bracket position, 4.5 mm cervical to the cusp. The M/F value is thus defined as a ratio of moment to force applied. For determining appropriate M/F values for three types of tooth movement, tipping, translation and root tipping, the magnitude of moment was varied with a constant 200 g force. Under such loading conditions, displacements of the tooth were analyzed.

Fig. 1 A schematic representation of the model of the upper canine. Solid triangles indicate restraints to avoid the sliding movement of the model.

Simulated tooth movement was then carried out by repositioning nodal points of elements constructing the alveolar bone. In this analysis, the repositioning of three nodal points of an element was induced in the direction of a principal stress, which was greater than the other in terms of the absolute value (Fig. 2). The amount of repositioning (D) was defined as follows.

$$D = k \log(S_r/S_t) \quad \text{where, } k; \text{ constant, } S_r; \text{ reference stress, } S_t; \text{ threshold level of stress}$$

The threshold level of stress for initiating bone remodeling was determined in a preliminary study⁹⁾ as $\pm 0.4 \text{ gf/mm}^2$. The shape of the model was repeatedly modified at the PDL-alveolar bone interface according to the amount of repositioning defined by the equation described above. Further, the elasticity of the PDL was changed from 35 to 20 gf/mm^2 , which was revealed in a previous study¹⁶⁾ of tooth mobility during orthodontic tooth movement, to investigate the influence on the rate of tooth movement.

Table 1 Mechanical properties of the tooth and compact and cancellous bones

Materials	Elastic modulus (gf/mm ²)	Poisson's ratio
Tooth	2.07×10^6	0.30
PDL	3.50×10	0.49
Compact bone	1.37×10^6	0.30
Cancellous bone	1.50×10^5	0.30

Fig. 2 Algorithms for simulating bone remodeling at the PDL-alveolar bone interface.

σ_1, σ_2 : principal stresses in the PDL
 Δm : amount of repositioning described in the text, as denoted by (D)
 N : a node of the shaded element in the PDL

Finally, the simulated tooth movements were examined in comparison with actual tooth movements observed in clinical orthodontics.

Results

As a result of displacement analysis, it was found that M/F values of 0.0, 13.0 and 15.0 mm produced crown tipping movement, translation and root tipping movement, respectively. Figure 3 shows the stress distributions in the PDL produced by three loading conditions with different M/F values. The results

Fig. 3 Stress distributions in the PDL in loading with the M/F values of 0.0 (A), 13.0 (B) and 15.0 mm (C). Lines with and without arrows at the ends indicate tensile and compressive stresses, respectively. $\longleftrightarrow$ and the value of stress indicate the scale of stress

Fig. 4 Simulated tooth movements under three different force systems (A : M/F=0.0 mm, B : M/F=13.0 mm and C : M/F=15.0 mm), represented by arrows. Resorption and new bone deposition induced at the PDL-alveolar bone interfaces are also depicted.

indicated that the M/F value of 13.0 mm generated almost uniform stress distributions in the PDL, *i. e.* uniform tensile and compressive stresses were induced in the mesial and distal aspects, respectively. Meanwhile, the values of 0.0 and 15.0 mm produced a transi-

tion of stress from tensile to compressive and *vice versa*.

Figure 4 represents the simulated tooth movements depicted with resorption and deposition of the alveolar bone. The M/F value of 0.0 mm produced resorp-

tion near the distal alveolar crest and the mesial apex, and new bone deposition near the distal apex and the mesial alveolar crest, indicating crown tipping movement in the distal direction. For the M/F value of 13.0 mm, uniform bone resorption and deposition were induced in the distal and mesial aspects, producing a translation of the tooth. In the case of the M/F value of 15.0 mm, bone remodeling was limited to the apical zone, indicating root tipping movement in the mesial direction. Thus, it was demonstrated that principal stresses and the directions were key determinants to bone remodeling, tensile and compressive stresses were specifically pertinent to deposition and resorption of the alveolar bone, and the threshold level of stress was existent for bone remodeling.

Figure 5 shows the amount of tooth movement evaluated at the cusp and apex of the tooth. The amount of tooth movement was changed in proportion to bone remodeling, however, changes in the mechanical property of the PDL, or elasticity, altered the rate of tooth movements. These findings strongly emphasize that the rate of tooth movements is affected by the elastic property of the PDL, *i. e.* high and low elasticities of the PDL decrease and increase the rate of movement of the tooth crown, which is clinically observed as a three-phase tooth movement³⁾.

Discussion

It is of great importance for achieving optimal tooth movement to better understand the association between external forces and bone remodeling^{1,3)}. However, various determinants exist between the two factors. Currently, it is speculated that orthodontic tooth movement is occurred according to the following sequence. External forces first produce biomechanical changes as stresses in the PDL, which are converted to such dimensional changes of the PDL as strains. The strains initiate cellular activities, and then bone remodeling for tooth movement is finally induced.

With respect to bone remodeling, biomechanical and biochemical studies have been conducted. Biomechanical studies revealed an association between strains or stresses and bone remodeling, indicating a

Fig. 5 The amount of tooth movement at the cusp and apex of the canine during simulation. Solid circle and open square indicate tooth movement associated with normal (35 gf/mm²) and reduced (20 gf/mm²) elasticities of the PDL.

different mechanism of bone remodeling during tooth movement^{8,9)} from that of long bones¹⁶⁻¹⁸⁾. In fact, the remodeling of long bones involves resorption and new deposition at the tensile and compressive areas. Such differences may be speculated to be due to the nature of stress or strain and the osteogenic nature of the periosteum of long bones, as was suggested by Maeda and Wood¹⁰⁾. Meanwhile, in a biochemical aspect, Saito et al.⁶⁾ and Yousefian et al.⁷⁾ demonstrated increases in Prostaglandin E synthesis, cellular proliferation and DNA synthesis produced by stimulation of PDL cells with mechanical stretching and positive hydrostatic pressure. However, the association between mechanical components and bone remodeling has not been elucidated yet. Thus, an approach to investigate the association between mechanical factors and bone remodeling has long been anticipated.

This study was conducted to demonstrate the

hypotheses that bone remodeling is produced by principal stresses with orthogonal principal axes and that the tensile and compressive stresses are pertinent to deposition and resorption of the bone under a certain threshold level of stress, respectively. For this purpose, a numerical simulation technique was employed^{9-11,13}. This technique is based upon finite element analysis⁸), which employs a concept to represent an object as an analytic model consisting a finite number of element connected at the corresponding nodes. With a known load or force, unknown quantities such as stresses or strains are first analyzed in a computer system. Nodal repositioning is then induced according to an assumed equation to determine the magnitude and direction.

Although the amount of tooth movement was not completely identical to that of actual tooth movement, bone remodeling was actually induced in this analysis under such assumptions that bone resorption and deposition are produced in the direction of principal stress axis by compressive and tensile principal stresses and that a threshold level of stress is approximately $\pm 0.4 \text{ gf/mm}^2$. From these findings, the following implications for bone remodeling observed during orthodontic tooth movement may be speculated. Since orthodontic tooth movement consists of three phases³), *i. e.* initial, lag and post-lag phases, the rate of tooth movement is different in each of the phases. During the initial and post-lag phases, tooth movement may be induced in response to stresses in the PDL in an almost proportional manner. During the lag phase, the rate of tooth movement decreases in general because of the hyalinization of the PDL^{2,4}) which means an increase in the elasticity. This phenomenon was demonstrated in this analysis in terms of the rate of remodeling or tooth movement, *i. e.* it was confirmed that lag phase was pertinent to the increase of the elasticity of the PDL structure which further produced a reduced tooth movement.

It is shown that the proposed technique in this article is available for exploring the mechanism of such biological phenomena, at least relevant to mechanical loading, as bone remodeling. In the future, this method would provide useful information for biological phenomena, if integrated with histological

and biochemical findings.

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