Three-dimensional Stress Analysis of Tooth/Implant-Retained Long-Span Fixed Dentures

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Purpose: *The aim was to assess the influence of connection of the canine teeth to implant-retained long-span fixed dentures on stress in mandibular bone using finite element analysis.* ***Materials and Methods:*** *Each 3-dimensional model included bone, 6 implants, both natural canines, and superstructures. Each model simulated 1 of 4 prosthetic designs: a tooth/implant-retained 1-piece superstructure (One-piece), 3-piece superstructures with an anterior and 2 posterior segments with unconnected teeth (UnConnect), 3-piece superstructures with the teeth connected to the posterior segments (PostConnect), and 3-piece superstructures with the teeth connected to the anterior segment (AntConnect). A nonlinear elastic modulus was applied to the periodontal ligament (PDL). Maximum intercuspal (IP), canine-protected (CP), and group-function (GF) occlusions were simulated.* ***Results:*** *The maximum stresses in the peri-implant regions of the bone were lower for the One-piece than for the other superstructures. In PostConnect and AntConnect, the maximum stress in the PDL was lower than that in UnConnect, but the stress in the peri-implant bone was comparable in those 3 models. The stresses were lower in the GF model than in the CP model. The stress created in the peri-implant bone was insensitive to the modes of the teeth/implant connection in long-span fixed dentures.* ***Conclusion:*** *Within the limitation of the mechanical analysis, it is suggested that the connection of the canine tooth to the implant-retained long-span superstructures is an acceptable option in partially edentulous patients.* INT J ORAL MAXILLOFAC IMPLANTS 2007;22:710–718

Key words: *dental implants, finite element analysis, periodontal ligament, tooth-implant support*

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Presented at the 83rd General Session & Exhibition of the International Association for Dental Research, Baltimore, Maryland, March 2005.

It is unclear whether natural teeth should be incorporated as abutments in implant-retained fixed dentures. The literature suggests that tooth/implant–connected fixed dentures perform adequately[1–6]; however, physiologic and mechanical complications, including loss of osseointegration,[7] cement failure,[8,9] abutment screw loosening,[10] and prosthesis and abutment fractures[7] have been noted in retrospective reports. Clinical studies have also shown that a tooth connected to an implant can exhibit intrusion into the supporting bone, regardless of the implant system and the method of connection.[11]

Biomechanical studies have shown increased peri-implant stresses in the bone associated with short-span prostheses retained by a tooth and an implant as a result of the higher bending moment caused by the cantilever effect in the system.[12–15] However, tooth/implant-retained long-span fixed dentures have not been fully assessed in relation to the stress in the supporting oral tissues. The scarcity of data on this in the literature may be partially attributed to the enormous model sizes required for evaluation of the bone and full-arch prosthesis. Large 3-dimensional models often present problems that

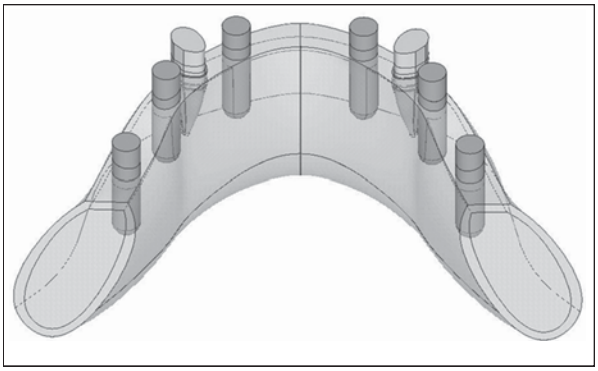


Fig 1 The finite element model of the mandibular bone with the canines and 6 implants at the lateral incisor, first premolar, and first molar locations on both sides of the arch.

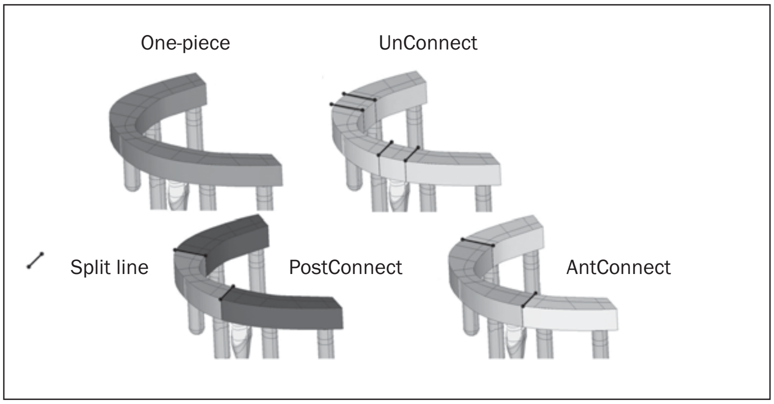


Fig 2 The superstructures modeled: One-piece (a 1-piece denture retained by the canines and implants); UnConnect (3-piece superstructures consisting of an anterior segment and 2 posterior segments with unconnected canine teeth); PostConnect (3-piece superstructures with the canine teeth connected to the posterior segments); and AntConnect (3-piece superstructures with the canine teeth connected to the anterior segment).

are difficult to solve without advanced computer resources.

Another problem with most previous in vitro studies has been their inability to estimate stress in the periodontal ligament (PDL), which has been known for its nonlinear structural behavior. This has prevented relative comparison of the stresses in the periodontal tissues of the natural teeth with those in the peri-implant bone. When a tooth displaces under occlusal loads, the PDL becomes stiff as the root surface gets close to the bone surface.[16,17] That is, the elastic modulus of the PDL increases as its strain level increases. Recently, finite element models have been used to solve nonlinear problems of the PDL to reproduce precise tooth movements[18–20]; however, this technique has not been applied to evaluate the designs of tooth/implant-retained superstructures.

The aim of this study was to investigate the stress distribution in mandibular bone supporting tooth/implant-retained long-span fixed superstructures with different modes of connection. The diagnostic criterion of inclusion of the canine teeth with multiple implants in the support of long-span superstructures was assessed with the nonlinear finite element method.

MATERIALS AND METHODS

Finite Element Models

A graphic preprocessor of a finite element program (Ansys 8.1; Ansys, Canonsburg, PA) was used to construct mathematical models (Fig 1) of the mandibular cortical and cancellous bone, 2 natural canines with PDL, 6 osseointegrated implants with abutments, and fixed superstructures (Fig 2). Because the canine teeth have the highest retention rate among all the teeth in the elderly population,[21,22] the model with the canine teeth remaining in the mandible bilaterally was regarded as relevant to situations encountered in the prosthodontic decision-making process.

The mandible was modeled with a cancellous core surrounded by 1.5-mm-thick cortical bone. The horizontal length between the right and left alveolar crests in the first molar region was 48 mm. The mandible was 11 mm wide at the incisor region, 12 mm wide at the first premolar region, and 14 mm wide at the second molar region. In the vertical plane, the mandible was 30 mm high at the incisor region, 34 mm high at the premolar region, and 26 mm high at the second molar region.

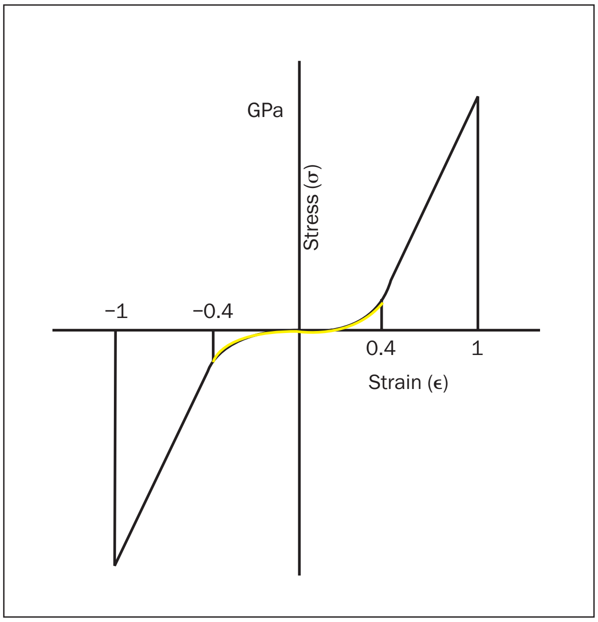


Fig 3 Stress-strain curve used for the PDL. Rigid characteristics, over 0.4 or under −0.4 in strain, were represented by straight lines (E = 7.192×10^{-3} GPa). Soft condition under a strain of −0.4 to 0.4 was simulated by the yellow curve ($\sigma = 1.498246 \times 10^{-2} \epsilon^3$).

To simulate implants, 6 cylinders 4 mm in diameter and 10 mm in length were embedded at the lateral incisor, first premolar, and first molar locations on both sides of the arch. Right and left canines were also constructed. The buccolingual and mesiodistal diameters of the canine root at the cervical level were 6 and 4.5 mm, respectively, and the length of the canine root was 12 mm. A 0.3-mm-thick PDL was attached to the outer surface of each canine root.

Each model included 1 or more horseshoe occlusal rims (ie, simplified superstructures) designed as follows (Fig 2):

- One-piece: A 1-piece rim as a fixed complete denture retained by the canine teeth and implants
- UnConnect: 3-piece rims with an anterior and 2 posterior implant-retained superstructures with unconnected canine teeth
- PostConnect: 3-piece rims with the same anterior and posterior superstructures with the canine teeth connected to the posterior segments
  AntConnect: 3-piece rims with the same anterior and posterior superstructures with the canine teeth connected to the anterior segment

The height of the rims was 6 mm, and the width was 5 mm in the anterior region and 7 mm in the posterior region. It was assumed that separated segments did not mechanically affect each other at their proximal contacts.

Material Properties

All the materials were considered isotropic and homogeneous. The cortical and cancellous bone, teeth, implants, and superstructures were assumed to be linearly elastic materials.[23,24] The elastic moduli used were 10.7 GPa for cortical bone, 0.907 GPa for cancellous bone, 14.7 MPa for tooth structure, and 117 GPa for the prostheses.[26–30] The Poisson ratios were 0.30 for cortical bone, 0.30 for cancellous bone, 0.31 for tooth structure, and 0.33 for the prostheses.[26–30]

The nonlinear material property for the PDL was used to simulate the movement of the canines. Two phases of the stress-strain relationships were determined (Fig 3). For the rigid phase, the highest elastic modulus was obtained in a preliminary analysis by assuming that the root apex in the socket was displaced 120 µm under a vertical occlusal load of 250 N. This has been reported as approximately the highest bite force that can physiologically be loaded on a healthy mandibular canine.[31] For a PDL with a thickness of 0.3 mm, a compression of 120 µm results in a strain of –0.4. Based on these values, the constant elastic modulus for the rigid ligament in a strain more than 0.4 (in tension) or less than –0.4 (in compression) (straight lines in Fig 3) was 7.192×10^{-3} GPa. This was close to 6.8×10^{-3} (GPa), the modulus used to simulate tooth movement under the maximum chewing force.[27]

Based on a previous report[32] indicating that the stress of the PDL is expressed by a cubic function of strain in a small tooth movement, the following approximated equation was obtained for strain between –0.4 and 0.4 (yellow curve in Fig 3) so that the curve presented a smooth shift to the straight lines:

$$\sigma = 1.498246 \times 10^{-2} \epsilon^3$$

where σ represents stress and ϵ represents strain. This equation was used with the finite element analysis software to represent the nonlinear material property of the PDL. To test the validity of the equation for the soft phase of the ligament, an index ratio of tooth displacement proposed by Mühlemann[16] was calculated. In the canine model used in the present study, the ratio of displacement under a horizontal load of 100 g to that under a load of 500 g was 0.59379. This was close to 0.6, the value reported achieved in Mühlemann's experiment, which indicates that the present model satisfactorily simulated small tooth movement.

Loading and Boundary Conditions

The interfaces between the materials were assumed to be bonded or osseointegrated (Fig 4). Each model was meshed by elements determined by 8 nodes in

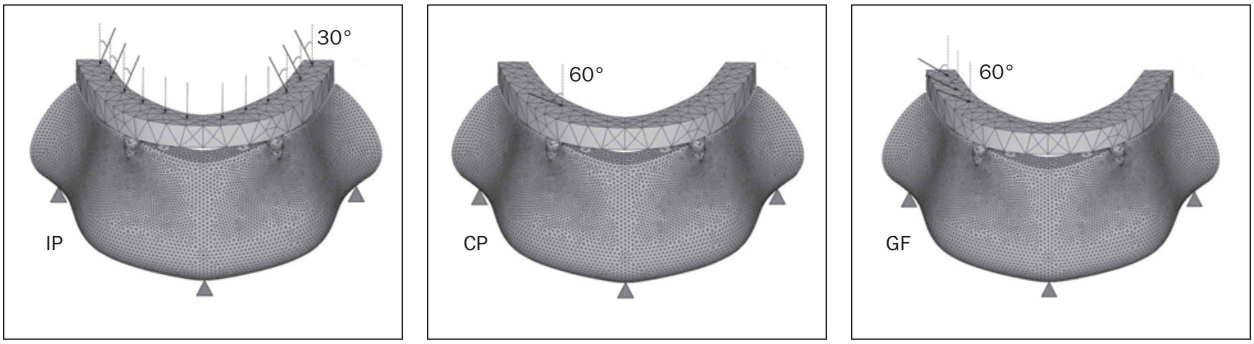


Fig 4 The meshed models with loading and boundary conditions. Each arrow indicates an off-axis oblique load on the center of an occlusal surface. The gray triangles represent the fixation at the lower surface of the mandible. IP = simulated maximum intercuspal position; CP = simulated canine-protected occlusion; GF = simulated group function occlusion.

the tetrahedral bodies. Each model consisted of approximately 410,000 elements and 97,000 nodes. Static loads were applied on the occlusal surfaces. They were located in the occlusal rims; the opposing maxilla was assumed to be fully dentate or restored with fixed dentures. As with the maximum intercuspal contacts (simulation IP), a vertical load of 20 N was simultaneously directed on each of the incisors and canines, and an oblique load of 40 N was directed on the premolars and first molars in a direction 30 degrees buccal to the vertical. The loads were based on a previous study that reported the maximum biting forces of subjects with fixed cross-arch prostheses in natural dentition.[33]

Two patterns of working side contacts in the lateral excursion of the mandible were simulated. For the canine-protected occlusion (Simulation CP), an oblique load of 9 N was loaded on the right canine in a direction 60 degrees lingual from the vertical. For the group function occlusion (Simulation GF), an oblique load of 3 N was loaded simultaneously on each of the right premolars and the first molar in the same direction as for Simulation CP.

A displacement of zero for each node on the outer surface of the lower third of the mandibular bone simulated the support of the masseter and medial pterygoid muscles, which attach to the outside and inside of the mandible angle, respectively. For all simulations, the von Mises' equivalent stress distributions were calculated.

RESULTS

Stress peaks were observed at the cervical regions of the implants and the canine abutments in the cortical bone. In all the simulations, the One-piece model showed relatively constant stresses throughout the entire abutment vicinity; maximum stresses were the lowest for this superstructure. In Simulation IP, stress peak values at the canines and the posterior implants in the models with separated superstructures (UnConnect, PostConnect, and AntConnect) were at least twice those seen in the 1-piece model (Fig 5). The highest maximum stress in the bone (10.4 MPa) was recorded in the region adjacent to the canine in the AntConnect model (Fig 6). The highest maximum stress around the implants was shown in the region adjacent to the premolar implant in the PostConnect model (10.0 MPa). The maximum stresses in the cancellous bone were observed in the apical region of the implants and were considerably lower than those in the cortical bone. Vertical tooth movement in the axial direction was greatest in the UnConnect model (108.1 μm), while considerably less tooth movement was seen in the other models (average, 2.15 μm).

In Simulation CP, the highest maximum stress of 2.1 MPa was observed at the region adjacent to the right canine in the UnConnect model (Figs 7 and 8). Vertical tooth movement was greatest in the UnConnect model (1.49 μm), while considerably less tooth movement was seen in the other models (average 0.05 μm). In Simulation GF, the maximum stress of approximately 1.3 MPa was found at the lingual cervical region of the right canine in the cortical bone for the UnConnect, PostConnect, and AntConnect models (Fig 9). There were no noticeable differences in the maximum stress distributions among these models (Fig 10). The vertical tooth movements for all the models were less than 0.01 μm.

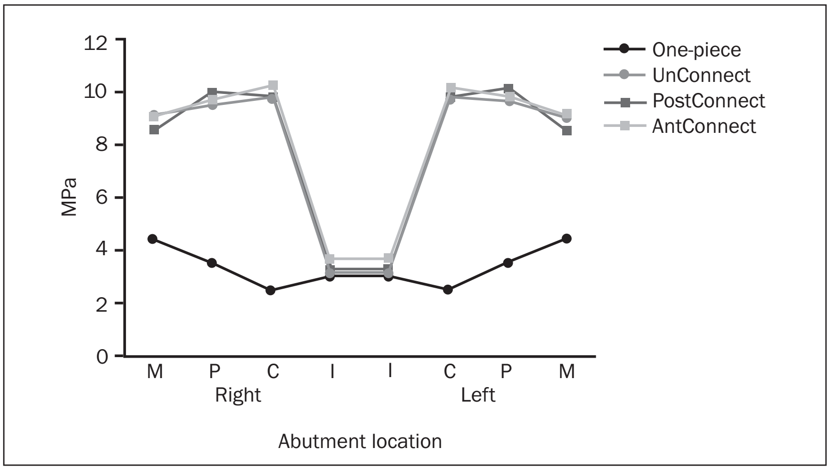


Fig 5 The maximum equivalent stresses in the vicinity of the canines and implants under Simulation IP. I = implant at the lateral incisor location, C = natural canine, P = implant at the first premolar location, M = implant at the first molar location.

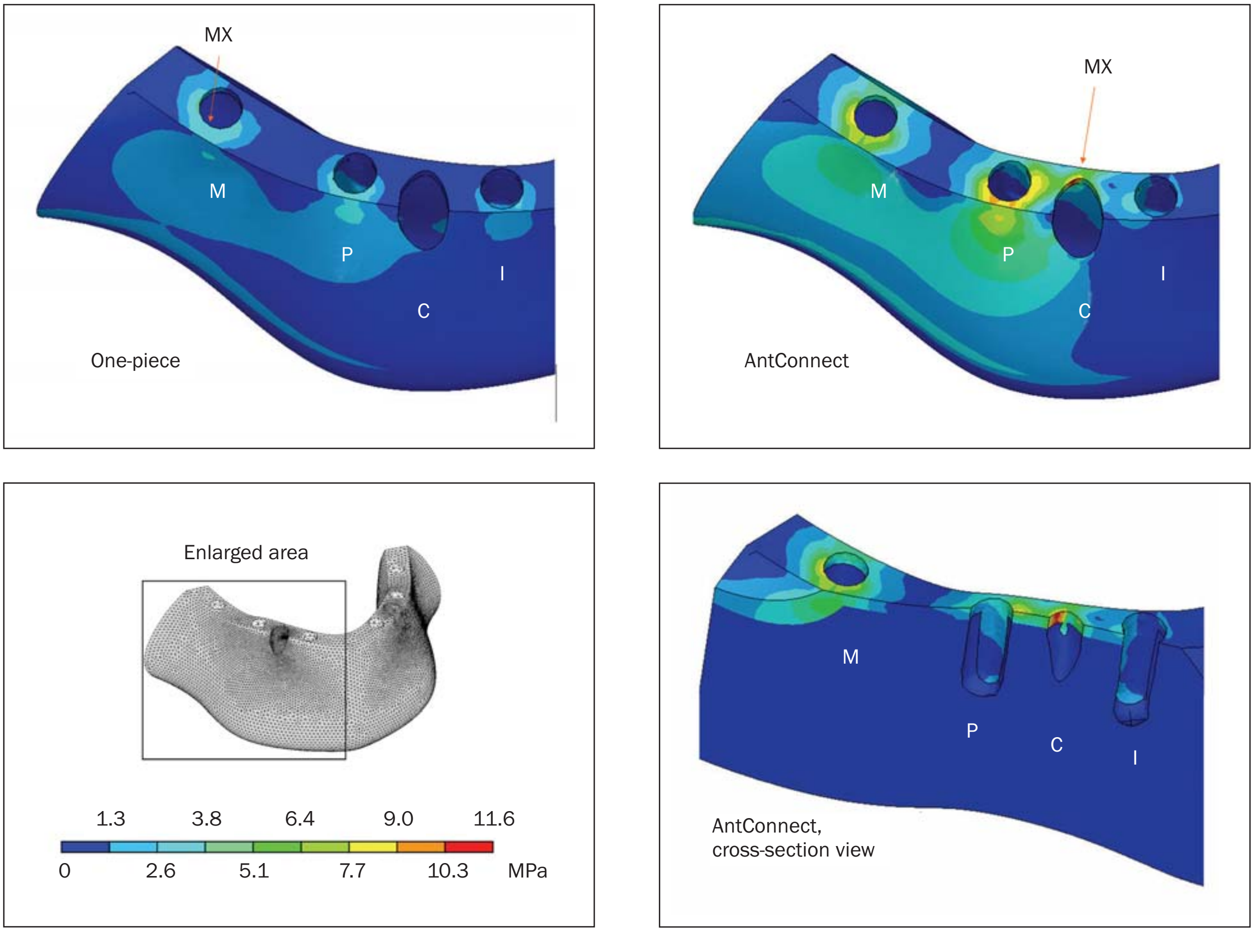
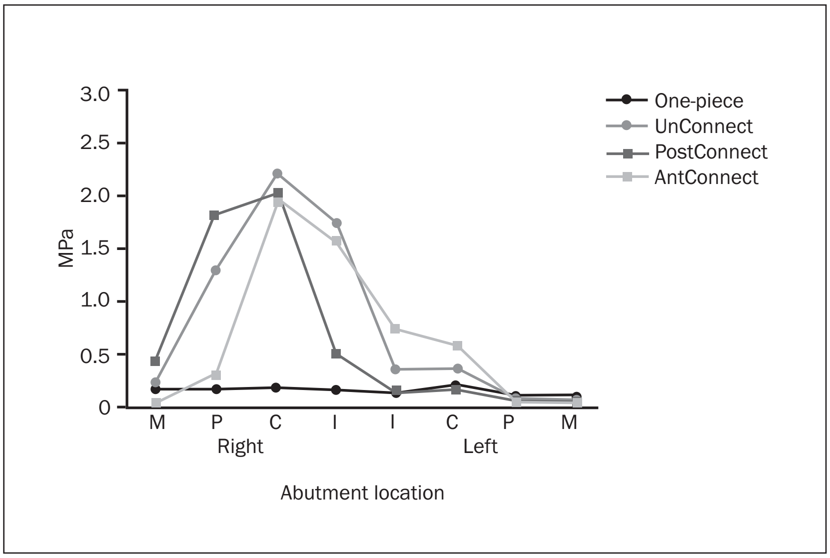


Fig 6 Equivalent stress distributions in the cortical bone of the One-piece and AntConnect models under Simulation IP. Nine colors were used to indicate the various stress levels, with red indicating the region of greatest stress and blue indicating the region of lowest stress. MX represents the site of the maximum stress. See legend to Fig 5 for abbreviations.

Fig 7 Maximum equivalent stresses in the vicinity of the canines and the implants under the Simulation CP occlusion. See legend to Fig 5 for abbreviations.



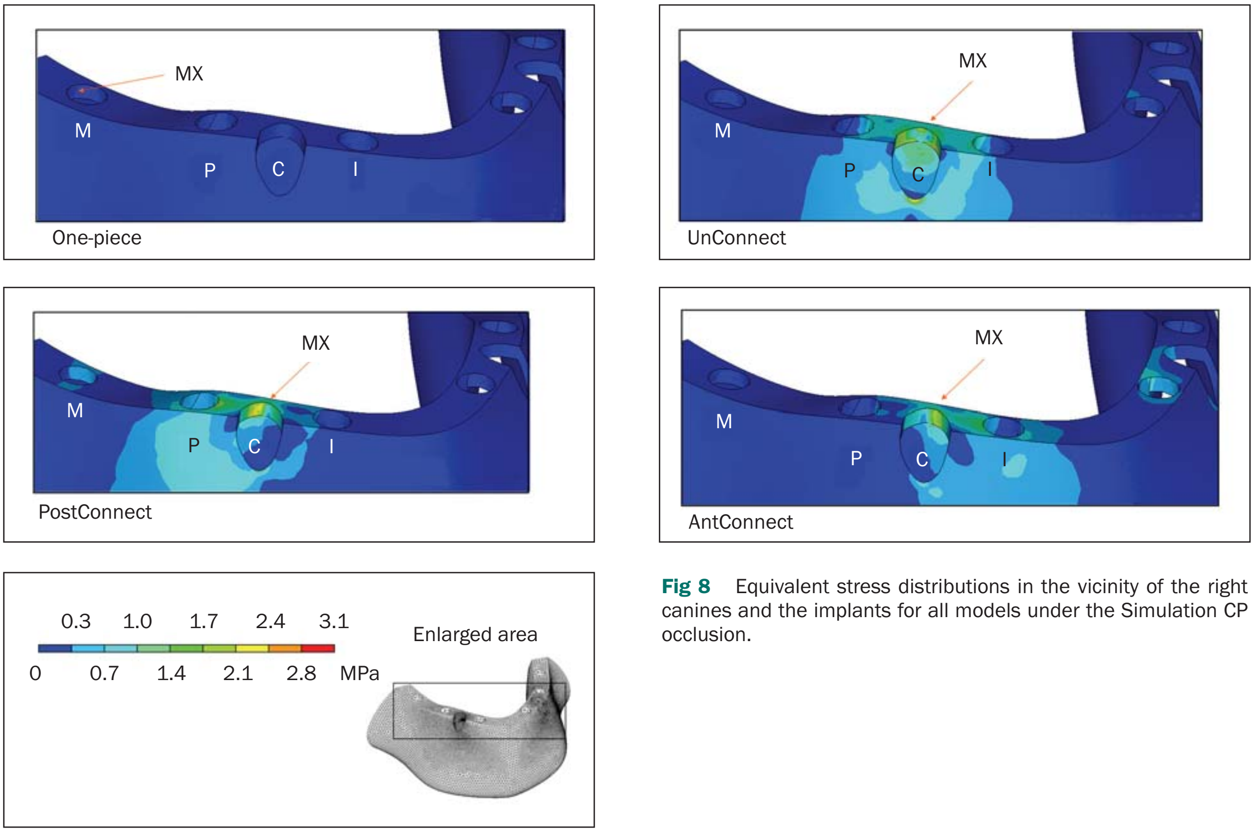


Fig 8 Equivalent stress distributions in the vicinity of the right canines and the implants for all models under the Simulation CP occlusion.

DISCUSSION

The 1-piece superstructure was effective in suppressing stress in the bone for the tooth/implant dual retaining system. This result was in accordance with the authors' previous study utilizing implant-retained fixed partial dentures (FPDs).[23] The relatively low maximum stress recorded in this model might be attributed to the superior ability of the structure to transfer loads. It is speculated that a horizontal component of the load was offset by loads on the other locations in the broad 1-piece structure, in contrast to the separated superstructure, where such compensation could not be expected.[23]

The separated superstructures, on the other hand, have certain benefits. The use of separated super-

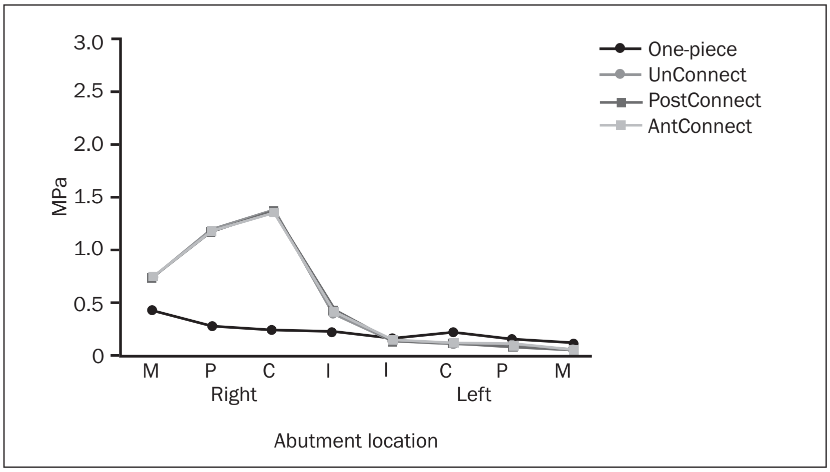


Fig 9 Maximum equivalent stresses in the vicinity of the canines and the implants under Simulation GF. See legend to Fig 5 for abbreviations.

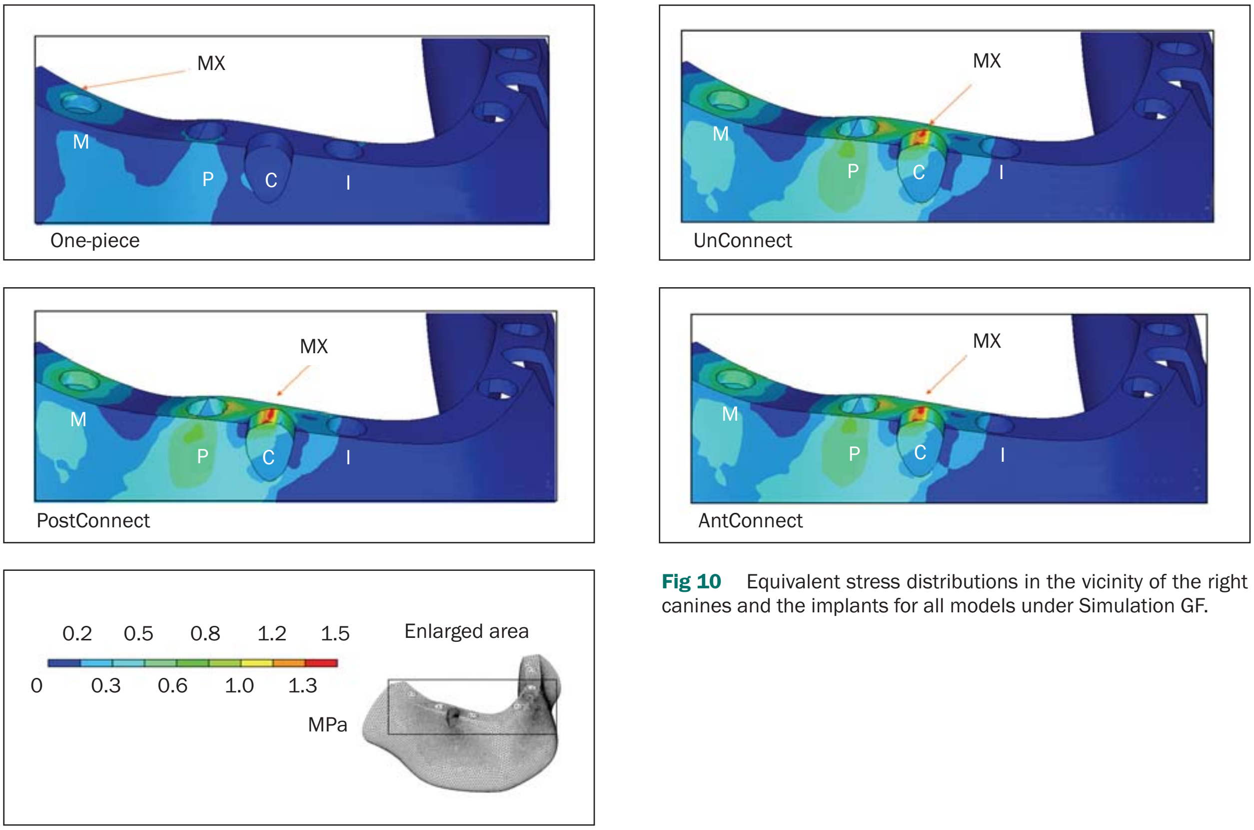


Fig 10 Equivalent stress distributions in the vicinity of the right canines and the implants for all models under Simulation GF.

structures minimizes the cost of repair and remake when a local failure occurs in an implant-retained prosthesis. The present study was conducted to evaluate the stress in the bone created by superstructures with different modes of connection to the canines. In the models with separated superstructures (UnConnect, PostConnect, and AntConnect) under the simulations IP and GF, the stresses in the implant vicinities were insensitive to the location of connection to the canines. The fact that the stresses near the posterior implants connected to the canine (PostConnect) were not lower than those separated from the canine (UnConnect, AntConnect) indicated that the use of the canine to support posterior segment did not suppress the stress in the peri-implant bone, probably because of the considerable difference in resilience between the PDL and the osseointegrated implant.[12–15]

The use of the canines to support the superstructures contributed to considerable declines in tooth movement; however, it did not cause a noticeable rise of peak stress in the entire peri-implant bone.

These findings do not support those of previous in vitro studies that found that a high concentration of peri-implant stress was produced in 3-unit prostheses retained by a tooth and an implant.[14,15] The stress might critically increase in a short-span prosthesis supported by a single implant and a tooth, probably because of the cantilever effect in the 3-unit prostheses. However, the stress created by superstructures supported by 2 or more implants was insensitive to the incorporation of the canine, suggesting that this mode of prosthesis support may be an acceptable treatment option in the patient with a partially edentulous mandible.

Because slightly higher stress was seen in the canine vicinity under simulation CP than that under simulation GF, group-function occlusion is recommended for the working-side occlusal contacts for the separated superstructures. This result was in conflict with the findings of the authors' previous study on implant-retained FPDs.[23] The inconsistency might be attributed to the natural canines used in the present study in contrast to the implant placed at the same location in the previous study. The stress concentration in the periodontal tissue under simulation CP would be emphasized by a firm contact at a small area on the root surface, while the stress could be well distributed by rigid osseointegration over a large area between the implant surface and bone.

One may question the result that the maximum von Mises stresses in the bone around the right canine were similar among the various models in simulation GF, even though the canine was connected to the loaded posterior segment in the PostConnect model but separated in the UnConnect and AntConnect models. Further investigation indicated that the principal compressive stress dominated at the lingual cervical region of the periodontal ligament in the PostConnect model, while the tensile stress dominated in the UnConnect and AntConnect models. It is hypothesized that compressive stress was created at the lingual cervical region by the lingual movement of the canine connected to the posterior segment, while the tensile stress was created by the gap between the lingually distorted bone and the canine that was not connected to the posterior segment, resulting in von Mises stresses of similar levels.

The maximum stresses shown in the models with separated superstructures were well below the reported critical threshold for detrimental effects on the human cortical bone (60 MPa).[34] However, the result was based on bite forces and an occlusal contact scheme within the range of normal function. The resultant stresses cannot be ignored as a risk factor, because they could potentially cause absorption or degeneration of the bone under fatigue or parafunctional occlusal loading. Further study will be required to assess the influence of more severe loading situations on stress in the supporting structures of tooth/implant-retained prostheses. On the other hand, the maximum stresses around the canines reached a similar level to those around the posterior implants. Therefore, the connection of the canines to fixed dentures is unlikely to cause disuse atrophy of the periodontal tissues, which has been suggested as one of the causes of natural tooth intrusion in tooth/implant-retained dentures.[35,36]

CONCLUSION

Less stress was induced in the PDL when the canines were connected to the anterior or posterior segments; however, connection of the canines was not associated with a noticeable rise of the maximum stress in the peri-implant bone. Within the limitations of the mechanical analysis used in this study, it can be concluded that the inclusion of the natural canines to the implant-retained long-span fixed dentures does not increase the stress in the supporting structures; thus, this may be a reasonable treatment option in the partially edentulous patient.

ACKNOWLEDGMENT

This study was supported by Grants in Aid for Scientific Research nos. 14571840 (NW) and 16591936 (NW) from The Ministry of Education, Science, and Culture of Japan.

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