Evaluation of Influence Factors to Reduce Mechanical Stress on the Marginally Resected Mandibular Bone Against Dental Implant-supported Occlusion

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Abstract: This study aimed to evaluate the mechanical stress on resected mandibular bone against occlusal force using dental implant without any bone grafting by finite element analysis to reduce the risk of the bone fracture. A model of marginal resection of the symphysis of the mandible, in which the bone height of the region was 5, 10 or 15 mm, was prepared. Two, four, or six implant-supported fixed prostheses (superstructure) or overdenture were set up in the model and loaded with 500N of occlusal force. The von Mises stress on the resected region was the highest when two implants were bilaterally placed at positions closest to the resected region. The von Mises stress value on the resected region could be high enough to induce the bone fracture. The mechanical stress was reduced up to < 50 % by adding implant at posterior position and connecting all implants. The presence of superstructure on 4 or 6 implants significantly decreased the von Mises stress when the residual bone height was 10 or 15 mm. Use of 6 implants showed no significant advantage at the stress reduction compared to use of 4 implants. When the residual bone height was 5 mm, reinforcement of the residual bone or bone graft should be considered to avoid the bone fracture. Although the present results were obtained under restrictive conditions, the number of implant, implant position, and prostheses style could reduce the von Mises stress and the risk of bone fracture on the resected region.

Key words: Implant, von Mises stress, Mandibular resection, Finite element analysis

Introduction

Tumor ablation of the mandible involves loss of marginal or segmental bone with the surrounding soft tissue. Needless to say, the remaining teeth present after mandibular bone resection should be sufficient to support removable dentures. However, when mandibular bone resection results in a totally edentulous mandible, dental implantation is a reliable treatment option to rehabilitate occlusal function.

A microvascular bone flap can be used to reconstruct a segmental or marginal mandibular defect at the implant placement site12,13, however, microvascular surgery is a relatively invasive procedure. As a less invasive reconstructive procedure, free bone grafting is often indicated for marginal bone defects of the mandible14. However, there are some concerns with this method, such as the limited amount of soft tissue available to cover the graft material and a relatively high resorption rate of the grafted bone. Particularly, tension-free suture to secure bone healing is difficult due to an inadequate amount of mucosal membrane and the presence of scar tissue at the tumor ablative site.

Vertical distraction osteogenesis is another option to augment bone tissue in sites with marginal mandibular defects. However, a sufficient bone height is needed for this procedure to place the distraction device. In addition, bone resorption because of a non-vascularized graft could trigger peri-implantitis even if the bone augmentation and implant placement procedures have been successfully completed. Therefore, the use of dental implants without bone grafting in cases with marginal bone deficiencies of the mandible could be a viable treatment option. However, it has been reported that the possibility of dental implant-related bone fracture should be considered in patients with atrophied mandibles14,15. Moreover, an unbalanced occlusal force could increase the risk of fracture in the resected region of the mandible16.

These reports indicate occlusal force by dental implants is traumatic force to possibly induce pathological fracture at the resected region in the mandible. Besides the atrophied regions, the position of the inferior alveolar nerve should be considered when placing a dental implant in the mandible. Therefore, implant placement should be planned to achieve minimal mechanical stress on the atrophic region in consideration of anatomical limitations.

Finite element analysis (FEA) has been widely used to simulate mechanical stress on the bone and/or dental implant without performing invasive procedures17,18. Using this advantage, a FEA model of a totally edentulous mandible after tumor ablation was established to evaluate the influence of occlusion on the resected bone region in the present study.

The position and the number of the implant, the length of the residual bone height, and prostheses style (fixed or removal prostheses) were particularly considered to establish an optimized planning for dental implantation into the marginally resected mandible without any bone grafting to reduce the risk of the bone fracture at the resected region.

Materials and Methods

Mandibular defect and dental implant model

A mandibular defect model was created using computer-aided design software (3-Matic; Materialize NV, Leuven, Belgium) based on the Digital Imaging and Communication in Medicine data of a totally edentulous mandible. Three types of mandibular defects according to the residual bone height (5, 10, or 15 mm; Fig. 1A) were created at the midline of the mandible. To simulate the strength of the residual bone against the occlusal forces via a dental implant-supported denture, FEA was performed using Mechanical Finder software (Research
Figure 1. A scheme of the models used in the present study. (A) Implants position, height of residual bone, and superstructure are shown. (B) The distances of implants from the resected region are shown. The anterior, middle and posterior implants are indicated by red, yellow and blue, respectively.

Figure 2. Patterns of implant position. The anterior, middle and posterior implants are indicated by red, yellow and blue, respectively. (A) Six implants. (B-D) Two implants in the anterior, middle, and posterior positions. (E-G) Four implants in the anterior/posterior, anterior/middle, and middle/posterior positions.

Center of Computational Mechanics, Inc., Tokyo, Japan) to simulate implant placement. Dental implants (3.75 mm in diameter; 10 mm in length) were created (Fig. 1A) and bilaterally placed at 5 (anterior), 15 (middle), and 25 (posterior) mm from the defect margin (Fig. 1B). The Poisson’s ratio of the bone model was 0.40 and the Young’s ratio was automatically calculated based on Keyak’s formula. The Poisson’s ratio of the implant was 0.19 and the Young’s ratio was 10800 kgf/mm². There were 242,033–281,384 triangular shell elements and 52,079–57,700 nodes according to the number and lengths of the implants. This study was conducted according to the principles of the Declaration of Helsinki and has been approved by Ethical Committee of Yokohama City University Hospital (Authorization number: B100101001).

Dental implants simulation and FEA

The stress on the residual bone against occlusal forces was measured by FEA. Seven patterns of dental implant positions were created (Fig. 2A-G): (1) bilateral anterior, middle, and posterior implants; (2) bilateral anterior implants; (3) bilateral middle implants; (4) bilateral posterior implants; (5) bilateral anterior and posterior implants; (6) bilateral middle and posterior implants; and (7) bilateral middle and posterior implants. Based on these seven patterns of dental implant positions, three heights of residual bone, and with or without the superstructure (SS) of the dental implants resulted in 42 FEA models. To limit loading conditions, the mandibular ramus was constrained from the X, Y and Z directions. The loading force of occlusion was referred to previous study, which reported that the bite force of 2-implant-supported removal full-prostheses and 6-implant-supported fixed full-prostheses was 416 and 516 N, respectively. According to this report, 500 N was defined as the loading force uniformly in any conditions, and the von Mises stress (measured in MPa) on the residual bone was calculated by FEA. These points were equally loaded. When the stress was loaded without the SS, the stress was directly and equally loaded on each of the implants (Fig. 3A). Three loading points that corresponded...
Results

The von Mises stress value of the resected bone region in each pattern is shown in Fig. 4. The von Mises stress in the pattern of 2 implants in anterior position was the highest in any residual bone height, and regardless of the presence of SS. The von Mises stress in the pattern of 2 implants in posterior position was the lowest in any residual bone height, and regardless of the presence of SS. The von Mises stress in the pattern of 4 implants in anterior and middle position was the second or third highest. The von Mises stress in the pattern of 4 implants in middle and posterior position was the second lowest in the pattern without SS, while the value was the second to forth lowest in the pattern with SS. The von Mises stress in the pattern of 6 implants was the third to fifth lowest in the pattern without SS, while the value was the second to third lowest in the pattern with SS. The von Mises stress in the pattern with SS was consistently lower than that in the same pattern without SS. The stress reduction of 4 or 6 implants was significantly greater than that of 2 implants (Fig. 5A). The von Mises stress in the pattern of 2 implants showed no difference in any residual bone height (Fig. 5B). The von Mises stress in the pattern of 4 or 6 implants without
SS was significantly higher than that with SS when the residual bone height was 10 or 15 mm (Fig. 5C). Regarding the influence of residual bone height, the shorter the residual bone height, the greater von Mises stress (Fig. 6A-D). There were no other correlations among the implant length, residual bone height, and von Mises stress. The presence of SS in the pattern of 2 implants showed no significant difference in any residual bone height (Fig. 7A). The von Mises stress on the 15 mm-residual bone in the pattern of 4 or 6 implants with SS was significantly lower than that with SS in the model using 4 or 6 implants, and the residual bone height is 15 or 10 mm.

**Discussion**

The results of the present study showed that von Mises stress on the resected bone region against occlusal forces was strongest when two dental implants were placed close to the resected region and
A short running title: Naohito Tamai et al.: Mechanical Stress on the Resected Mandibular Bone

The bone strength can decrease by up to ≤50% due to various factors, such as bone quality and aging10-12), indicating that the threshold of bone fracture could be less than 30 MPa in elderly patients. This value seems to increase the risk of fracture of the resected bone region. Even more, the threshold could be further lowered in the resected bone, which is a stress gathering part. The present study suggests that implants should be placed as far as possible from the resected region in order to minimize the mechanical stress on the resected area. However, overdenture on two implants located far from the resected regions seems to be unstable. And, if those implants are connected each other, stress around peri-implant bone is expected to remarkably increases. Therefore, clinically, 4 or 6 implants support fixed prosthesis could be a reliable option to reduce the von Mises stress on the resected region. Use of a one-piece superstructure can reduce mandibular flexure and decrease the stress against the loading force13,15). In fact, superstructure on 4 or 6 implants significantly decreased the von Mises stress on the resected region in the present study, although it depended on the residual bone height in the resected region. The significant difference was seen when the residual bone height was 15 or 10 mm. As mentioned above, von Mises stress on the bone resected region does not exceed 60 Mpa when the bone height was 10 mm and more, but it could be over 100 Mpa according to occlusal condition when the bone height was 5 mm7. Therefore, reinforcement with titanium plate on inferior mandibular boarder should be considered when the residual bone height was 5 mm; otherwise bone grafting should be considered. Regarding of using 6 implants, no benefit was seen even though those implants were connected in the present study, indicating use of 4 implants is sufficient to reduce the von Mises stress on the resected region.

If the height of the mandible is insufficient to accept a long implant because of anatomical reasons, tilted implants may be indicated. Tilting a distal implant could contribute to stress distribution around an implant supporting a fixed prosthesis13,15). It was reported that tilted implants reduced stress around the bone and implants15). While, it was also reported that a tilted posterior implant in the mandible induced greater stress around the peri-implant bone15). A review by Del Fabbro and Ceresoli15) found no significant difference between axial and tilted implants in regard to marginal bone loss during the early to mid-observation period.

This study simulated the anterior part of the mandible, in which the frequency of the marginal bone resection due to gingival carcinoma is less than the posterior part. Even though posterior part of the mandible is marginally resected, either two-implant supported overdenture or all-on-4 technique, that would not influence mechanical stress on the resected region by reducing occlusal force to the region, could be still indicated rather than the anterior part. Therefore, present study evaluated the anterior part of the mandible, but further investigation will be needed to widely indicate dental implant supported occlusal rehabilitation after marginal mandibular resection on any site in the mandible.

This study demonstrated the mechanical stress on the resected bone region of the mandible to support a removable or fixed prostheses. The von Mises stress on the resected bone region could be reduced up to less than 10 MPa by use 4 implants including 2 implants placed as far distally and bilaterally as possible from the resected bone area. And, the presence of superstructure significantly decreased the stress of the resected region. Although the present results were obtained under restrictive conditions, within the limitations of the study, it was concluded that the number of implants, implant position, and prostheses style could reduce a risk of bone fracture on the resected region. Dental implant therapy without any bone grafting after marginal mandibular

mostly weakest when placed farther from the resected region. Two implants near the resected region increased the von Mises stress regardless of whether the implants were connected. The difference in von Mises stress between the closer area (anterior position) and the more distant area (posterior position) was more than two-fold in the pattern without superstructure and more than three-fold in the pattern with superstructure. That is to say, the von Mises stress on the resected bone region was decreased by up to <50% by changing the implant insertion position to more distant area from the resected region. The threshold of bone fracture is reported to be 60 MPa in the compact bone of young adults, although the von Mises stress on the resected region is dependent on the loading force7). Murakami et al.7) reported that the loading point influenced the von Mises stress and that the von Mises stress on the resected region against the mean maximum bite force of an adult male does not exceed 60 MPa if the bone height is ≥9 mm. That study also reported that with a residual bone height of the resected region of 5 mm, the von Mises stress against the mean bite force of an adult male was nearly 100 MPa, which is sufficiently strong to fracture the bone when an occlusal force of approximately 500 N was loaded on a single point close to the resected region. The present data obtained by providing a loading force of 500 N equally to three points of the occlusal plane and with a maximum von Mises stress of approximately 20 MPa (two implants at the closest positions from the resected region) suggested that the von Mises stress on the resected region could be reduced up to 20% by equalizing the loading forces. Moreover, the stress could be reduced up to less than 10% of the potential maximum forces by positioning implants further from the resected region.

Figure 7. Influence of residual bone height on the von Mises stress. (A) No significant difference of the von Mises stress is seen in the model using 2 implants. (B) The von Mises stress of the model using 4 or 6 implants with SS is significantly lower for the model of 15 mm in residual bone height than those of 10 and 5 mm.
resection could be a treatment option, but reinforcement of the bone or bone graft procedure should be considered when the residual bone height is 5 mm and less.

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Conflict of Interest

The authors have declared that no conflict of interest.

References