Investigation of Mucosa-Induced Residual Ridge Resorption Under Implant-Retained Overdentures and Complete Dentures in the Mandible

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\textbf{Purpose:} This study aimed to investigate and compare the residual ridge resorption (RRR) induced by an implant-retained overdenture (IRO) and associative biomechanics and by a conventional complete denture (CD) without implants. \textbf{Materials and Methods:} Cone beam computed tomography was used to quantify RRR in a three-dimensional (3D) manner before and after 1 year of treatment with either IROs or CDs. Twenty patients were treated with IROs, and nine patients were treated with CDs in the mandible. Their maximum bite forces were recorded. The same sets of high-resolution scan images were used to create patient-specific 3D finite element analysis models. The hydrostatic stresses, contact surface deformation, and strain energy absorption in soft tissue mucosa were correlated with the changes in RRR for patients with and without implants. \textbf{Results:} With the IROs, contact surface deformation on the mucosa was two times greater than with CDs (0.32 ± 0.23 mm vs 0.16 ± 0.06 mm) and was in agreement with the amount of RRR measured, which was also two times higher for the IRO than the CD (–3.8% ± 4.5% vs –1.9% ± 0.4%). Taking into account the differences in bite forces with and without implants, which again were twice as high with IROs, the hydrostatic stress within the mucosa was found to correlate well to the RRR map measured over the 1-year interval of treatment. \textbf{Conclusion:} IROs resulted in at least twice the RRR as CDs. This could be caused by the higher hydrostatic stress and less effective energy absorption capabilities of the mucosa underneath the IRO. While implants associated with the IRO provide stronger bite force, they could potentially concentrate hydrostatic stress and cause greater RRR compared to a conventional CD. \textit{Int J Oral Maxillofac Implants} 2015;30:657–666. doi: 10.11607/jomi.3844

\textbf{Key words:} bite force, blood flow, bone remodeling, cone beam computed tomography, denture, finite element analysis, hydrostatic pressure, mandible, mucous membrane, permeability

Current evidence from bone remodeling studies relevant to complete dentures (CDs) and implant-retained overdentures (IROs) strongly advocates functional pressure as one of the most important etiologic factors in residual ridge resorption (RRR).\textsuperscript{1–5} When two implants are used to retain dentures, bite forces can increase considerably,\textsuperscript{6–10} but this could lead to more severe RRR\textsuperscript{11,12} in the posterior mandible distal to the implants compared to a conventional CD. With implant-supported overdentures (which use four or more implants), reduced resorption\textsuperscript{13–15} and bone apposition\textsuperscript{16–20} have been observed in the posterior region of the mandible, probably because less pressure is exerted on the soft tissue mucosa and the underlying bone and most forces are transferred to the implants.

When the soft tissue mucosa underneath the denture base is compressed, the blood flow that supplies nutrients to and removes metabolites from the bone can be affected, potentially leading to resorption.\textsuperscript{21,22} Maruo et al\textsuperscript{23} demonstrated that the amount of RRR versus the pressure-induced blood flow rate exhibits a simple linear regression ($R = 0.766$). Because most denture wearers are in late middle age, the blood supply to
the mandible mainly originates from the subperiosteal plexus of vessels and therefore is very susceptible to diminished circulation under denture pressure.\textsuperscript{24} The blood pressure in the venous capillary is quite low, within the range of 15 mmHg (venous) to 35 mmHg (arterial), equivalent to 2.0 to 4.7 kPa.\textsuperscript{25}

When the epithelial layer of the mucosa is subjected to loading, there will be cellular swelling, increased nuclear size, and intercellular edema.\textsuperscript{26} This inflammatory response of the cells and surrounding tissue may contribute to a change in the permeability of the mucosal tissue, which may further compromise blood circulation. If the hydrostatic pressure that develops in the mucosa underneath the denture exceeds the blood pressure in the mucosa blood vessels, blood flow will be decreased and may even temporarily cease altogether as a result of the combination of active arteriolar closure and passive capillary obstruction.\textsuperscript{27} However, there has been limited clinical exploration to quantify the correlation between hydrostatic pressure and resultant RRR. This study aims to investigate the RRR induced by two types of denture treatments, specifically a CD and an IRO, in clinical application across a 1-year interval and correlate it to hydrostatic stress and other associative biomechanics, namely, contact surface deformation and strain energy absorption. The authors hypothesize that the mucosal hydrostatic stress plays a significant role in RRR and that its magnitude is influenced by the bite force exerted on the denture and the resultant contact surface deformation in the mucosa, as well as the strain energy absorption capabilities of the mucosa underneath the dentures. The established association of RRR with hydrostatic pressure will provide critical insights into the mechanism of RRR taking place for different types of dentures.

**MATERIALS AND METHODS**

**Imaging, Denture Fabrication, and Bite Force Measurement**

Ethical approval to carry out this study was obtained from the Ethics Committee of Universiti Teknologi MARA, Malaysia (600-RMI [5/1/6], 20th April 2009). All recruited patients underwent diagnostic cone beam computed tomography (CBCT) of the mandible before the provision of new CDs in both arches. A duplicate denture containing barium sulfate was worn during imaging to enable clear definition of the bone, mucosa, and dentures, from which RRR patterns and the mucosa thickness could be analyzed three-dimensionally (3D). Participating patients could not have had any extractions within the previous 6 months.

For those patients with sufficient bone to host implants 11 or 13 mm long, two implants (Ankylos, Dentsply) were placed in the canine regions of the mandible. After 2 months, the implants were exposed and telescopic male abutments were attached (Ankylos SynCone, Dentsply). The mandibular CD was converted to an IRO by incorporating the corresponding female metal sleeves inside its fitting surface. Both groups of patients underwent a second series of CBCT scans taken for bone measurement after 1 year.

The CBCT images were taken with an i-CAT machine (Imaging Sciences International), which was set at 120 kVp, 18.45 mAs, 20-second acquisition time, 13-cm field of view, and voxel size of 0.30 mm. The digital files of the images were acquired and stored for quantitative and modeling analyses.

After patients had become comfortable wearing their prostheses, unilateral maximum bite force was measured. They were asked to bite on a 200-N compression load cell (LMB-A-200N) placed in the molar region as hard as they possibly could. The load cell was connected to a data logger (PCD-300B) and a computer. Each bite recording lasted for a few seconds, and measurements were carried out three times on each side of the jaw. The patients were allowed a 5-minute rest period between recordings. They were not given any feedback on their bite force and were not allowed to see the readings. The highest recorded force was used as the value for maximum bite force.

**Measurements of Bone Volume Change**

The two 3D models obtained from the diagnostic CBCT scan prior to treatment and the CBCT scan taken 1 year posttreatment were superimposed in Mimics version 14.1 (Materialise) and subsequently exported into another software program (3-matics version 5.1, Materialise) to produce color maps that revealed the magnitude of the RRR after 1 year.\textsuperscript{28} The RRR results for both IRO and CD scenarios were quantified by measuring the changes in bone volume between the pre- and posttreatment models. The region of interest comprised the area from about 5 mm distal to the implants up to the retromolar area just anterior to the ascending ramus to avoid the effect of CT artifacts.

**Finite Element Models**

Two male participants, one from the IRO group and the other from the CD group, who were of similar age (around 62 years old) and who scored the highest maximum bite force value in their respective treatment groups, were selected as representative models for a finite element analysis (FEA). Complete 3D models of the mandible, mucosa, and denture were created from their diagnostic CBCT images. The patients’ CT image data from the pre-treatment scans were imported into ScanIP (version 4.3,
Figs 1a to 1f  Finite element modeling procedures.

Fig 1a  Cross section of a CBCT image showing the different greyscales of the denture, mandibular bone, and soft tissue mucosa.

Fig 1b  Three-dimensional masks created for each structure in .stl format: denture (azure), mucosa (pink), and jawbone (orange).

Fig 1c  Solid models created by NURBS in IGES format.

Fig 1d  Superimposition required to position the implants for the IRO, including pretreatment scan (light orange), 1-year follow-up scan (dark red), implants (dark blue), and implant models (grey).

Fig 1e  Final model imported and meshed in ABAQUS 6.9.2.

Fig 1f  Boundary and loading conditions have been assigned to the model. Chewing forces are shown by the red arrows, and areas of fixation are indicated by blue nodes, whereas the mucosa is hidden from the picture.

Simpleware) for segmentation, as shown in Fig 1. Three individual masks were created to present the mandibular bone, denture, and mucosa based on grayscale values of each pixel and normalized to a range from 0 to 255; the thresholds of each mask were determined by sampling the localized counts (Fig 1a, right). Because of the relatively low density of the oral mucosa compared to other oral tissues, this was created by offsetting the contrast of the outer layer of the cortical bone, thereby producing a layer of minimum thickness at 1.0 mm.

All three masks in each image stack were then exported in .stl format and further processed using 3D parametric modeling software (Rhinoceros 4.0, Robert McNeel & Associates), as shown in Fig 1b, to create geometric models. The surface mesh on the masks formed a scaffold for constructing free-form parametric surfaces with the nonuniform rational B-spline (NURBS) function (Fig 1c). The manipulated surfaces were then solidified and exported as IGES files for FE modeling in ABAQUS 6.9.2 (Dassault Systèmes).

In ABAQUS 6.9.2, the adaptive mesh control was set to have a maximum elemental size of 1 mm with the maximum deviation factor at 0.05 for the curvature control in all components (Fig 1e). Further mesh refinement was set to 0.5 mm on the interfaces between denture and mucosa. After a mesh convergence test, similar to previous studies, the final meshes comprised 669,042 (376,974 degrees of freedom) and 727,743 (423,598 degrees of freedom) tetrahedral elements for the CD and IRO models, respectively (Fig 1e).
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For the IRO, one extra step was required to place a pair of dental implants into the model. The implants and abutments were modeled in SolidWorks 2012 (Dassault Systèmes, Solidworks Corp). To ensure the correct locations of the implants, the CT scan at 1 year after placement was superimposed onto the pretreatment model in Rhinoceros 4.0, where the implant models were matched to the implants' masks (Fig 1d).

The material properties of cortical and cancellous bone were considered to be isotropic and linearly elastic, as has been done in numerous previous studies.31–33 The mechanical properties of the titanium alloy (titanium-aluminum-vanadium) implants and the denture were obtained from O'Brien32 and Satoh et al34 and the mucosa from Isaksson.33 These values are summarized in Table 1, and all mechanical properties were assumed to be homogenous and isotropic.35,36

In both treatment cases, cortical and cancellous bone was considered bonded, as occurs for their biologic function. For the IRO, the implants were assumed to be fully osseointegrated by tissue ingrowth from the surrounding bone structure37–39 by assigning a full-tie constraint in ABAQUS. Both the dentures were slightly offset from the mucosa surface of the mandible, and the displacement was generated upon loading. As such, the model was allowed to initiate the surface-to-surface contact between the denture base and the mucosa.

As suggested by Gibbs et al40 in a clinical study, a localized load was applied to each side of the dentures using 40% of the measured maximum bite force in the participants by assuming a nearly symmetric loading condition (Fig 1f). The load was applied in the vicinity of the first molar in a vertical direction. This loading scenario has been considered as isometric bilateral biting of the mandible in the literature,41 and similar magnitudes of force have been adopted for mandibular loading in other FEAs.42–45

The boundary conditions were prescribed to the distal ends of the condyles, where they are connected to the joints with the maxilla. Early FEAs showed that jaw rotations have limited effects on the local stress distribution, and the boundary conditions are usually applied to the remote temporomandibular joint.41 Thus, full kinematic constraints of all degrees of freedom were applied here to effectively prevent rigid body motion of the mandibular model.35,41

Hydrostatic Stress

To determine the hydrostatic stress, a FORTRAN subroutine (UVARM, User Defined Output Field Requirement) was implemented in ABAQUS and determined by one-third of the sum of the principal or normal stresses as follows:

\[
\sigma_{\text{hydro}} = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) = \frac{1}{3} (\sigma_\text{x} + \sigma_\text{y} + \sigma_\text{z})
\]  

Strain Energy Absorption

To further assess the overall cushioning role that the mucosa plays in these two different prosthetic configurations, the absorption of strain energy in the mucosa was used to measure the severity of the disturbance brought to the mucosa under compression. As defined in Equation 2, total strain energy density was approximated by summing the products of the stress and strain components of all elements (\( n \) is the total number of elements in the mucosa under stress).

\[
\text{SED} = \frac{\sum (\sigma \cdot e \cdot V)}{2 \sum V} = \frac{1}{2} \sum \left( \begin{array}{c}
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e_x \\
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\end{array} \right) \cdot V
\]  

RESULTS

Twenty-nine patients participated in the study, 20 patients in the IRO group (12 women and 8 men) and 9 in the CD group (3 women and 6 men). Their ages ranged from 52 to 79 years at recruitment; the average age was 67 years. The history of denture wearing varied from no experience to almost 25 years of denture wearing.

Maximum Bite Forces

The mean bite force in the participants with IROs was 110 ± 32 N, nearly twice that of the CD wearers (63 ± 15 N) (Tables 2 and 3). For the FE models, the male participants selected scored the highest maximum bite force value in their respective treatment group, and the load used for each case was 40% of the actual participant’s load (137.6 N and 76.6 N for IRO and CD, respectively).

Bone Volume Change

RRR was first measured in terms of the percentage change in bone volume that took place after a period of 1 year of wearing the prostheses. RRR occurred...
predominantly in the denture-bearing areas: occlusally in the molar regions and more lingually in the premolar areas. The mean reduction in bone volume associated with IROs was 3.8% ± 4.5%, which is around twice that of CDs (1.9% ± 0.4%) (Tables 2 and 3). The RRR in the former treatment case was almost double that of the CD participants.

The changes in residual ridge thickness are plotted in Figs 2a and 2b for the CD and IRO configurations, respectively. The scale ranges from –2.0 mm to +2.0 mm for bone apposition and resorption. White areas indicate minor or no change. Under the CD, white is dominant across the entire base contact region, and a small amount of pink indicates minor height reductions. In contrast, the frequent appearance of red and maroon at the posterior ends of the IRO indicates severe bone resorption.

Hydrostatic Stress Distribution
Based on the FEA results of these two patient cases, the hydrostatic stress contours of the mucosa under the CD (Fig 2c) and the IRO (Fig 2d) were compared. In these two plots, dark blue indicates the most severe compressive hydrostatic stress under the denture bases, and red indicates the least effect (neutral status, ie, neither compressive nor tensile). Green regions designate a medium range of the compressive hydrostatic stress, close to systolic blood pressure (140 mmHg, approximately 19 kPa).

The mucosa under the CD demonstrated a fairly low and uniform hydrostatic stress distribution from the anterior to the posterior part of the residual ridge. In contrast, the mucosa under the IRO exhibited higher hydrostatic stress magnitude and a more concentrated distribution on the occlusal and lingual surfaces of the residual ridge in the molar and premolar regions, respectively. For the individual patients, the volumetric average of hydrostatic stress over the contact region was –34.53 ± 8.07 kPa for the IRO and –23.32 ± 0.81 kPa for the CD, representing a 32.5% reduction. The peak stress values also diminished from 128.5 kPa for the IRO to 66.1 kPa for the CD between these two cases.

When the contours of hydrostatic stress were compared with the contours of RRR, good agreement was observed for both the IRO and the CD. For the CD case, the low FE hydrostatic stress correlates well with the minimal RRR observed after 1 year of treatment. For the IRO, the areas with high hydrostatic pressure corresponded very well with the areas of predominant resorption, which were on the occlusal and lingual surfaces of the residual ridge in the molar and premolar regions, respectively.

Contact Surface Deformation
From the FE models, the total compressed contact areas between the mucosa and denture in these two cases were calculated as 4,608.7 mm² (CD) and 2,833.4 mm² (IRO). Figure 3 combines the contact status and surface normal deformation to compare the deformation of the contact surfaces of the CD (Fig 3a) with that of the IRO (Fig 3b). With a total force of 76.6 N over the CD, the maximum contact deformation of the mucosa was 0.58 mm in the vertical direction. The entire contact region (2,762 nodes under contact) deformed fairly uniformly, with an area average deformation of 0.16 ± 0.06 mm, which agreed very well with the hydrostatic pressure contour. For the IRO, while the total bite force (137.6 N) applied was approximately 1.8 times that applied under the CD, the maximum contact deformation was 1.19 mm, more than double

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that of the CD in the posterior region of the denture. Nevertheless, the corresponding area average deformation was 0.32 ± 0.23 mm (more than 1,708 nodes under contact), approximately doubling that of the CD.

When an equal load of 137.6 N (68.8 N on each side) was applied for both the IRO and the CD, the increased bite force on the CD certainly led to further mucosal deformation, but the deformation pattern did not change significantly (Fig 3c). Furthermore, the same bite force still resulted in higher maximum deformation on the IRO than on the CD, resulting in more concentrated disturbance to the local mucosa.

**Energy Absorption**

Figure 4 graphs the results of energy absorptions at their respective bite loads. Despite the load ratio of 1.8:1, the mucosa beneath the IRO stored only 47.8% more strain energy than the CD because of the concentration of localized hydrostatic stress, as presented in Fig 2.
DISCUSSION

Mechanical loading is recognized as one of the major causes of bone apposition and resorption in denture wearers. The hydrostatic stress in mucosa has been considered a key factor in disturbing local microcirculation of tissues surrounding the bone, thereby affecting its mineralization pathway. In this study, the hydrostatic stress distributions generated by the patient-specific 3D FE models showed a good correlation with the in vivo measurements of RRR in two different clinical treatment scenarios, namely, CD and IRO. The visualization of hydrostatic stress could provide clear biomechanical evidence of how hydrostatic stress may affect the local blood supply in mucosa.

To further illustrate the difference in hydrostatic pressure observed between these two treatment scenarios, the corresponding hydrostatic stresses on the contact interface between the mucosa and the denture are shown in Fig 5, in which the curvilinear...
distance was measured from the center of the incisors to the retromolar area along the residual ridge. Since the mandibles exhibited good anatomical and loading symmetry along the sagittal plane, hydrostatic stress was plotted on the right-hand side of the mandible only. It was evident that the distribution of hydrostatic stresses along the mucosa-residual ridge interface differed considerably between the IRO and the CD. The CD developed a relatively more even pressure distribution at an average of about 17.7 ± 4.81 kPa, which led to much lower RRR (Fig 2a). The localized pressure increased to a level around 30 kPa in the loading area, which appeared to cause a certain extent of RRR in the same location. In contrast, the IRO generated an uneven distribution of hydrostatic pressure. The pressure rose sharply in the posterior area and the peak values were about twice that of the CD. The bite force, based upon clinical measurements, for the IRO case was 1.8 times that of the CD case, but the resultant peak hydrostatic stress led to a twofold difference along this contour path. Interestingly, the area below the trend line, which is a measure of the effective force supported by the mucosa, of the IRO was only 1.13 times that of the CD, indicating that a substantial portion of the bite force was borne by the implants.

Another possible explanation for the current clinical observations may be that a much smaller denture-bearing area was available to support the IRO posteriorly compared to the CD, which had the entire denture-bearing area available to share the load (Fig 2). After deformation, the average denture-bearing area of contact was 4,608.7 mm² for the CD and 2,833.4 mm² for the IRO; these values are fairly close to those reported in the literature (around 4,000 mm² for the former and about half that for the latter). When two implants are placed in the canine regions, the mucosa area available posteriorly to support the overdenture is further reduced, to about half of the in vivo measurements. The longer the interabutment distance anteriorly, the smaller the mucosa area available to support the denture posteriorly. When combined with the higher bite force that is typically associated with an IRO, the smaller contact area may cause more localized RRR (twice that of the CD). Furthermore, by virtue of the IRO design, free rotation of the denture during mastication may result in enhanced posterior loading. Since a conventional CD might move around during functioning, there may not be a particular area of highly concentrated stress, as happens in the IRO situation.

When an IRO is fabricated to be mainly mucosa-supported, some portion of the masticatory force will be shared by the implants anteriorly. This is evidenced by the extremely low hydrostatic pressure recorded in the mucosa in the anterior region in the distance from 0 to 41 mm (Fig 5), where the implant is located. Upon moving in a posterior direction, the hydrostatic pressure increased steadily and had a peak in the first molar area, where the biting force was exerted. For the CD, although hydrostatic pressure also reached a peak in the molar region, the peak value was much lower than that in the IRO and the hydrostatic pressure was more uniformly distributed across the entire denture-bearing area.

The results of energy absorption analysis revealed that the mucosa under the CD stored deformation energy more efficiently than that under an IRO. This implies that an IRO may enable a patient to achieve a higher biting force but could likely induce RRR in the posterior mandible because of the unevenly distributed hydrostatic pressure and reduced cushion effect in terms of energy absorption efficiency.

Although the IRO generated more localized RRR than the CD, the benefits of higher mastication forces allowed by the use of implants should be taken into consideration. It must be pointed out that the current implementation of implants largely follows clinical experience, and there is considerable latitude for optimizing the implant locations, lengths, angles, and other factors to transfer the load onto the mucosa more uniformly, leading to improved stress distribution and energy absorption.

It must be acknowledged that there are several limitations associated with the FE modeling in this study. First, a pair of bilateral bite forces was used instead of unilateral bite forces in the FEA, which does not represent how the human mouth commonly functions. Second, only a vertical force on a single tooth was applied in the analysis. Further investigation is necessary to explore the effects of loading multiple teeth or loading in different force directions (eg, transverse). Furthermore, the bone density values in the CBCT scan cannot be calibrated to make a heterogenous FE model. As Field et al. suggested, a heterogenous distribution of materials can affect potential bone remodeling activities. In this study, identical material properties were applied to these two cases to create a similar baseline situation for comparison purposes, and the heterogenous effect should be considered in future studies. Similar material properties for the other critical component, mucosa, were adopted from the literature for the same purpose; however, individual variations may require attention. Future work can be carried out to optimize the arrangement of the IRO, including implant positions, lengths, abutment angles, etc, to generate more uniformly distributed hydrostatic pressures. With the increasing popularity of implant therapy and rapid advancements in computed tomography, there is potential to develop a patient-specific treatment plan in clinical applications that may provide the least disturbance to blood flow in the mucosa to better suit individual residual ridge conditions.
CONCLUSIONS

Within the limitation of this three-dimensional finite element analysis and short-term clinical study involving 29 participants, the implant-retained overdenture led to at least twice as much residual ridge resorption as the complete denture. This could be a result of the onset of higher hydrostatic stress associated with the overdenture. While implants provide the patient with higher bite forces, they could potentially concentrate hydrostatic stress and give rise to higher residual ridge resorption.

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