Original Article

Anchorage Effects of a Palatal Osseointegrated Implant with Different Fixation:
A Finite Element Study

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Abstract: The purpose of this study was to compare the anchorage effect of the osseointegrated implant with different fixation types using finite element analysis. Three fixation types were investigated. fixation type 1: implant neck in the oral-palatal cortical bone and implant tip in the cancellous bone; fixation type 2: implant neck in the oral-palatal cortical bone and implant tip in the nasal-palatal cortical bone; fixation type 3: implant neck in the oral-palatal cortical bone and implant tip projecting into the nasal cavity. Three finite element models were constructed. Each consisted of two maxillary second premolars, their associated periodontal ligament (PDL), alveolar bones, palatal bone, palatal implant, and a transpalatal arch. Another model without an implant was used to compare with the previous models. The horizontal force (mesial five N, palatal one N) was loaded at the buccal bracket of each second premolar. The stress was calculated in the PDL and implant surrounding bone. The result showed that the palatal implant could significantly reduce von Mises stress (maximum von Mises stress was reduced 30%) and evenly distribute stress in the PDL. The stress magnitude and distribution in the PDL was almost the same in the three implant models. These results suggest that different implant fixation types have almost the same anchorage effects. (*Angle Orthod* 2005;75:593–601.)

Key Words: Implant; Anchorage; Finite element analysis

INTRODUCTION

Anchorage is a prerequisite for the orthodontic treatment of dental and skeletal malocclusions with fixed appliances.[1] Implants, as a means for orthodontic anchorage, are gaining increased importance in orthodontic treatment because of the limitation and acceptance problems of conventional intra- or extraoral anchorage aids.[2,3] The median-sagittal region of the hard palate[4,5] was described as a suitable location for implant placement because orthodontic patients generally have a complete dentition. This region is surgically very well accessible and offers excellent periimplant conditions because of the attached mucosa.

In clinical treatment, a palatal osseointegrated implant is often used to connect with the second premolar by a transpalatal arch (TPA) to increase anchorage as shown in Figure 1, and a six-mm implant is often used. The implant tip might be in different places (cortical bone or cancellous bone) because the bone height is not identical in all cases. Different implant tip positions lead to different types of fixations, ie, fixation type 1 (unicortical fixation): implant neck in the oralpalatal cortical bone and implant tip in the cancellous bone; fixation type 2 (bicortical fixation): implant neck in the oral-palatal cortical bone and implant tip in the nasal-palatal cortical bone; fixation type 3: implant neck in the oral-palatal cortical bone and implant tip projecting into the nasal cavity.

The question is whether different fixation types have some effect on anchorage. Most clinical investigations on direction of forces and moments applied have not been well documented. Anchorage is related to peri-

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

odontal stress,[6] and the anchorage effect of a palatal implant can be defined by the redistribution of periodontal ligament (PDL) stress of the natural tooth connected with the palatal implant. However, there are no published attempts to explore the relation between implant tip position and anchorage effect quantitatively.

In the past two decades, finite element analysis (FEA) has become an increasingly useful tool for predicting 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 in terms of stress and strain.

The purpose of this study was to analyze and compare quantitatively the effects on the anchorage produced by different types of implant fixation by investigating the stress responses in the PDL and the surrounding implant bone using FEA.

MATERIALS AND METHODS

Model

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 the dimensions and morphology found in a standard dental anatomy textbook.[7] The outmost boundary of the tooth was first defined, and the tooth was sectioned into cross-sections creating 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, 2002, San Francisco, CA).

Next, the PDL, alveolar bone, palatal implant, palatal bone, bracket, band, and TPA were created. The bracket, band, and transplatal arch were combined as one connected device to simulate a bracket and TPA welded to the band in the clinic (Figure 2B). The PDL width was assumed as 0.25 mm, and alveolar cortical bone was assumed as 1.0 mm. A cylinder implant was assumed to be 3.3 mm in diameter and nine mm in length, and the abutment was three mm long. The TPA was assumed to be 1.33 mm in diameter, the distance between the centers of two premolars was 42.8 mm. The palatal bone had a cortical surface thickness of 2.0 mm for the oral-palatal cortical bone, a cancellous thickness of 5.0 mm, and cortical surface of 1.0 mm in the direction of the nasal floor.

Models 2 and 3 were the same as model 1 except for palatal bone thickness. The palatal bone in model 2 had a cortical surface thickness of 2.0 mm for the oral-palatal cortical bone, a cancellous thickness of 3.5 mm, and a cortical surface of 1.0 mm in the direction

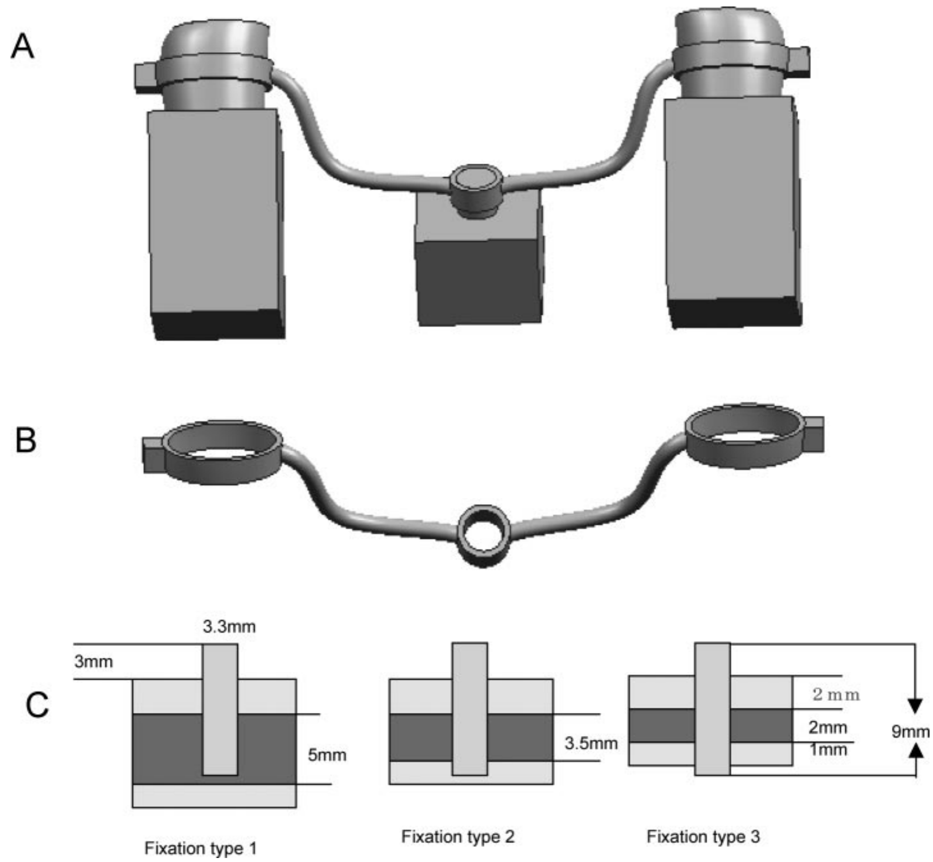

FIGURE 2. (A) Three-dimensional model comprising maxillary second premolars, periodontal ligament, alveolar bone, implant, palatal bone, transpalatal arch, bands, and brackets. (B) The connective device combing bands, brackets, and transpalatal arch together. (C) Three fixation types of implant. Fixation type 1: implant neck in the oral-palatal cortical bone and implant tip in the cancellous bone; fixation type 2: implant neck in the oral-palatal cortical bone and implant tip in the nasal-palatal cortical bone; fixation type 3: implant neck in the oral-palatal cortical bone and implant tip projecting into the nasal cavity.

of the nasal floor. The palatal bone in model 3 had a cortical surface thickness of 2.0 mm for the oral-palatal cortical bone, a cancellous thickness of 2.0 mm, and a cortical surface of 1.0 mm in the direction of the nasal floor. Models 1, 2, and 3 were constructed to simulate separately fixation types 1, 2, and 3 (Figure 2C). The three models were selected because they are common according to clinical reports.[5,8]

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 each had the same geometry in the second premolar, PDL, alveolar bone, bracket, and band. The bracket and the band were combined into a device to simulate a bracket welded on the band.

Elements and nodes

Elements and nodes were created by Unigraphics NX volume mesher (Figures 4 and 5). Tetrahedral three-dimensional elements were used in this study. Four-node linear cells were used because they are good at meshing arbitrary geometries.[9] Different element size may affect the value of stress; the same size element in the same material was used in four models. Furthermore, the accuracy of the results of FEA also depends on the fineness of the mesh. Therefore, small elements of similar size were used to uniformly mesh the area of interest (PDL, implant) for the stress analysis (Table 1).

The bone-implant interface was treated as a fully bonded surface to simulate osseointegration as bone-PDL interface and PDL-tooth interface. Tooth-band interface and implant-TPA interface were also created as fully bonded to simulate cemented band and fixed contact between TPA and implant. Fully bonded function was achieved by creating common faces at the interface to simulate a condition where the bodies were ‘‘welded’’ or ‘‘glued’’ together, which ensured that the connectivity will be maintained at the interface.[10]

Material properties

Each material was defined to be homogenous and isotropic. The physical properties of the constituent

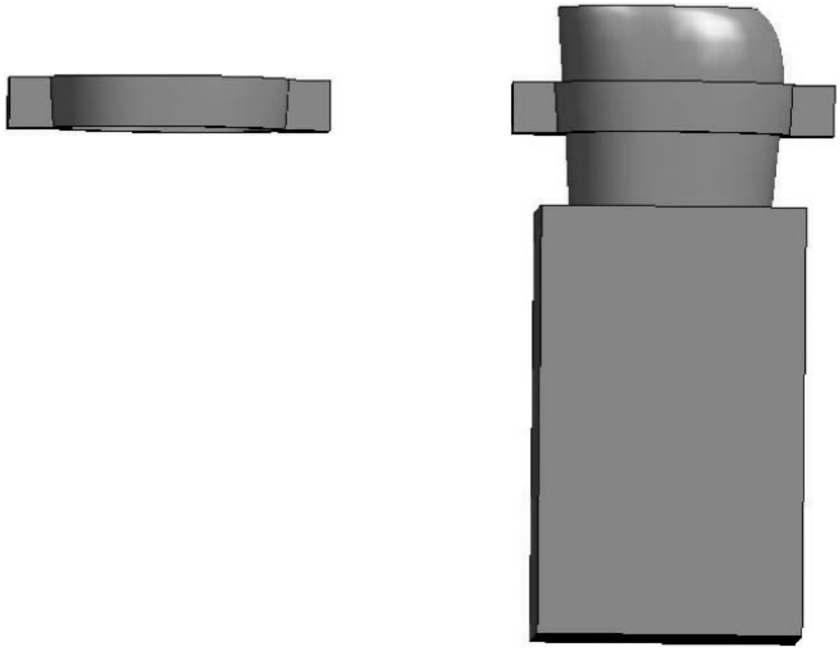

FIGURE 3. Three-dimensional model comprising maxillary second premolars, periodontal ligament, alveolar bone, band, and bracket; band and bracket was combined together.

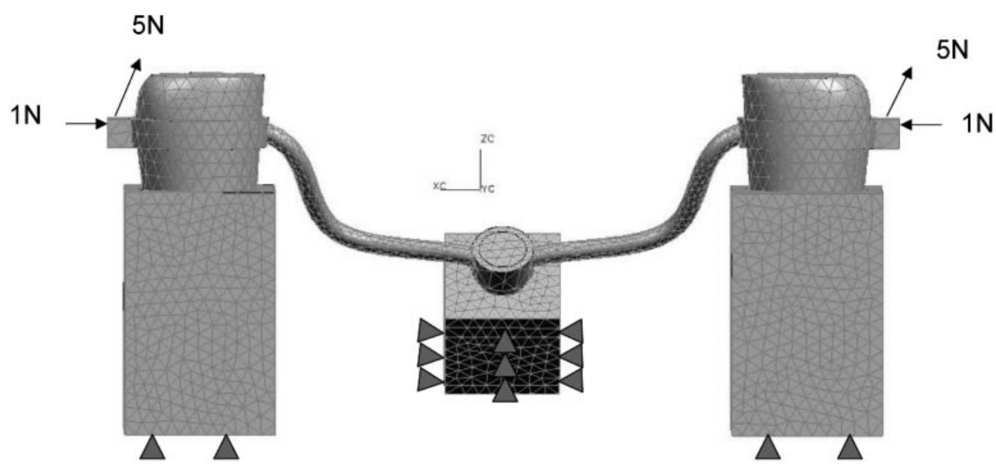

FIGURE 4. Three-dimensional finite element model with implant. The combined force (5N mesial direction, 1N palatal direction) is shown as black arrows, whereas boundary conditions in which model were fixed in place are triangles.

materials comprising the model were based on a review of the literature[9–11] (Table 2).

Constraints and loads

Models 1, 2, and 3. All nodes on the lateral edges of the palatal bone mesh were fully constrained so that no displacement could occur; on the bottom of the bone volume, no restrictions to the nodal displacements were imposed, allowing the bone to bend.[12] The boundary conditions were fixed at the base of the alveolar bone.[2] A combined horizontal force (mesial direction five N, palatal direction one N) was applied at the buccal bracket of each premolar band (Figure 4). 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 premolar extraction in one step.[13]

Model 4. To compare models with implants, boundary conditions were fixed at the base of the alveolar bone.[2] The force was same as in the other three models (Figure 5). Von Mises Stress (kPa) and displacement (mm) were calculated and presented in colorful contour bands. Von Mises stress was selected be-

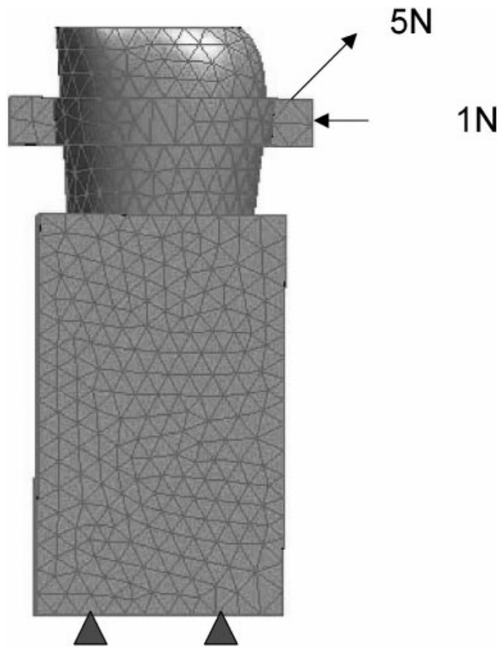

FIGURE 5. Three-dimensional finite element model without implant. The combined force (5N mesial direction, 1N palatal direction) is shown as black arrows, whereas boundary conditions in which model were fixed in place are triangles.

TABLE 1. Nodes and Elements in the Study

	Nodes	Elements
Model 1	12,205	60,354
Model 2	12,072	59,807
Model 3	11,764	57,973
Model 4	5145	26,304

TABLE 2. Material Properties of Constituent Materials[a]

Material	Young's Modulus (MPa)	Poisson's Ratio
Dentin[b]	19,600	0.30
PDL[c]	1	0.45
Cortical bone[b]	13,700	0.26
Cancellous bone[b]	1370	0.30
Steel[d]	193,000	0.30
Titanium pure[d]	107,000	0.30

[a] PDL indicates periodontal ligament.
[b] From Vasquez et al.[11]
[c] From Jones et al.[9]
[d] From Unigraphic user manual.[10]

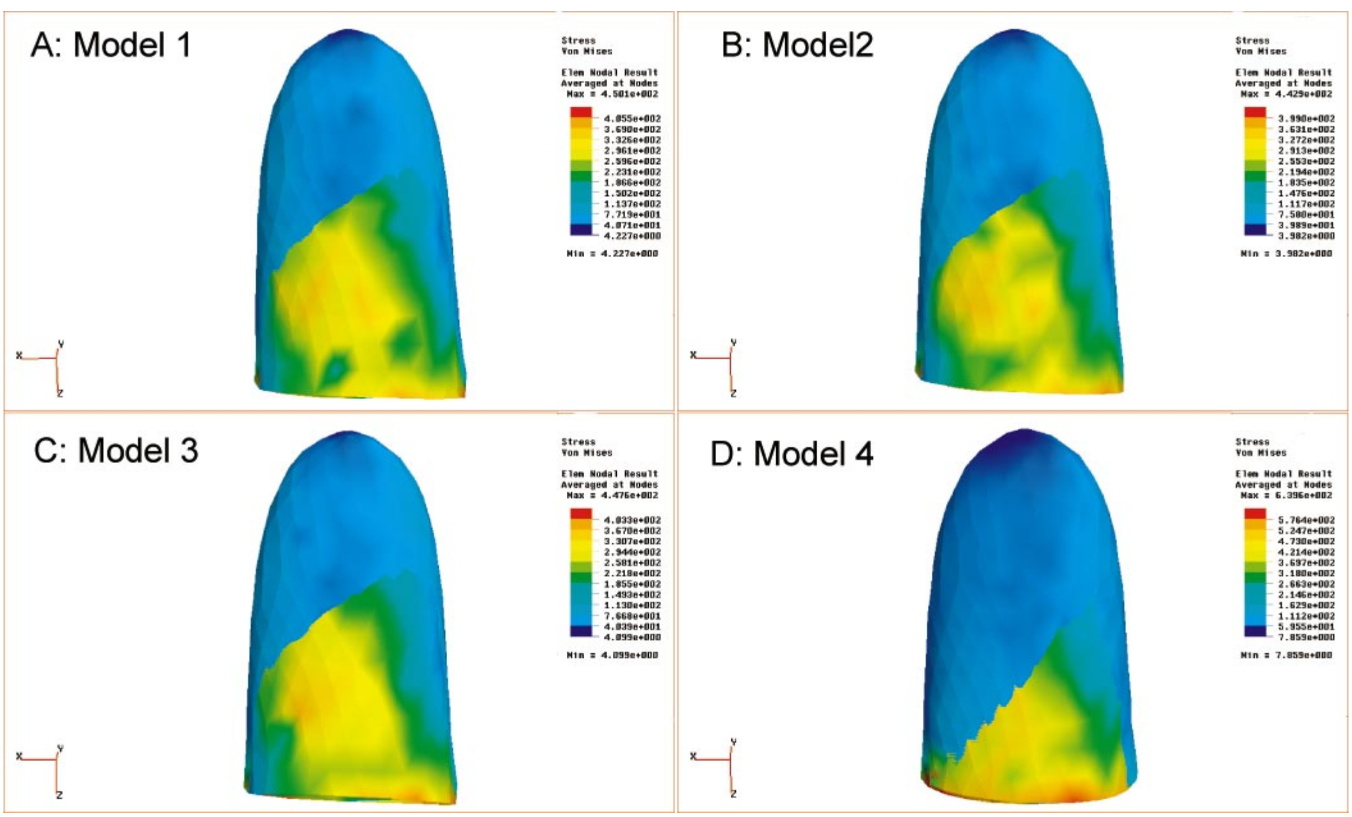

FIGURE 6. Von Misses stress in the periodontal ligament of left maxillary second premolar. Colors indicate the magnitude of the stress. (A) Fixation type 1; (B) fixation type 2; (C) fixation type 3; (D) without implant.

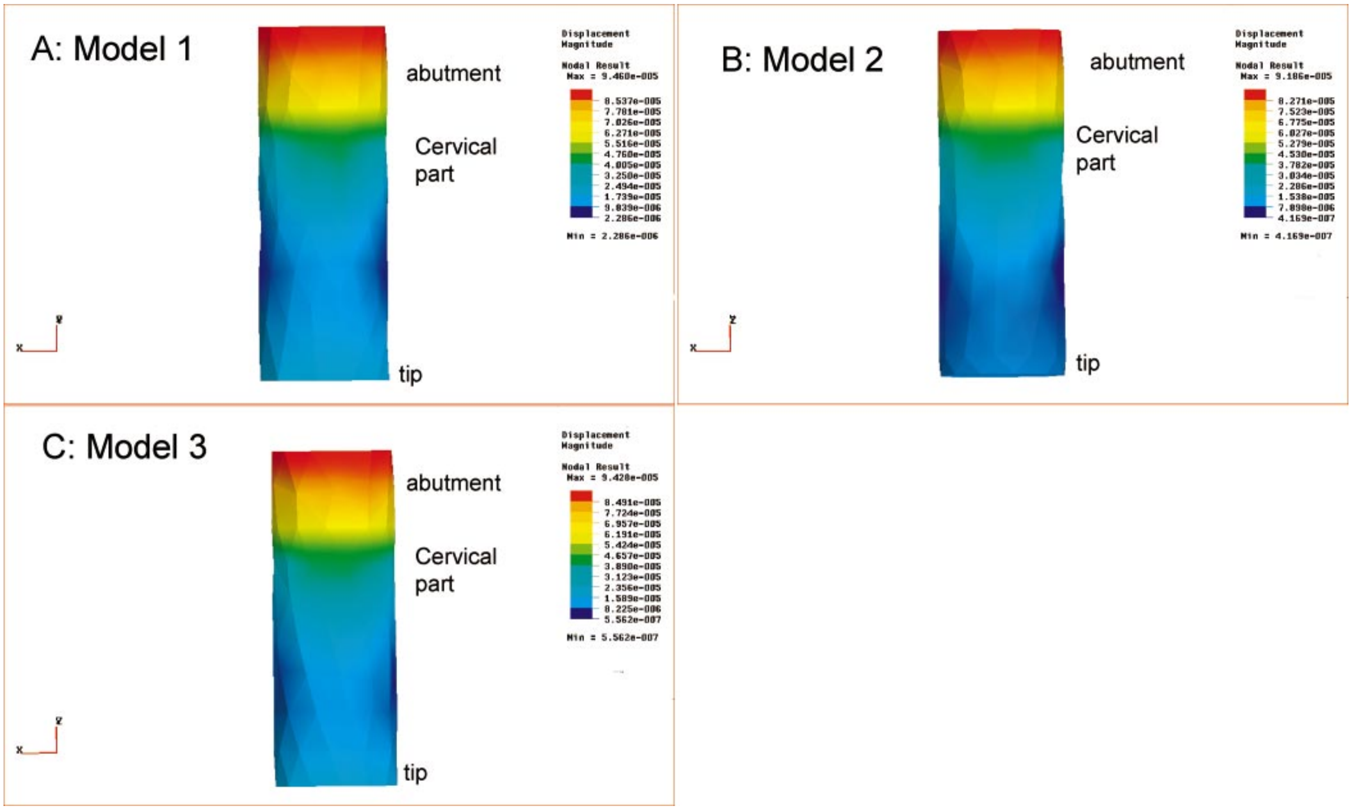

FIGURE 7. Displacement in the implant-bone interface. Colors indicated the magnitude of the displacement. (A) Fixation type 1; (B) fixation type 2; (C) fixation type 3.

cause it is a scalar quantity that includes all components of the stress tensor and allows a comprehensive comparison between models.[14]

RESULTS

Figure 6 showed the change in stress distribution in the PDL with different types of fixation. Because there was no significant difference on stress magnitude and distribution between the right and left periodontal parts in models 1–3, we just extracted the left premolar to compare PDL stress with model 4.

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 in the PDL at the cervical margin. The stress decreased toward the apex. However, the von Mises stress in model 4 was far higher than those in models 1–3. The main stress in the PDL was only concentrated on the cervical part in model 4, whereas it also was on the middle part in models 1–3. The same PDL stress distribution is shown in the three models with implants. This showed that the implant could make even distribution of the PDL stress.

Figure 7 shows the displacement of the implant. The maximum displacement occurred in the abutment of the implant, and the displacement decreased sharply toward the implant tip. The displacement of the implant showed no significant differences in the three models, and this suggests that the implants have the same stability with different fixations.

Figure 8 shows the stress in the bone surrounding the implant. A larger portion of the external load was carried by the cervical cortex, and the stress declined sharply in the deeper regions of the cortical bone. The bone stress near the implant tip was very low.

Table 3 showed the maximum stress in the PDL and bone surrounding the implant. The implant could reduce the PDL stress about 30%. Three implant fixation types showed the same maximum von Mises stress in the PDL.

DISCUSSION

The purpose of this investigation was to analyze the anchorage effect of palatal osseointegrated implants under different types of fixation. To accomplish this analysis, we constructed three finite element models to simulate the clinical situation. The three models were the same except for the fixation type. The same boundary condition was used for alveolar bone. The same size and type element were created for the same material. The same mesh refiner was performed in the same place until the percentage error of the re-

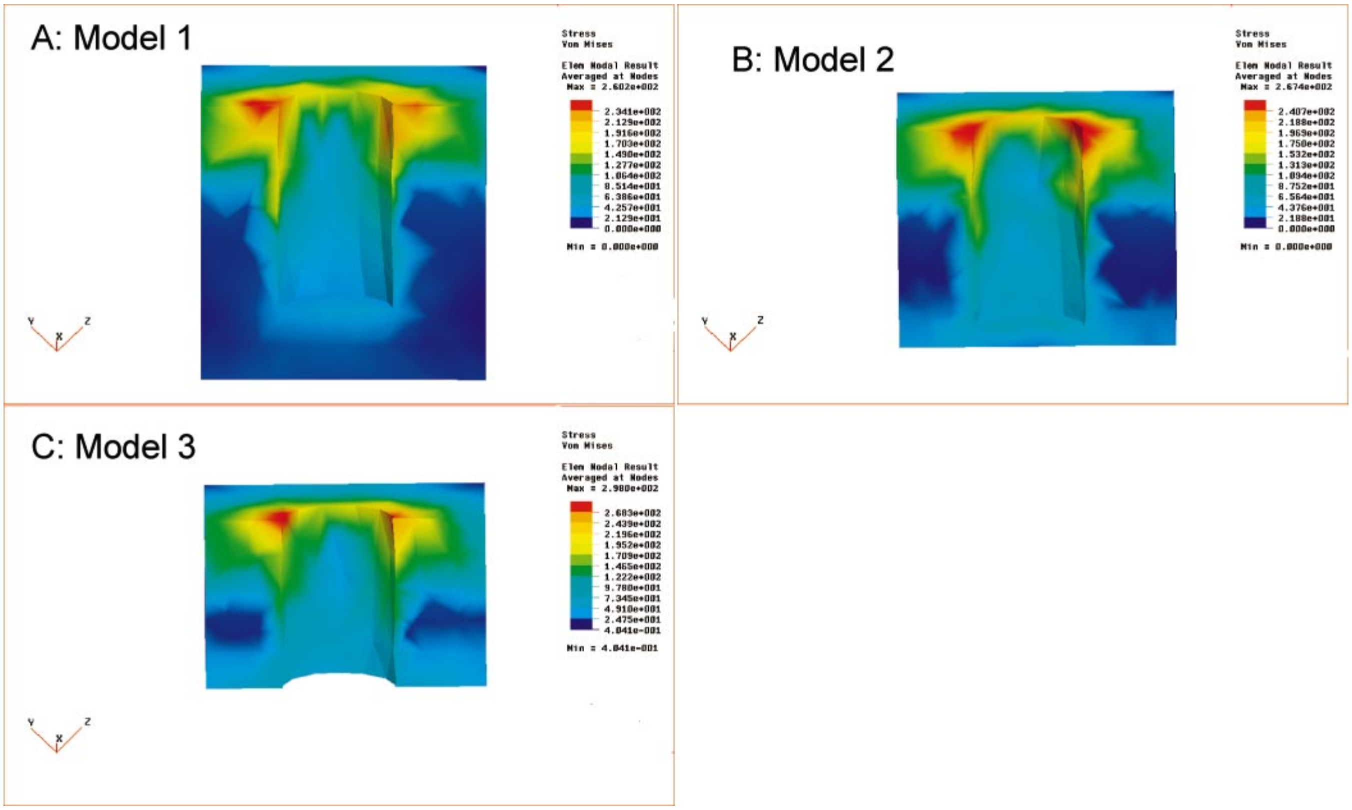

FIGURE 8. Von Misses stress of the implant surrounding bone in the midsagittal clipping. Colors indicate the magnitude of the stress. (A) Fixation type 1; (B) fixation type 2; (C) fixation type 3.

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

	Fixation	PDL Stress (kPa)	Implant Surrounding Bone (kPa)
Model 1	Type 1	450.1 (−29.63%)[b]	260.2
Model 2	Type 2	442.9 (−30.75%)[b]	267.4
Model 3	Type 3	447.6 (−30.02%)[b]	298.0
Model 4	No	639.6	

[a] PDL indicates periodontal ligament.

[b] The PDL stress percentage changes compared with model 4.

sult stress was lower than 5%, which is the widely accepted level of confidence for the stress percentage error[10] (Unigraphic software can show the stress percentage error of analysis). The resultant stress in a model without an implant was compared with stress produced in the models with implants.

The limitations of our model included approximation of the material behavior and shapes of the tissues.

As in previous studies,[15,16] the PDL was modeled as a 0.25-mm layer of uniform thickness and was treated as linear-elastic and isotropic, although the PDL exhibits anisotropy and nonlinear viscoelastic behavior because of tissue fluids.[17] The PDL value was selected because it agreed with the human tooth movement.[9] 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 palatal bone was simplified as two mm in oral-palatal and one mm in nasal-palatal cortical bone and different cancellous thickness. In fact, the degree of osseous closure of the suture palatine median is different, and the cortical bone volume and quality change with age.[18] However, there are no reliable data. As in another study,[19] it was assumed that a 100% implant-bone interface was established. However, the percentage of direct bone-to-implant contact varied from 34% to 93%, with an average value of 75.5%.[13] A 100% bone apposition was almost never obtained at the surface of dental implant.[20] Similar to a previous study, the boundary condition was assumed at the base of the alveolar bone[2] and all nodes on the lateral edges of the palatal bone[12] because there was no agreement for giving the boundary condition for bone segments.[2,11,12,21]

In each model, the highest stress concentration in the PDL was localized at the cervical margin. This might be because of the fact that the orthodontic force was 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. McGuinness et al[21] reported the same distribution with the exception that an osseointegrated implant was modeled. However, comparing models 1–3 with model 4, it was found that the implant led to an even stress distribution in the PDL (Figure 6). This might be due to the fact that the implant changed the initial center of rotation of the anchorage tooth and the movement of the tooth was bodily movement.

The implant markedly reduced the von Mises stress of the PDL, distributing the PDL stress evenly. 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 because of the rigid connection of the TPA. The anchorage effect depended on the implant stability and the rigidity of the TPA. Figure 7 revealed that the implant displacement difference was less than 5%, which is generally agreed to limit the accuracy of the result.[10] Consequently, there was the same implant stability in the three models. This could be partly explained in Figure 8, which shows that the stress concentrations occurred in the palatal cortical bone and the bone stress near the implant tip was very low. The difference of bone near the implant tip had little effect on the implant displacement. This suggests that the fixation of the implant tip in cortical bone could not enhance stability of the implant.

Our conclusions agree well with the study of Van Oosterwyck et al.[12] Although the finite element models they created just included implant and surrounding bone, they also found that the influence of bicortical fixation could be negligible when cancellous bone of sufficient quality (elastic modulus more than 700 MPa) was present, and in our study the cancellous bone was assumed as 1370 MPa. Because the bone between the cortical bones in the median-sagittal region was considered as a dense cancellous bone or as low-density cortical bone,[22] the modulus was higher than 700 MPa. Some types of TPA have been reported that included the use of a 0.8×0.8–mm edgewise wire[5] and a 1.0-mm-diameter round wire,[4] and they reported a small mesial movement of the anchored premolars. In this study we used a more rigid archwire to make the TPA. It was this same implant stability and rigidity of TPA that offered the same anchorage effect.

Although an orthodontic force can cause continuous tooth movement, in this study only the initial tooth movement was considered. Therefore, in the future, addition modeling may be needed along with a time-dependent FEA. However, the model does provide quantitative results of the complex three-dimensional stresses caused by mesiodistal forces during orthodontic treatment. The model revealed that the palatal osseointegrated implant is a useful clinical tool to increase anchorage, and different fixation types of implant showed almost the same anchorage effects. It should be noted that this theoretical study, which has no empirical basis for clinical application, involved many assumptions; the findings may have to be changed if the assumptions were unrealistic. Therefore, the resultant values should be interpreted only as a reference to aid clinical judgment.

CONCLUSIONS

- According to the FEA, the implant significantly lowered the PDL stress, distributing the stress evenly.
- Three kinds of implant fixation showed almost the same PDL stress level and distribution. It is suggested that different fixation types might all have the same anchorage effects.

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