치의학 박사학위 논문

Comparison of implants placed in mandible and reconstructed fibula using finite element analysis

유한 요소 해석을 이용한 하악골과 재건된 비골에 식립된 임플란트의 비교

2018 년 8 월

서울대학교 대학원
치의학과 치과보철학 전공

허 경 회

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지도교수 권 호 범

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-Abstract-

Comparison of implants placed in mandible and reconstructed fibula using finite element analysis

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Purpose: The purpose of this study was to compare dental implants placed in mandible and reconstructed fibula under the same loading conditions using three-dimensional finite element analysis.

Materials and methods: Two three-dimensional finite element models were developed to analyze biomechanical behaviors of implants placed in mandible and reconstructed fibula. Mandible model was composed of the mandibular segment, implant systems, and two-unit splinted implant-supported crowns. Fibula model included the same components except that the mandible was replaced with a reconstructed fibula. In the implant-abutment joint with abutment screw, preload was achieved. Oblique loading of 150 N was applied to the occlusal surfaces of the splinted crowns at 11.54 degrees to apico-coronal direction. The stress distribution patterns and the maximum von Mises stress of the individual components were compared.

Results: In the supporting bones, stress was concentrated in the cortical bone around the implant neck. After screw tightening and before the imposition of oblique loads, the pattern and values of the von Mises stresses were similar between the mandible and fibula models. The highest von Mises stresses in the cortical bone were 6.7 MPa in the mandible model and 7.1 MPa in the fibula model. After application of oblique loads, the highest von Mises stresses in the cortical bone were 11.5 MPa in the mandible model and 25.2 MPa in the fibula model. In the implant systems, the highest stress concentration was observed in the abutment screws in all models. After screw tightening and before the application of oblique loads, the stress distributions of the two models were similar to the ones before loading. The highest von Mises stresses in the abutment screws and abutments were 115.7 MPa in the mandible model and 115.1 MPa in the fibula model. After application of oblique loads, the maximum von Mises stress on the implants was 113.5 MPa in the mandible model and 116.2 MPa in the fibula model.

Conclusion: Within the limits of this study, the splinted implant-supported fixed prosthesis placed in the reconstructed fibula might be a successful treatment option for the patient who underwent mandibular reconstruction based on biomechanical behaviors.

Key Words : Finite element analysis, fibula, mandible, mandibular reconstruction, implant, preloading

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CONTENTS

I . INTRODUCTION

Mandibular reconstruction with a fibula free flap has recently become one of the favored treatment options after mandibulectomy.[1,2] Several studies have reported favorable esthetic and functional outcomes due to the high cortical bone proportion and mechanical rigidity of the fibula.[3-6] Success and survival rates of implant placement in the reconstructed fibula have been reported to be considerably high.[7-9] Jaquiery et al. studied the vertical bone resorption around implants in the reconstructed fibula. During the one-year observation period, the mean level of attachment was similar to that of implants placed in the normal bone, but the radiologically measured vertical bone loss was rather lower.[7] Kramer et al. demonstrated that a fibula free flap provides consistent, reliable, and predictable reconstruction results with implants.[8] Chiapasco et al. reported that implants placed in a reconstructed fibula demonstrated normal integration comparable to that in an intact mandible, with a success rate of 98.6% and survival rate of 93.1%.[9] Smolka et al. evaluated the efficacy of mandibular reconstruction treatment strategies, and reported that the survival rate of an implant in the fibula was 92% over 9 years.[1] Therefore, a fibula graft is considered to be the optimal method for reconstruction using implants after mandibulectomy.

The fibula has a long dimension with a thick cortical bone layer, making it favorable for reconstruction of the mandible.[10,11] In addition, the donor site is easy to access, enabling the removal and resection at once. Flaps are relatively hairless and thin paddles that can be lifted from the mobile diaphragm and can be used in the mouth.[10] However, its achievable bone height and diameter are lower than those of the normal mandible.[12] The limited height and width of the fibula often create prosthetic challenges for mandibular reconstruction. Because the dimensions of the fibula are smaller than those of the intact mandible, the maxillomandibular space for prosthodontic treatment is increased. As a result, when prosthodontc treatment was performed, the osseointegrated implant has a high crown-implant ratio. The crown-implant ratio is one of the biomechanical prosthetic factors implicated in implant failure.[13-15] Because of an increased moment arm, an undesirable crown-implant ratio could result in excessive lateral load that would increase the stress concentration on the cervical supporting bone.[16,17] Crown height is also related to lever arm mechanics. Vertical loads transferred through the long axis of the implant are not noticeably affected by crown height. However, because the direction of occlusal load is off-axis with a significant lateral vector, a moment arm is created that increases stress concentration at the implant neck.[18] This limitation becomes even more critical in partial or hemimandibulectomy patients, where one side of the mandible is intact, creating a difference in supporting bone height. This could result in poor implant-crown ratios and unfavorable loading conditions. The overloading may cause stress concentration around the implant, which could result in bone resorption or component fracture.[19-22] Sugiura et al. compared the various finite element models to investigate the critical threshold stress that lead to bone resorption by strain measurement in vivo. In addition, various finite element models using the fibular graft were evaluated. The reconstructed model showed a clear stress concentration in the cortical bone around the screw and the critical threshold for bone resorption was about 50 Mpa.[20] Additional information is needed for a complete understanding of the bone resorption around the implant, but both modeling and remodeling at the interface of the overloaded implant are known to increase, which can lead to bone loss.[21] Thus, implant-supported fixed prostheses in the reconstructed fibula usually demonstrate unfavorable biomechanical properties.[23] Biomechanical evaluation is therefore important to reduce the failure of dental implants in the reconstructed fibula.

When the abutment is connected to the implant, a tightening torque is applied as a moment to the head of the screw. This applied moment is then transferred along the interface of the abutment screw thread surfaces and implant bore threaded surfaces, creating a contact force that clamps the abutment and implant.[24,25] The clamping force is called the preload, which may affect stress distribution between the prosthesis and implant and between the implant and supporting bone. If properly applied, the preload on the abutment and implant result in a firm connection and behavior of the abutment and implant as a single integrated unit, while the opposite may increase the risk of screw loosening or component fracture between the abutment and implant.[26-28]

Three-dimensional finite element analysis (FEA) provides information that is difficult to measure directly in the human maxillofacial area, and thus is an acceptable research method for predicting the biomechanical characteristics of dental implants.[29-31] Clinicians can better interpret the results of FEA studies and correctly estimate these results in clinical situations by understanding the basic theories, applications, and limitations of FEA in implant dentistry. Several studies were conducted to analyze the implants on the normal edentulous and partially edentulous mandibles. Meijer et al. constructed a three-dimensional model of the edentulous mandible with two dental implants. Stress distribution patterns were compared for splinted implants by a bar structure with non-splinted implants.[32] As a result, only a slight difference in stress concentration was observed between the models. Analysis of the reconstructed mandibular bone model was further advanced by Tie et al. who developed a mandibular reconstructed model via autologous bone grafts with different areas. Stress distribution of cortical bone was evaluated by applying vertical force.[33] In these models, there was no superstructure on the reconstructed mandible. Nagasao et al. reported the stress distribution patterns on the various types of reconstructed mandibles with a bar structure.[34] The stress around the implant fixtures varied greatly depending on the models. Although many studies have used FEA to investigate the stress distribution around implants in intact mandible[32,35,36], few studies have analyzed the stress distribution around implants in reconstructed fibula using this analytical method, taking into account occlusal forces and preload. The purpose of this study was to compare the stress distribution around dental implants placed in mandible and the fibula models under the same loading conditions by using three-dimensional finite element analysis.

Ⅱ. MATERIALS AND METHODS

Two three-dimensional finite element models were developed to analyze an implant-supported fixed prosthesis placed either in the intact mandible or in the grafted fibula using computed tomography (CT) data from a patient. The patient was a 24-year-old female who had undergone mandibulectomy and reconstruction with a fibula free flap. One model was composed of the mandibular segment, implant systems, and two-unit splinted crowns and termed mandible model. The other model included the same components except that the mandible was replaced with a fibula and termed fibula model. The external geometries of the mandible and the fibula were extracted mesiodistally as 25 mm long segments using the commercial 3D segmentation software Amira (FEI, Hillsboro, OR). Geometries were then exported to a meshing program (Visual-Mesh, ESI Group, Paris, France) as tetrahedral meshes. Meshes of two implants with two-unit splinted crowns were created and placed in the middle of the bone blocks. External connection type implants (Osstem US system, Osstem Implant Co., Busan, Korea) that measured 4 mm in diameter and 10 mm in length were used. The distance between two implants at the implant shoulder was 4 mm. Meshes of splinted crowns were created in accordance with the opposing maxillary dentition. A height of the crown was about 26 mm in the fibula model. For the intact mandible, the normal mandibular segment of the contralateral side with the same mesiodistal length was used. The height of the crown was about 11 mm in the mandible model. CT data and implant data were then converted into stereo-lithography (STL) files composed of triangular surface elements. Tetrahedral elements for the finite element analysis were constructed volumetrically with a meshing program (Visual-Mesh, ESI Group, Paris, France). The simulation models are shown in Fig. 1. The finite element models were composed of six components which were the cortical bone, cancellous bone, implants, gold screws, abutments and crowns. The total number of nodes and finite elements were 12,360 and 44,688 for the fibula model, and 15,204 and 56,994 for the mandible model.

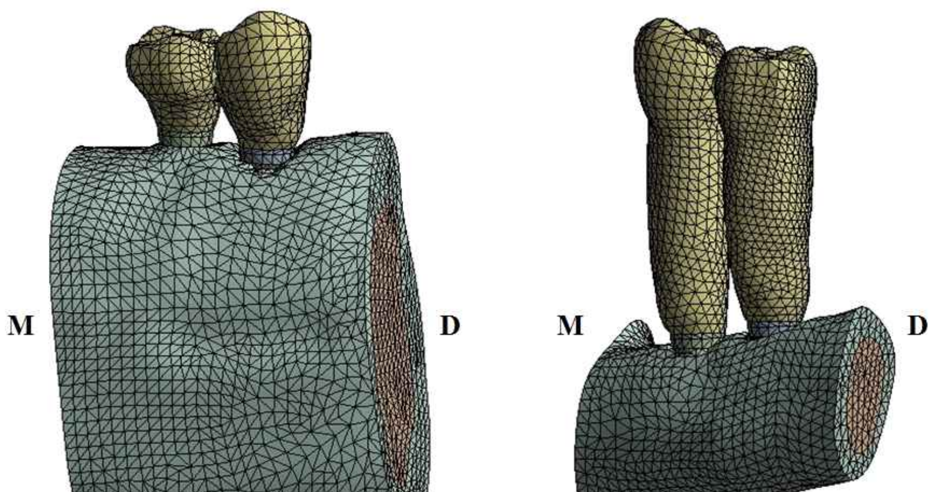

Fig. 1. Three-dimensional finite element models. (a) Splinted implant-supported crowns in mandible model, (b) Splinted implant-supported crowns in fibula model. M, mesial side; D, distal side.

Mechanical properties of the materials were based on previous studies.[37,38] Cortical bone and cancellous bone were considered to have anisotropic, linear elastic, and homogeneous material properties. The elastic modulus and the Poisson ratio in each direction are summarized in Table I.

The implant prostheses were considered to be made of zirconia crowns, the screws of the implants of gold alloy, and the implants and abutments of titanium. The material properties of the crowns, screws, fixtures, and abutments were based on previous studies and are summarized in Table II.[31,39] To simplify calculations, titanium, gold alloy, and zirconia were assumed to be linearly elastic and isotropic.

Table 1. Bone properties[37,38]

Properties	Cortical bone	Cancellous bone
E_x	12,500	210
E_y	26,600	1,148
E_z	17,900	1,148
G_{xy}	4,500	68
G_{yz}	7,100	68
G_{zx}	5,300	434
v_{xy}	0.18	0.055
v_{yz}	0.23	0.055
v_{zx}	0.31	0.322

Ei, Elastic modulus (MPa); Gi, Shear modulus (MPa); v, Poisson ratio. x-direction is anteroposterior; y-direction is apicocoronal; z-direction is buccolingual.

Table 2. Elastic moduli and Poisson Ratios of the materials[31,39]

Component	Elastic modulus (MPa)	Poisson ratio
Zirconia	210,000	0.27
Gold alloy	100,000	0.3
Titanium	106,000	0.34

To connect the implant and the abutment, the screw was placed. After assembling the implant system, the screw was tensioned in the apicocoronal direction. Based on previous studies,[25,40] the screw was preloaded with 500 N by a virtual pre-tensioned spring element.[41,42] The interfaces between the cancellous bone and cortical bone, cancellous bone and the implant, and cortical bone and the implant were assumed to be perfectly bonded. The Coulomb friction model was employed for contacts between other components.[43] In this study, the friction coefficient of the surface between the abutment and the implant was set to 0.16. The friction coefficient of the surface between the abutment and the screw, and between the screw and the implant were both set to 0.2.[40,43,44]

Oblique loading was applied to the crowns in both models. The occlusal force was designed to challenge the supporting bones, but the magnitude and direction were kept within normal range. Based on previous studies,[38,33,34,45] the magnitude of the oblique loading was 150 N. The ratio of the horizontal to vertical components was 1:5. Oblique loads were applied at 11.54 degrees to the apico-coronal direction.

Nodes in the mesial and distal surfaces of the bone segments were fixed in all directions (Fig. 2). The effects of the loads on the fibula and mandible were investigated. Commercial finite element software (ANSYS v14.5, Swanson Analysis System Inc., Houston, PA) was used for finite element analysis. The reconstructed fibula with two dental implants was compared to a normal mandible with two dental implants. Oblique loading was applied to the normal mandible model using the same conditions as used for the reconstructed mandible model. After the preload was applied, stress distributions were analyzed with or without oblique loading. Comparisons of stress distributions were performed using measurements of the maximum von Mises stress values and analyzing the patterns of the von Mises stresses. The protocols and procedures of the study were reviewed and approved by the Institutional Review Board at Seoul National University Dental Hospital.

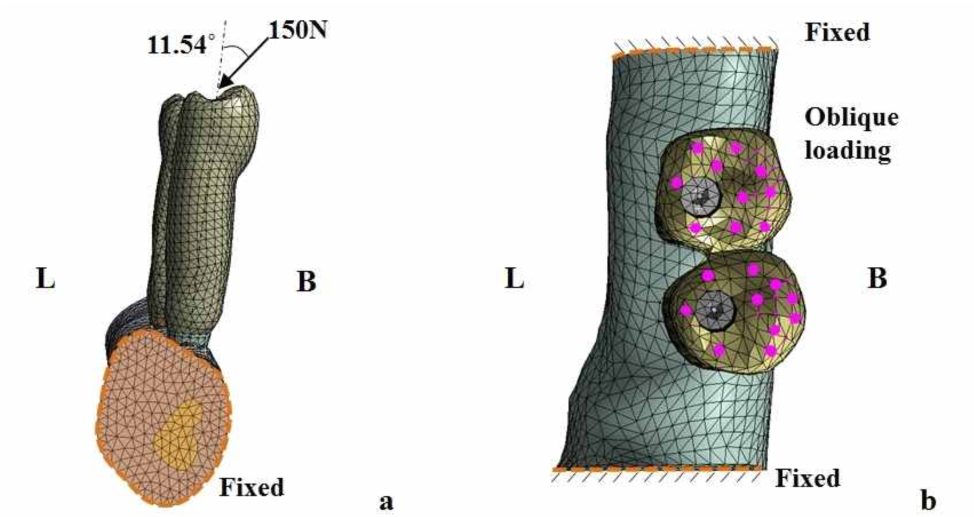

Fig. 2. Application of occlusal force. (a) Occlusal force of 150 N was applied at 11.54 degrees to the apico-coronal direction, (b) Nodes in the mesial and distal surfaces of the bone blocks were fixed and the locations where the occlusal forces were distributed were indicated by pink dots. B, buccal side; L, lingual side.

Ⅲ. RESULTS

The highest stress concentrations were observed in the abutment screws in all models regardless of the oblique load (Table III). The maximum stress areas were located at the surface between the abutment and implant (Fig. 3). In the supporting bone, the maximum stress was concentrated in the cortical bone around the implant neck (Fig. 4). Once the highest stress was achieved, a slight reduction in stress continued to the buccal and lingual sides along the cortical bone. In the implant system, stress was concentrated in the head of the screw and inferior surface of the abutment. Cross-sections revealed stress propagation from the interface between the abutment and the abutment screw to the implant (Fig. 5).

Table 3. The highest von Mises stress values (MPa) in the individual components with or without oblique load (150 N)

Components	Mandible model		Fibula model	
	No oblique load	Oblique load	No oblique load	Oblique load
Cortical bone	6.7	11.5	7.1	25.2
Cancellous bone	0.5	0.4	0.3	1.3
Crown	20.9	34.3	19.9	37.3
Abutment	83.4	102.2	86.9	112.2
Screw	115.7	113.5	115.1	116.2
Implant	59.8	73.4	57.7	97.1

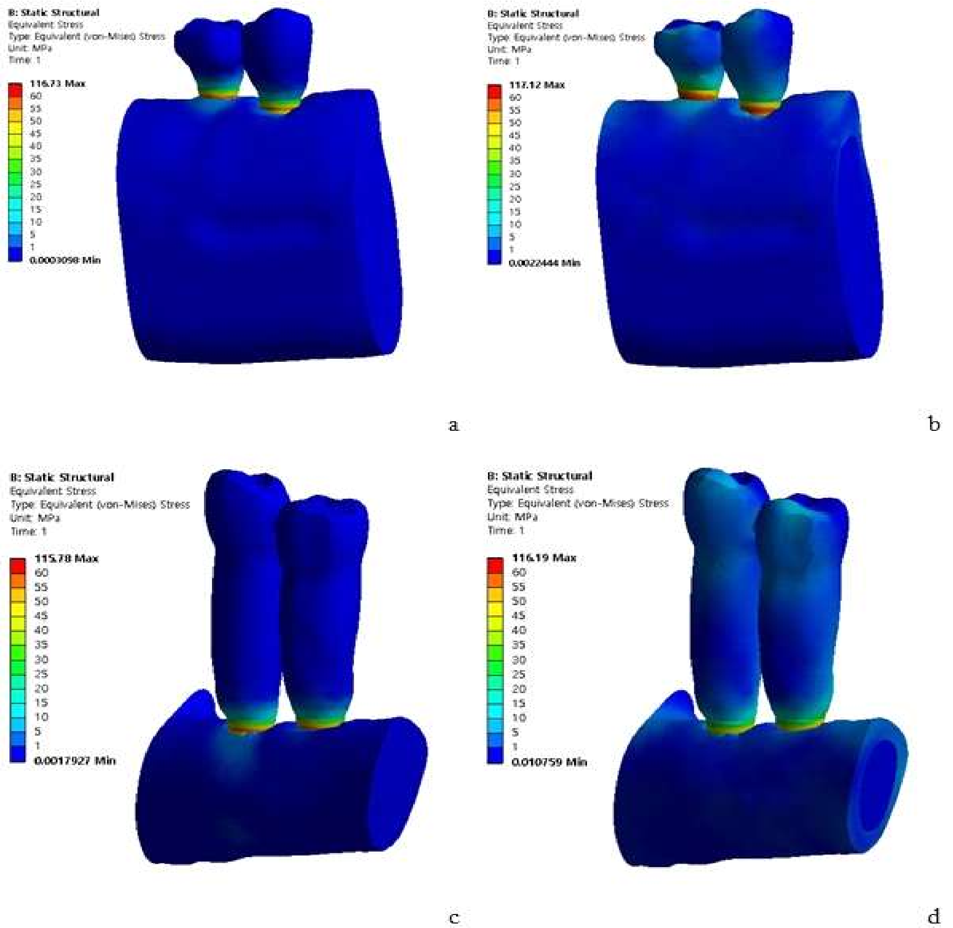

Fig. 3. Stress distributions on the models with or without oblique loading. The maximum stress was concentrated in the surface between the abutment and implant. The left side of the figure shows the mesial direction and the opposite side shows the distal direction. (a) Stress distributions on mandible model without oblique load, (b) Stress distributions on mandible model with oblique load, (c) Stress distributions on fibula model without oblique load, (d) Stress distributions on fibula model with oblique load.

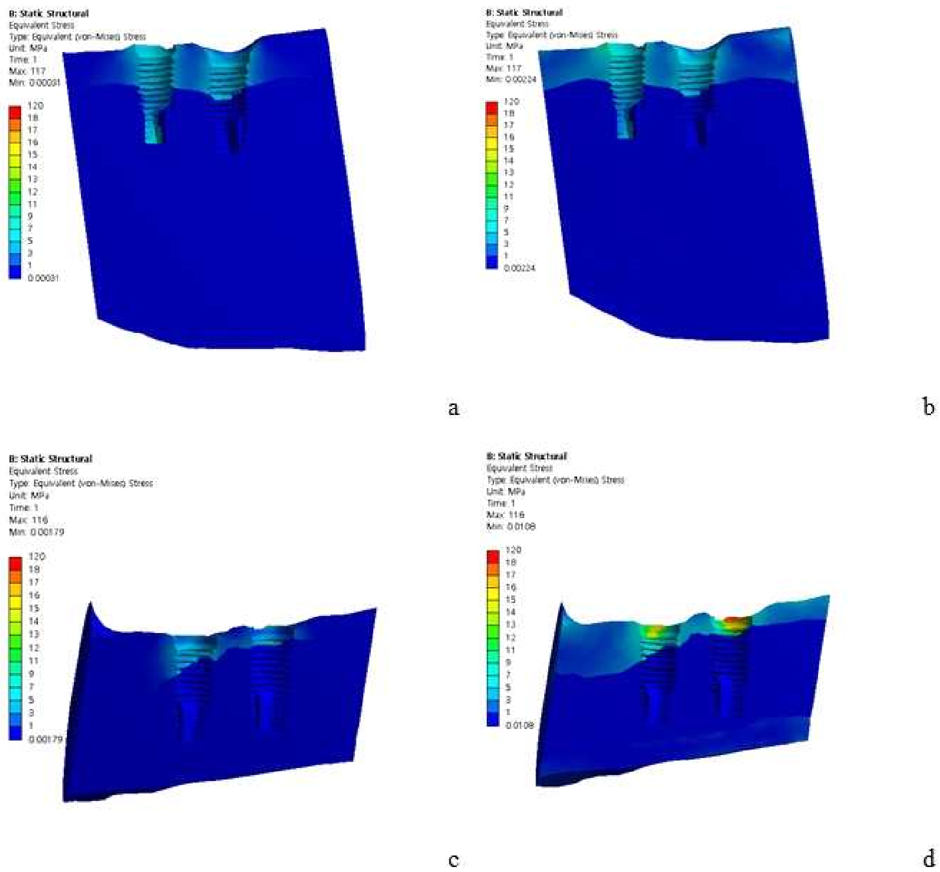

Fig. 4. Stress distributions in supporting bones with or without oblique loading. Both models showed high stress concentrations in the cortical bone around the implant neck. The highest von Mises stress values in the fibula model was higher than that in the mandible model. The left side of the figure shows the mesial direction and the opposite side shows the distal direction. (a) Stress distributions on mandible model without oblique load, (b) Stress distributions on mandible model with oblique load, (c) Stress distributions on fibula model without oblique load, (d) Stress distributions on fibula model with oblique load.

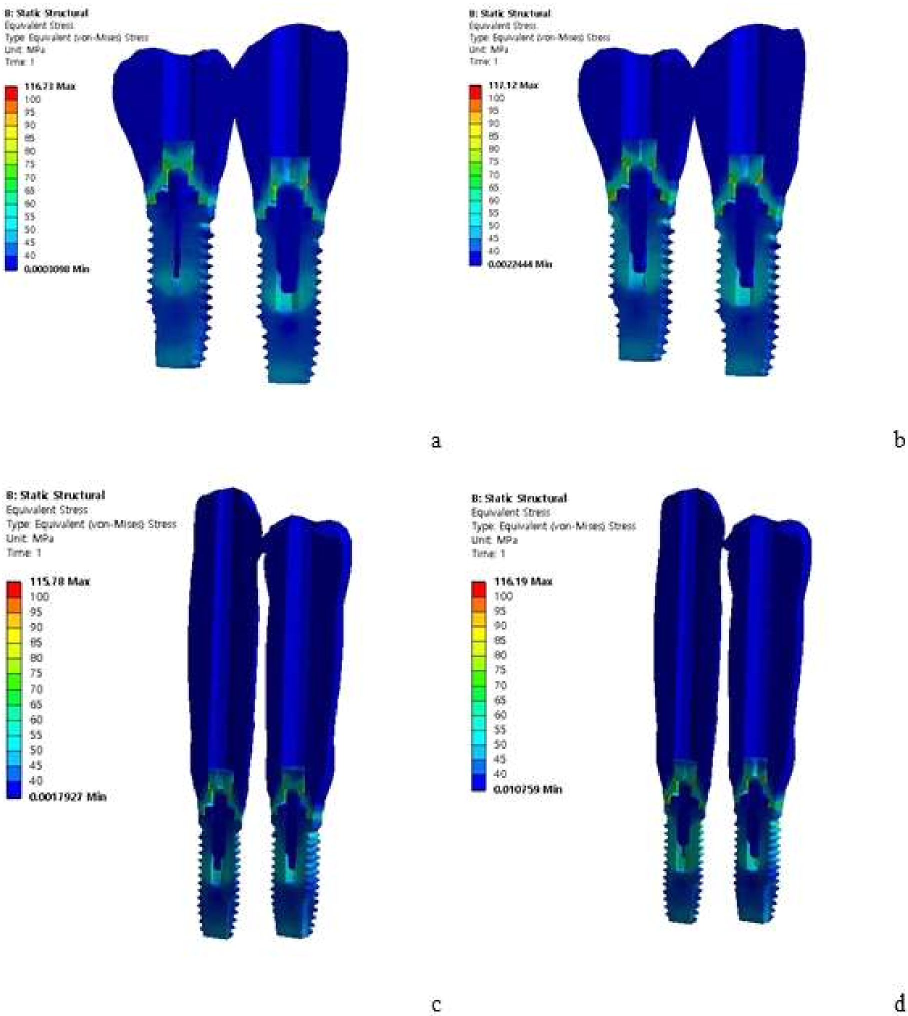

Fig. 5. Stress distributions in implant components with or without oblique loading. In both models, the maximum stress was concentrated in the abutment screw. The left side of the figure shows the mesial direction and the opposite side shows the distal direction. (a) Mandible model without oblique load, (b) Mandible model with oblique load, (c) Fibula model without oblique load, (d) Fibula model with oblique load.

In the supporting bones, after screw tightening and before the imposition of oblique loads, the pattern and values of the von Mises stresses were similar between the fibula and mandible models. Stress was uniformly distributed along the cortical bone of the fibula and mandible (Fig. 3). The highest von Mises stresses in the cortical bone were 6.7 MPa in the mandible model and 7.1 MPa in the fibula model. After imposition of oblique loads, there were remarkable differences between the models (Fig. 6). The highest von Mises stresses in the cortical bone were 11.5 MPa in the mandible model and 25.2 MPa in the fibula model. The highest von Mises stresses in the cancellous bone were 0.4 MPa in the mandible and 1.3 MPa in the fibula. The maximum von Mises stresses in the cortical and cancellous bone in the fibula model were 219.1 % and 325.0 % greater than those in the mandible model.

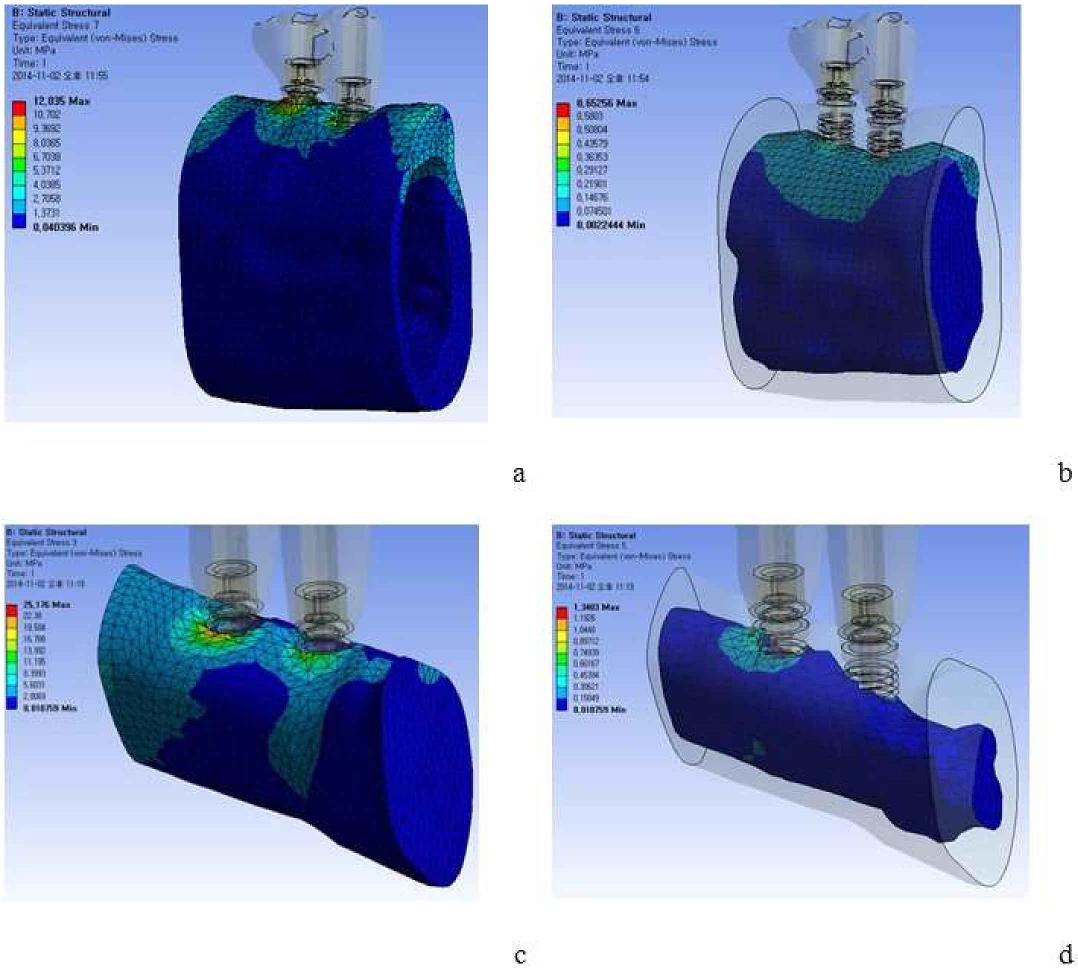

Fig. 6. Stress distributions in cortical and cancellous bones with oblique loading. High stress concentrations occurred in the cortical bones and hardly occurred in the cancellous bones in both models. The left side of the figure shows the mesial direction and the opposite side shows the distal direction. (a) Stress distribution of cortical bone in mandible model, (b) Stress distribution of cancellous bone in mandible model, (c) Stress distribution of cortical bone in fibula model, (d) Stress distribution of cancellous bone in fibula model.

In the implant systems, the stress distributions of the two models were similar before imposition of oblique loads (Fig. 4). The highest von Mises stresses in the abutment screws and abutments were 115.7 MPa and 83.4 MPa in the mandible model, versus 115.1 MPa and 86.9 MPa in the fibula model. The highest von Mises stresses in the crown were 20.9 MPa in the mandible model, versus 19.9 MPa in the fibula model. The highest von Mises stresses in the implant were 59.8 MPa in the mandible model, versus 57.7 MPa in the fibula model (Table III). After imposition of oblique loads, the maximum von Mises stresses on the implants were different between the two models; 73.4 MPa in the mandible model and 97.1 MPa in the fibula model. However, in other prosthodontic components there were no prominent differences between the two models. In the mandible model, the maximum von Mises stresses of the crown, abutment, and abutment screw were 34.3 MPa, 102.2 MPa, and 113.5 MPa. In the fibula model, the corresponding von Mises stress values of the crown, abutment, and abutment screw were 37.3 MPa, 112.2 MPa, and 116.2 MPa (Table III).

Ⅳ. DISCUSSION

The present study demonstrated the stress distributions and maximum von Mises stresses of implants and supporting bone due to screw preload and oblique occlusal load. This study used mandible and fibula models with osseointegrated implants. Because the reconstructed fibula had a shorter vertical height than the intact mandible, the crown height of the fibula model (26 mm) was approximately 2.4 times greater than that of the mandible model (11mm). The maximum von Mises stress value in the cortical bone of the fibula (25.2 MPa) with oblique loading was 2.2 times higher than that of the mandible model (11.5 MPa). This result is in accordance with those reported in previous studies.[13-17] Sotto-Maior et al. investigated the influence of crown-implant ratio, retention system, and occlusal loading on stress concentration in short implants. High crown-implant ratios made the largest contributions to increased stress concentrations in single crowns supported by implants.[46] Nissan et al. reported the effect of crown-implant ratio and crown height space on stress distribution. Crown height was also an important determinant of biomechanical effects, and prosthetic failure occurred when the crown height space was greater than 15 mm.[47] In contrast, other studies have reported that the crown-implant ratio does not influence implant survival rate.[48,49] In a systematic review, the crown-implant ratio of implant-supported reconstructions did not influence peri-implant crestal bone loss. Therefore, an unfavorable crown-implant ratio for implants placed in the fibula was considered to be clinically acceptable.[49]

The quality and quantity of surrounding bone can also have a large impact on the stress distribution around the implant. There are no periodontal ligaments around the dental implants compared to natural teeth, and the dental implants and surrounding bones are exposed to various levels of stress caused by occlusal forces.[50] Kitagawa et al. investigated the effect of cortical bone thickness and young's modulus on the stress distribution around the implant by using three-dimensional finite element analysis.[51] As the thickness of the cortical bone increased, the maximum von Mises equivalent stress decreased. When the thickness of the cortical bone increased from 0.5 to 2.0 mm, the maximum von Mises equivalent stress reduction rates increased to 36% and 41%, respectively. As Young's modulus of the cortical bone increased from 5 GPa to 25 GPa, the maximum von Mises equivalent stress increase rates increased to 271 % and 298 %, respectively. This study also confirmed the influence of the quality and quantity of cortical bone on the stress distribution. In this study, the models were constructed by extracting CT images of the patient who underwent real mandibular reconstruction. Therefore, the thickness of the cortical bone in the patient's mandible and reconstructed fibula differed, and the thickness of the cortical bone in the bone block was different depending on the location. It did not have a constant cortical bone thickness anywhere on the model. However it could be a better reference because it is closer to the real clinical situations. In general, the thickness of the cortical bone in the mandible is known to vary greatly depending on the presence or absence of the tooth and the location in the mandible. According to a study by Schwartz-Dabney and Dechow, the thickness of the cortical bone in the posterior edentulous area of the mandible ranged from 2.1 mm to 2.7 mm.[37] On the other hand, the fibula is known to have a cortical bone similar to or slightly thicker than the mandible. Matsuura et al. reported that eighty fibulae obtained from cadavers showed that the average thickness of the cortical bone was 2.7 mm.[52] Frodel et al. found that the median cross-sectional thickness of the fibular cortical bone was 3.0 to 4.2 mm.[53] They suggested that the cortical bone of the fibula was as thick as the cortex of other bones used for grafts. Moscoso et al. reported that about 66.7% of the cross-sectional area of the fibula was cortical bone.[54] The elastic modulus of the cortical bone could also have a large effect on the stress distribution.[37,51] In this study, the physical properties of the mandible and reconstructed fibula were set equal. Although the elastic modulus, shear modulus, and Poisson ratio values were different in each direction, anisotropy was given to the properties of the cortical bone, but there was a limit in setting the values of the mandible and the fibula to be the same. These physical properties were factors that could have a great effect on the stress distribution. Future studies would be needed to give different physical properties to each model and to reflect the actual changes in the model depending on the position of the bone block.

Bone morphology is regulated by mechanical loading thus, loading conditions may result in bone remodeling.[55] Although there is insufficient data to determine the limit of stress at which bone resorption begins, several studies have attempt to find the critical threshold for bone resorption.[56,57] Previous studies showed that a compressive stress of approximately 40 MPa in cortical bones would be physiological to the bone, while the critical threshold for bone resorption would be around 50 MPa.[20,58,59] In this study, the maximum von Mises stress value in the cortical bone of the fibula was 25.2 MPa under the oblique loading of 150 N, compared to 11.5 MPa for the mandible. Although the peak value of von Mises stress in the fibula was considerably greater than that in the mandible, this value was in the physiological range where bone formation predominates over bone resorption in both mandible and fibula models. The loading conditions applied in this study were adopted from previous studies.[33,34,38,45] However, depending on the oral cavity area and patient characteristics, the occlusal force can vary considerably.[60] A parafunction such as bruxism or clenching may increase the occlusal force. Further studies should be undertaken using various level of bite force.

The preload provides a firm connection between the implant fixture and the abutment, and affects the stress distribution on the supporting bone and implant system. The present study showed that the preloaded screw generated stress concentration on the cortical bone around the implant fixture. This result is consistent with those reported in previous sdudies.[28,61] There was no prominent difference in stress distribution on the supporting bones and implant systems between the fibula and mandible models in the absence of oblique loads. In this study, after applying the preload and before imposition of oblique loads, the maximum von Mises stress value in the cortical bone of the fibula was 7.1 MPa, while that of the mandible was 6.7 MPa. Although the implant preload affected the stress distribution of the surrounding bone, the von Mises stress values were within physiological range and clinically acceptable. In the implant systems, the maximum von Mises stress values ranged from 57.7 MPa to 115.7 MPa. Higher stress values under preload do not jeopardize implant systems because the stress is still lower than the endurance limit of commercial implant components, which was reported to be 259.9 MPa.[62]

FEA has the advantage to provide detailed quantitative and qualitative results regarding biomechanical responses in dentistry. However, its accuracy is limited by the assumptions made, including model geometry, loading forces, and material properties. In the present study, although cortical bone and cancellous bone were considered to be anisotropic, the properties of other materials were assumed to be homogenous and isotropic because of the limited physical data available. A static load was applied to the model. However, a realistic occlusal load is a dynamic chewing movement. Hence, dynamic occlusal loading should be considered in future studies. The mandible exhibits complex biomechanical behavior under functional loading due to its complex structure. In the present study, the mesial and distal surfaces of the fibular and mandibular segments were constrained in all directions. This was adopted in the two models to reflect any possible elastic deformation that may be encountered clinically. However, the biomechanical mandibular flexure could build up stress in the fixed prosthesis.[63] It is necessary to address these problems in future studies.

Despite need for further studies, it is fair to say that a fibula reconstruction with implants is clinically acceptable, although the implant placed in the fibula provides a less favorable stress distribution than one placed in the intact mandible.

Ⅴ. CONCLUSION

Within the limits of this study, the splinted implant-supported fixed prosthesis placed in the reconstructed fibula might be a successful treatment option for the patient who underwent mandibular reconstruction based on biomechanical behaviors.

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-국문초록-

유한 요소 해석을 이용한 하악골과 재건된 비골에 식립된 임플란트의 비교

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허 경 회

연구 목적 : 본 연구의 목적은 하악골 재건술을 시행한 환자에서 동일한 하중 조건을 가했을 때 하악골과 재건된 비골 부위에 식립된 임플란트 주위의 응력 분포를 3차원 유한 요소 해석을 이용하여 비교 하는 것이다.

재료 및 방법 : 하악골 절제술 및 비골을 이용한 하악골 재건술을 시행한 환자의 컴퓨터 단층 촬영 영상을 이용하여 두 개의 3차원 유한 요소 모델을 제작하였다. 하악골 모델은 하악골, 임플란트 시스템 및 2개의 연결된 임플란트 지지형 고정성 크라운으로 구성하였다. 비골 모델은 하악골 모델에서 하악골을 재건 된 비골로 대체하였으며 나머지 구성 요소는 하악골 모델과 동일하였다. 임플란트 고정체와 지대주 및 지대주 나사 사이에는 전하중을 부여하였다. 150 N 크기의 경사 하중을 보철물의 교합면에 협설측 방향으로 11.54 도의 각도로 적용하였다. 3차원 유한 요소 분석을 통해 응력의 분포 양상과 최대 등가 응력 (von Mises stress) 을

비교 평가하였다.

결 과 : 임플란트 주위 골에서는 임플란트 경부의 피질골에서 가장 높은 응력 집중이 관찰되었다. 전하중을 부여하고 경사 하중을 부여하지 않은 상태에서 최대 등가응력 값은 하악골 모델에서 6.7 MPa, 비골 모델에서 7.1 MPa 로 나타났다. 경사 하중을 가했을 때는 최대 등가 응력 값이 하악골 모델과 비골 모델에서 각각 11.5 MPa, 25.2 MPa 의 값을 보였다. 임플란트 시스템에서는 두 모델 모두 임플란트 지대주 나사에서 가장 높은 응력 집중이 나타났다. 전하중을 부여하고 경사 하중을 부여하지 않은 상태에서 최대 등가 응력 값은 하악골 모델에서 115.7 MPa, 비골모델에서 115.1 MPa 이었다. 경사 하중을 가했을 때는 하악골 모델과 비골 모델에서 각각 113.5 MPa, 116.2 MPa 의 값을 보였다.

결 론 : 이 연구의 한계 내에서, 비골을 이용한 하악골 재건술을 시행한 환자에서 재건된 비골에 위치한 임플란트 지지 고정성 보철물은 정상적인 하악골에 위치한 경우 보다 응력 분포 측면에서 불리한 면이 있지만 생체 역학적으로 성공적인 치료 옵션이 될 수 있다.

주요어 : 유한 요소 분석, 비골, 하악골, 하악골 재건술, 임플란트, 전하중

학 번 : 2013-31210

감사의 글

대학원 과정을 무사히 마치고 이 논문을 시작하여 마무리하기까지 많은 도움을 주신 여러 은사님과 동료, 가족에게 감사의 말씀을 전합니다.

치과보철과 수련 및 박사 과정에 있어 따뜻한 충고와 조언으로 진료와 연구에 있어서 귀중한 가르침과 영감을 주신 권호범 교수님께 깊은 감사를 드립니다. 평범한 치과의사인 저에게 학문적 도전이라는 소중한 경험을 할 수 있는 기회를 주셨습니다.

치과보철학이라는 학문의 깊이와 열정을 일깨워주시고, 이번 논문 심사에도 열과 성을 다해주신 임영준 교수님과 김명주 교수님께도 깊은 감사를 드립니다. 바쁘신 와중에도 본 논문 심사를 위해서 꼼꼼히 살펴주신 치주과학교실의 구기태 교수님과 연세대학교 치과대학 보철과학교실 박영범 교수님께도 감사드립니다.

치과보철학교실의 허성주 교수님, 한중석 교수님, 곽재영 교수님, 김성훈 교수님, 김성균 교수님, 여인성 교수님, 윤형인 교수님과 의국 동기 및 선후배님들에게도 이 자리를 빌어 감사의 말씀을 전합니다.

오늘의 제가 있기까지 많은 사랑과 정성으로 보살펴주시고 어른이 된 지금까지도 지원을 아끼지 않으시는 부모님께 깊은 감사를 드리며, 제가 하는 모든 일을 응원 해주시는 장모님, 항상 제가 올바른 길을 걸을 수 있도록 동기부여를 해주시는 하늘나라에 계신 장인어른께도 깊은 감사를 드립니다.

마지막으로, 저의 모든 일에 의미를 부여해주고 인생의 가장 큰 선물이자 축복인 아내 유예신과 소중한 보물 지율, 주원에게 고마움과 사랑하는 마음을 전합니다.

2018년 7월

허 경 회