A finite element simulation of initial movement, orthodontic movement, and the centre of resistance of the maxillary teeth connected with an archwire

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SUMMARY The purpose of this article is to simulate long-term movement of maxillary teeth connected with an archwire and to clarify the difference between the initial tooth movement and the long-term orthodontic movement. Initial tooth movement was calculated based on the elastic deformation of the periodontal ligament. Orthodontic tooth movement was simulated based on the bone remodeling law of the alveolar bone, while consequentially updating the force system. In the initial tooth movement, all teeth tipped individually due to an elastic deflection of the archwire. In the long-term movement, the maxillary teeth moved as one united body, as if the archwire were a rigid material. Difference of both movement patterns was due to the change in force system during tooth movement. The long-term movement could not be predicted from the initial tooth movement. Movement pattern and location of the centre of resistance in the long-term movement were almost the same as those in the initial tooth movement as calculated by assuming the archwire to be a rigid material.

Introduction

Immediately after a force is applied to a tooth, it moves by an elastic deformation of the periodontal ligament (PDL). This is the initial tooth movement. Maintaining this state, the mechanical stress in the PDL produces an apposition and resorption of the alveolar bone, that is, the bone remodeling, which results in orthodontic tooth movement. The biological mechanism is different from that of initial tooth movement.

When a force or a moment is applied to a single tooth without restraint, the force system is not changed as the tooth moves. In this case, the pattern of orthodontic tooth movement is almost the same as that of initial tooth movement. For example, when only a mesiodistal force is directly applied to a crown of tooth, the tooth tips and rotates. In addition to the force, applying an appropriate moment for preventing the tipping will result in bodily movement of the tooth. These are well recognized in clinical orthodontics. Therefore, many calculations (Tanne et al., 1988; Vollmer et al., 1999; Geramy, 2001) and measurements (Burstone and Pryputniewicz, 1980; Dermaut et al., 1986; Yoshida et al., 2001) of the initial tooth movements have been carried out to predict long-term orthodontic tooth movement.

Recently, for many clinical cases, where multiple teeth are connected with a wire, initial tooth movements have been calculated using the finite element method (FEM; Sung et al., 2003; Reimann et al., 2007; Sia et al., 2007; Jeong et al., 2009). In these cases, the force systems will be changed when the teeth move. Such force systems are statically indeterminate problems in statics. The movement pattern is also different from that which occurred in the initial tooth movement. In one example, a transpalatal arch had no effect in the initial tooth movement (Bobak et al., 1997). In another example, individual incisors moved independently in the initial tooth movement, although the anterior tooth segment was blocked with a wire (Reimann et al., 2007). These results will be contradictory to clinical experiences, where the transpalatal arch prevents a rotation of the molars, and the tooth segment blocked with a wire moves as one united body (Park et al., 2005; Yamada et al., 2009). In order to clarify mechanics of these movements, simulations of long-term orthodontic tooth movement must be necessary (Kojima and Fukui, 2008).

The purpose of this article is to elucidate long-term orthodontic movement of maxillary teeth connected with an archwire. For this purpose, a simulation method presented in the previous article (Kojima et al., 2007) was used. We discussed how the maxillary teeth moved as one united body in relation to the location of the centre of resistance (CR).

Materials and methods

Archwire

All maxillary teeth are connected with an archwire. If stiffness of the archwire is extremely low, namely, its...
Tooth model

The mechanical response of each tooth supported with the PDL is replaced by a tooth element, which represents the three-dimensional movement produced by elastic deformation of the PDL when forces and moments act on the tooth. The calculation method of the tooth element has been explained in detail in the previous article (Kojima et al., 2007). In this method, the tooth and the alveolar bone are assumed to be rigid bodies, while the PDL is a linear elastic film (Young’s modulus: 0.13 MPa, Poisson’s ratio: 0.45) with a uniform thickness of 0.2 mm. These elastic moduli were determined so that the initial tooth mobility of the upper first premolar calculated by the FEM was consistent with that measured in vivo by Goto (1971). This procedure has been explained in the previous article (Kojima and Fukui, 2010). Node of the tooth elements of each maxillary tooth is connected directly to the archwire node.

To calculate the tooth elements, surface models of the tooth are made based on a dental study model (121D–400C; Nissin Dental Products Inc., Kyoto, Japan). This procedure consists of the three steps as described below. Firstly, sectional images of the dental study model are taken using a dental cone beam computed tomography (CBCT), AZ300CT (Asahi Roentgen, Co., Ltd., Kyoto, Japan). Secondly, using 3D modeling software, 3D-Doctor (Able Software Corp., Lexington, Massachusetts, USA), the stereolithographic (STL) model whose surface is patched with small triangular plates is constructed. Thirdly, the STL model is converted to a finite element model using meshing software, ANSYS AI*Environment (ANSYS, Inc., Canonsburg, Pennsylvania, USA).

Assuming the maxillary arch is to be moved by using a miniscrew implant (Park et al., 2005), a distal force of 2 N is applied to the canine bracket at an angle of 30 degrees. Contact forces between the neighboring teeth are neglected.

Calculation for long-term orthodontic tooth movement

Orthodontic tooth movement is produced by resorption and apposition of the alveolar bone (bone remodeling). The bone remodeling rate is assumed to be in proportion to the mean stress $\sigma_m$ in the PDL. Denoting the amount of bone resorption (and apposition) (μm) per unit time (day) and unit stress (kPa) by a coefficient $C$ [μm/(day·kPa)], orthodontic tooth movement depends on a parameter $CT$, where $T$ is the elapsed time. Because $C$ is an unknown value at the present time, the progress of tooth movement is indicated by the parameter $CT$.

During a small time increment at any time $T$, orthodontic tooth movement is achieved by the procedure below.

1. Distributions of the mean stress $\sigma_m$ in the PDL are calculated when orthodontic force is applied to the teeth connected with the archwire.
2. Amounts of absorption or apposition of the alveolar bone, which is in proportion to $\sigma_m$, are calculated. Outer surface of the PDL is moved by the bone remodeling, thereby the PDL is stretched or compressed. This deformation produces stresses in the PDL.
3. Summing up the stresses induced by the bone remodeling, forces to move the tooth (tooth movement forces) are calculated.
4. The tooth movement forces are applied to the teeth connected with the archwire.

By repeating the above procedure, the teeth move step by step. The force system acting on the teeth is updated with the tooth movement. Tooth movement is controlled by stress level in the PDL and is not dependent on configuration and structure of the alveolar bone.

The detailed calculation method has been explained in the previous article (Kojima et al., 2007). We developed a computer program for the above-mentioned calculation. A pre–post processor of FEM, FEMAP V6.0 (Enterprise Software Products, Inc., Pa, USA), was used for illustrating the tooth movement and the deformation of archwire.

The CR

The CR of multiple teeth connected with an archwire is defined in the same way as a single tooth. Assuming an ideal rigid blocking of all teeth, the arch is translated without rotation when applying a force to the CR. In order to realize the rigid blocking, the archwire is made with a rigid material, namely, Young’s modulus of the archwire is assumed to be an extremely large value, $E = 200 \times 10^{10}$ GPa. For finding a force position that produces translation of the arch, namely, for finding a location of the CR, movements of the arch are simulated when changing the force position. In order to apply the force at any position,
a rigid power arm is bonded to the archwire. Trial and error simulations with changing the force position are necessary until a location of the CR is determined.

**Results**

For the low stiffness archwire, when an upward distal force of 2 N is applied to the canine bracket, the result of the initial tooth movement of the maxillary arch is illustrated in Figure 1A. The initial tooth positions before movement are illustrated with hidden red lines. Please note that the magnitude of movement of the central incisor was only 5.7 μm (0.0057 mm). To make the difference in tooth positions before and after the movements easier to understand, the actual tooth displacements are magnified 300 times. Distributions of mean stress in the PDL are indicated by color contour. Maximum and minimum values of the mean stress of all teeth, $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$, are indicated in the figures.

**Figure 1** Movement patterns in the case of the low stiffness archwire. (A) Initial tooth movement. The canine moves in the force direction and the other teeth tip. Namely, the crown moves distally and the root apex moves mesially. All teeth move individually due to the elastic deflection of the archwire. (B) Long-term orthodontic movement. The incisors slightly extrude and tip due to the elastic deflection of the archwire. The maxillary arch moves distally and rotates counterclockwise, as if the archwire were a rigid material.
After a long time elapsed ($CT = 733 \, \mu m/kPa$), the central incisor moved distally by 2.0 mm. At this time, the pattern of orthodontic tooth movement is illustrated in Figure 1B. For the high stiffness archwire, initial tooth movement and orthodontic tooth movement are illustrated in Figure 2A and 2B.

In the case where the archwire is assumed to be a rigid material, initial tooth movement and orthodontic tooth movement are illustrated in Figure 3A and 3B. For each movement, the CR of the maxillary arch could be determined. Their locations were indicated with solid circles (●).

**Discussion**

**Movement pattern of maxillary arch**

In the initial tooth movement with the low stiffness archwire, the canine intruded in the force direction, but the other teeth tipped (Figure 1A). Although all teeth were connected to the archwire, the teeth moved individually due to elastic deflection of the archwire. The force applied to the canine...
was not distributed to the other teeth. This movement pattern was in accordance with the calculation by Reimann et al. (2007), in which individual incisors moved independently in anterior tooth segment blocked with a wire.

After a long time elapsed, the movement pattern changed from that in the initial tooth movement. This change was clearly understood by comparing between Figure 1A and 1B. In the long-term orthodontic movement, elastic deflection of the archwire was not noticeable, namely, the maxillary teeth moved distally and rotated counterclockwise as one united body. Rigid blocking of the maxillary teeth with the archwire was achieved. Change in the movement pattern was produced by change in the force system. In the long-term movement, the force applied to the archwire was distributed evenly to all teeth.

In clinical settings, movement patterns in which the maxillary teeth moved as one united body have been observed (Park et al., 2005; Yamada et al., 2009). The mechanics of these movements was clarified by the present simulations (Figures 1B and 2B).

**Figure 3** Movement patterns in the case where the archwire is a rigid body. (A) Initial tooth movement. (B) Long-term orthodontic movement. All teeth must move as one united body. The centre of resistance (CR) can be defined. The locations of CR of both movements are almost the same. Their movement patterns are similar to those of long-term movement with the elastic archwires (Figures 1B and 2B).
movement. This difference should be noted when an initial movement calculated by FEM is used to estimate the orthodontic movement. In general, long-term movement is difficult to predict from the initial movement or the initial force system.

When using the high stiffness archwire, elastic deflection of the archwire decreased in both the initial and the long-term tooth movement (Figure 2A and 2B). Based on the beam theory, elastic deflection is inversely proportional to the flexural rigidity of the archwire, $EI$, where $E$ is Young’s modulus and $I$ the moment of inertia of cross-section. In the case of a rectangular cross-section of width $b$ and height $h$, the $I$ is calculated by the equation $I = bh^3/12$. The $EI$ of the high stiffness archwire, 1602 N·mm², is approximately eight times as much as that of the low stiffness archwire, 215 N·mm². This increase in the flexural rigidity decreased the elastic deflection of the archwire. In Figure 2B, there was almost no deflection of the archwire, namely, the archwire behaved as a rigid body. As a result, this movement pattern was the same as that in the case where the archwire was assumed to be a rigid material (Figure 3B).

Elastic deflection of the archwire is also proportional to applied force $P$. Including the inverse effect of the flexural rigidity $EI$, the elastic deflection is proportional to a parameter $P/EI$. An increase in applied force $P$ is equivalent to a decrease in the flexural rigidity of archwire $EI$.

Absolute value of the maximum stress in the PDL during the initial movement was approximately three times that during the long-term movement (Figures 1 and 2). This may be attributed to pains experienced in the initial period of orthodontic treatment.

**The CR of maxillary arch**

When the archwire was a rigid body, the elastic deflection was reduced to zero and the maxillary teeth had to move as one united body in both initial movement and long-term movement (Figure 3A and 3B). Both movements were alike in type. And locations of the CR were almost the same. These movements were also similar to the long-term orthodontic movement produced by the elastic archwires (Figures 1B and 2B).

By comparing Figure 3A with Figures 1B and 2B, we found that the long-term movement with the elastic archwire could be predicted from the initial movement with the rigid archwire (Figure 3A). In the same way as this, location of the CR in the long-term movement with the elastic archwire could be estimated from the initial movement with the rigid archwire. This method for estimating the CR is similar to that presented by Jeong et al. (2009). Instead of the rigid archwire, they connected the maxillary teeth with many unrealistic wires in order to distribute the applied force evenly on the teeth. The location of the CR obtained by their calculation was approximately the same as those indicated in Figure 3A and 3B. Alternatively, Reimann et al. (2007) have calculated the initial tooth movement of an anterior tooth segment that has been connected with a very stiff wire of $1.38 \times 1.92$ mm. However, the anterior teeth did not move as one united body; each tooth moved independently. In their calculation, if stiffness of the wire were more increased, all teeth would move as one united body so that the CR of the anterior tooth segment would be obtained.

Rotational direction of the maxillary arch is controlled by the direction of orthodontic force. When a force applied in line with the CR, the arch is translated without rotation. In the case of Figure 3 where the line of action of force passed below the CR, the force produced a counterclockwise moment about the CR, thereby the arch was rotated counterclockwise. If we want to rotate the arch clockwise, the force direction will be changed in such a way that the line of action of force passes above the CR.

**Simulation method of long-term tooth movement**

The alveolar bone and the teeth were assumed to be rigid bodies. This assumption has been validated by the preliminary calculation in which the tooth and the alveolar bone were assumed to be elastic bodies.

It is well known that stress–strain relation of the PDL has strong non-linearity. The Young’s modulus of the PDL rapidly increases with an increase in applied force. In the previous article (Kojima and Fukui, 2010), we have demonstrated the non-linear property of the PDL had almost no effect on the long-term tooth movement. Therefore, we assumed the PDL to be a linear elastic material in the present article.

The elastic moduli of the PDL, that is, Young’s modulus $E$ and Poisson’s ratio $v$ were selected for a light force level. We determined $E = 0.13$ MPa and $v = 0.45$ by referring to in vivo tooth mobility measured by Goto (1971). In this case, bucocolingual and axial movements of the upper premolar became 30 and 15 μm, respectively, when applying a force of 1 N (100 g-force). These amounts of movement are reasonable in comparison with other in vivo measurements (Parfitt 1959; Muhlemann, 1960). If the $E$ increases to 10 times, $E = 1.3$ MPa, movements of the premolar decrease to one-tenth, 3 and 1.5 μm at 1 N. These amounts will be too small for normal teeth. In order to determinate the two elastic moduli, tooth mobility data in the two different directions were necessary. Except for Goto’s data, any measurements of tooth mobility in the two directions for the identical tooth could not be found in other studies. This is the reason why we used the data measured by Goto (1971).

Tooth movement is produced by resorption and apposition of the alveolar bone (bone remodeling). And, the bone remodeling rate is assumed to be in proportion to the mean stress $\sigma_m$ in the PDL. This assumption has not yet been demonstrated. Under the present situation when the biological mechanism of orthodontic tooth movement has
not been fully clarified, verification of the simulation method must be based on comparisons between calculated tooth movements and observations in the clinical setting. The movement pattern calculated in the present article in which the maxillary teeth moved as one united body has been observed in clinical settings (Park et al., 2005; Yamada et al., 2009). And, the simulation results were reasonable from a mechanical perspective. However, more quantitative comparisons are necessary to validate the simulation method.

In the dental study model used for fabricating the FEM model, the teeth were arranged with almost bilateral symmetry. When applying symmetric forces to the arch, it was expected movement of the left half of the arch was identical to that of the right one. Therefore, we fabricated the FEM model for only the left side of the arch. This is a usual technique in FEM. Jeong et al. (2009) have calculated a location of CR of the maxillary arch using a FEM. Although they used a whole arch model, the CR was located in the symmetry plane of arch. If the arch has considerable non-symmetry, the location of CR will deviate from the center plane of arch. Then, whole model of the arch will be necessary to determine the CR.

Calculation models of the teeth used in the present article were made based on the CBCT images. This method can be used for making individual tooth models and enables us to simulate the long-term orthodontic tooth movement for the individual patient. This will be helpful for clinical treatment planning.

Conclusions

The finite element simulations clarified movement mechanics of the maxillary teeth connected with the archwire. Movement pattern of the long-term orthodontic movement was different from that of the initial tooth movement. This result must be kept in mind when initial tooth movements are calculated or measured.

Location of the CR of maxillary arch in the long-term movement could be estimated from the initial tooth movement calculated by assuming the archwire to be a rigid material.

References


