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Biomechanical analysis of implant-supported prostheses in a severely resorbed mandible using 3-dimensional finite element method

심한 골흡수가 있는 하악에서
임플란트지지-보철치료에 대한 삼차원 유한요소
분석을 이용한 생체역학적 분석

2019 년 8 월

서울대학교 대학원
치의과학과 치과보철과 전공
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Submitting a master's thesis of Dental Science

June 2019

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Confirming the master's thesis written by Ghaith Alom

June 2019

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ABSTRACT

Biomechanical analysis of implant-supported prostheses in a severely resorbed mandible using 3-dimensional finite element method

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1. Purpose

The purpose of this study was to evaluate the biomechanical behavior of a buccal cantilever and to compare it with other prosthetic designs to determine the best design in terms of stress distribution within the bone of a buccally resorbed partially edentulous mandible.

2. Material and methods

Based on patient computed tomography (CT) scan data, three finite element models were created. Each model composed of the severely resorbed mandible, the first premolar, the second molar and the implants that replaced the second premolar and the first molar. The first model had two implants placed based on bone quantity creating a buccal cantilever (CP2). The second model had two prosthetic-driven implants (BP2). The third model had three prosthetic-driven implants (BP3). In all models preload of 466.4 N on the abutment screw was applied. A load simulating chewing cycle was applied at seventy-five degrees to the occlusal surfaces of the prostheses. The maximum load magnitude was 262 N. The maximum von Mises stresses were demonstrated and compared in cortical and cancellous bone as well as the implant components.

3. Results

The results showed that the cantilever model exhibited better stress distribution compared to the other models. The overall maximum von Mises stress in each model was concentrated on the premolar abutment for CP2 (1036 MPa), on the molar screw for BP2 (982 MPa) and on the premolar abutment for BP3 (922 MPa). In the cortical bone, the maximum von Mises stress was around the neck of the implants with values as follows: 293 MPa in CP2, 348 MPa in BP2 and 791 MPa in BP3. For the cancellous bone von Mises stress was concentrated at the apex of the premolar implants for BP2 and BP3. For CP2 the maximum von Mises stress was around the

implant neck. The recorded values were 26 MPa in CP2, 348 MPa in BP2 and 791 MPa in BP3. Von Mises stress peaks in the implants components did not exhibit significant difference.

4. Conclusion

Considering the severely resorbed partially edentulous posterior mandible, placing implants based on the available bone quantity is more desirable than prosthetic-driven implant placement in terms of biomechanical behavior. The cantilever model created the highest maximum von Mises stress among the three models with regard to the prosthesis. However, when considering the bone, the cantilever model recorded the lowest maximum von Mises stress.

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Keywords : Implant supported fixed prosthesis, Biomechanical behavior, Bone resorption, Cantilever, Maximum von Mises stress, Finite element method.

Student Number : 2017-27639

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I. Introduction

A cantilever is a projecting beam or member supported on one end.[1] A cantilever fixed dental prosthesis is a fixed complete or partial denture in which the pontics are cantilevered, retained and supported by one or more abutments.[1] By incorporating a cantilever, the possibility of using more units in a fixed dental prosthesis (FDP) is enabled in some clinical situations and that could save time, effort and cost and could prevent preparation of sound tooth structure in some clinical situations. As for jaw rehabilitation with implants, compromised bone could necessitate bone regenerative procedure such as bone grafting which involves more complicated treatment than cantilevered prosthesis. Therefore, cantilever could act as an alternative treatment option if performed under careful planning.[2]

As cantilever length increases, the bending moment of occlusal forces increases according to the leverage. Therefore stress and strain in the bone surrounding implants adjacent to the cantilever increase, as was shown in previous finite element analysis (FEA) studies.[3,4] This increase in stress, which might express an overload to the implant could lead to biological complications such as marginal bone loss.[5-7] Cid et al. compared a full arch implant supported fixed prosthesis with a distal cantilever ≤ 15 ㎜, distal cantilever >15 ㎜ and without cantilever after 5 years of loading. It was found that the presence of a cantilever significantly influenced bone levels. However, the length of the cantilever did not exhibit a significant influence on bone levels.[5] However, Kim et al. investigated the effect of a cantilever in implant supported partial FDPs after a minimum of one year of loading and reported a correlation between marginal bone loss and arm length of the cantilever. Kim et al. noted that when the location of the cantilever was analyzed, the cantilevered partial FDP resulted in significantly higher bone loss compared to a non-cantilevered partial FDP only in the posterior mandible.[6] Romeo et al. also reported a correlation between the cantilever length and marginal bone loss. They found that every 1 ㎜ increase in cantilever length led to an extra marginal bone resorption of 0.099 ㎜ 7 years after implant loading.[8] Mumcu et al. reported after a follow up period of 3 years that cantilever fixed prostheses caused higher marginal bone loss than non-cantilever prosthesis regardless of implants locations. Contradictory findings were reported by other authors who confirmed the absence of a correlation between marginal bone loss and the cantilever prosthesis.[2,9,10] Hälg et al. found that a cantilever prosthesis resulted in a mean marginal bone loss of 0.23 ㎜, while a non-cantilever prosthesis resulted in a mean marginal bone loss of 0.09 ㎜ after an average follow-up period of 5.3 years. Therefore no statistically significant difference was reported.[2] Wennström et al. reported no difference in marginal bone loss between cantilever partial FDPs and non-cantilever partial FDP over 5 years of follow-up.[9] Palmer et al. compared the mesial and distal bone levels of 2-unit cantilever partial FDPs supported by single implants over a period of 3 years, and found no significant difference in marginal bone loss between the cantilever side and the non-cantilever side at any time during the 3 years of follow-up.[10] Many other authors reported a minimum implant survival rate of 97% for implants supporting a cantilever prosthesis after various observation periods ranging from 1 to 10 years.[8,11-15] The high survival rate could refer to how even though cantilever effect amplifies occlusal loads, the bone surrounding implants can still withstand the amplified load if proper planning is achieved.

Aside from biological complications, cantilevers could lead to prosthetic mechanical complications. Kim et al. found a higher frequency of technical complications with cantilever partial FDP which scored 91.7% technical success, while non-cantilever partial FDP scored 97.5% technical success (excluding porcelain fracture in the evaluation criteria).[6] Zurdo et al. performed a systematic review where it was found that after 5 years of follow-up, cantilever partial FDPs scored a mean survival rate of 91.9% with fracture of the implant as a main failure cause, while non-cantilever partial FDPs scored a mean survival rate of 95.8%. Regarding the technical issues in the supra-structure, cantilever partial FDPs recorded a mean occurrence frequency of 20.3% while non-cantilever partial FDPs recorded a mean occurrence frequency of 9.7% with minor porcelain fracture and screw loosening as the most common issues.[16] In a systematic review including studies with a mean follow-up period of 5 years, Romeo et al. reported that the most common technical complication in cantilever FDPs was veneer fracture with a cumulative estimate of 10.1%. The rest of complications were with cumulative estimates as follows- abutment screw fracture at 1.6%, screw loosening at 7.9% and decementation at 5.9% with no framework fracture reported.[17] However, Maló et al. reported that metal ceramic framework fracture in cantilever FDPs occurred in 1.6% of prostheses. Prosthetic screw loosening was the other mechanical complication, occurring in 7.3% of prostheses.[15] Palmer et al. found that the occurrence of abutment screw loosening was relatively high. They studied cantilever 2-units partial FDPs supported by one implant of 4-5 ㎜ in diameter. Of the twenty-eight subjects treated, ten subjects exhibited screw loosening in a 3 years follow-up.[10] Brosky et al. found a correlation between screw loosening and distal extension length when the ratio of the distal extension to the anteroposterior spread was 2:1. The study focused on full arch mandibular FDPs and out of the sixty-five retaining screws, seven screws were found to be loose.[18] In contrast, Capelli et al. reported a prosthesis success rate of 100% after a follow-up period of 5 years. The study aimed to investigate all-on-four prostheses, and considered a total of 342 implants.[11]

With regard to cantilever location, in many studies the location of cantilever was shown not to influence the outcome, in contrast to the length of the cantilever. Romeo et al. compared mesial and distal cantilever partial FDPs. In a study in 2003, it was found that distal cantilevers slightly but not significantly exhibited higher marginal bone loss in comparison to mesial cantilever. It should be noted that distal cantilever in their study had a mean length of 6.77 ㎜, whereas mesial cantilever had a mean length of 5.33 ㎜- explaining the difference in marginal bone loss between the two types of cantilevers. There was only one prosthetic failure in the mesial cantilever group whereas none in distal cantilever group. The non-significant difference between the mesial and distal cantilevers was later confirmed by the authors in another study in 2009.[8,13] Palmer et al. found that there was no difference between mesial and distal cantilevers in 2-units partial FDPs in all aspects except screw loosening which happened in six distal cantilever partial FDPs but not in any mesial cantilever partial FDPs. However, it should be noted that the sample size of the distal cantilevers was far greater than the mesial cantilever sample size; 24 distal compared to 4 mesial.[10] In completely edentulous mandibles, if implants are placed interforaminally to support an FDP with the most anterior implant lingually-positioned, the anterior part of the FDP will act as a cantilever while the distal extensions act as a posterior cantilever. Brosky et al. investigated that clinical situation and reported that the length of the anterior cantilever was found to have no correlation with screw loosening whereas the length of the posterior cantilever was significantly correlated. However, according to the studied sample, the ratio of the anterior cantilever to the anteroposterior spread to the posterior cantilever was 1:1:2 making it an unfair comparison between the anterior and posterior cantilevers with respect to cantilever length.[18]

Bone resorption happens as a consequence of tooth extraction. It occurs horizontally and vertically.[19,20] In the posterior maxilla, vertical buccal bone resorption forces implants to be placed palatally to the natural position of the teeth. Creating a buccal cantilever as a result.[21] As for posterior mandible, if no bone grafting is considered, the buccal bone resorption will force implants to be placed lingually to the natural position of the teeth. Creating a buccal cantilever. However, if the buccal bone is not resorbed entirely, prosthetic-driven implant placement in the remaining buccal bone will prevent the formation of a buccal cantilever. Besides, it would result in a higher crown-to-implant ratio.

To compare different implant supported FDP designs, the finite element method is a valid tool. This method allows for investigation of the prosthesis behavior, different implant designs, materials and bone under different loading directions and magnitudes.[22,23] Through FEA, tracing stress and visualizing its distribution and the corresponding deformation is possible.[22] Then, by reflecting FEA findings on the real clinical situation, predictions about implant longevity can be made because the stress and strain transferred by implants to the surrounding bone leads to biological bone reactions which are known as bone modeling and remodeling as to adapt to mechanical loads.[24,25]

The purpose of this study was to evaluate the biomechanical behavior of a buccal cantilever and to compare it with other prosthetic designs to determine the best design in terms of stress distribution within the bone of a buccally resorbed partially edentulous mandible.

Ⅱ. Material and methods

Modeling: Cone-beam computed tomography images of a mandible were obtained from a patient's record after an informed consent was acquired. The images were reconstructed with volumetric data with a cross section thickness of 0.2 ㎜. The cross sections were exported in DICOM format after reconstruction. Cortical and cancellous bone and dental tissues were separated using the segmentation function in an image processing software (Mimics, Materialise). The segmented images were converted into a three-dimensional model in STL format. The three-dimensional model was then imported to a meshing program (Visual mesh, ESI group) to be meshed. The bone segment to be studied was cut from the entire mandible model and included first premolar to the mesial and second molar to the distal. To eliminate the effect of the model end, the distance from the most mesially planned implant to the mesial side was 8 ㎜. While the distance from the distal end to the most distally planned implant was 12 ㎜. Both distances are in the acceptable range of more than 4.2 ㎜ as previously reported.[26] The buccolingual section of the edentulous ridge is shown in Fig. 1. Virtual placement of the implants was completed by placing Osstem GS System implant models in the designated areas with custom abutments and crowns designed using a CAD/CAM program (Implant studio, 3Shape). The abutments and crowns designing process was assisted by the superimposition of the 3D-scan of the patient's lower jaw stone model from a lab scanner (D1000, 3Shape). The morphology of the crowns was identical in all the models to allow for the same occlusal contacts among all the models. Cement-retained crowns were used in the present study with a cement thickness of 50㎛.[27] The periodontal ligament was also modeled with a thickness of 0.2 ㎜ based on previous studies.[28,29]

Taking into account the bone shape and inferior alveolar nerve canal 8.5 ㎜ long implants were mainly used. The models used in this study (Table 1, Fig. 2, 3) are as follows. Model CP2 which comprised two 4 ㎜ in diameter 8.5 ㎜ long implants placed based on the bone quantity creating a buccal cantilever. The crown height was 8.9 ㎜ for the premolar and 10.98 ㎜ for the molar resulting in a crown-to-implant ratio of 1:1 for the premolar and 1.3:1 for the molar. Model BP2 which comprised two prosthetic-driven 4 ㎜ in diameter 8.5 ㎜ long implants creating long neck abutments. The crown height was 15.34 ㎜ for the premolar and 13.54 ㎜ for the molar. That corresponds to crown-to-implant ratio of 2:1 for the premolar and 1.6:1 for the molar. Model BP3 which comprised three prosthetic-driven implants including two 3 ㎜ in diameter 6.75 ㎜ long thin implants for the molar and 4 ㎜ in diameter 8.5 ㎜ long implant for the premolar. The crown height was 15.34 ㎜ for the premolar, 13.59 ㎜ for the molar median implant and 11.60 ㎜ for the molar distal implant. The crown-to-implant ratio was 1.8:1 for the premolar, 2:1 for the median molar implant and 1.7:1 for the distal molar implant. The 3mm thin implants that were placed were one-piece implants.

The crown height was measured as the distance from the plane that parallels the neck of the implant and intersects with the highest point of the crown.

Material Properties: The material properties used in this study were adopted mainly from studies based on experiments. The cortical and cancellous bone were considered orthotropic materials (a subset of anisotropic materials) whose material properties change depending on the direction, unlike the isotropic materials which have the same properties in all directions. O'mahony et al. reported that orthotropic material properties increased the stress levels in cortical bone by 20-30% compared with isotropic cortical bone.[30] All other materials, including titanium for the implant fixtures, abutments and abutment screws, gold for crowns, self-cure resin cement, dentin and periodontal ligaments, were considered isotropic materials. All of these are listed with references in Table 2.

Interface Condition: Osseointegration was assumed to be 100% and applied by sharing nodes between the implant and the bone.[4,31,32] The contact between the abutment, implant and implant screw was set to a frictional contact with friction coefficient of 0.3.[33,34]

Elements and Nodes: Tetrahedral elements were used in models meshing. Finer elements were meshed along the implant-bone interface as shown in Fig. 4. The number of elements and nodes for each model are provided in Table 3.

Loads and Boundary Conditions: The terminal nodes in the mesial and distal sides of each model were constrained in all directions. In an attempt to simulate the human chewing process, one cycle of dynamic occlusal force with a variable magnitude and constant direction was applied on multiple areas on the occlusal surface of both crowns. The concept of one chewing cycle load pattern consists of two factors: time and load magnitude. The load magnitude is simply applicable but since long periods of time are difficult to simulate, the real chewing cycle was reduced by 1000 times in the simulation. Moreover, in the masticatory cycle, the mandible moves around the maximal intercuspal position but does not strictly bite vertically. Therefore, the occlusal force applied on the cusps is variable in both direction and magnitude. However, due to the lack of experimental findings in literature regarding variable direction, only the load magnitude was simulated as variable, while the load direction remained constant. The variable magnitude of the one chewing cycle (Fig. 5) is in accordance with experimental findings.[35] The load was distributed on the occlusal surface of both crowns. The force acting points are shown in Fig. 6. Screw preload was applied to the titanium abutment screws at 466.4 N as determined through experimentation.[36]

Analysis: Analysis was achieved by a solving program (Visual performance, ESI group) and screening of the results was performed by a viewing program (Visual viewer, ESI group). Maximum von Mises stress values in bone and implant components were compared and the ratios of the values were provided.

Ⅲ. Results

The overall maximum von Mises stress in each model was concentrated in the premolar abutment for CP2 with a recorded value of 1036 MPa, in the molar screw for BP2 with a recorded value of 982 MPa and in the premolar abutment for BP3 with a recorded value of 922 MPa.

For cortical bone, regardless of the model, the highest von Mises stresses were mainly located around the neck of the implants. The maximum von Mises stress in cortical bone of each model was as follows: 293 MPa for Model CP2 and located at the buccal area of the bone surrounding the neck of the premolar implant, 348 MPa for Model BP2 and located mesially at the neck of the premolar implant and 791 MPa for Model BP3 and located at the distolingual bone surrounding the neck of the most distal implant. The locations of the highest stress in cortical bone are shown in Fig. 7. For cancellous bone, in Model CP2 the highest von Mises stress was 26 MPa and was located as in the cortical bone; i.e. at the buccal area of the bone surrounding the neck of the premolar implant. In Model BP2 the highest von Mises stress was 263 MPa and was located lingually at the apex of the premolar implant. In Model BP3, the highest von Mises stress was 186 MPa and was located lingually at the apex of the premolar implant. The locations of highest stress in cancellous bone are shown in Fig. 8. The values of maximum von Mises stress in bone are provided in Fig. 9. The maximum stress in cortical bone increased in the following order: CP2, BP2, BP3 with CP2:BP2:BP3 ratio of 1: 1.2: 2.7.

Regarding implant components, the locations of the highest stress were in the hexes of the implants and abutments and in the necks of the abutment-screws. For the one-piece implants in BP3 the locations of highest stress were at the concaved part of the abutment. As for the maximum stress values, CP2 abutments recorded values of 1036 MPa and 1003 MPa for the premolar and molar respectively which were higher than the maximum von Mises stress values in BP2 abutments, 961 MPa and 941 MPa for the premolar and molar respectively. BP3 premolar abutment recorded a value of 922 MPa. For the implants, the descending order of the maximum von Mises stress was as follows: BP2 molar implant, 974 MPa; CP2 premolar implant, 913 MPa; CP2 molar implant, 892 MPa; BP2 premolar implant, 877 MPa; BP3 premolar implant, 861 MPa; BP3 mesial molar implant, 625MPa; BP3 distal molar implant, 566 MPa. For screws, the descending order of maximum von Mises stress was as follows: BP2 molar screw, 982 MPa; CP2 premolar screw, 970 MPa; CP2 molar screw, 946 MPa; BP2 premolar screw, 843 MPa; BP3 premolar screw, 831 MPa. Maximum stress values are shown in Fig. 10.

Ⅳ. Discussion

The results of the overall maximum von Mises stress in each model showed that Model CP2 created the highest maximum von Mises stress among the three models which was located at the abutment of the premolar implant which had the longest buccal extension among the abutments in the three models.

Regarding the locations of peak von Mises stress in cortical and cancellous bone, the results revealed that the highest von Mises stresses were mainly concentrated around the neck of the implants in correspondence with most FEA studies.[37-39] For cancellous bone, the location of the maximum von Mises stress in Model CP2 was also at the neck of the implant. However, for Models BP2 and BP3 it was at the apex of the premolar implant exactly at the same location in both models. This high stress value could be due to the thin cancellous bone covering the apex of the implant and it seems to cause no harm to bone since the cancellous bone at this site is covered with thick cortical bone.

With respect to maximum von Mises stresses in bone for the three models, Model CP2 exhibited the lowest von Mises stress peaks for both cortical and cancellous bone representing the best stress distribution capability among the models. CP2 was then followed by BP2 which had two implants placed in buccal cortical bone allowing for a shorter cantilever but longer neck for the abutments; this resulted in a higher crown-to-implant ratio than Model CP2. Crestal implants with longer buccal cantilever in this clinical situation exhibited more favorable stress distribution than buccally placed implants with longer neck abutments and shorter buccal cantilever. In accordance with that result, Gonda et al. in a finite element study compared three models of implant supported prostheses: a model with low bone resorption and a mesial cantilever, a model with low bone resorption and a distal cantilever and a model with severe bone resorption and no cantilever. The results revealed higher stress values in the bone of the model with severe bone resorption which had higher crown-to-implant ratio compared to the other models.[38]

In ascending order of maximum von Mises stress values in bone, Model BP2 was followed by Model BP3. Model BP3 had the same premolar implant as in BP2. However, in BP3, two 3 ㎜ thin implants were placed for the molar instead of one 4mm implant resulting in a bone contact surface equals to a 6 ㎜ wide implant. Therefore, BP3 had larger bone contact surface than BP2 and CP2. Nevertheless, as revealed, a larger bone-implant interface could lead to higher maximum stress value in agreement with a study by Iplikçioğlu et al. in which they compared a 3-units FPD (fixed partial denture) supported by three 3.75 ㎜ diameter implants with an FPD supported by two 4.1 ㎜ diameter implants of the same length.[40]

Another factor that should be considered when analyzing such results is the loading conditions. The loading conditions affect the stress distribution and can alter the outcome; this was demonstrated by Gonda et al. who compared four units FPDs (two premolars and two molars) supported by four implants in the posterior mandible with the same FPD supported by three implants leaving a mesial cantilever. The considered loading conditions were the posterior load and the normal occlusion. For the posterior load in the molar area, the mesial cantilever indicated that a lower number of implants could reduce the stress. For normal occlusion on all four units, both models showed the exact same stress which meant that the loading condition affected the outcome.[38] Supporting this concept, Stegaroiu et al. concluded in a study that a 3-unit FPD supported by three 4 ㎜ diameter implants had comparable results to 3-unit FDP supported by two 4 ㎜ diameter implants but only under an axial load. Better results were observed for the three implants model under buccolingual loading.[4]

Multiple studies reported that the larger bone-implant interface due to increasing the number of implants leads to a lower stress peak in bone; this was reported by Huang et al. who studied a 2-units FPD supported by three 3.75 ㎜ diameter implants or by two implants- one is 3.75 ㎜ in diameter and one 5 ㎜ in diameter. It was found that the three implants model had lower stress peak in bone.[31] Bölükbaşı et al. also found a lower stress peak in bone when increasing the number of implants, and added that the localization of implants has an influence as well.[37]

In this study, increasing the bone implant interface by increasing the number of implants failed to reduce the peak stress. The reason behind this may be that the two 3 ㎜ diameter implants were less surrounded with cortical bone than the 4 ㎜ diameter implant whose width allowed more coverage by the buccal cortical plate. The cortical bone-implant interface areas were as follows; in Model BP3, the sum of the middle implant (11.97 $㎜^2$) and the distal implant (15.86 $㎜^2$) was 27.83 $㎜^2$. In Model BP2, the distal implant had a 39.52 $㎜^2$ cortical bone contact surface area which is 1.4 times greater. Since the cortical bone elastic modulus is 10 times of that of cancellous bone, the cortical bone is 10 times stiffer; i.e. more resistant to elastic deformation. Therefore the cortical bone surrounding the implants provides higher support compared to cancellous bone and since BP2 implants had stronger support than BP3 implants, the maximum von Mises stress values tended to be higher in BP3.

From a biological perspective, plaque control for three implants is more difficult than two implants due to the extra inter-implant space that has to be cleaned on a regular basis. Cleansing tools would include interdental brushes or stiffened-end floss since the crowns are splinted.

With respect to implant components, implant bodies and abutments had the high values of stress concentrated in the line angles of the hexes. This localized stress seems to not affect the titanium due to its strength. However, the high levels of stress in the abutment screws were spread out and not concentrated, potentially leading to failure. The failure of the screw could either be from fracture, bending or screw loosening. Screw loosening according to Patterson et al. occurs when the external load exceeds the screw preload; i.e. the clamping force provided by the screw.[41] While Brosky et al. suggested that screw loosening occurs due to alternating tension and compression applied on the screw.[18]

In cantilevered prostheses, the length of the cantilever multiplies the load applied to the abutment, thus prompting screw loosening.[42] In a comparison of a three units FPD supported by two implants creating a cantilever as a first model and a two units FPD supported by two implants without a cantilever as a second model, with an oblique load applied on the cantilevered pontic for the first model and on the prosthetic crown for the second model, Kunavisarut et al. found that the maximum von Mises stress in the screw beside the cantilever was twice that of the screw of the loaded crown in the second model.[43]

Regarding long neck abutments; i.e. a high crown-to-implant ratio as seen in BP2 and BP3, the high crown-to-implant ratio magnifies the bending moment of the horizontal component of an oblique load. English suggested that crown to implant ratios of 2:1 or more along with a cantilever can cause a mechanical failure, including screw loosening.[44]

With regard to this study, the maximum von Mises stresses in screws decreased in this order: BP2 molar, 982 MPa; CP2 premolar, 970 MPa; CP2 molar, 946 MPa; BP2 premolar, 843 MPa; BP3 premolar, 831 MPa. Models CP2 and BP2 exhibited similar screw stresses and thus undergo the same potential of any screw mechanical failure. Model BP3 exhibited the lowest screw peak stress, which may be due to the stability provided by the two one-piece implants.

V. Conclusion

Considering the severely resorbed partially edentulous posterior mandible, placing implants based on the available bone quantity is more desirable than prosthetic-driven implant placement in terms of biomechanical behavior. The cantilever model created the highest maximum von Mises stress among the three models with regard to the prosthesis. However, when considering the bone, the cantilever model recorded the lowest maximum von Mises stress.

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TABLES

Table 1. Models analyzed in the study.

Model	Number of implants	Diameter of implants	Length of implants	Location of implants
CP2	2	4 ㎜	8.5 ㎜	Crestal bone
BP2	2	4 ㎜	8.5 ㎜	Buccal bone
BP3	3	1×4 ㎜ 2×3 ㎜	8.5 ㎜ for 4 ㎜ wide implant 6.75 ㎜ for 3mm wide implants	Buccal bone

Table 2. Material properties used in the study.

Material	Elastic Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)
Cortical Bone[45]	E_1(26.6), E_2(17.9), E_3(12.5)	v_{12}(0.28), v_{13}(0.21), v_{23}(0.19)	G_{23}(7.1), G_{31}(5.3), G_{12}(4.5)
Cancellous Bone[30-46]	E_1(1.148), E_2(0.210), E_3(1.148)	v_{12}(0.055), v_{13}(0.322), v_{23}(0.010)	G_{23}(0.068), G_{31}(0.434), G_{12}(0.068)
Dentin	20 [47,48]	0.31 [49]	
PDL	2.7×10^{-3} [29]	0.45 [49]	
Pure Titanium	103 [50]	0.3 [49]	
Gold Alloy	100 [51]	0.3 [49]	
Resin Cement	6 [52,53]	0.28 [54,55]	

E_1 is the elastic modulus in the mesiodistal axis. E_2 is the elastic modulus in the superoinferior axis. E_3 is the elastic modulus in the buccolingual axis. vxy is the poisson's ratio for strain in the y-direction when loaded in the x-direction.

Table 3. Number of nodes and elements of each model.

Model	Nodes	Elements
CP2	237,366	1,294,444
BP2	182,009	960,446
BP3	357,665	2,012,447

CP2: two 4mm diameter implants placed based on the bone quantity. BP2: two 4mm diameter prosthetic-driven implants. BP3: three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter.

FIGURES

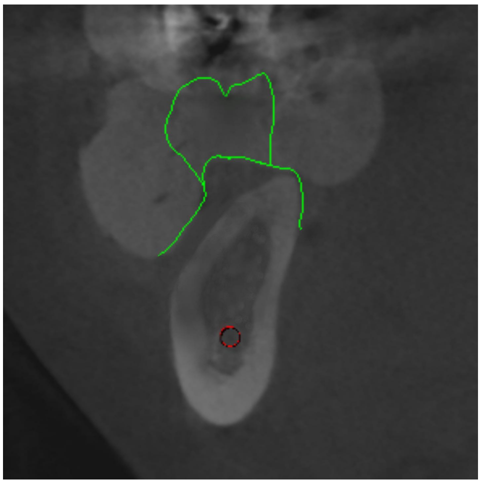

Figure 1. Buccolingual section of the edentulous ridge taken from the computed tomography scan. Green outline refers to the naturally positioned molar crown. The red circle refers to the inferior alveolar nerve canal.

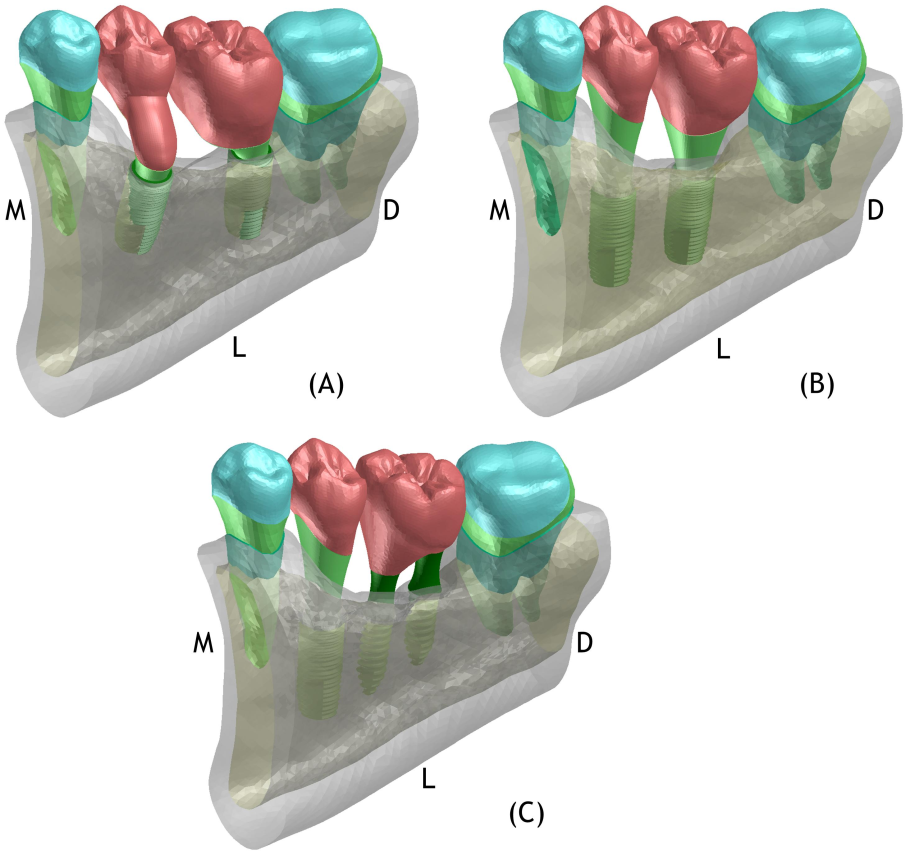

Figure 2. Lingual view of the three models. (A): CP2 – two 4mm diameter implants placed based on the bone quantity. (B): BP2 – two 4mm diameter prosthetic-driven implants. (C): BP3 – three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter. M: mesial, D: distal, L: lingual.

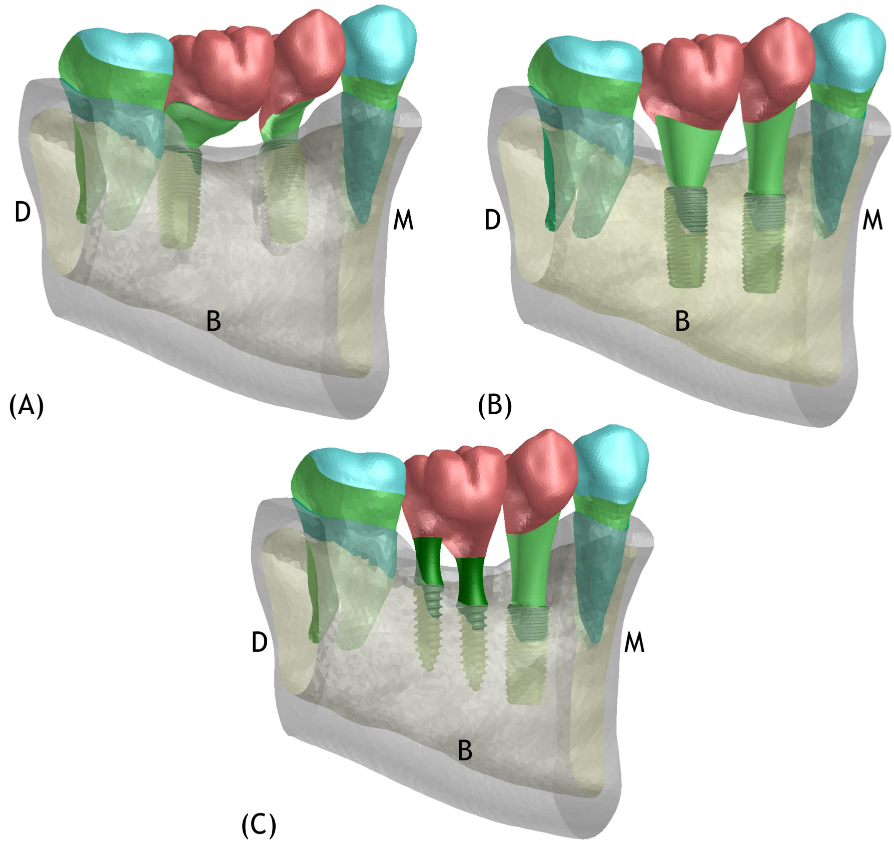

Figure 3. Buccal view of the three models. (A): CP2 – two 4mm diameter implants placed based on the bone quantity. (B): BP2 – two 4mm diameter prosthetic-driven implants. (C): BP3 – three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter. D: distal, M: mesial, B: buccal.

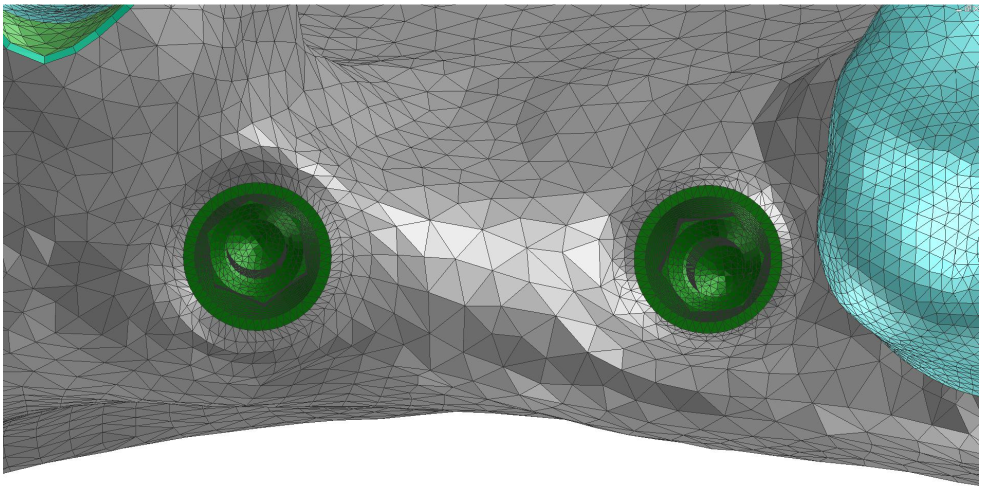

Figure 4. Finer tetrahedral elements surrounding the necks of the implants for better stress distribution around the necks.

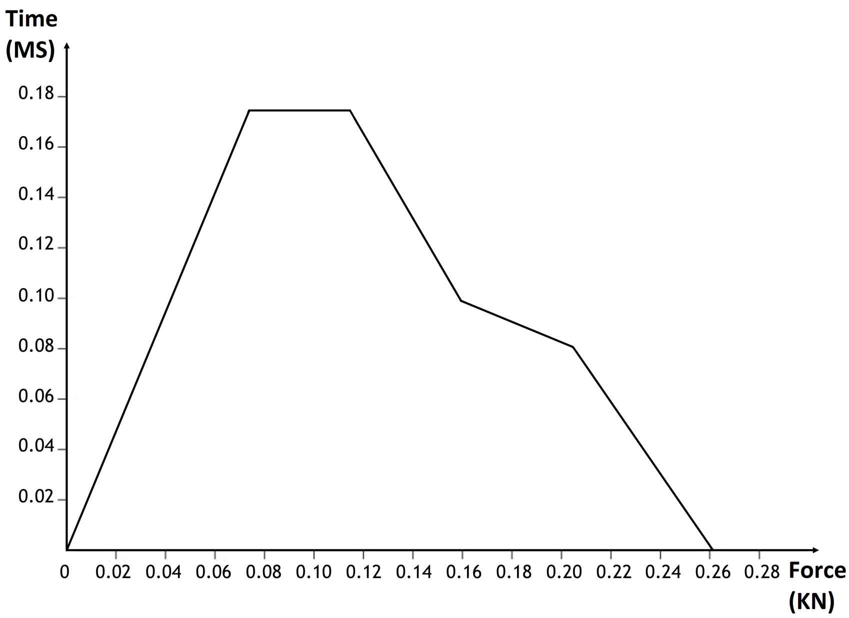

Figure 5. One chewing cycle of the occlusal load.

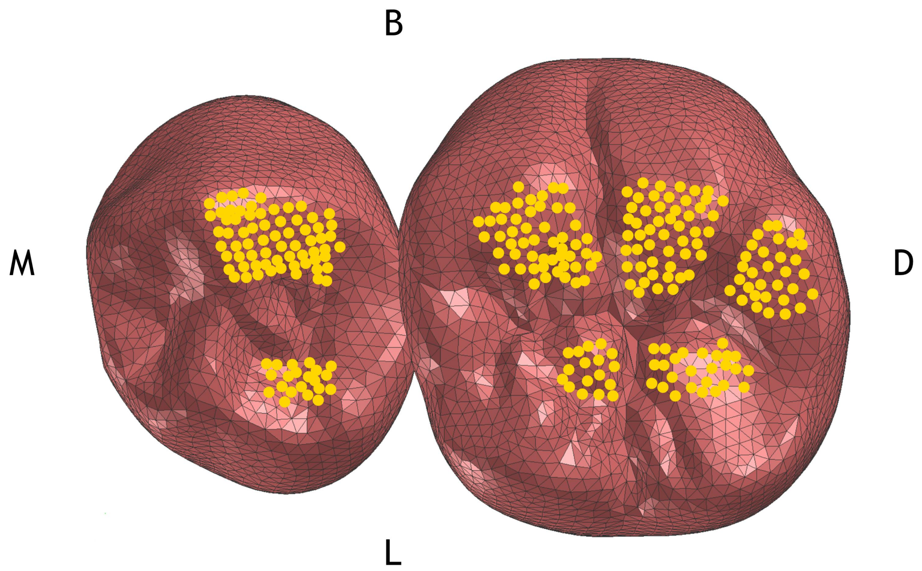

Figure 6. Force acting points distributed on the buccal cusps and some parts of lingual cusps of the prosthesis. B: buccal, L: lingual, M: mesial, D: distal.

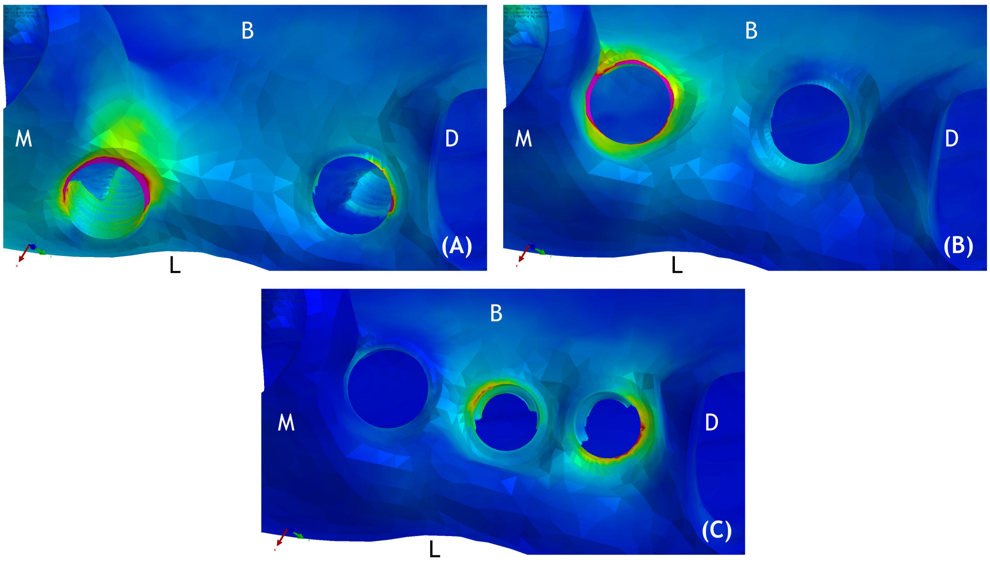

Figure 7. Locations of maximum von Mises stress in cortical bone in the three models. (A): CP2 – two 4mm diameter implants placed based on the bone quantity. (B): BP2 – two 4mm diameter prosthetic-driven implants. (C): BP3 – three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter. B: buccal, L: lingual, M: mesial, D: distal.

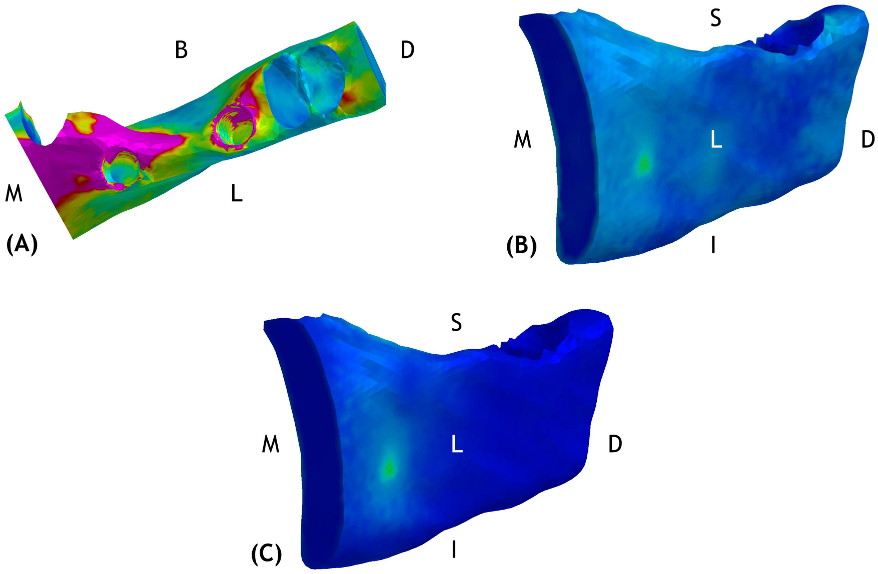

Figure 8. Locations of maximum von Mises stress in cancellous bone in the three models. (A): CP2 – two 4mm diameter implants placed based on the bone quantity. (B): BP2 – two 4mm diameter prosthetic-driven implants. (C): BP3 – three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter. B: buccal, L: lingual, M: mesial, D: distal, S: superior, I: inferior.

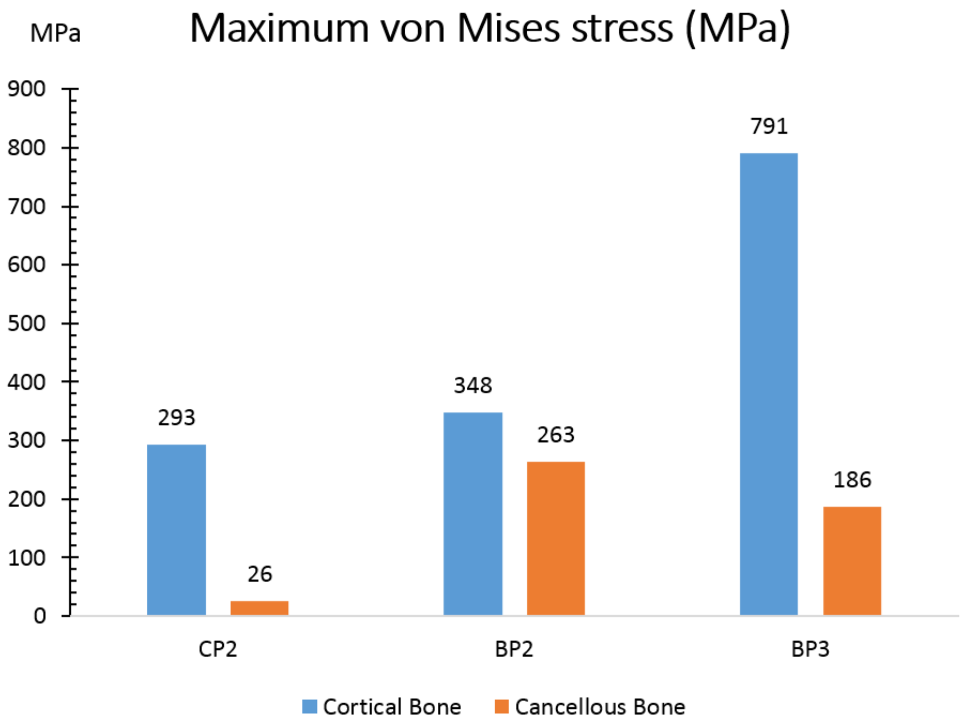

Figure 9. Maximum von Mises stress in cancellous and cortical bone in the three models. CP2: two 4mm diameter implants placed based on the bone quantity. BP2: two 4mm diameter prosthetic-driven implants. BP3: three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter.

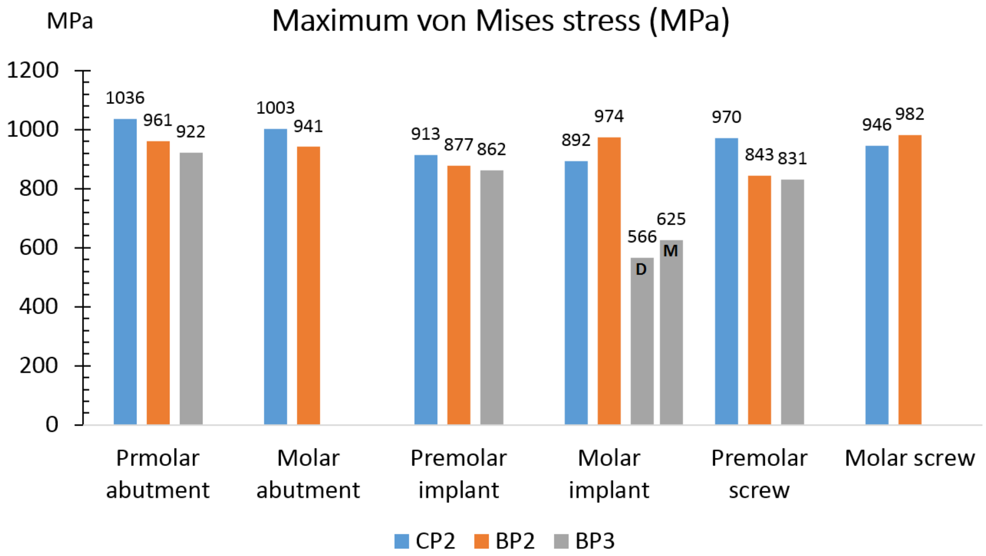

Figure 10. Maximum von Mises stress in the implant components of the three models. For Model BP3, D refers to the distal molar implant and M refers to the mesial molar implant. CP2: two 4mm diameter implants placed based on the bone quantity. BP2: two 4mm diameter prosthetic-driven implants. BP3: three prosthetic-driven implants, of which one was 4mm in diameter and two were 3mm in diameter.

국문초록

심한 골흡수가 있는 하악에서 임플란트지지-보철치료에 대한 삼차원 유한요소 분석을 이용한 생체역학적 분석

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1. 목 적

이 연구의 목적은 협측 골흡수가 동반된 하악 부분 무치악 모형에서 협측 캔틸레버가 있는 보철물의 생체역학적 움직임을 평가하고, 여러 보철물 설계 디자인을 비교하는 것이었다.

2. 방 법

환자의 CT 영상을 기반으로 총 3개의 유한요소 모형을 제작하였다. 유한요소 모형은 제2소구치와 제1대구치가 결손된 하악 구치부에 임플란트가 식립되고 제1소구치와 제2대구치가 포함된 모형이었다. 첫 번째 모형(CP2)은 골 양에 기반하여 2개의 임플란트가 식립된 모형이었고 보철물에 협측 캔틸레버가 존재하였다. 두 번째 모형(BP2)은 보철물을 기준으로 식립된 2개의 임플란트가 포함되었다. 세 번째 모형(BP3)은

보철물을 기준으로 식립된 3개의 임플란트가 포함된 모형이었다. 모든 모형에서 466.4N의 전하중이 지대주나사에 가해졌다. 저작력을 가정한 하중이 교합면에 75도로 가해졌다. 피질골, 해면골 및 임플란트 구성요소에서 최대등가응력이 관찰되었다.

3. 결 과

캔틸레버 모형이 다른 디자인 만큼 우수한 응력 분포를 나타내었다. 최대등가응력은 모형 CP2와 모형 BP3에서는 제1소구치 지대주에, 모형 BP2 에서는 대구치지대주에 집중되었다. 피질골에서 최대 등가 응력은 주로 임플란트 경부 주위에 집중되었으며 CP2에서 293 MPa, BP2 에서 348 MPa, 그리고 BP3 에서 791 MPa 이었다. 해면골에서는 CP2를 제외하고 모두 소구치 부위 임플란트의 첨부에 최대등가응력이 집중되었고, CP2에서는 응력이 임플란트 경부 주변에 집중되었다. 해면골에서의 최대등가응력은 CP2 에서 26 MPa, BP2 에서 348 MPa, BP3에서 791 MPa 이었다. 최대등가응력의 최대값은 CP2 와 BP2에서 유의미한 차이가 없었다.

4. 결 론

골흡수가 심한 부분 무치악 하악에서 골의 양을 기반으로 임플란트를 식립했을 때 보철물을 기준으로 식립하는 방법 만큼 좋은 결과를 보여주었다. 캔틸레버 보철물이 있는 모형에서는 보철물에서 가장 큰 최대등가응력이 관찰되었다. 골에서는 캔틸레버 보철물이 있는 모형에서 가장 작은 최대응가응력이 관찰되었다.

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주요어 : 임플란트-지지 보철물, 생역학적 분석, 골흡수, 캔틸레버, 등가응력, 유한요소방법

학 번 : 2017-27639