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***The Angle Orthodontist:* Vol. 75, No. 3, pp. 378–385.**

Anchorage Effect of Various Shape Palatal Osseointegrated Implants: A Finite Element Study

Fengshan Chen;[a] Kazuto Terada;[b] Kooji Handa[c]

ABSTRACT

The purpose of this study was to compare the anchorage effects of different palatal osseointegrated implants using a finite element analysis. Three types of cylinder implants (simple implant, step implant, screw implant) were investigated. Three finite element models were constructed. Each consisted of two maxillary second premolars, their associated periodontal ligament (PDL) and alveolar bones, palatal bone, palatal implant, and a transpalatal arch. Another model without an implant was used for comparison. The horizontal force (mesial 5N, palatal 1N) was loaded at the buccal bracket of each second premolar, and the stress in the PDL, implant, and implant surrounding bone was calculated. The results showed that the palatal implant could significantly reduce von Mises stress in the PDL (maximum von Mises stress was reduced 24.3–27.7%). The von Mises stress magnitude in the PDL was almost same in the three models with implants. The stress in the implant surrounding bone was very low. These results suggested that the implant is a useful tool for increasing anchorage. Adding a step is useful to lower the stress in the implant and surrounding bone, but adding a screw to a cylinder implant had little advantage in increasing the anchorage effect.

KEY WORDS: Implant, Anchorage, Finite element analysis.

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INTRODUCTION Return to TOC

Anchorage is one of the main factors for determining the success of orthodontic treatment. Headgears, transpalatal arches (TPAs), and Nance appliances are routinely used to establish anchorage during clinical treatment. However, many patients reject headgear wear because of social and esthetic concerns, and the success of this treatment depends entirely on patient cooperation.[1] In addition, headgears are often used only for a part of the day and may be associated with injury by their wires in the facial area.[2] Although some studies[3,4] show that a TPA was capable of enhancing anchorage by increasing the resistance of molars to movement, Bobak et al[5] found that the presence of a TPA had no ability to modify orthodontic anchorage. In most studies on Nance appliances, anchorage loss was unavoidable, and reduced hygiene under the acrylic resin button was associated with inflammation of the soft tissue.[6,7]

Implants, as a means of enhancing orthodontic anchorage, are gaining increased importance in orthodontic treatment because of the limitations and acceptance problems of conventional intraoral or extraoral anchorage aids.[8–10] Some studies have shown that dental implants placed in the alveolar bone are resistant to the orthodontic force.[11–14] However, there is no available alveolar site for implant placement because orthodontic patients generally have a complete dentition. Thus, some other anatomic sites such as the palatal region were used as alternative sites.[15–18]

Janssens et al[15] reported onplant use for palatal anchorage to extrude the unerupted maxillary first molars. Block and Hoffman[16] introduced a subperiosteal disc of 10 mm diameter. Klees et al[17] used a screw-type implant with height of eight mm and a wide diameter of 4.5 mm, whereas Wehrbein et al[18] introduced a small 3.3 mm diameter implant with a low to medium four and six mm length. Almost all these studies showed that a palatal implant could offer an increased anchorage effect.

Various shapes of palatal implant (eg, cylindrical, step, screw) for orthodontic anchorage have created confusion because most clinical investigations on direction of forces and moments applied have not been well documented. Anchorage is related to periodontal stress,[19] and the anchorage effect of a palatal implant can be defined by the redistribution of the periodontal ligament (PDL) stress of the natural tooth connected with the palatal implant. However, there are no published attempts to explore the relation between the shape of the implant and the anchorage effect quantitatively.

In the past two decades, finite element analysis (FEA) has been increasingly used for the prediction of the effects of stress on the tissues in orthodontics. FEA is a mathematical method in which the shape of complex geometric objects and their physical properties are computer constructed. Physical interactions of various components of the model are then calculated for stress, strain, and deformation.

In clinical treatment, a palatal osseointegrated implant is often used with a TPA to connect with the second premolar to increase anchorage as shown in Figure 1. The purpose of this study was to analyze and compare quantitatively the anchorage effect of various implants by investigating the stress responses in the PDL, implant, and implant surrounding bone.

MATERIALS AND METHODS Return to TOC

Models

Four models were created in this study. Model 1 (Figure 2A) was composed of two maxillary premolars, PDL, alveolar bone, palatal implant, palatal bone, bracket, band, and TPA. A maxillary second premolar was created by manually designing the tooth according to a standard dental anatomy textbook.[20,21] The outmost boundary of the tooth was first defined, and sectioning the tooth into cross sections created the third dimension. The tooth was reconstructed by inputting three-dimensional coordinates, defining the shape of the tooth into the Unigraphics Nx 1.0 (Unigraphic Solutions Inc, Plano, Texas, 2002). Next the PDL, alveolar bone, palatal implant, palatal bone, bracket, band, and TPA were created. The bracket, band, and TPA were combined as one connected device to stimulate the bracket, and TPA welded to the band in the clinic (Figure 2B). The PDL width was assumed to be 0.25 mm. A cylinder implant was assumed to be 3.3 mm in diameter and nine mm in length, and the abutments were three mm long (Figure 2C). The TPA was assumed to be 1.33 mm in diameter, and the distance between the centers of the two premolars was 42.8 mm.

Models 2 and 3 were constructed based on model 1. Model 2 used a step cylinder implant (a cylinder-shaped implant with a superperiosteal step). The subperiosteal part measured six mm in length and was identical in shape to the cylinder implant. The superperiosteal step in the abutment was one mm long and 4.3 mm in diameter (Figure 2C).

Model 3 used a screw cylinder implant (a cylinder-shaped implant with a superperiosteal step and a subperiosteal threaded surface). The superperiosteal step in the abutment was one mm long and 4.3 mm in diameter. The subperiosteal thread had nine steps (Figure 2C).

Another model (Figure 3), composed of the left maxillary second premolar, PDL, alveolar bone, bracket, and band, was defined as model 4. Model 4 and models 1–3 had the same geometries in the second premolar, PDL, alveolar bone, bracket, and band. Bracket and band were combined to form a device to stimulate the bracket welded on the band.

Elements and nodes

Elements and nodes were created by the Unigraphics NX volume mesher (Table 1). Tetrahedral three-dimensional elements were used in this study. Four-node linear cells were used instead of 10-node quadratic elements because the latter significantly complicate the computation of contact pressures. Because different element sizes may affect the value of stress, the same size element in the same material was used in the four models including 1.78 mm for PDL, 2.54 mm for alveolar bone, 2.58 mm for tooth, 1.27 mm for implant, 5.74 mm for connected device, and 2.05 mm for the implant surrounding bone. The bone-implant interface was treated as a fully bonded surface to stimulate osseointegration as bone-PDL interface and PDL-tooth interface. Tooth-band interface and implant-transpalatal interface were created as a rough surface contact (corresponding to infinite friction coefficient) to simulate cemented band and fixed contact between the TPA and implant (Figure 4).

Material properties

Each material was defined as homogenous and isotropic. The physical properties of the constituent materials comprising the model were based on a review of the literature (Table 2).[5,22,23]

Constraints and loads

Models 1, 2, and 3. The boundary conditions were fixed at the base of the palatal bone and alveolar bone (Figure 4). A combined horizontal force (mesial direction 5N, palatal direction 1N) was applied at the buccal bracket of each premolar band. The force direction was selected to simulate the mesiodistal force in the clinic because the width between canines is a little narrower than that between premolars. The size of the force was heavy enough to close the space of the first premolars extraction in one step.[24]

Model 4. To compare models with implants, boundary conditions were fixed at the base of the alveolar bone (Figure 5). The force was the same as in the other three models. Of course, we never applied such a heavy a force on a single tooth in clinical treatment.

Von Mises stress (kPa) was calculated and presented in colorful contour bands. Von Mises stress was selected because it represents the overall stress intensity and distribution.

RESULTS Return to TOC

Because Models 1–3 were symmetrical, we just extracted the left premolar to compare PDL stress with model 4.

Figure 6 shows the change in stress distribution in the PDL in response to different force magnitudes. Stress magnitudes were denoted by a series of colors, as shown in the spectrum display to the right of the plot. In each model, the highest von Mises stress was on the PDL at the cervical margin. The stress decreased toward the apex. However, the von Mises stress in model 4 was far higher than that in models 1–3. Similar PDL stress distribution is shown in models 1–3.

Figures 7 and 8 show the implant and surrounding bone stress. The largest implant and surrounding bone von Mises stress were shown in model 1. The stress declined steadily from the cervical part to the apex. The lowest implant and surrounding bone were shown in model 2.

Table 3 shows the maximum stress in the PDL, implant, and implant surrounding bone. Model 4 showed the largest stress. The implant can reduce the PDL stress by about 24.3–27.7%. The third kind of implant showed almost the same anchorage effect.

DISCUSSION Return to TOC

The purpose of this investigation was to use the finite element method to analyze the anchorage effect of different shapes of palatal osseointegrated implants. To accomplish this analysis, we constructed three appropriate finite element models to simulate the clinical situation. The resultant stress in a model without an implant was compared quantitatively with stress produced in the models with implants.

In each model, the highest stress concentration in the PDL was localized at the cervical margin. This might be due to the orthodontic force applied in the buccal bracket of each premolar. Because the line of force was not through the center of resistance of the tooth, the movement of the tooth was a tipping movement. McGuiness et al[25,26] reported the same distribution with the exception that an osseointegrated implant was modeled.

In this study, the implant markedly reduced the von Mises stress of the PDL. In engineering terms, an implant acts like a bar elastically supported by the surrounding bone. The anchorage loads were transmitted from the tooth to the implant due to the rigid connection of the TPA. The anchorage effect depended on the implant stability and the rigidity of the TPA. The simple orthodontic implant caused the highest stress in the surrounding bone. By adding a superperiosteal step to the implant, the stress decreased significantly. The step improved the stability of the implant-bone complex by osseointegration between the implant step and bone.[24]

Increasing the step cylinder implant surface by means of a screw has no value in decreasing the stress in the implant and surrounding bone. The reason might be that the screw could not distribute the stress smoothly and causes a stress concentration.[27] However, the stress was of such low magnitude that it was unable to produce a failure in the implant,[16] and the osseointegrated implant was able to withstand orthodontic forces.

Several types of TPA have been reported, including the use of a 0.032 × 0.032–inch edgewise wire[14] and a 0.040-inch diameter round wire.[13] However, even this was reported to result in a small amount of mesial movement of the anchored premolars. In this study, we used a more rigid archwire to make the TPA. It is the same implant stability and rigid TPA that offered almost the same anchorage effect in this study.

Gedrange et al[27] studied the same palatal implants, although they used a pig model and force was applied directly on the implant. They also found that the best result was recorded in implants with a superperiosteal step. The use of threads provided no improvement in load capacity.

The FEA has been widely used in engineering, but its application to health science is relatively new. The real-life multiple variable, like the principal difficulty in simulating the mechanical behavior of tooth movement with a palatal implant as anchorage, was the modeling of human bone tissue and its response to applied mechanical force.

To make the model simulate the clinic, a lot of effort was used to make the same conditions except for the implant shape (eg, the same size and type element for the same material, same contact type between different materials in the same area). That the number of elements and nodes in model 3 is largest may be due to mesh mating other than element size. However, certain assumptions are needed to make the modeling and solving process possible. The resultant values should be interpreted only as a reference to aid clinical judgment.

The limitations of our model included the approximation in the material behavior and shapes of the tissues. We assumed, as in other studies,[27,28] that a 100% implant-bone interface was established. However, in the clinic the percentage of direct bone-to-implant contact varied from 34– 93% with an average value of 75.5%.[24] A 100% bone apposition was almost never obtained at the surface of dental implant.[29] As in previous studies,[30–34] the PDL was modeled as a 0.25-mm layer of uniform thickness and was treated as linear-elastic and isotropic, even though the PDL exhibits anisotropy and nonlinear viscoelastic behavior because of tissue fluids.[35] There are no reliable and adequate data that pertain to anisotropic and nonlinear properties of the PDL. In addition, the cortical and cancellous bones were simplified because no available data exists to show the shape of cancellous and cortical bones. The tooth was simplified as a homogeneous body without tips because the force transmitted to the PDL was not significantly affected by adding the internal and external tooth structure. The shape of the dental root described in this study represented the most common morphologic feature of second premolars, but the wide variation in morphologic conditions among normal individuals may affect applicability of the analysis.

Although there were some assumptions, complex reality can be simplified, assuming that proportions and effect accurately reflect reality.[36] The general validity, model geometry, and element shape of the current model were sufficient to provide insight into the interaction of orthodontic forces and palatal implants related to this investigation. Because the orthodontic force can cause continuous tooth movement, the current results may only be applicable to the initial tooth movement. A time-dependent FEA is needed in the future.

CONCLUSIONS Return to TOC

The three kinds of implants showed almost the same anchorage effort by reducing the maximum von Mises stress in the PDL by 24.3–27.7%. This suggested that adding a step or screw to an implant had little effect in increasing the anchorage. However, adding a step could lower the stress in the implant and surrounding bone, but adding a screw had little effect on lowering the stress in the implant and surrounding bone.

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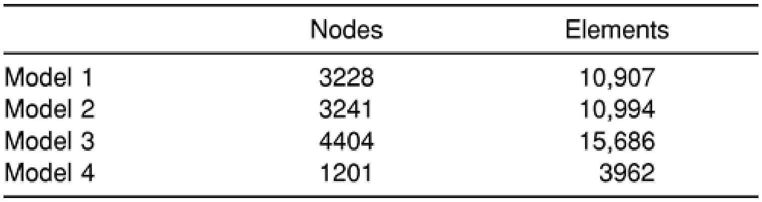
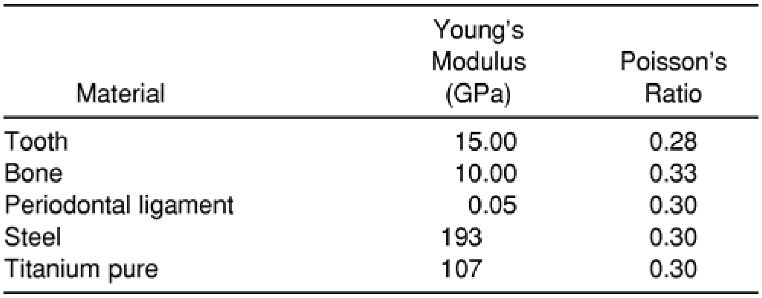
TABLES Return to TOC

TABLE 1. Nodes and Elements in the Study



	Nodes	Elements
Model 1	3228	10,907
Model 2	3241	10,994
Model 3	4404	15,686
Model 4	1201	3962

TABLE 2. Material Properties of Constituent Materials



Material	Young's Modulus (GPa)	Poisson's Ratio
Tooth	15.00	0.28
Bone	10.00	0.33
Periodontal ligament	0.05	0.30
Steel	193	0.30
Titanium pure	107	0.30

TABLE 3. Von Mises Stress (Maximum) in the PDL, Implant, and Surrounding Bone

	Cylinder	PDL Stress Implant (KPa)	Implant Stress (KPa)	Implant Surrounding Bone (KPa)
Model 1	Simple	374 (−26.1%)[a]	1063	221.2
Model 2	Step	383.2 (−24.3%)[a]	786.4	78.6
Model 3	Screw	365.7 (−27.7%)[a]	982.2	105.6
Model 4	No	506.1		

[a] The periodontal ligament (PDL) stress percentage changes compared with Model 4.

FIGURES

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FIGURE 1. Palatal implant used as an orthodontic anchorage in the clinic. The second maxillary premolars are anchored by the implant through the transpalatal arch

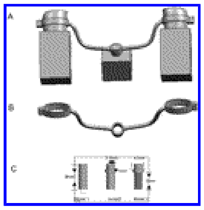

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FIGURE 2. (A) Three-dimensional model comprising maxillary second premolars, periodontal ligament (PDL), alveolar bone, implant, palatal bone, transpalatal arch, bands, and brackets. (B) The connective device combing bands, brackets, and transpalatal arch together. (C) Three types of implant: 1. simple implant cylinder implant, 2. step cylinder implant, and 3. screw cylinder implant

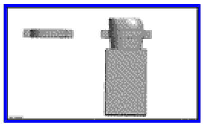

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FIGURE 3. Three-dimensional model comprising maxillary second premolars, periodontal ligament (PDL), alveolar bone, band, and bracket; band and bracket were combined together

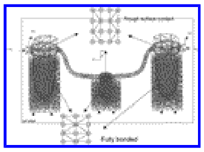

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FIGURE 4. Three-dimensional finite element models with implant. Band-tooth interface and implant–transpalatal arch were assumed as a rough contact (above), implant-bone interface, periodontal ligament (PDL)–bone interface, and PDL-tooth interface were assumed as fully bonded (lower). The combined force (5N mesial direction, 1N palatal direction) was applied on the bracket (—▶), whereas boundary conditions in which the models were fixed at the base of bone (▲)

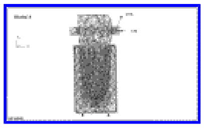

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FIGURE 5. Three-dimensional finite element models without implant. The combined force (5N mesial direction, 1N palatal direction) was applied on the bracket (—▶), whereas boundary conditions in which the models were fixed at the base of bone (▲)

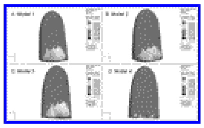

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FIGURE 6. Von Misses stress in periodontal ligament (PDL) of left maxillary second premolar under the combined force (5N mesial direction, 1N palatal direction). Colors indicate the

magnitude of the stress. (A) A simple cylinder implant. (B) A step cylinder implant. (C) A screw cylinder implant. (D) Without implant

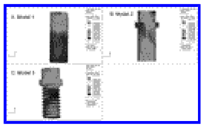

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FIGURE 7. Von Misses stress in implant-bone interface when the left maxillary second premolar was under the combined force (5N mesial direction, 1N palatal direction). Colors indicate the magnitude of the stress. (A) A simple cylinder implant. (B) A step cylinder implant. (C) A screw cylinder implant

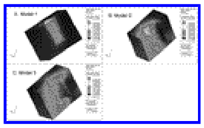

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FIGURE 8. Von Misses stress in implant surrounding bone when the left maxillary second premolar was under the combined force (5N mesial direction, 1N palatal direction). Colors indicate the magnitude of the stress. (A) A simple cylinder implant. (B) A step cylinder implant. (C) A screw cylinder implant.

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