− ORIGINAL ARTICLE −

Anchorage effect of palatal osseointegated implant on teeth with simulated bone loss: A finite element study

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骨吸収を想定した歯における矯正用パラタルインプラントの固定効果に関する有限要素法を用いた研究

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Abstract : The purpose of this study was to compare the anchorage effect of the osseointegrated implant connected on the second premolar with different alveolar bone loss using the finite element analysis. Four models with the implant and four models without the implant were constructed. Four levels of alveolar bone loss (0, 2, 4 and 6 mm) were studied. The model with the implant was consisted of two maxillary second premolars, their associated periodontal ligament and alveolar bones, palatal bone, palatal implant and transpalatal arch. The model without the implant was used to compare with the model with the implant. The horizontal force (mesial 5N, palatal 1N) was loaded at the buccal bracket of each second premolar. The stress in the periodontal ligament, implant and surrounding bone were calculated. The results showed that the palatal implant could significantly reduce von Mises stress (maximum von Mises stress was reduced from 29.63% to 44.30% with the alveolar bone loss from zero mm to six mm) and make stress even distribution in the periodontal ligament. The stress in the implant and surrounding bone was very low. These results suggested that palatal implant is a good tool to enhance the anchorage of teeth with alveolar bone loss.

抄録：本研究の目的は，第二小臼歯部の歯槽骨の吸収程度とこれに連結したインプラントによる加強固定の効果について，有限要素法を用いて検討することとした。歯槽骨の吸収の程度を４段階（0，2，4，6mm）設定し，それぞれインプラント有りと無しのモデルについて調べた。インプラントのあるモデルは，左右側の上顎第二小臼歯，歯根膜，歯槽骨，口蓋骨，パラタルインプラント，インプラントと小臼歯とを連結するパラタルバーで構成した。インプラントのないモデルは，上述のモデルにおいてインプラントを除外し，他は同じとした。水平力として，近心方向に5Nと口蓋方向に1Nを両側の上顎第二小臼歯の頬側ブラケットに負荷した。この荷重を負荷した時，歯根膜，インプラントとその周囲の骨に現れる応力を算出した。その結果，インプラントを用いることで，設定した0～6mm歯槽骨の吸収したモデルにおいて，von Mises stressが歯根膜部で29.63～44.30%の減少した。インプラントとその周囲の骨に現れる応力は，きわめて小さかった。このことより，歯槽骨の吸収を起こしている歯に対して，加強固定の

ためにパラタルインプラントが有効であることが示唆された。

1. Introduction

The percentage of adult patients who seek orthodontic treatment has increased significantly in recent decades[1]. These patients often have bone loss in posterior teeth, which is often used as anchorage teeth. Excessive orthodontic force with advanced periodontal bone loss may traumatize the periodontium, and increased apical pressure because reduced bony support may contribute to apical root resorption[2]. Additional anchorage aid is often required for the posterior teeth with alveolar bone loss (ABL).

Routinely, headgears, transpalatal arches (TPAs) and Nance appliances are used to enhance anchorage during clinic treatment. However, many patients rejected headgear wear because of social and esthetic concerns and the success of this treatment depends entirely on patient cooperation[3]. In most studies on TPAs[4] and Nance appliance[5, 6], anchorage loss was unavoidable.

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[7, 8]. The median − sagittal region of the hard palate[9, 10] 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 peri − implant conditions due to the attached mucosa. Palatal implant is often used to connect with the second premolar by a transpalatal arch to increase anchorage as shown in Fig. 1. There are some clinical studies[9, 10] showed that a palatal implant could offer enough anchorage effect. However, the alveolar condition of anchorage teeth was not well documented. The implant anchorage effect on the teeth with ABL has not been sufficiently explored. Hence there is a necessity to explore what occurred when the implant was used as an anchorage on the teeth with different ABL. As we know, an anchorage is related to periodontal stress[11] ; the anchorage effect of palatal implant can be explained by the redistribution of the periodontal ligament (PDL) stress of the natural teeth connected with the palatal implant.

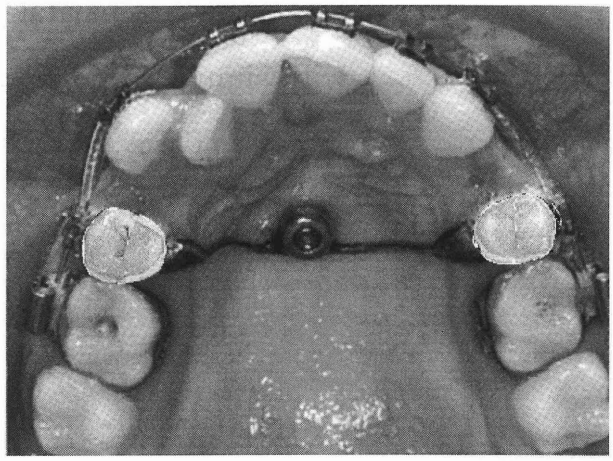

Fig. 1. Palatal implant used as an orthodontic anchorage in the clinic. The second maxillary premolars were anchored by the implant through the transpalatal arch.

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 component of the model are then calculated in terms of stress and strain.

The purpose of this study was to analyze the anchorage effect of the palatal implant by investigating periodontal stresses when the second premolar at different levels of alvelor bones loss.

2. Material and method

2.1 Model

2.1.1 Models with the implant: Model 1-4

Model 1(Fig. 2A) was composed of two maxillary premolars, PDL, alveolar bone, palatal implant, palatal bone, bracket, band, and TPA. The maxillary second premolar was created by manually designing the tooth according to dimension and morphology found in a standard dental anatomy textbook[12]. 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.2002 California). Next the PDL, alveolar bone, palatal implant, palatal bone, bracket, band, and TPA were created. The bracket, band, and transplatal archwire were combined as one connected device to simulate bracket and transpalatal archwire welded to the band in the clinic. The PDL width was assumed as 0.25 mm, and alveolar cortical bone was assumed as 1.0mm. A cylinder implant was assumed as 3.3 mm in diameter and 9.0 mm in length and the abutment was 3.0 mm long. The TPA was assumed as 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 2.0mm for the oral-palatal cortical bone, a cancellous thickness of 5.0mm and cortical surface of 1.0mm in the direction of the nasal floor. Model 2, 3, and 4 were the same as Model 1 except the alveolar bone level was lower 2, 4, and 6 mm separately.

2.1.2 Models without an implant: Model 5-8.

Model 5 (Fig. 2B) was gotten by deleting the implant and palatal bone from Model 1. Model 5 and Model 1 had the same geometries in the second premolar, PDL, alveolar bone, bracket TPA, and band. Model 6, 7, and 8 were the same as Model 5 except the alveolar bone level was lowered 2, 4, and 6 mm separately. Bracket and band were combined to a device to simulate the bracket welded on the band. Models with and without the implant were summarized in Table 1.

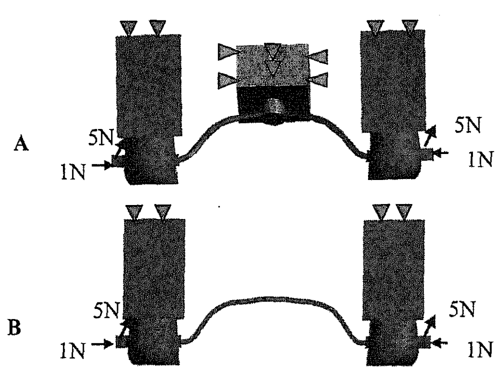

Fig. 2. The finite element models without alveolar bone loss of the second premolar used in this study. The combined force (5N mesial direction, 1N palatal direction) was applied on the bracket, whereas boundary conditions in which model were fixed at all later sides.
A): with the implant. B): without the implant.

Table 1. Models in this study

Alveolar bone loss	with implant	without implant
0 mm	Model 1	Model 5
2 mm	Model 2	Model 6
4 mm	Model 3	Model 7
6 mm	Model 4	Model 8

2.2 Elements and nodes

Elements and nodes were created by Unigraphics NX volume mesher (Fig. 2). Tetrahedral three-dimensional elements were used in this study. Four-node linear cells were used since it was good at meshing arbitrary geometries[13]. Different element size may affect the value of stress; the same size element in the same material was used in all models. Furthermore, the accuracy of the results of FEA also depends on the fineness of the mesh. Therefore, small elements of the similar size were used to uniformly mesh the area of interest (PDL, implant) for the stress analysis (Table 2).

The bone-implant interface was treated as 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 a 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 "weld" or "glued" together, it ensured the connectivity will be maintained at the interface[14].

Table 2. Nodes and elements in the study

	Nodes	Elements
Model 1	12,205	60,354
Model 2	10,348	49,517
Model 3	9,856	46,856
Model 4	9,218	43,486
Model 5	5,145	26,304
Model 6	4,248	21,037
Model 7	3,915	19,199
Model 8	3,651	17,851

2.3 Material properties

Each material was defined to be homogenous and isotropic. The physical properties of the constituent materials comprising the model were based on a review of the literature[13-15] (Table 3). Of course, the finding would change if this assumption were unrealistic.

Table 3. Material properties for the of constituent materials

Material	Young's modulus (MPa)	Poisson's ratio
Dentin [a]	19,600	0.30
PDL [b]	1	0.45
Cortical bone [a]	13,700	0.26
Cancellous bone [a]	1,370	0.30
Steel [c]	193,000	0.30
Titanium pure [c]	107,000	0.30

a) from Vasquez M et al.[15],
b) from Jones ML et al.[13],
c) from Unigraphic user manual[14]

2.4 Constraints and loads

2.4.1 Models with the implant: Model 1-4.

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[16]. The boundary conditions were fixed at the base of the alveolar bone[4]. A combined horizontal force (mesial direction 5N, palatal direction 1N) was applied at the buccal bracket of each premolar band (Fig. 2A). The force direction was selected to simulate the mesio-distal force in the clinic because the width between canines was 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[17].

2.4.2 Models without an implant: Model 5-8

In order to compare models with implants, boundary conditions were fixed at the base of the alveolar bone[4]. The force was the same as models with the implant (Fig. 2B). Von Mises stress (KPa) was calculated and presented in colorful contour bands. Von Mises stress was selected because it was a scalar quantity that included all components of the stress tensor and allows comprehensive comparison between models[18].

3. Results

Fig.3 showed the implant and surrounding bone stress, which increased with ABL. A larger portion of the external load was carried by the cervical cortex, the stress declined sharply in deeper regions of the cortical bone. The bone stress near implant tip was very low. The highest stress was showed in Model 4.

Fig. 4 showed the change in stress distribution in the left PDL in different ABL. The left PDL was selected because there was no significant difference on stress magnitude and distribution between the right and left periodontal parts in the same model with the implant. 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. However, in the same level of ABL, the von Mises stress in the model with the implant was far lower than those in model without the implant respectively. Furthermore, the main stress of PDL was distributed more widely in the models with the implant than that in the models without the implant. This showed that the implant could make PDL stress have a trend of even distribution. The highest PDL stress among models with the implant was in the Model 4 whereas the highest stress among models without the implant was in the Model 8.

Fig. 5 showed the maximum values of von Mises stress changes with ABL. The application of the same force after a reduction in the bone support of 2, 4, and 6 mm generate an increasing stress in the PDL. The increasing speed of stress with ABL in the models with the implant was far lower than that in the models without the implant.

4. Discussion

The purpose of this investigation was to use finite element method to analyze the anchorage effect of palatal osseointegrated implants on the teeth under different ABLs. To accomplish this analysis, we constructed four finite element models with the implant to simulate implants used as anchorage on the teeth with different ABLs. Four models were the same except alveolar bone level. 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 result stress was lower than 5%, which was the widely accepted level of confidence for convergence criteria[14]. The

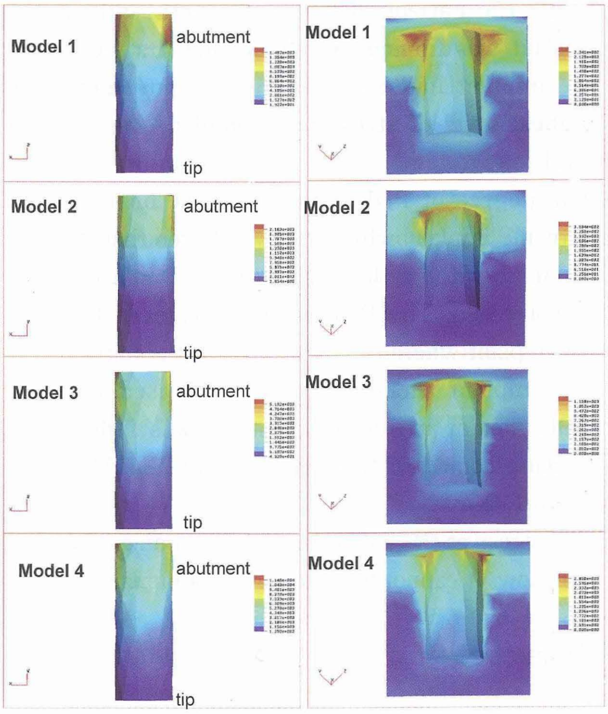

Fig. 3. Von Mises stress of implant and the implant surrounding bone in the mid-sagittal clipping.

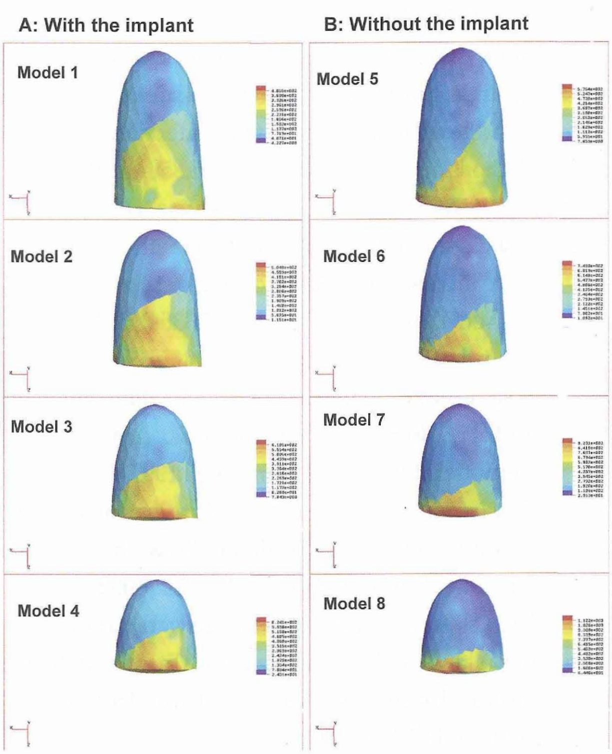

Fig. 4. Von Mises stress in the PDL of left maxillary second premolar with different alveolar bone loss, Colors indicate the magnitude of the stress. A): with the implant. B): without the implant.

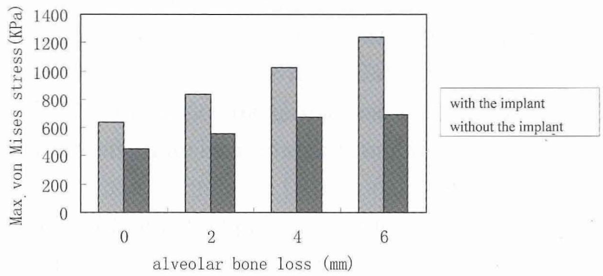

Fig. 5. Maximum von Mises stress changed in different levels of alveolar bone loss.

resultant stress in the model with an implant was compared with stress produced in the model without the implant in the same ABL.

To complete the analysis, certain assumptions are needed. The resultant values should be interpreted only as a reference to aid clinical judgment. The limitations of our models included approximation in the material behavior and shapes of the tissues.

As in previous studies[19, 20], 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[21]. The PDL value was selected because it agreed with the human tooth movement[13]. 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 2mm in oral-palatal and 1mm nasal-palatal cortical bone and 5mm cancellous thickness. In fact, the degree of osseous closure of the suture palatine median is different and the cortical bone volume and quality changes with ages[22]. As in another study[23], it was assumed that a 100% implant-bone interface was established. However, the percentage of direct implant-bone contact varied from 34 to 93% with an average value of 75.5%[17]. A 100% bone apposition was almost never obtained at the surface of dental implants[24]. The boundary condition was assumed at the base of the alveolar bone[4] and all nodes on the lateral edges of the palatal bone[16], because there was no agreement for giving the boundary condition for bone segment [4, 15, 16, 25].

The implant and surrounding bone stress increased with the bone loss. The highest stress concentration was localized in the palatal cortical bone. The similar finding has been presented by Meijer et al.[26]. The stresses in the implant surrounding bone were lower than 3.17 MPa, which are of such low magnitude that they are unable to produce an implant failure [27]. Therefore, the osseointegrated implant is able to withstand orthodontic forces and may function as adequate anchor unit.

In the models without an implant, the PDL stress increased fast with ABL under the same load. Tipping movements resulted in an increased level of stress at the cervical margin of the PDL. This is in agreement with the other studies[28].

In the models with the implant, the PDL stress increased slowly with ABL and has a trend of even distribution. Because the TPA connected the implant to the premolar in the crown; the orthodontic force was transmitted from the tooth to the PDL and to the implant at the same time. Relatively more force was transmitted to the implant when the teeth had more ABL; this was proved by the increased stress of the implant and surrounding bone stress (Fig. 3) when the implant was used as an anchorage on the second premolar with more ABL. The implant reduce the maximum PDL stress 29.63% without alveolar bone lose and 44.30% in the 6 mm ABL. Even distribution might be explained by the different position of rotation center of the teeth with the implant and without the implant in the same level of ABL.

The orthodontic force can cause continuous tooth movement, however initial tooth movement considered in this study. Therefore, in the future, additional modeling may be needed along with a time-depend finite element analysis. However, the model does provide quantitative results of the complex 3-dimensional stresses caused by mesio-distal forces during orthodontic treatment. It revealed that palatal osseointegrated implant was a useful clinical tool to increase anchorage for the patients with ABL. It should be noted that the wide variation in morphologic condition and material properties among normal individuals may affect applicability of the analysis. The resultant values should be interpreted only as a reference to aid clinical judgments.

5. Conclusion

From 0 mm to 6 mm ABL, four models with the implant were compared with four models without an implant. According to FEA,

1. under the horizontal force, the teeth without the implant was tipping movement and the teeth with the implant had a trend of body movement, the highest level of stress was found at the cervical level.
2. The degree of PDL stress increase on the teeth with the implant with ABL was lower than that on the teeth without the implant. From 0 mm to 6 mm alveolar loss, The PDL stress increased 50% with the implant whereas 93.83% without the implant.
3. The implant anchorage effect increased with the ABL. Maximum von Mises stress was reduced by implant from 29.63 % to 44.30 % with the ABL from 0 mm to 6 mm.
4. The stress of the implant and surrounding bone was very low. It cannot lead to the fail of implant.

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