Finite Element Analysis of Bone around a Dental Implant Supporting a Crown with a Premature Contact

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Objective: *To investigate the influence of a premature contact caused by an implant-retained crown (IRC) on stress and strain distributions in bone surrounding the implant using the finite element method.*
Material and Method: *A 3D finite element (FE) model of a section of a mandible with a single tooth dental implant, an IRC, and two adjacent teeth was created. Three rigid plates were used to represent the antagonist teeth. Modeling the antagonist teeth using the rigid plates removed the necessity to create FE models for the antagonist teeth, their periodontal ligament, and the maxilla. Moreover, this new approach also allowed the premature contact height to be easily varied by changing the positions of the rigid plates. In the present study, premature contact heights of 0, 50, 100, 150, 200 and 250 μm were considered. The FE contact analysis was employed. All materials were assumed to be linear elastic and isotropic.*
Results: *The magnitudes of von Mises stresses in the bone change drastically when there was a premature contact. For example, the von Mises stress increased from 9.68 MPa in the case with no premature contact to 49.92 MPa in the case with the premature contact height of 50 μm. In addition, the magnitude of the major principal strain in the marginal bone reached the pathologic overload of 4000 με when the premature contact height was 100 μm or higher.*
Conclusion: *The influence of premature contacts is very high and the premature contact height of an IRC over 100 μm should be avoided as much as possible to provide longevity of dental implants.*

Keywords: *Premature contacts, Finite element method, Dental implants, Teeth, Contact analysis*

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Currently, placement of dental implants is a gold standard for replacement of missing teeth. Although successful clinical treatments by dental implants have been reported(1-3), failure of osseo-integration still sometimes occurs(4-6). In contrast to natural teeth, there is no periodontal ligament between dental implants and their surrounding bone. The periodontal ligament acts as a shock absorber between a root and surrounding bone and it also contains mechanoreceptors. Without the periodontal ligament, mechanoreceptors will also be absent. The absence of mechanoreceptors results in poor detection of bite forces with small magnitudes. This subsequently increases the tendency of occlusal overloading, which can cause peri-implant bone loss and implant failure(7). When dental implants are used, it is therefore advisable to remove the sources of occlusal overloading as much as possible. One of the

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common sources of occlusal overloading is premature contacts between implant-retained crowns (IRCs) and their antagonist teeth[7-9]. By definition, premature contacts between IRCs and their antagonist teeth are the initial contacts between them that interfere with the motion of the mandibles. These premature contacts cause occlusal overloading by preventing efficient and natural load sharing among dental implants and teeth. Several studies have been performed to analyze premature contacts. Isidor[8] performed an animal study to analyze the influence of excessive occlusal loads caused by a prosthesis that was in supra-occlusal contact with an antagonist splint. The author concluded that occlusal overloading could be the main factor in loss of osseointegration in previously osseointegrated implants. Miyata et al[9] performed an animal study to investigate the influence of controlled occlusal overloading on bone around dental implants. They found that bone resorption around dental implants tended to increase when premature contact heights of 180 μm or more were introduced to the suprastructures of dental implants. Ikeda et al[10] studied the tooth pain threshold in humans in respect of premature contact heights. They found that premature contact heights of less than 100 μm did not produce any cold water triggered pain or occlusal pain.

The finite element method is frequently used to determine stresses in bone around dental implants. However, a few finite element (FE) investigations have been performed to study premature contacts. Takayama et al[11] used FE analysis to study a premature contact in a lower complete denture. In their study, a premature contact was modeled by applying forces on one side of the occlusal surface of the lower complete denture. This caused the movement between the mucosal surface of the denture and the mucosa. The magnitudes of the forces employed were not obtained from *in vivo* experiments but were set based on numerical reasons. As a result, only discussion on relative values of stresses at various positions and movements of the denture was available in the paper. Nagahara et al[12] used FE analysis to study displacements and stress distributions in the temporomandibular joint (TMJ) during clenching. The FE model employed included the TMJ and a mandible with teeth. A premature contact was modeled by pulling the mandible upward while restraining the occlusal surface of the premature contact tooth. The case with no premature contact was modeled by restraining all teeth instead of one tooth. Modeling a premature contact in this way represents only the extreme case where the premature contact height is so high that only the premature contact tooth is in contact with its antagonist teeth.

Complex FE analysis methods such as the FE contact analysis can be very beneficial for modeling different clinical situations[13-16]. Modeling a premature contact problem can actually be done by employing the FE contact analysis with the maxilla, mandible, periodontal ligament and all teeth placed in the actual positions. However, it is unfortunate that there is virtually no study on premature contacts using this type of detailed analysis. The main reason may be that the FE contact analysis is expensive since it needs both large human and computational resources. Nevertheless, studies of premature contacts by experiments, both in humans and animals, are even more difficult and more expensive. In fact, some information, such as stresses in human bone, can be very difficult to obtain from experiments. To obtain stresses in bone from experiments, strains in bone must be first measured and, after that, stresses can be computed from the measured strains. The measurement of strains in bone is complex and can be quite expensive. The difficulties in performing experiments discourage studies of premature contacts with varied parameters.

The objective of the present study was to investigate the effect of a premature contact caused by an IRC by using the FE contact analysis. The parameter under consideration was the premature contact height. A 3D FE model of a section of a mandible with a single tooth dental implant (STDI), an IRC, and two adjacent teeth was used for the investigation. In order to vary the premature contact height without much difficulty, rigid plates were used to represent the antagonist teeth. The premature contact was obtained by using appropriate relative positions of these rigid plates. The premature contact height was varied by changing these relative positions. The antagonist teeth, their periodontal ligament and the maxilla are deformable bodies and will actually deform when the antagonist teeth are in contact with the IRC and mandibular teeth. Accordingly, careful consideration of how the rigid plates should be moved was employed. The effect of different premature contact heights was observed through stress and strain distributions in the bone around the STDI.

Material and Method

In order to model a premature contact caused by an IRC, it is straightforward to create a 3D FE model with the maxilla, mandible, and all teeth placed in the actual positions. The STDI and the IRC can then be placed in the positions that cause the premature contact. After that, the contact analysis can be performed. The premature contact height can be changed by changing the height of the IRC. Nevertheless, creating a 3D FE model with such detailed components is a time consuming and expensive process. In addition to that, changing the height of the IRC requires remeshing. This exacerbates the difficulty even further since it is almost the same as creating a new 3D FE model for each premature contact height. In the present study, a 3D FE model of a section of a human mandible including teeth, an STDI, and an IRC was created. The maxillary teeth were modeled by rigid plates. The main advantage of modeling the maxillary teeth by the rigid plates is that the mesh of the maxillary teeth, their periodontal ligament, and the maxilla can be neglected. In addition, the premature contact height can be easily varied by changing the positions of the rigid plates. Therefore, the preprocessing time can be considerably reduced. The process of contact was obtained by moving the rigid plates toward the mandibular teeth. The maxilla, the maxillary teeth, and their periodontal ligament are deformable bodies. Since they were not modeled, the rigid plates had to be moved in such a way that the movements of the plates reasonably represented the movements of the occlusal surfaces of the maxillary teeth under deformation. To construct the 3D FE model, a 3D geometric model of the mandible and teeth used in the present study was first created from CT images. The CT images were imported into Mimics 8.1 (Materialise NV, Belgium) to create the 3D geometric model. Geometric models of the STDI and IRC were then added. Fig. 1 shows the obtained geometric model. It consisted of the STDI, IRC, cortical bone, trabecular bone, second premolar, second molar, and periodontal ligament. The STDI included an abutment and a fixture. From the obtained geometric model, the 3D FE mesh was then created in Patran 2004 (MSC. Software Corporation, USA). In the present study, four-noded tetrahedral elements were used to construct the mesh. The total number of nodes and elements were 65541 and 297814, respectively.

The IRC was made of a porcelain fused to metal crown. The shape of the fixture was screw-shaped. The diameter of the fixture was 4.1 mm and the length was 10 mm. For the tooth socket, the thickness was modeled as 0.3 mm[17]. The thickness of the periodontal ligament was modeled as 0.2 mm[18,19]. The thickness of the cortical bone was 2.2 mm. This value was averaged from the CT images. Three rigid plates were created for the IRC, second premolar and second molar as shown in Fig. 1. The material properties used in the model were obtained from the literature[20-27] and shown in Table 1. All materials were assumed to be linear elastic and isotropic. All material properties in Table 1 were taken exactly as they were presented in the references except for the properties of the cortical bone. The modulus of elasticity and Poisson's ratio of the cortical bone were averaged from the orthotropic properties of the cortical bone reported by Ashman and Van Buskirk[27].

The analysis was performed in Marc-Mentat 2005r3 (MSC. Software Corporation, USA). For the boundary conditions, nodes on both ends of the mandible were restrained. The implant was assumed to be osseointegrated. The touch contact, which is one of the contact types available in the Marc-Mentat program, was used to model all the contacts. Under this contact type, surfaces of contacting bodies are allowed to slide along as well as to separate from each other.

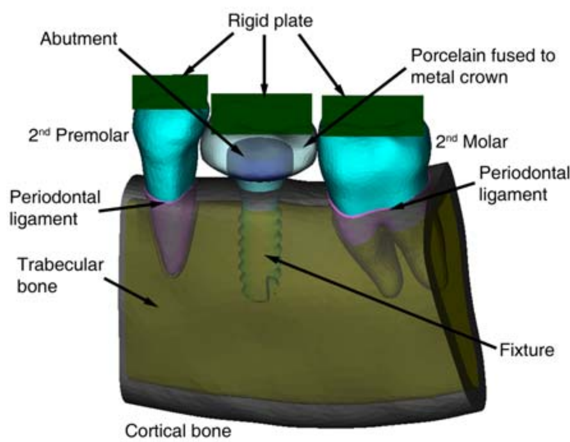

Fig. 1 Geometric model of the STDI, IRC, adjacent teeth, and mandible

Table 1. Material properties used in the analysis

Material	Modulus of elasticity (MPa)	Poisson's ratio
Cortical bone[27]	14,500	0.323
Trabecular bone[20-22]	1,370	0.300
Titanium[23,24]	110,000	0.300
Periodontal ligament[25]	50	0.490
Tooth[26]	18,600	0.350
Gold alloy[20]	91,000	0.330
Porcelain[20]	67,200	0.300

The whole dental implant system consisting of the STDI and IRC is much stiffer than natural teeth. In addition, teeth are also supported by the periodontal ligament, which is a very soft material. As a result, the movement of the dental implant system under occlusal loads is smaller than the movements of natural teeth under the same loads. In the present study, all maxillary teeth were assumed to be natural teeth although they were modeled using the rigid plates. Based on the information reported by Misch[28], the vertical deformation of a tooth can be approximately as large as six times that of a dental implant system. It means that the vertical stiffness of a dental implant system is approximately as large as six times that of a tooth.

In the occlusion with a premature contact by the IRC, first, the dental implant system contacts its antagonist teeth and the contacts between the teeth adjacent to the dental implant system and their antagonist teeth then follow. If the premature contact height is equal to Δ, the combined vertical deformation of the dental implant system and its antagonist teeth must reach the magnitude of Δ when the teeth adjacent to the dental implant system are in contact with their antagonist teeth. Since the vertical deformation of a tooth is approximately six times that of the dental implant system, it means that, in order to have the combined vertical deformation of Δ, the dental implant system must deform by $\Delta/7$ while the antagonist teeth by $6\Delta/7$. This subsequently indicates that, for the premature contact height of Δ, the contacts between the teeth adjacent to the dental implant system and their antagonist teeth start when the dental implant system attains the vertical deformation of $\Delta/7$.

To model the premature contact with the height of Δ, the rigid plate for the IRC shown in Fig. 1 was initially placed at the occlusal surface of the IRC. However, the rigid plates for the second premolar and second molar were initially placed above each of the teeth by the distance of $\Delta/7$. After that, these three rigid plates were moved down to simulate biting. The movements of the plates were divided into two steps. In the first step, the three plates were moved down together by the distance of $\Delta/7$. Note that during this first step, the second premolar and second molar were not in contact with their corresponding plates. Only at the end of the first step, did these contacts begin. Thus, at the end of the first step, the dental implant system attained the vertical deformation of $\Delta/7$. In the second step of the movements, the plates for the dental implant system and the adjacent teeth were moved down independently. Since the vertical deformation of each tooth was assumed to be six times that of the dental implant system, the rigid plates for the second premolar and second molar were moved down by the distance six times that of the plate for the dental implant system. In the second step, the plate for the dental implant system was moved further down by the distance of 5 μm while those for the second premolar and second molar by 30 μm. These numbers were derived from the work by Misch[28]. Fig. 2 shows the schematic illustration of the rigid plate movements.

As mentioned earlier, the touch contact was used to model all the contacts. These contacts included the contacts between the rigid plates and the IRC as well as its adjacent teeth. In addition, there were also the contacts between the IRC and its adjacent teeth. Six load cases were analyzed in the present study. They were the cases with premature contact heights of 0, 50, 100, 150, 200 and 250 μm. The first case where $\Delta = 0$ was the control case in which there was no premature contact at all. The premature contact heights of the other cases were based on the premature contact studies in humans by Carlsson and Haraldson[29], Ikeda et al[10] and Falk et al[30] and the animal experiments conducted by Miyata et al[9].

Results and Discussion

In the present study, the distributions of the von Mises stress and the major principal strain in the bone surrounding the STDI were investigated. The von Mises stress is a scalar variable that is defined in terms of all the individual stress components and, therefore, is a good representative of the state of stresses. It has been extensively used in biomechanical studies

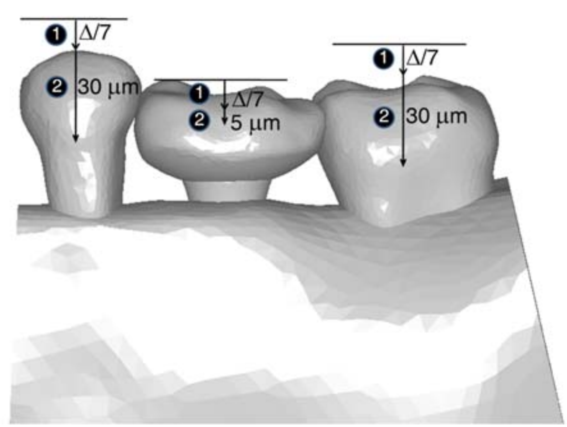

Fig. 2 Schematic illustration of the rigid plate movements

of bone[21-23,31,32]. The major principal strain is the principal strain component that has the maximum absolute value. The principal strains are considered as important parameters for bone adaptation[33]. In the present study, the distributions of stress and strain are shown in the mesial-distal and buccal-lingual planes (see section a-a and b-b in Fig. 3).

Fig. 4 shows the von Mises stress distributions for all the cases. Note that the implant is excluded from the illustrations for clarity. It can be seen from Fig. 4 that, as commonly expected, when the premature contact height increased, the von Mises stress increased in both mesial-distal and buccal-lingual planes. For all premature contact heights, the increases were more pronounced in the region around the STDI neck than in the other regions. The region around the STDI neck is the cortical bone. Sevimay et al[31] and Juodzbalys et al[32] also reported high von Mises stresses in the cortical bone. It is evident that the surface area between the implant and the cortical bone is much smaller than the surface area between the implant and the trabecular bone. In addition, the cortical bone is more than ten times stiffer than the trabecular bone. These are the reasons that high stresses and high stress increments were found in the cortical bone. For the region outside the STDI neck region, the stress increases on the mesial and distal aspects became noticeable only in the case with the premature contact height of 250 μm. Even for this case, the increases were observable only in the small region near the bottom tip of the STDI. As for the buccal and lingual aspects, the increases outside the STDI neck region became noticeable only in the cases with the premature contact heights of 200 and 250 μm.

Since stresses are one contributing factor of marginal bone loss[34], the stress distributions in the cortical bone around the STDI neck were compared in more details. For each premature contact height, the stresses along the paths from the outer surface to the inner surface of the cortical bone shown in Fig. 5 were compared in order to find the maximum stress within these paths. The maximum stresses for all premature contact heights are shown in Table 2. It can be seen from the table that even when the premature contact height was only 50 μm, the maximum stress increased from that of the control case considerably by 415.70%. As mentioned earlier, according to the experimental study by Ikeda et al[10], premature contact heights of less than 100 μm did not produce any cold water triggered pain or occlusal pain. Therefore, the premature contact height of 100 μm may be taken as

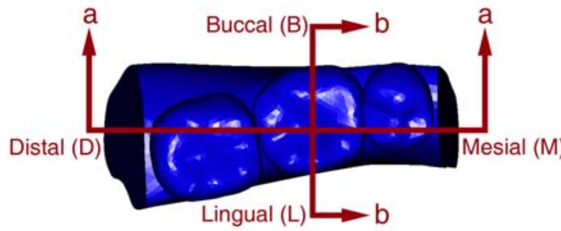

Fig. 3 Section planes for stress and strain comparison

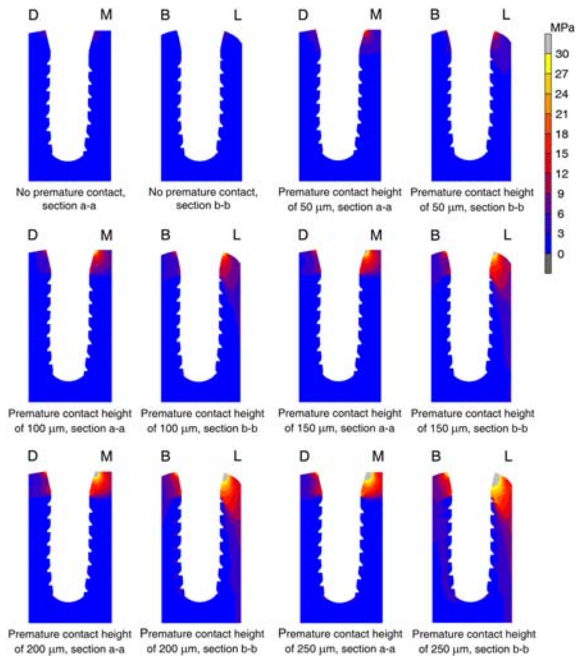

Fig. 4 Comparison of stress distributions

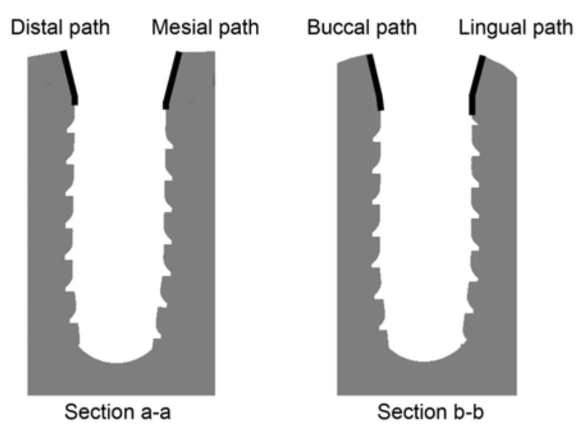

Fig. 5 Paths for stress comparison

Table 2. Comparison of the maximum von Mises stresses between the control and premature contact cases

Case	Maximum von Mises stress (MPa)	Stress increment from the control case	
		MPa	%
Control (no premature contact)	9.68	-	-
Premature contact height of 50 μm	49.92	40.24	415.70
Premature contact height of 100 μm	72.69	63.01	650.93
Premature contact height of 150 μm	98.07	88.39	913.12
Premature contact height of 200 μm	120.87	111.19	1,148.66
Premature contact height of 250 μm	148.43	138.75	1,433.37

the tooth pain threshold. From Table 2, this premature contact height of 100 μm results in a very high stress increase of 650.93%. Since the STDI and the bone are in contact without the periodontal ligament, which provides mechanoreceptors, the premature contact height at the pain threshold for the STDI should be higher than 100 μm. Fig. 6 shows the obtained relationship between the premature contact height and the maximum von Mises stress from Table 2. In addition, Fig. 7 shows the relationship between the premature contact height and the percentage increase of the maximum von Mises stress from the control case. It can be seen from the two figures that the maximum stress increases significantly and almost linearly with respect to the premature contact height.

Fig. 8 shows the major principal strain distributions. As expected, it can be seen that the magnitudes of the major principal strain both in mesial-distal and buccal-lingual planes increased when the premature contact height increased. Similar to stresses, high strain magnitudes occurred in the region around the STDI neck. When the premature contact height was 100 μm or higher, the strain magnitudes in the immediate vicinity of the STDI neck exceeded 4000 με. Based on Frost's mechanostat theory that relates bone modeling and remodeling to strain magnitudes, the bone that is subjected to strain magnitudes of over 4000 με is classified as pathologic overload, which causes the bone resorption[35]. From the obtained results, the area of the pathologic overload increased with the premature contact height. Note that the obtained area of the pathologic overload for the premature contact height of 100 μm was very small. The area of the pathologic overload found in this study agrees well with the area of the marginal bone loss observed in real patients treated by dental

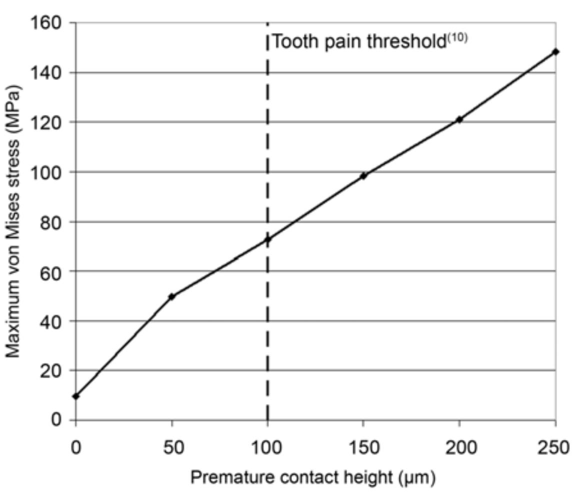

Fig. 6 Maximum von Mises stress versus premature contact height

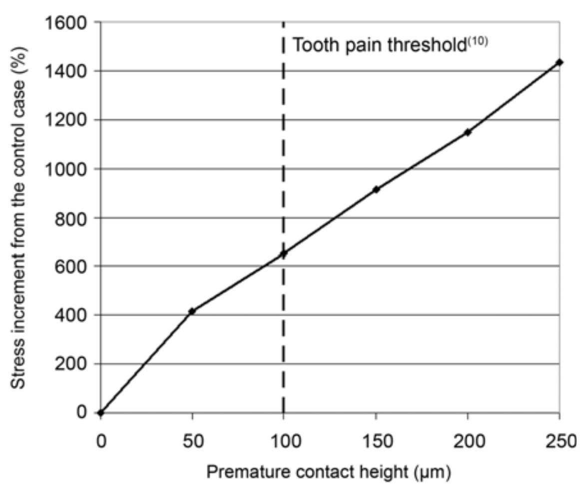

Fig. 7 Stress increment from the control case versus premature contact height

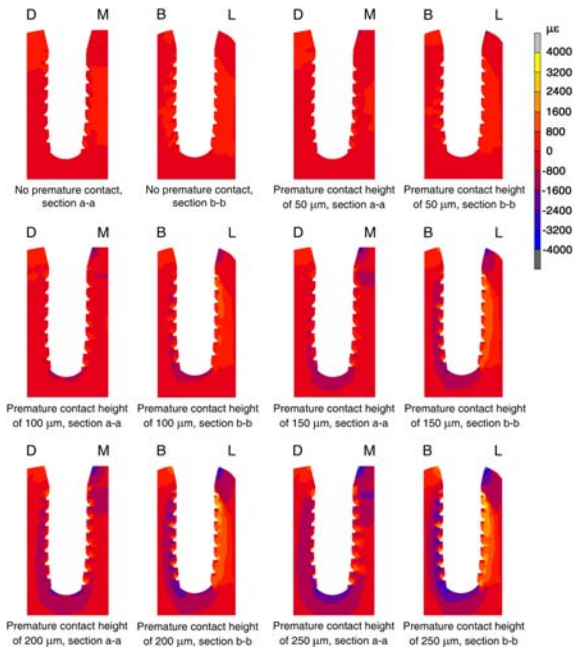

Fig. 8 Comparison of strain distributions

implantation(34,36,37). As for the trabecular bone around the STDI threads, although the premature contact increased the strain magnitudes in this region quite noticeably, except for the premature contact heights of 200 and 250 μm, the strain magnitudes did not reach the pathologic overload of 4000 με. Even in the cases with the premature contact heights of 200 and 250 μm, the area of the pathologic overload in the trabecular bone was found only in a very small region at the thread near the STDI neck.

Conclusion

In the present study, the influence of a premature contact on stress and strain distributions in bone around an STDI was investigated. A realistic 3D FE model of a section of a mandible with an STDI, an IRC and two adjacent teeth was used as a representative subject. Rigid plates were used to simulate the antagonist teeth. The obtained results show that the magnitudes of von Mises stresses in the bone changed significantly when the premature contact occurred in the IRC. High magnitudes of stresses and strains were observed in the cortical bone. The area of high stresses and strains agrees with the area of the marginal bone loss observed in real patients. According to the present study, the influence of premature contacts on stress and strain distributions of bone surrounding dental implants is very high. The FE results suggest that premature contact heights of 100 μm or more lead to high stain levels that are considered as the pathologic overload in the marginal bone. Since the lack of the periodontal ligament in dental implants raises the pain threshold, dental implants have a higher tendency towards occlusal overloading. The premature contact height of an IRC over 100 μm should be avoided as much as possible in order to provide long-term stability of dental implants.

Acknowledgments

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การวิเคราะห์ไฟไนต์เอลิเมนต์ของกระดูกรอบรากเทียมที่รองรับครอบฟันที่มีการสบก่อนตำแหน่งกำหนด

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***วัตถุประสงค์**: เพื่อศึกษาผลของการสบก่อนตำแหน่งกำหนด (premature contact) ที่เกิดจากครอบฟันซึ่งยึดอยู่กับรากเทียม ที่มีต่อหน่วยแรงและความเครียดในกระดูกที่อยู่รอบรากเทียมโดยใช้วิธีไฟไนต์เอลิเมนต์*

***วัสดุและวิธีการ**: การศึกษาเริ่มจากการสร้างแบบจำลองไฟไนต์เอลิเมนต์ 3 มิติของส่วนตัดขากรรไกรล่าง รากเทียม ครอบฟัน และฟันข้างเคียง ในส่วนของฟันคู่สบจะจำลองด้วยการใช้แผ่นแข็งเกร็ง (rigid plates) สามแผ่น ซึ่งการจำลองฟันคู่สบด้วยแผ่นแข็งเกร็งนี้ ทำให้สามารถหลีกเลี่ยงการสร้างแบบจำลองไฟไนต์เอลิเมนต์ของฟันคู่สบ เอ็นปริทันต์ของฟันคู่สบ และขากรรไกรบนได้ นอกจากนี้แนวทางใหม่นี้ ทำให้สามารถเปลี่ยนระยะความสูงของการสบก่อนตำแหน่งกำหนดได้ง่าย โดยการเปลี่ยนตำแหน่งของแผ่นแข็งเกร็ง การศึกษานี้พิจารณาการสบก่อนตำแหน่งกำหนดที่ระยะความสูง 0, 50, 100, 150, 200 และ 250 ไมโครเมตร โดยใช้การวิเคราะห์ไฟไนต์เอลิเมนต์สำหรับปัญหาสัมผัสโดยสมมุติให้วัสดุทั้งหมดมีคุณสมบัติเป็นแบบเชิงเส้น และไอโซทรอปิก*

***ผลการศึกษา**: ขนาดของหน่วยแรง von Mises มีการเปลี่ยนแปลงอย่างมากเมื่อเกิดการสบก่อนตำแหน่งกำหนด ตัวอย่างเช่น หน่วยแรง von Mises เพิ่มขึ้นจาก 9.68 MPa ในกรณีที่ไม่มีการสบก่อนตำแหน่งกำหนด เป็น 49.92 MPa เมื่อมีการสบก่อนตำแหน่งกำหนดที่ระยะความสูง 50 ไมโครเมตร นอกจากนี้ขนาดของความเครียดหลักสูงสุดในขอบกระดูก (marginal bone) เพิ่มขึ้นถึงช่วงภาวะทำให้เกิดพยาธิสภาพ (pathologic overload) ที่ 4000 $\mu\varepsilon$ เมื่อมีการสบก่อนตำแหน่งกำหนดที่ระยะความสูงตั้งแต่ 100 ไมโครเมตรขึ้นไป*

***สรุป**: การสบก่อนตำแหน่งกำหนดมีผลอย่างมาก และควรหลีกเลี่ยงการสบก่อนตำแหน่งกำหนดที่เกิดจากครอบฟันซึ่งยึดอยู่กับรากเทียมที่ระยะความสูงตั้งแต่ 100 ไมโครเมตร ขึ้นไปให้มากที่สุดเพื่อให้รากเทียมสามารถใช้งานได้ยาวนาน*