Finite Element Analysis of Stress Distribution in Mandibles with Different Bone Types Loaded by Implant-Supported Overdentures with Different Localizations of Locator Attachments

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Purpose: Prosthetic rehabilitation of completely edentulous patients has been traditionally performed with complete dentures for many years. However, patient complaints are reported due to insufficient retention and high mobility of mandibular dentures. Therefore, in these patients, overdenture prostheses, which are usually made by placing at least two implants in the interforaminal region of the mandible, have become widespread. In these prostheses, bar, stud, magnetic, or ball and locator attachments are used. This study aimed to evaluate the stress on mandibles by an overdenture with locator attachments supported by two implants placed on three different bone types in three different regions. ***Materials and Methods:*** Finite element analysis (3D) was used to design a mandible and overdenture. Two implants and locator attachment systems were placed into the lateral incisor, canine, and premolar regions. In computer-generated mandible and overdenture models, a force of 100 N was loaded obliquely and vertically from the mandibular first molar teeth region; then, the values obtained from the forces were compared. Eighteen analyses were performed with two different loading options in nine different models. Von Mises, compressive, and tensile stress values were analyzed. ***Results:*** As the bone type changed from D1 to D3, the stresses on the bone increased in direct proportion. However, with all three bone types, lower tensile values were found in cortical bone in an above-implant removable prosthesis supported by an implant in the lateral incisor region. ***Conclusion:*** Biomechanically, the lateral incisor and canine regions were more advantageous than the first premolar tooth region in prosthesis designs where two implants were used in all bone types.
Int J Oral Maxillofac Implants 2021;36:851–862. doi: 10.11607/jomi.8872

Keywords: 3D, finite element analysis, overdentures

Complete dentures are traditionally used for the prosthetic rehabilitation of completely edentulous patients. The most common complaint about these dentures is the absence of retention and stability of the mandibular dentures. Implant-supported overdentures (IODs) resulted in improved retention and stability of mandibular dentures and increased patient satisfaction.[1]

IODs with two implants are the most preferred treatment for the rehabilitation of edentulous patients.[2] Many studies have found that overdentures supported by two implants are successful with regard to stability, retention, and patient satisfaction. Bar, stud, magnetic, or ball attachments have traditionally been used to retain implant overdentures, and then locator attachments (Zest Anchors) were presented as an alternative. This system has many advantages, such as its vertical height being low and therefore not requiring much interarch distance,[3] and it can compensate for an angle difference of up to 40 degrees between implants.[4]

The way stresses are transferred to the surrounding bone affects the success of implants.[5] These stresses have been analyzed by different methods, such as mechanical stress analysis, photoelasticity stress analysis, and strain measurements on bone surfaces.[6] Finite element analysis (FEA) has many advantages over other stress analysis methods, such as easy model simulation, certain modeling of complex geometries, and the ability to analyze the internal state of stress.[7]

The anterior mandible is known to be more suitable for implant placement. In this area, it is possible to insert implants into the lateral incisor, canine, and premolar regions.[8] This study aimed to examine the stresses

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Submitted July 29, 2020; accepted May 29, 2021.

Table 1 Groups of FEA Models

	Lateral region	Canine region	Premolar region
D1 bone	Model 1	Model 2	Model 3
D2 bone	Model 4	Model 5	Model 6
D3 bone	Model 7	Model 8	Model 9

Table 2 Properties of the Materials Used in the Study

Material	Young modulus (GPa)	Poisson ratio
Implant	110	0.35
Mucosa	0.003	0.45
Trabecular bone (D2 and D3 bone)	1.37	0.30
Cortical bone	13.7	0.30
Matrix	3	0.25
PMMA	3	0.35

on the implants inserted in different regions (lateral incisor, canine, and first premolar regions) of different types (D1, D2, D3) of bones using FEA.

MATERIALS AND METHODS

In the present study, finite element models that were developed for the stresses caused by the locator attachments on two implants placed in the lateral incisor, canine, and first premolar regions of the mandibular bones in D1, D2, and D3 bone types were examined.

A cone beam computed tomography (ILUMA, Orthocad, CBCT, 3M Imtec) image of a completely edentulous mandible was used for 3D modeling. The mandibular jawbone was chosen to be the division A type with a vertical size of 15 mm and a width of > 6 mm in the buccolingual direction. Nine 3D models were designed based on the types of bone (D1, D2, and D3) and location of implants (lateral region, canine region, and first premolar region) and generated with 3D-Doctor software. Nine groups of models were created (Table 1).

According to the localization of the mental foramen in the mandible, the implants (4.1 mm in diameter and 10 mm in length, Institut Straumann) were placed in the lateral incisor, canine, and first premolar regions. Locator attachments were selected according to the manufacturer's recommendation. The IOD design included a 10.7-mm-thick acrylic resin plate, which was a substitute for the overdenture component. The implants, locator attachments, and overdenture were scanned with an optic scanner (Smart Optics Activity 880, Sensortechnik). The models and data from the scanner were reformatted and recorded in standard triangle language (.stl) format. The models were imported into 3D modeling software (Rhinoceros, Robert McNeel & Associates), and cortical bone, trabecular bone, and mucosa were formed. D1, D2, and D3 types of bone were modeled according to Lekholm and Zarb's classification.[9] Additionally, a layer of mucosa with a thickness of 2 mm[10] was added to the resulting model.[8,10,11]

The implants were virtually inserted into the lateral regions, canine regions, and premolar regions, and the prosthetic components were placed in all 3D models. All models were combined and imported into the FEA software (Algor Fempro, Algor) to evaluate the stress distribution. All materials were considered to be isotropic, homogenous, and linearly elastic, and their properties are listed in Table 2. Flawless osseointegration was assumed to be demonstrated among the bone and implants.

In order to mimic clinical conditions, as many elements as possible were selected, and the elements were evenly distributed to the whole model. In this study, the number of elements that were used during the preparation of mathematical models including jaw models, dental implants, and superstructures ranged between 238,089 and 304,515, and the number of nodes ranged between 47,056 and 58,794. The number of elements and nodes in all meshed components are shown in Table 3. Boundary conditions describe the movements in nodes and their correlations. Thus, in each model, the retromolar region of the mandible and the mandibular base was bounded from load distribution and fixed at the connection points of the chewing muscles, so as not to prevent deformation of the mandible.

In each model, a force of 100 N was loaded vertically from the central fossa area of the mandibular first molar teeth region and 45 degrees obliquely, from the mesiobuccal cusp of the mandibular first molar.[12]

As a result of the 3D FEA, von Mises stresses in implants and tensile stress, compressive stress, and displacements in cortical and trabecular bone within the entire implant-bone interface were examined. In 3D elements, the greatest stress value occurs when all shear stress components are zero. When an element is in this position, normal stresses are called principal stress. The principal stress is divided into three as maximum principal stress, intermediate principal stress, and minimum principal stress. In general, σ_{xx} represents the greatest positive value, σ_{zz} shows the lowest negative value, and σ_{yy} indicates an intermediate value.

In the results of the analysis, the positive values indicate the tensile stress, and the negative values indicate the compressive stress. In a stress element, when the certain stress value of a strain type is greater, the stress element is under the influence of that strain type, and it is the strain type that needs to be evaluated.

Von Mises stress is defined as the beginning of deformation for tractile materials, such as metal, and calculated from the individual stress and strain components by the following equation:

$$\sigma_v = \sqrt{½[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)]}$$

In this way, the stresses that occur in the interface connections can be evaluated in terms of quality and quantity.

Table 3 Number of Elements and Nodes in All Meshed Components

Region	Elements	Nodes
D1 lateral incisor	238,179	47,056
D1 canine	238,089	47,522
D1 premolar	239,742	47,667
D2 lateral incisor	301,160	57,885
D2 canine	302,549	58,647
D2 premolar	304,515	58,794
D3 lateral incisor	292,341	56,645
D3 canine	253,360	50,983
D3 premolar	254,795	51,102

RESULTS

In the present study, reference points were determined to compare the extent of stress and deformation between different models, and the maximum values at these points were compared. Bones in the neck regions and surrounding areas of the implants and the vestibule and lingual surfaces of the mandible, where the implants were placed, were determined as reference points. A large number of cross sections were taken from these regions to determine the maximum values in the models. Cross sections and scales, where the maximum values at the reference points can be seen, are shown in Figs 1 to 4.

Stress, deformation, and displacement results are presented as colored images. In these images, each color describes a range of values. The value ranges are shown with a scale on the side of the images.

The von Mises stresses (maximum equivalent stresses) were analyzed for tractile materials like titanium, and principal stress values were defined for brittle materials, such as bone. The tensile stresses (maximum principal stress) and compressive stresses (minimum principal stress) were evaluated in the cortical bone around the neck region of implants in all models. The minimum principal stress values were larger than the maximum principal stress values in all models. The von Mises stresses were also determined at the implant-locator contact area for oblique and vertical loadings. Stress patterns were gained at all loading conditions, and oblique loading conditions exhibited higher stress values than vertical loading for cortical bone and implant structures.

The maximum equivalent stress values in the implants of each model under vertical loading are shown in Fig 5. The lowest von Mises stress values of the implants were observed in the lateral incisor region of D1 bone, and the highest values were in the premolar region of D2 bone (Fig 5).

The von Mises stress values in the locator attachment on the contact surface of the implant when the vertical load was applied were lowest in the lateral incisor region of D1 bone and highest in the premolar region of D1 bone (Fig 5).

Maximum and minimum principal stresses in the cortical bone under vertical and oblique loads are shown in Figs 1 and 3. The maximum tensile stress values were determined in the cortical bone in the buccal neck region of the implants as being lowest in the premolar region of D2 bone and highest in the canine region of D3 bone (Fig 6). The maximum stress in the bone was lowest in the lateral incisor region of D1 bone and highest in the premolar region of D3 bone (Fig 7). In trabecular bone, during vertical loading, the maximum principal stress values of D2 bone were 0.26 MPa in the buccal neck region of the implants in the lateral incisor and canine region and 0.47 MPa in the lingual neck region of the implants in the premolar region.

The compressive stresses in the cortical bone under vertical loading in the lingual neck region of the implants were –1.97 MPa in the canine region of the D1 bone. The maximum compressive stresses in cortical bone in the premolar region of D3 bone were obtained in the distal neck region of the implants (Fig 3). The minimum principal stress values were obtained in the bone in the lateral incisor region of D1 bone (Fig 8) and were –0.69 MPa in the distal neck region of the implants in the trabecular bone in the premolar region of D3 bone (Fig 4).

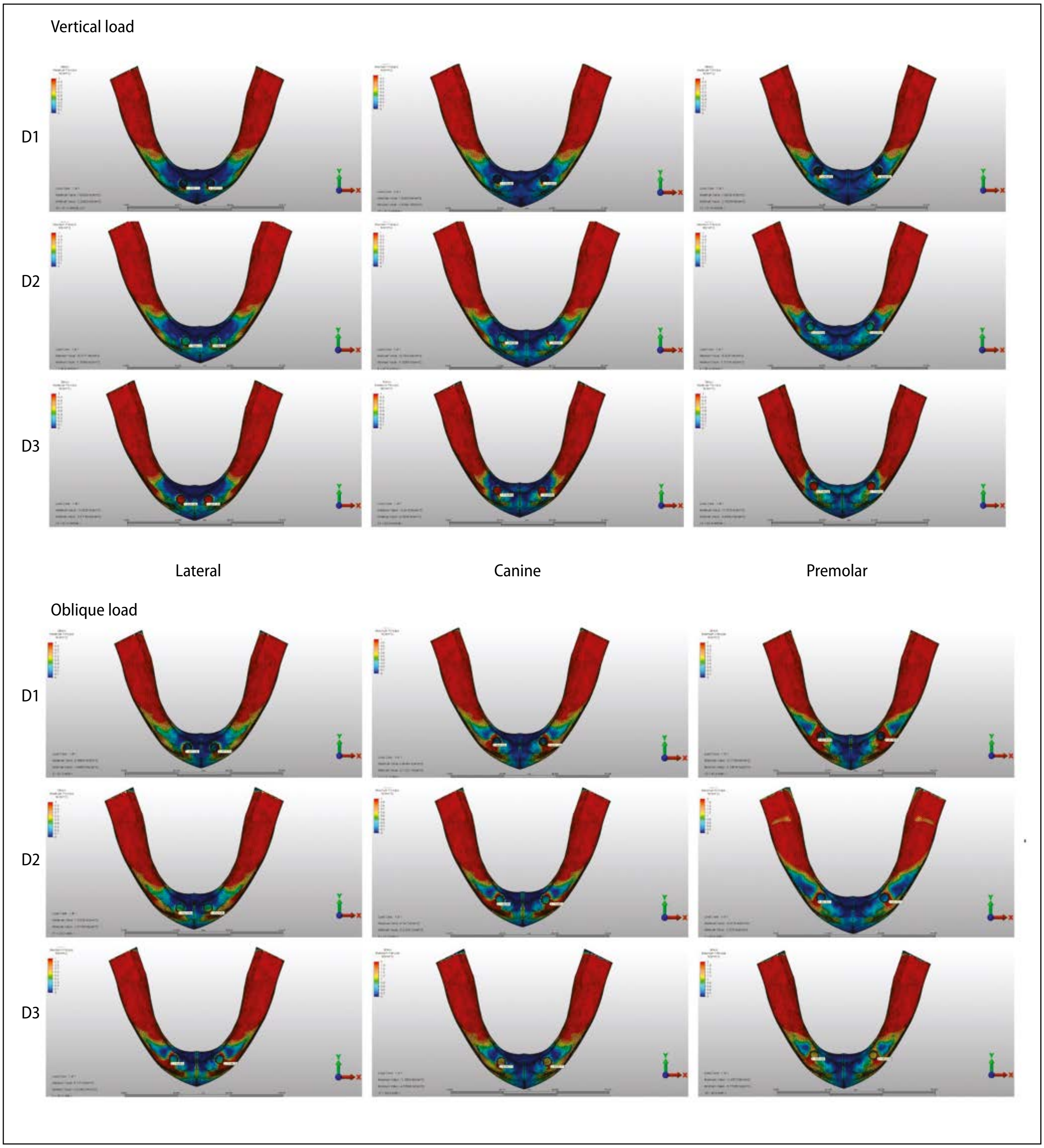


Fig 1 Maximum principal stress in the cortical bone under vertical and oblique loads.

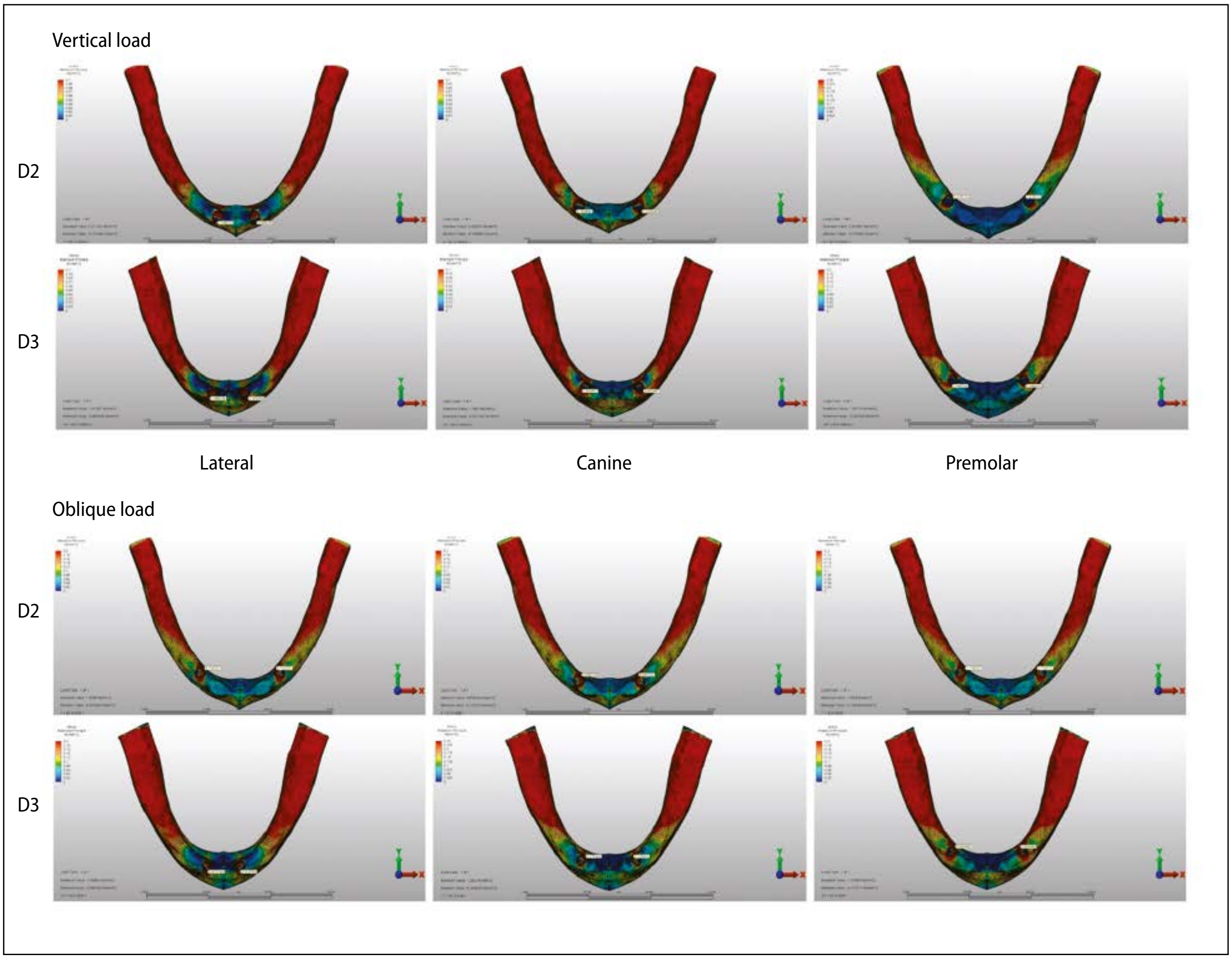


Fig 2 Maximum principal stress in the trabecular bone under vertical and oblique loads.

The maximum equivalent stress values of implants were the highest in the premolar region of D1 bone under oblique loading (Fig 5). The von Mises values in the locator attachment on the contact surface of the implant were lowest in the lateral incisor region of D2 bone and highest in the premolar region of D1 bone under oblique load (Fig 5). The maximum tensile stress values in the cortical bone in the buccal neck region of the implants were determined to be 1.04 MPa in the premolar region of D3 bone and 5.50 MPa in the premolar region of D1 bone. The maximum principal stresses in the bone were lowest in the lateral incisor and canine region of D1 bone and highest in the lateral incisor region of D3 bone (Fig 7).

The compressive stress values in the cortical bone in the mesial neck region of the implants were –4.44 MPa in the lateral incisor region of D1 bone and –8.07 MPa in the canine region of D2 bone (Fig 6). Maximum and minimum principal stresses in the trabecular bone under vertical and oblique loads are presented in Figs 2 and 4. Maximum principal stress values in trabecular bone were found to be 0.80 MPa in the lateral incisor region of D3 bone (Fig 8). Minimum principal stress values in trabecular bone were –1.01 MPa in the canine region of D3 bone under oblique loading (Fig 8).

The maximum equivalent stress values in the implants of each model under vertical loading are demonstrated in Fig 6. The von Mises stresses of the implant were lowest in the lateral incisor region of D1 bone and highest in the premolar region of D2 bone (Fig 5). In all models, the highest stresses were located in the neck region of the implants.

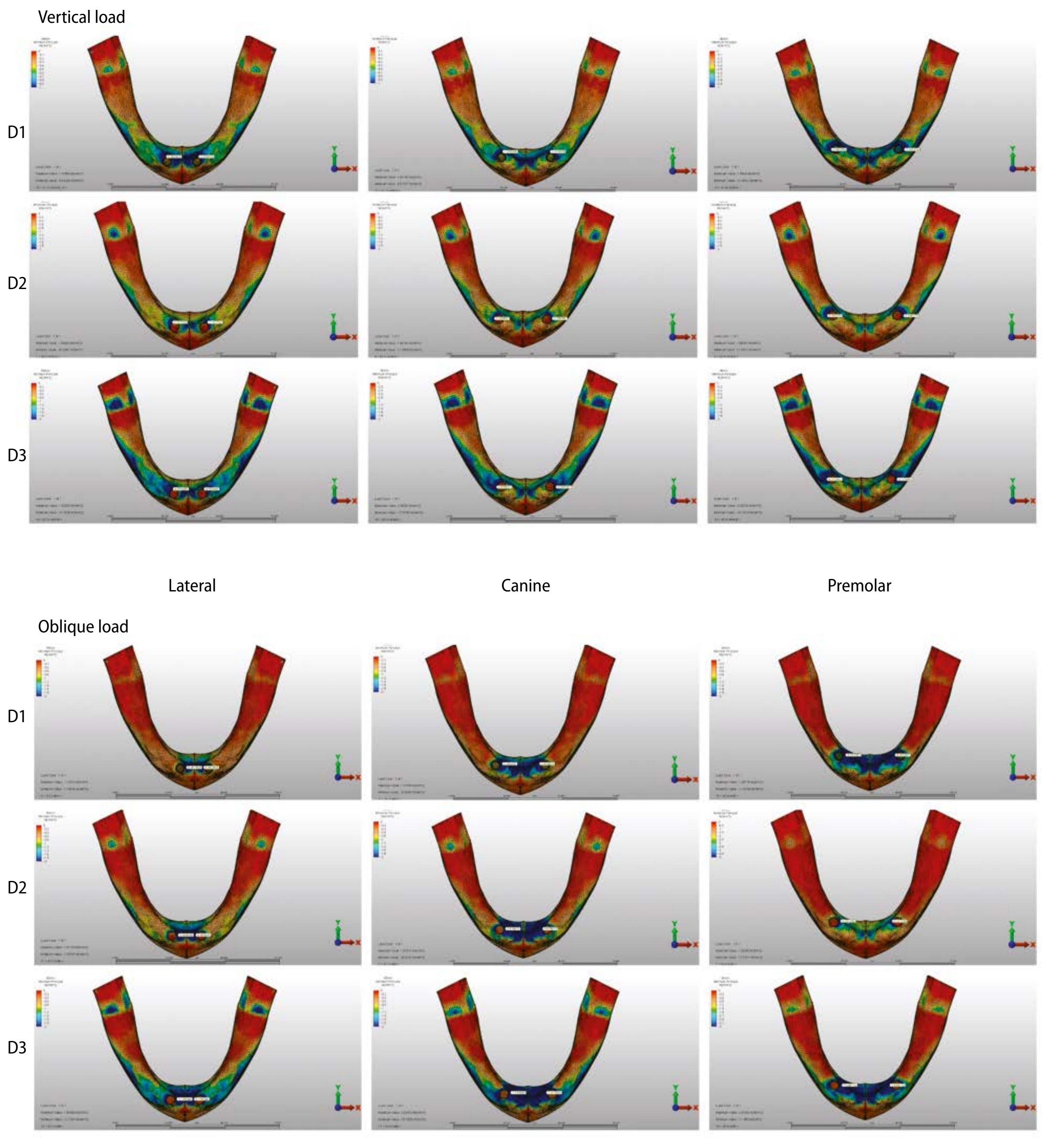


Fig 3 Minimum principal stress in the cortical bone under vertical and oblique loads.

The von Mises stresses in the locator attachment on the contact surface of the implant when the vertical load was applied were lowest in the lateral incisor region of D1 bone (16.07 MPa) and highest in the premolar region of D1 bone (21.59 MPa; Fig 5).

The maximum tensile stress values in cortical bone were determined in the buccal neck region of the implants as being lowest in the premolar region of D2 bone and highest in the canine region of D3 bone (Fig 6). The maximum stress in the bone was lowest in the lateral incisor region of D1 bone and highest in the premolar region of D3 bone (Fig 7). In trabecular bone under vertical loads, the maximum principal stress values of D2 bone were 0.26 MPa in the buccal neck region

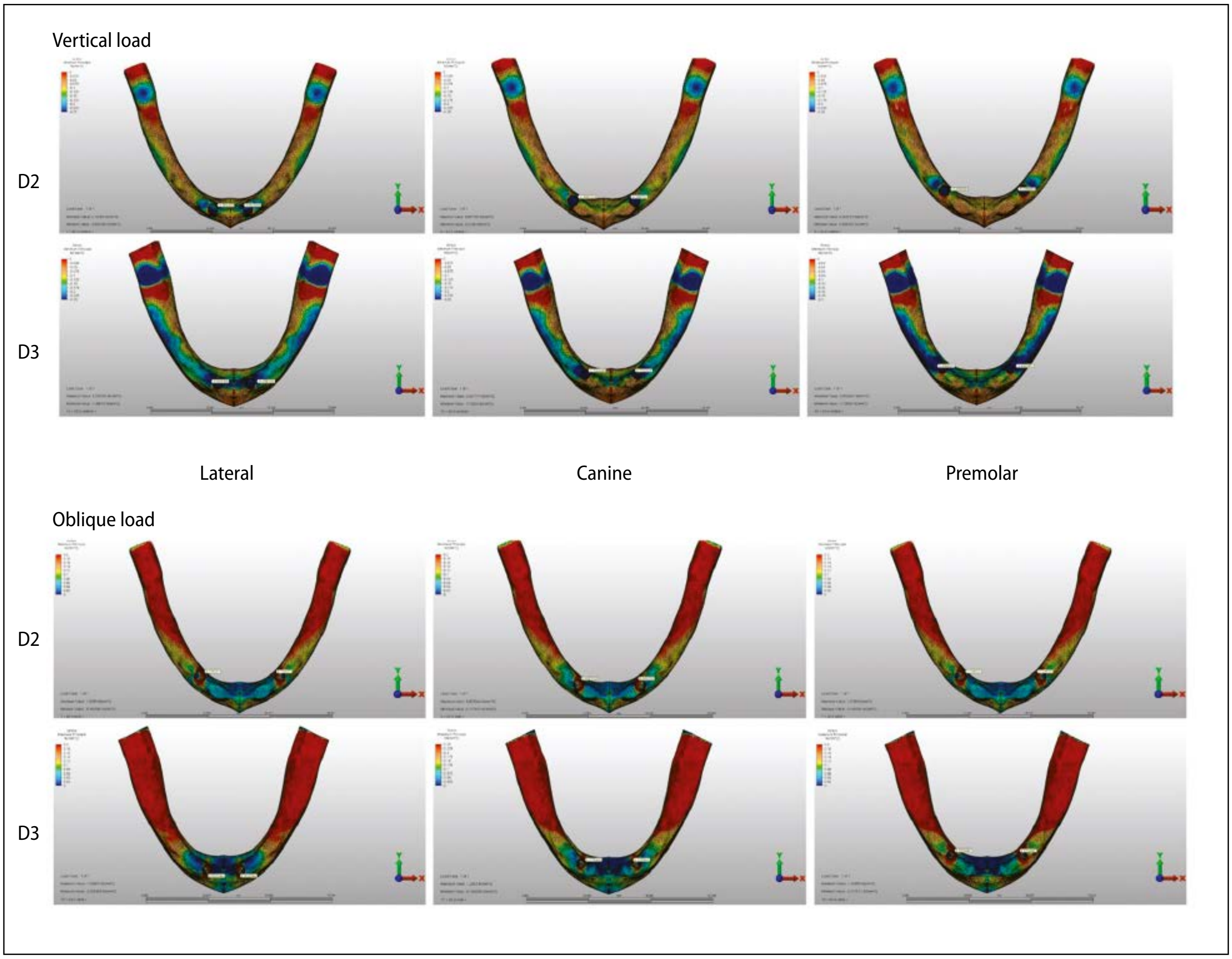


Fig 4 Minimum principal stress in the trabecular bone under vertical and oblique loads.

of the implants in the lateral incisor and canine region and 0.47 MPa in the lingual neck region of the implants in the premolar region (Fig 8).

When the vertical load was applied, the compressive stress values in the cortical bone in the lingual neck region of the implants were –1.97 MPa in the canine region of the D1 bone. The maximum compressive stresses in cortical bone in the premolar region of D3 bone were obtained in the distal neck region of the implants at –6.27 MPa (Fig 2). The minimum principal stress values were –9.53 MPa in the bone in the lateral incisor region of D1 bone (Fig 7).

The maximum equivalent stress values in the implants of each model when an oblique load was applied are shown in Fig 5. The von Mises stress value was lowest in the neck area of the implant in the lateral incisor region of D3 bone and highest in the premolar region of D1 bone (Fig 5).

The von Mises stress value in the locator attachment on the contact surface of the implant was lowest (21.16 MPa) in the lateral incisor region of D2 bone and highest (46.26 MPa) in the premolar region of D1 bone under oblique load (Fig 5).

The maximum tensile stress value in the cortical bone in the buccal neck region of the implants was determined to be 1.04 MPa in the premolar region of D3 bone and 5.50 MPa in the premolar region of D1 bone. The maximum principal stress in the bone was lowest in the lateral incisor and canine region of D1 bone and highest in the lateral incisor region of D3 bone (Fig 7).

The minimum principal stress values were –7.13 MPa in the bone in the lateral incisor region of D1 bone (Fig 7) and –1.01 MPa in the distal neck region of the implants in the trabecular bone in the canine region of D3 bone (Fig 4).

The compressive stress values in the cortical bone in the mesial neck region of the implants were –4.44 MPa in the lateral incisor region of D1 bone and –8.07 MPa in the canine region of D2 bone (Fig 4). The maximum principal stress values in trabecular bone were 0.80 MPa

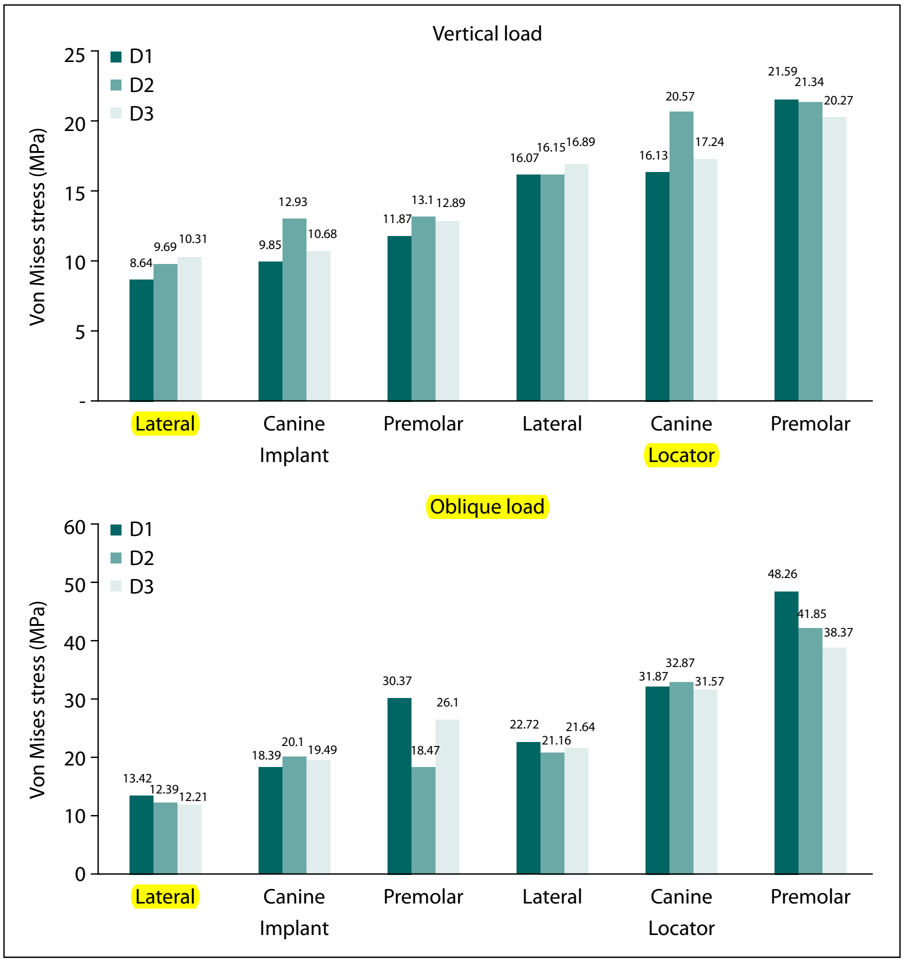


Fig 5 Comparison of von Mises stress values of implant and locator attachment under vertical and oblique loads.

in the lateral incisor region of D3 bone (Fig 2). The minimum principal stress values in trabecular bone were –1.01 MPa in the canine region of D3 bone (Fig 4) when oblique force was applied.

DISCUSSION

The present study examined the stresses caused by locator attachments on two implants placed in the lateral incisor, canine, and first premolar regions of the mandibular bones in D1, D2, and D3 bone types. A separate finite element model was prepared for each scenario.

It may be difficult to decide the number of implants to apply in completely edentulous patients.[13] In 2002, at the McGill Consensus Conference, it was argued that the first option in the treatment of mandibular complete edentulism should be removable dentures supported by at least two implants. It has been reported that high success rates can be achieved with a small amount of implant support.[2] Accordingly, the present study preferred to use two implants.

The high survival rates of implants placed in the interforaminal region for mandibular IODs were reported.[14] Implants are usually placed in the canine region to ensure good retention.[11,15] Taylor[16] concluded that placing implants in the lateral incisor area offers a mechanical advantage that ensures better stability for IODs. This results in decreased denture rotation and mobility, slowed resorption in the anterior region, and increased patient satisfaction. Therefore, the purpose of this study was to compare the FEA models of IODs with two implants, in which implants were inserted into the lateral incisor, canine, and premolar regions of three different bone types.

Different methods are used to evaluate changes that may occur in materials due to exposure of a structure to external factors, such as load, pressure, or heat. These are the brittle lacquer technique, strain gauges, photoelastic stress analysis, holographic interferometry, radio telemetry, thermographic analysis, and FEA methods.[5] FEA models provide a representation of a more detailed and complex geometric representation than other analyses.[5,17] For this reason, the FEA method is used for analyses.

Fig 6 Maximum and minimum principal stress values in the cortical bone under vertical and oblique loads.

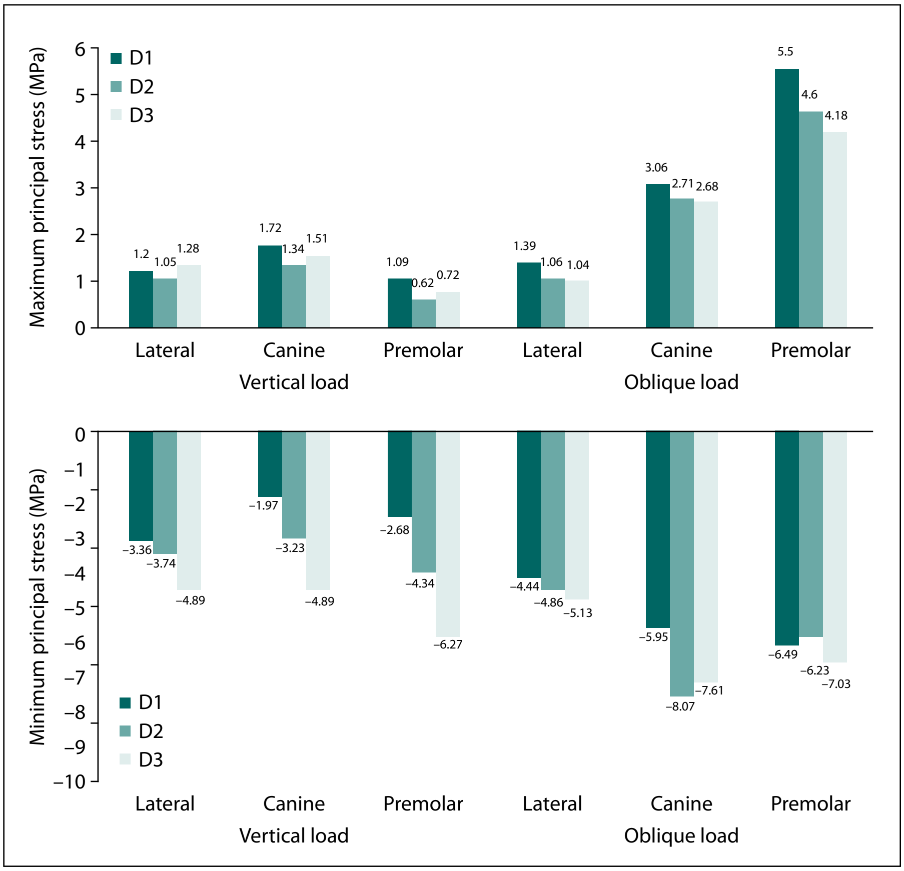
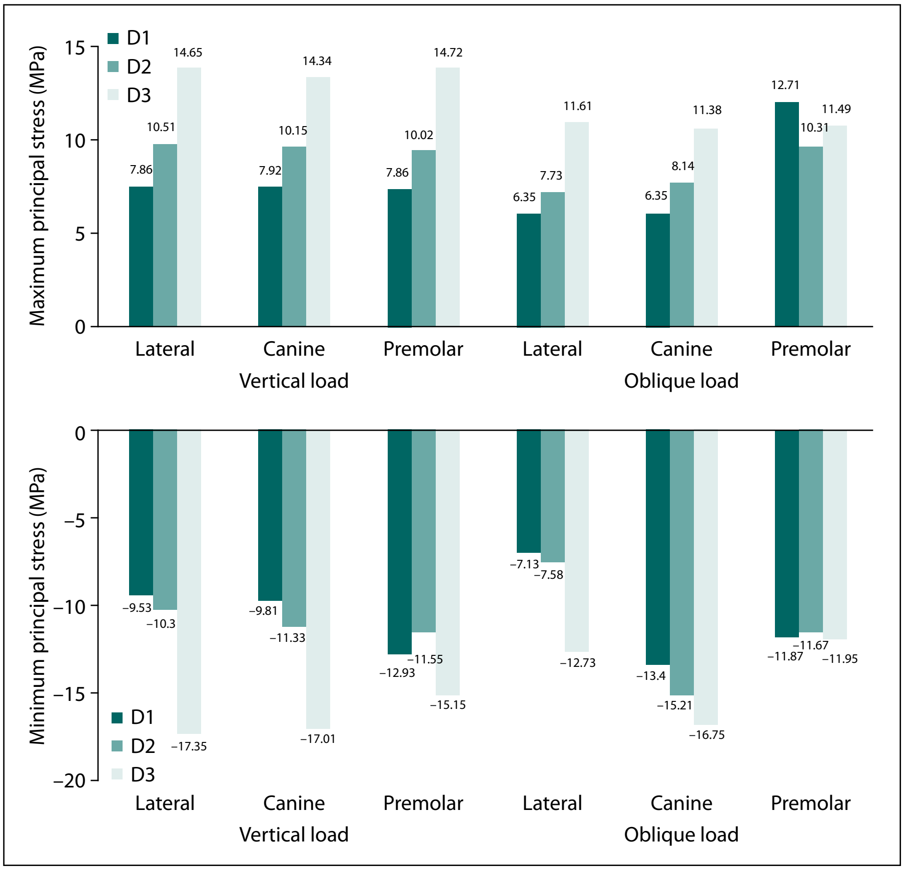


Fig 7 Maximum stress values in the bone under vertical and oblique loads.



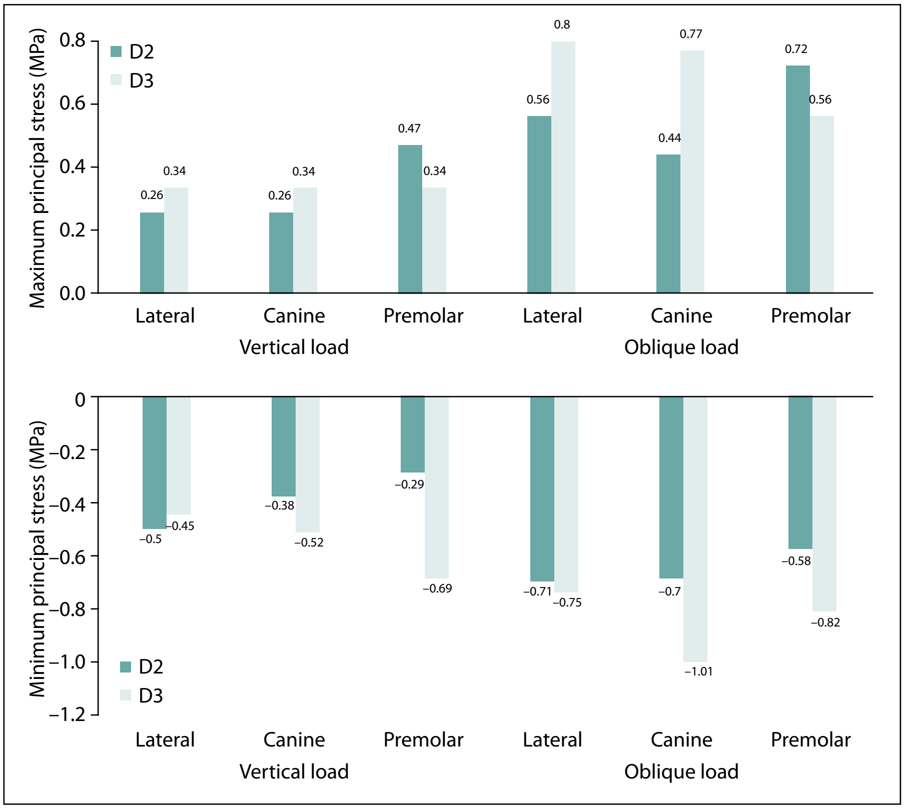


Fig 8 Maximum and principal stress values in the trabecular bone under vertical and oblique loads.

FEA studies by Meijer et al[18] have reported that deformation of the mandible has an effect on the extent of stress, and if the mandibular deformation is not taken into account, the analysis will be incomplete. Therefore, the present study determined the boundary conditions by immobilizing cortical and trabecular bone at the end of the retromolar bulge of the mandible, to allow for mandibular deformation.

Generally, in many FEA studies on mandibular IODs, a force of 100 N has been loaded from the center of the first molar tooth.[19,20] In the present study, the same amount of force was applied from the same region following previous studies.

Axial loads on the implants always coexist with lateral loads but do not have the same value or effect.[18] In the present study, the forces were applied vertically and obliquely at a 45-degree angle to determine the effect of the force in both directions. Some FEA studies have indicated that when a force is applied to the implant, the highest stress concentration value occurs around the neck area of the implant and decreases toward the apical of the implant.[6,21–23] The results of this study support these findings.

Bone density where implants are placed is another factor that affects the stresses occurring in bone. D1 bone density is frequently seen in the mandibular anterior region, while D2 and D3 bone densities are seen in the mandibular posterior region.[15] D4 bone density is mostly seen in the maxillary posterior region. Therefore, in the present study, all scenarios have been considered using the elasticity modulus and Poisson ratios corresponding to D1, D2, and D3 bone densities.

The elasticity modulus of cortical bone is higher than that of trabecular bone, so the cortical bone is stronger and less vulnerable to deformation.[24] In all bone types, the stresses on cortical bone are higher than those in trabecular bone.[25,26] The results of this study also support this finding.

Strain-type stresses must be within certain limits for the implants to be successful in the long term.[27,28] The maximum tensile stress of mandibular cortical bone has been reported to be 121 MPa in the literature.[26] In all models used in the present study, the highest stress values in cortical bone when oblique force was applied were 5.5 MPa in D1 bone of the premolar region, which is well below the stress resistance limit of cortical bone.

Recently, locator attachments have been preferred, especially in patients with insufficient occlusal vertical dimensions. These are rigid, durable, and of sufficient retention. They are also easy to apply, repair, and renew.[29] El-Anwar et al[30] stated that ball attachments cause higher stress than locator attachments. Yoda et al[31] also investigated the effect of attachment type in mandibular IODs, and they concluded that locator attachments generated the least stress accumulation in the bone. Therefore, in this study, the use of locator attachments was preferred.

The mandible is more resistant to compressive stress compared with strain-type stresses. Strain-type stresses should be within certain limits for the implants to be successful in the long term.[27,28] In this study, the highest stress value in cortical bone was found to be 17.35 MPa in D3 bone of the lateral incisor region when vertical force was applied on the implants. This value was close to 28 MPa, which is the resorption threshold value for cortical bone.[32] However, it is well below the highest compressive strength of cortical bone (167 MPa).[29]

Oblique forces applied on implants generate much more stress compared with vertical forces, which suggests that angled forces are more destructive.[33,34] When oblique force was applied, it was observed that the highest von Mises stress values on the implants were 30.37 MPa in D1 bone of the premolar region and that the fracture resistance of titanium alloy (900 MPa) had not been exceeded.

As the bone type changed from D1 to D3 bone, the stresses on bones increased in direct proportion. However, since locator attachments allow for minimum movement and elasticity, which is different from bar attachments, all the stresses that occurred were well below the threshold values required for bone resorption. However, lower stress values were found in cortical bone in the IODs by the implants located in the lateral incisor region in the mandibular models with all three bone types. Consistent with Misch,[15] the present study revealed that the occlusal force was intense in the molar region, and the lateral incisor area was the furthest away from this region. Therefore, implant placement in the lateral incisor area is as safe as in the canine region, which is the ideal location in cases where there will be no problem in terms of retention.

It was considered that, as the distance between implants in D3 bone increases, stresses may cause resorption in the bone since the values that cause biomechanical risks are approached. In mandibles with D1 and D2 bone types, all the values obtained in the present study did not approach the values that cause biomechanical risks in the bone. Therefore, the authors believe that such stresses will not cause any resorption in the bone. However, clinicians need to take this into account when making plans since bone density is decreased in patients with severely resorbed crests, which are often encountered in clinical practice, and consider that lower stress values may cause resorption in the bone.

The overdenture supported by the soft tissue is initially placed on the implants, so there will be some initial contact and deformation of the mucosa. However, in previous studies, the stress on overdentures and mucosa was found to be insignificant. The female and male parts of the attachment were one solid structure. Therefore, it was concluded that the loads were directly transferred from the superstructure to the implant and did not change the results of the studies.[35,36] In the present study, the results of the modeling to the properties and initial deformation (and thickness) of the mucosa were not sensitive, and this was one of the limitations.

The present study has provided experimental results; however, it should be noted that intraosseous stress around the implant and the physiologic stress threshold of jawbones may not be measured in clinical practice.[37] Studies that can provide insight into the quality and quantity of stresses that may cause marginal bone loss around implants are limited to animal experiments,[38] mathematical formulas,[39] and FEA studies.[40] It should be considered that the results obtained in this study are approximate due to the computer program used and the factors that depend on the analyzer since the FEA method is the basis of the mathematical equation solution.[41]

Another limitation of this study was that the geometry of the mandible was the same; however, the arch width could be varied among cases, and the distance from the anterior artificial part of the mandibular denture and the implant, the anteroposterior ratio, is also varied. The location of the implant could be further examined in different arch types.

Any firm conclusions drawn from these results should be supported by long-term clinical trials. Finally, lack of statistical evaluation disallows conducting any null hypotheses.

CONCLUSIONS

Within the limitations of this in vitro study, it can be concluded that the highest stresses due to vertical forces occurred in the buccal cortical bone in the neck of the implants. The oblique force caused more stresses. In prosthetic designs where two implants were used in all bone types, the lateral incisor and canine regions were more advantageous compared with the first premolar tooth region in terms of biomechanics.

ACKNOWLEDGMENTS

The authors wish to sincerely thank Dr Makbule Bilge Akbulut and Dr Bozkurt Kubilay Işık from Necmettin Erbakan University Faculty of Dentistry for providing great assistance and helpful comments. The authors reported no conflicts of interest related to this study.

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Zest Anchors introduces next-generation Locator R-Tx removable attachment system

Feb. 9, 2016

Zest Anchors has announced the introduction of the next-generation Locator R-Tx removable attachment system, which is designed to be stronger and simpler than the Locator but relies on the same restorative techniques as its predecessor.

DentistryIQ Editors

Zest Anchors has announced the introduction of the next-generation Locator R-Tx removable attachment system, which is designed to be stronger and simpler than the Locatorbut relies on the same restorative techniques as its predecessor.

Practical benefits of the Locator R-Tx include:

- DuraTec titanium carbon nitride coating, which is aesthetic, harder, and more wear resistant
- An industry-standard .050-in / 1.25-mm* hex drive mechanism (no special drivers are required)
- Dual-retentive features on the abutment and nylon retention insert that work in harmony with the redesigned denture attachment housing to allow for a 50% increase in pivoting capability (60 degrees between implants) and provide easier alignment and overdenture seating during insertion and removal for the patient
- The redesigned denture attachment housing also incorporates flats and grooves that resist movement and is anodized pink for aesthetics
- All-in-one packaging: A double-ended vial separately holds abutment and processing components, providing all the necessary components for the case with one part number

"Clinicians, implant manufacturers, and patients alike have come to trust the original Locator attachment system and helped propel it to market-leading status," said Steve Schiess, CEO of Zest Anchors. "We've listened to [input] from the **implant** community over the years and applied pragmatic improvements to this next generation design. We're confident the user experience with Locator R-Tx will be incrementally rewarding."

For more information about Locator R-Tx, visit zestanchors.com/rtx or call Zest Anchors' customer service at (800) 262-2310.