A Numerical Simulation of Orthodontic Tooth Movement Produced by a Canine Retraction Spring

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Tooth movements produced by a canine retraction spring were calculated. Although a gable bend and an anti-rotational bend were incorporated into the spring, the canine tipped and rotated initially. Retraction force decreased and moment-to-force ratio increased after the spring legs closed. Then, the initial tipping and rotation began to be corrected. As a result, the canine moved almost bodily after a prolonged period of time. Such tooth movements cannot be estimated from the initial force system. The gable bend decreased tipping movement, but increased rotational movement. On the other hand, the anti-rotational bend decreased rotational movement but increased tipping movement. In other words, one bend decreased the effect of the other, when both bends were incorporated in the spring.

Keywords: Orthodontics, Canine retraction, Finite element method

INTRODUCTION

Canine retraction is one of the basic techniques in orthodontic treatment. A representative method is achieved by using a retraction spring. Closing loops are fabricated in the spring and the teeth move by activation of the loop. This method is friction-free or frictionless technique in contrast to sliding mechanics. However, spring configuration has considerable effects on canine movement. A gable bend must be incorporated into the spring to prevent tipping of the canine. In addition, an anti-rotational bend must be included to prevent rotational movement. These bends produce moments to prevent such unfavorable movements. To estimate an appropriate magnitude of bends, initial moments produced by these bends have been calculated¹⁻³ and measured^{4,6}. Furthermore, a spring has been designed to produce appropriate initial moments⁷.

The authors carried out numerical simulations of orthodontic tooth movements by means of a three-dimensional finite element method. It was shown that the initial force system changed considerably with tooth movement^{8,9}. Therefore, tooth positions after a prolonged period cannot be estimated from the initial force system. Against this background, we sought to calculate the long-term tooth movements produced by a canine retraction spring. The effects of a gable bend and an anti-rotational bend were discussed from a mechanical point of view.

MATERIALS AND METHODS

Calculation method for tooth movement

The calculation methods have been mentioned in our previous articles^{8,9}. Thus, only the vital calculation methods will be addressed below.

In orthodontic tooth movement, the amount of force acting on a tooth is within several newtons. At this level of force, the initial tooth movement is produced by a deformation of the periodontal ligament (PDL), and is in proportion to the applied force¹⁰. The tooth and alveolar bone are assumed to be rigid bodies, and the PDL is assumed to be a linear elastic film (Young's modulus: 0.2 MPa, Poisson's ration: 0.47) with constant thickness of 0.2 mm⁸. Based on these assumptions, a relationship between applied force (moment) $\mathbf{f}$ and tooth displacement $\mathbf{u}$ is calculated. This relationship can be written as $\mathbf{Ku}=\mathbf{f}$ where $\mathbf{K}$ is a stiffness matrix of the tooth supported by the PDL.

Figure 1 shows a surface model of the tooth used to calculate the matrix $\mathbf{K}$. One surface of the PDL is bonded to dentin and the other surface is bonded to the alveolar bone. Normal stresses, σ_1 , σ_2 , σ_3 , and shearing stresses, τ_2 , τ_3 , are assumed to act within the PDL. The PDL is divided into small triangular regions, and the stresses in each region are assumed to be identical. Stiffness matrix $\mathbf{K}$ is then calculated by the following procedure: (1) unit displacement (translation or rotation) is applied at the bracket position; (2) through tooth kinematics, the deformation of PDL (*i.e.*, strains and stresses in the PDL) are

calculated for each small region; and (3) integrating the stresses over the root, the total forces and moments acting on the tooth are calculated.

A tooth moves as a result of absorption and apposition of the alveolar bone, which is assumed to occur in a normal direction to the outer surface of the PDL. It is also assumed that the amount of bone remodeling is in proportion to a mean stress $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$ in the PDL. The amount of absorption (apposition) per unit stress and unit time was denoted by a coefficient C . This coefficient is assumed to be the same in all teeth. At any given

time T , a tooth movement in the next small time increment ΔT is calculated by the following procedure: (1) absorption of the alveolar bone in each small region, Δt , is calculated as $\Delta t = -C \sigma_m \Delta T$; (2) normal stress σ_1 required to move a tooth by the distance Δt in each small region is calculated as $\sigma_1 = -C \sigma_m E' \Delta T / \Delta t$. E' is $E' = E / (1 - \nu^2)$, where E and ν are Young's modulus and Poisson's ratio of the PDL respectively; (3) tooth moving force R (i.e., total forces and moments to move the tooth) is calculated by integrating σ_1 over the root; (4) displacement u of the tooth produced by R (i.e., tooth movement in ΔT) is calculated using $K u = R$.

Tooth movement u for each tooth is calculated from the stress distribution in the PDL, and then the teeth are moved by u . By repeating this procedure, the tooth positions at a given time T can be obtained. As indicated in the equations above, the absorption of alveolar bone or the tooth movement is controlled by a parameter CT . At present, since the value of C is uncertain, CT is used to indicate the progress of tooth movement.

Calculation model

At the left maxillary, a second premolar and a first molar are used as anchorage, and a canine is retracted in the distal direction. Surface models of the teeth are made based on a dental study model (AM-10, Nissin Dental Products Inc., Kyoto, Japan). Configuration of the retraction spring is adapted from a commercial retraction spring (Maxillary Cuspid Retractor, Left A-521, Rocky Mountain Morita Corp., Tokyo, Japan), as shown in Fig. 2. This spring has low stiffness due to the multiple loops. It is made from a 0.016-inch elastic square wire of cobalt-chromium-nickel-molybdenum alloy (Young's modulus: 200 GPa, Poisson's ratio: 0.3).

The spring is activated to open the spring legs by 3 mm distance. Angles of gable bend GB and anti-rotational bend ARB are changed. The spring and brackets are ligated firmly to prevent sliding against each other. It is assumed that the spring is not deformed in the bracket slot. In clinical situations, there is clearance between the spring and the bracket slot, and between the spring and the ligature wire. These clearances are ignored in the present calculation, and so forces and moments (torque) of the spring are completely transmitted to the bracket.

RESULTS

In the spring with neither the gable bend nor anti-rotational bend ($GB=0$, and $ARB=0$), tooth movements with time CT are shown in Figs. 3(a), (b), and (c). Distributions of mean stress σ_m in the PDL are

Fig. 1 Surface model of tooth for calculating relationship between applied force and tooth displacement.

Fig. 2 Configuration of canine retraction spring with gable bend and anti-rotational bend.

(a) Initial activation

(b) $CT=200 \mu\text{m/kPa}$ (c) $CT=1000 \mu\text{m/kPa}$

Fig. 3 Tooth movement produced by retraction spring without both bends: (a) Initial activation; (b) $CT=200 \mu\text{m/kPa}$; and (c) $CT=1000 \mu\text{m/kPa}$.

indicated by color contours. At initial activation ($CT=0$), a force of $F_0=1.2 \text{ N}$ acted on the canine and moment-to-force ratios became $M_1/F_0=2.5$ and $M_2/F_0=0.06$. The moments M_1 and M_2 tended to prevent tipping and rotation respectively. Stress in the PDL of canine was higher than those of the anchor teeth. At $CT=200 \mu\text{m/kPa}$, the canine moved distally by $u=2.2 \text{ mm}$ and the anchor teeth moved mesially by 0.8 mm . At this time, activation of the spring (gap between spring legs) became almost zero. The canine tipped by $\alpha=5.9^\circ$ from the buccal viewpoint, and it rotated by $\beta=9.6^\circ$ on the occlusal plane. The center of tipping movement was located at one-third root length from the apex. After a prolonged period ($CT=1000 \mu\text{m/kPa}$), both the displacement and tipping angle of canine hardly changed ($u=2.2 \text{ mm}$, $\alpha=5.7^\circ$). However, the rotational angle of canine decreased to $\beta=5.7^\circ$. The force acting on the canine F decreased as the teeth moved, and the activated spring went back to the initial configuration (Fig. 4). With the decrease in F , moment-to-force ratios M_1/F and M_2/F increased rapidly. Therefore, the rotational angle β , which increased initially, decreased with time CT (Fig. 5).

In the spring with both the gable bend and the anti-rotational bend ($GB=30^\circ$ and $ARB=50^\circ$), tooth movements are shown in Figs. 6(a), (b), and (c). Although the amount of activation was the same as that in the case without both bends, the initial force

Fig. 4 Variation of force and moment-to-force ratios acting on canine with time CT (without both bends).

Fig. 5 Variation of translation, tipping angle, and rotational angle of canine with time CT (without both bends).

acting on the canine became almost twice ($F_0=2.0$ N), and initial moment-to-force ratios increased to $M_1/F_0=7.8$ and $M_2/F_0=0.85$. At $CT=200$ $\mu\text{m}/\text{kPa}$ when the spring legs almost closed, the canine moved distally by $u=2.5$ mm and the anchor teeth moved mesially by 0.9 mm. At this time, the canine

(b) $CT=200$ $\mu\text{m}/\text{kPa}$

(a) Initial activation

(c) $CT=1000$ $\mu\text{m}/\text{kPa}$

Fig. 6 Tooth movement produced by retraction spring with gable bend and anti-rotational bend: (a) Initial activation; (b) $CT=200$ $\mu\text{m}/\text{kPa}$; and (c) $CT=1000$ $\mu\text{m}/\text{kPa}$.

Fig. 7 Variation of force and moment-to-force ratios acting on canine with time CT (with gable bend and anti-rotational bend).

Fig. 8 Variation of translation, tipping angle, and rotational angle of canine with time CT (with gable bend and anti-rotational bend).

tipped by $\alpha = 5.0^\circ$ and rotated by $\beta = 9.5^\circ$. These values were about the same as those in the case without both bends. After a prolonged period ($CT = 1000 \mu\text{m/kPa}$), the displacement hardly changed ($u = 2.4 \text{ mm}$). However, the tipping and rotational angles of canine decreased to $\alpha = -0.9^\circ$ and $\beta = -3.4^\circ$ respectively. Moment-to-force ratios M_1/F and M_2/F increased rapidly, when the force acting on the canine F decreased with time CT (Fig. 7). After the spring legs closed ($CT > 100 \mu\text{m/kPa}$), the amount of F was larger than that in the case without both bends. The tipping and rotational angles of canine, α and β , decreased below zero and become negative values (Fig. 8).

When angles of the gable bend GB and anti-rotational bend ARB were changed respectively, the force F_0 acting on the canine at initial activation, the tipping angle α , and the rotational angle β of the canine at $CT = 1000 \mu\text{m/kPa}$ are shown in Figs. 9 and 10. These figures show the effects of gable bend and anti-rotational bend on tooth movement. The force F_0 increased with an increase in GB , when only the gable bend was incorporated (Fig. 9, $ARB = 0$). When F_0 became 1.92 N at $GB = 30^\circ$; the maximum

Fig. 9 Variation of initial force, tipping angle, and rotational angle of canine with gable bend.

Fig. 10 Variation of initial force, tipping angle, and rotational angle of canine with anti-rotational bend.

equivalent stress of 1790 MPa was produced in the spring. The tipping angle decreased but the rotational angle increased in proportion to GB . When only the anti-rotational bend was incorporated (Fig. 10, $GB = 0$), the force F_0 hardly changed with increase in ARB . The rotational angle decreased but tipping angle increased in proportion to ARB . The change in α was considerable.

DISCUSSION

Finite element methods have been used to calculate stress in the PDL during initial tooth movement¹¹⁻¹⁵. Recently, long-term orthodontic tooth movements for a single-root tooth were calculated^{16,17}. Furthermore, we proposed a simulation method for typical clinical situations where many teeth connected with a wire moved at the same time^{8,9}. The same method was used in the present study. Simple assumptions were adopted as a first step for simulation of this nature; otherwise uncertain factors included in the calculation would only complicate the method and results. These assumptions have been discussed in a previous article⁹.

The human periodontal ligament has a fiber structure and anisotropy. Furthermore, the stress-strain relation is nonlinear¹⁸⁾. The thickness of PDL varies at different positions in the root¹⁹⁾. These factors have been included in recent calculations of the stress distribution in PDL^{20,21)}, but how these factors affect tooth movement have not been clarified. In this study, therefore, it was assumed that the PDL was a linear elastic film and its thickness was the same in all teeth.

The most important factor affecting tooth movement is the bone remodeling law that describes the relationship between the apposition of the alveolar bone and the mechanical stimulus. In particular, an excessive orthodontic force produces hyalinization of the PDL and undermining bone resorption, impeding efficient bone remodeling. This phenomenon suggests that there is a maximum stress above which the bone remodeling rate decreases. However, this phenomenon has not been fully confirmed²²⁾, and experimental data required for this calculation have not been found. If useful data were available, we would be able to include this effect in our calculation. Under these circumstances, we simply assumed that the resorption rate was proportional to the mean stress in the PDL. The calculated results in this study are valid only in a light force range wherein bone remodeling occurs depending on stress.

Although both the gable bend and anti-rotational bend were incorporated into the spring, the canine tipped and rotated immediately after activation. Initial moment-to-force ratios produced by both the bends were not sufficient to prevent tipping and rotation. In the case without both bends, the initial tipping and rotation remained after a prolonged period. On the other hand, when both bends were included, the initial tipping and rotation were corrected over time. After a prolonged period, the canine became upright, and was derotated. The final position of teeth depended on tooth movements during the period when the retracting force was decreasing and the moment-to-force ratios were increasing. The initial force system changed with tooth movement. Therefore, the final position of teeth cannot be estimated from the initial force system.

When gable bend GB was increased, tipping angle of canine decreased (Fig. 9). However, retraction force F_0 increased. An excessive retraction force will produce hyalinization of the PDL and undermining bone resorption, thereby impeding efficient tooth movement. This increase in retraction force makes it impossible to incorporate a large gable bend. In addition, high stress was produced in the spring by the gable bend. At $GB=30^\circ$, the stress in the spring became 1790 MPa, and this value was close to the elastic limit of cold-worked cobalt-chromium-nickel-

molybdenum alloy (2000 MPa). On the other hand, the rotational angle of canine, θ , increased in proportion to GB . Therefore, the gable bend reduced the effect of anti-rotational bend.

When anti-rotational bend ARB was increased, rotational angle of canine, θ , decreased, whereas retraction force F_0 hardly changed (Fig. 10). An excessive anti-rotational bend produced opposite (negative) rotation. On the other hand, the tipping angle of canine, ϕ , increased in proportion to ARB . Therefore, the anti-rotational bend reduced the effect of the gable bend.

As discussed above, the gable bend and anti-rotational bend prevented tipping and rotation of the canine respectively. However, when both bends were incorporated into the spring, one bend decreased the effect of the other. This phenomenon has been examined in clinical conditions by Nishikawa *et al.*²³⁾. In the case without gable bend ($GB=0$), the rotational angle of canine could be reduced to zero by incorporating an anti-rotational bend of $ARB=10^\circ$ alone (Fig. 10). When a gable bend was added to prevent tipping, the rotational angle of canine increased. Finally, when the angles of anti-rotational bend and gable bend were increased to $ARB=50^\circ$ and $GB=30^\circ$ respectively, both the angles of tipping and rotation of canine could be reduced to about zero (Fig. 6(c)). The same effect is expected in different retraction springs, and the effect will be noticeable in clinical situations.

Results obtained in this study were reasonable from a mechanical point of view; however, they have not been confirmed from a clinical point of view. This confirmation is left for a future work. Simplistic assumptions used in the present calculation would be insufficient to predict tooth movements in clinical situations. If the calculated results were different from clinical tooth movements, the assumptions should be reconsidered and modified. For example, clearance between the spring and bracket slot was ignored in the present calculation. However, clearances exist in clinical situations and torque of the spring may not be transmitted to the bracket. As a result, the canine will tip in the bucco-lingual direction. Such effects of clearance on tooth movement should be considered in the future study.

In a restricted condition where assumptions used in the present calculation are valid, tooth movement produced by a canine retraction spring could be calculated. From the calculated results, the mechanical effects of the gable bend and anti-rotational bend could be clarified. Furthermore, not only canine movement, but anchor teeth movement also, could be estimated quantitatively. Therefore, the simulation method in this study should be utilized to examine which kind of retraction method is appropriate, or to design springs for efficient canine retraction.

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