Finite element analysis and clinical complications in mandibular implant-overdentures opposing maxillary dentures

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A R T I C L E   I N F O

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A B S T R A C T

Denture fracture is a common clinical complication caused by improper material selection, design, or fabrication technique. This study aimed to investigate the effect of two attachment systems on fracture risk of the implant-overdentures (IOD) via finite element analysis (FEA), using the force distributions obtained from patients’ occlusal analyses and to compare the obtained results with the clinical complications associated with these attachments. A three-dimensional jaw model comprised of the edentulous bones was constructed. Three types of mandibular prostheses including complete denture (CD) (model LCD), IOD with Locator attachment (model LID-L), and IOD with telescopic attachment (model LID-T), as well as a maxillary CD (model UCD) were assembled. The vertical occlusal forces at anterior and posterior quadrants were obtained from the patients wearing mandibular CDs or IODs. The FEA results were further compared with the mechanical failures of different prostheses observed at patient recalls. In overall, the fracture risk of mandibular prostheses was lower than the maxillary compartments. The UCD opposing LCD underwent higher strains than that opposing LID-L and LID-T, which was mostly concentrated at the anterior mid-palatal polished surface. On the other hand, LID-L showed the lowest strain, followed by LID-T, and LCD. The obtained results were consistent with the clinical complications observed in the patient recalls.

1. Introduction

In spite of the significant enhancements of material properties and fabrication methods, fracture of the denture base still accounts for 64% of the total denture damages (Vallittu et al., 1993; Narva et al., 2001), resulting in increased costs, extra visits to the dentist, and patient embarrassment who must remain without denture while being repaired (Gonda et al., 2010). A number of fabrication failures such as poor material selection, high porosity, and presence of excessive uncured residual monomer are also associated with the increased risk of denture fracture. The lack of adaptation to the denture bearing area caused by continual ridge resorption could also make dentures more susceptible to deformation and fracture. It has been shown that the stress concentration at the midline stress area of the maxillary conventional complete dentures (CDs) is relatively higher compared to the mandibular CDs (Prombonas and Vlissidis, 2006).

Denture fracture occurs mostly during mastication (Vallittu et al., 1993) with occlusal biting forces significantly lower than the static failure strength of the denture base. However, repeated mastication loads lead to significant decays in the mechanical properties and fatigue of the denture material in the long term (Vallittu et al., 1994, 1996; Narva et al., 2005). Moreover, natural wetness of the oral environment could intensify formation of microcracks due to the fatigue phenomenon, which further propagate and result in denture fracture (Vallittu et al., 1994). The acrylic polymers such as polymethyl methacrylate (PMMA) which are widely used as denture base materials, show glassy behaviour at room or the oral cavity temperatures, and thus provide low flexural fatigue resistances (Narva et al., 2001).

Dental implants are being recently utilized to improve retention and stability of the removable prostheses. The implant-overdentures (IODs) are generally supported by particular attachment systems with different mechanisms of retention (Alsiyabi et al., 2005; Yunus et al., 2016). Telescopic attachment is among the most-widely used types which consists of an inner telescopic crown cemented to an abutment, and a corresponding removable outer telescopic crown (Langer et al., 2000). The function of this attachment is based on a friction grip between the inner and outer crowns, thus a minimal height of 5 mm is required for an effective retentive grip. In cases of limited inter-occlusal heights, shorter attachment designs such as Locator attachments are preferred (Pasciuta et al., 2005). The Locator attachment which works by nylon

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self-aligning feature, presents a dual retention and occupies less space in the denture base due to its shorter height (Evitmovska et al., 2009).

In implant prostheses, the force distribution is expected to be different from those without implants (Fontijn-Tekamp et al., 2000). A number of longitudinal clinical reports have shown that IODs required a high level of prosthetic maintenance (Andreetti et al., 2010; Goodacre et al., 2003) as the strain concentration around the components (Gonda et al., 2007) attached to the fitting surface of IODs may lead to increased risk of loosening and fracture (Takahashi et al., 2015). The fracture risk of the mandibular implant prostheses is approximately 80% (Walton and MacEntee, 1993), while the opposing conventional maxillary dentures show 38% of fracture incidence (Walton and MacEntee, 1994). Although the relatively high fracture incidence could be addressed using denture reinforcements with metal frameworks, this approach incurs additional costs to the patients (Payne and Solomons, 2000).

The strain distribution within the denture is often evaluated by applying a certain amount of occlusal load at a specific location. However, this approach mostly fails to accurately reproduce the clinical force applied intraorally on the denture (Gonda et al., 2010; Cheng et al., 2010) due to the different magnitudes of the bilateral occlusal forces at the anterior and posterior quadrants in complete edentulous situations (Khuder et al., 2017). Therefore, determining the actual distribution of occlusal load generated clinically in various quadrants could assist in more accurate simulation of the denture function upon biting.

The aims of this study were to investigate the strain distributions in mandibular IODs with two different attachments and their opposing maxillary CD using the clinically determined occlusal force distribution and to compare the obtained strain distributions with those of maxillary and mandibular CD prostheses. The clinical complications associated with the strain distributions in the telescopic- and Locator-retained mandibular IODs were also compared.

2. Materials and methods

A diagnostic cone beam computed tomography (CBCT) image of an edentulous patient, taken prior to implant placement, was selected to develop the 3D model of the maxillary and mandibular jaw bones. The image was transferred into a DICOM file using i-CAT Vision software (version 1.7.1.10, Imaging Sciences International Inc., Hatfield, PA) and then imported into InVesalius software (Version 3.0-Beta 5, 2007–2013, CTI- Renato Archer Information Technology Center, Campinas, Brazil) to allow data review in the 3D Standard Triangle Language (STL) format.

The mucosal tissues with respectively 1.5 mm and 2 mm thicknesses at the mandible and maxilla (Uchida et al., 1989) were developed in the STL files using Geomagic design X software (version 2016.1.0, 3D Systems Inc. Rock Hill, SC). A 3D laser scanner (3D Capture 2014, 3D System Inc., Rock Hill, SC) was used to obtain the images of maxillary and mandibular dentures of the same patient, dental implant, and two abutment types with their corresponding telescopic or Locator attachments, followed by transferring into the STL files. The implant body was simulated with no threads in order to reduce the model complexity and thus the analysis time. It was also not the intention of this study to analyze the strain distribution at the implant/bone interface, which has been extensively investigated. The dimensions of the dental implants, abutments, and their attachments are given in Table 1.

The STL files for bone, mucosal tissue, acrylic dentures, abutments, and implants with their attachments were exported into Geomagic Design X software for triangular mesh construction in 3D point nodes, gaps filling, and noise removal. A subsequent cloud point was then transferred into the solid bodies using Autosurface option of Geomagic design X software, followed by importing into SolidWorks software (Premium version 2016 ×64 Edition, SolidWorks®, Waltham, MA) for analysis.

For simulation of the implant fixtures, two implants were positioned on each side of the arch at the canine area. The top of these implants were placed 1 mm submerged below the cortical bone level as recommended by the implant manufacturer. Above the implant head, a hole was generated in the denture base using Geomagic design X software to accommodate the abutment and attachment cap according to the dimensions of each attachment type (Fig. 1).

Four basic models including maxillary conventional complete denture (UCD), mandibular conventional complete denture (LCD), mandibular IOD with Locator attachment (LID-L), and mandibular IOD with telescopic attachment (LID-T) were constructed to simulate different prosthesis types. The UCD and LCD models were assembled in the following sequence; maxillary and mandibular acrylic dentures, mucosal tissue, cortical bone, and cancellous bone. The LID-L and LID-T models were also assembled in the following order; acrylic dentures, implant attachments (Locator and telescopic, respectively), abutments, implants, mucosal tissue, cortical bone, and cancellous bone. The implant metal cap models for both attachments were assembled following their structures according to the manufacturers’ instructions where a cylindrical cap for the telescopic attachment and a cap with nylon male for the Locator attachment were positioned (Table 1).

The superimposed acrylic dentures with tissues, implants, and attachments were sectioned for both maxillary and mandibular models. Each section was corrected when necessary using Cubify Sculpt Software (Version: V2014. 64-Bit, Copyright 1993–2015 3D Systems, Inc. Rock Hill, SC) to achieve the optimal fit between the impression surface of the prostheses and the underlying parts of the attachment assembly.

Constraints for the maxillary denture were determined bilaterally following union of the maxilla to the skull base in a W shape (Cheng et al., 2010). The mandible was also constrained bilaterally at its lower border (Uchida et al., 1989), condyle, and angle areas (Marinescu et al., 2005). The models were assumed static, linear, elastic, and isotropic with solid meshes. The number of nodes and elements of different denture models are given in Table 2, while the material properties used in the finite element analysis (FEA) are presented in Table 3.

For the vertical occlusal load simulation, the mean percentages of occlusal force distribution in 23 patients with conventional CDs, and 23 patients with mandibular IOD were determined using a computerized occlusal analyser system (T-scan III, Tekscan Inc., South Boston, MA). The patients were instructed to clench with their prostheses on a horse-shoe shaped metallic sensor in order to measure the occlusal forces at the anterior right and left quadrants from central incisor to canine, as well as the posterior right and left from 1st premolar to 2nd molar teeth (Khuder et al., 2017) (Fig. 2). The actual occlusal forces of different study groups were measured and compared in a pilot study using a digital dynamometer device (model IDDK 200, Kratos–Equipamentos Industriais Ltd, Cotia, Brazil). As there was no significant difference between the mean force values measured in two study groups, the higher value (150 N) was considered as the actual occlusal force for further analyses. This force was applied simultaneously in the vertical direction to mimic the maximal intercuspal position upon biting and distributed between four quadrants according to the predetermined relative occlusal forces for two patient groups (Fig. 2). The obtained occlusal forces at different quadrants were further employed in the FEA analyses to determine the areas with high tensile or compressive strain concentrations.

The frequency of mechanical complications related to fracture of the mandibular prostheses and abutment/attachment loosening or dislodgement were retrieved from the three-years records of the patients with implant treatment. The data were dichotomized into with or without complications and the clinical complications associated with the telescopic and Locator attachments were compared by the Statistical Package for Social Science (SPSS; Version 20; IBM Corp., Armonk, NY, USA) software using Chi-square test at p < 0.05.

Ethical approval was obtained from the Medical Ethics committee.
University of Malaya [DF CO1513/0074(P)]. All participants were provided with the printed information sheets in English or Malay languages regarding the study aims and prior patients’ consents were obtained.

3. Results

Table 4 presents the mean percentages of occlusal force at four arch quadrants obtained from the T-Scan III occlusal analyses of 23 patients in each group. These data were further used to determine the absolute values of vertical force at each quadrant required in the simulation studies.

According to Fig. 3, the tensile strain on polished surface of the UCD model when opposed by LCD (1254 µε) compared to that opposing LID model (1055 µε) indicated less fracture vulnerability of the latter maxillary model (Table 5).

In the LCD model, the tensile strain was mostly concentrated at the incisal notch between the lateral incisor and canine, followed by the lingual flange area, while less strain was observed on the lower sulcus border of the lingual flange area (Table 6 and Fig. 4). The strains at the labial frenal area, labial flange polished surfaces, and denture base impression surface were compressive. On the other hand in both LID-L and LID-T models, the strain was distributed anteriorly in the midline and mesially to the attachment locations. The highest tensile strains were located at the incisal notch, followed by lingual and labial flange areas in the polished surfaces. The strains on the labial frenal area, lower sulcus border of lingual flange area in the polished surfaces, and denture base impression surface were compressive. Moreover, the highest tensile strain at the incisal notch was observed in the LCD (135 µε), followed by LID-T (116 µε), and LID-L (91 µε), which shows a higher fracture susceptibility of LCD at this region.

In terms of strain distributions in the LID-L and LID-T models, the maximum tensile strain values in both models were found in the acrylic denture/attachment interface (561 µε) and Fig. 5). Moreover, the maximum tensile strain in the acrylic denture/telescopic attachment interface (561 µε) was higher than that of Locator (323 µε), which probably results in increased fracture risk when the telescopic attachment is used.

The frequencies of mechanical complications in patients wearing IOD with telescopic or Locator attachments are given in Table 8 and Fig. 6. Attachment complications were observed in all the patients wearing telescopic-retained IOD, mostly related to dislodgement of the attachment cap. In contrast, a significantly lower failure ratio was observed in patients with Locator-retained IODs.

4. Discussion

For vertical occlusal load simulation, previous studies applied 40% of the maximum bite force bilaterally at the first molars of the prostheses and with the assumption of a nearly symmetric loading condition at left and right sides (Ahmad et al., 2015; Gibbs et al., 1981). However in this study, the force generated upon biting in maximal intercuspation was not uniformly distributed at the anterior and posterior arch quadrants. In particular, application of a smaller proportion of the
The strains generated on polished and impression surfaces of the UCD model were respectively tensile and compressive, regardless of the opposing mandibular denture type. A previous study which utilized brittle lacquer coating materials (Matthews and Wain, 1956) showed a higher tensile stress distributed at the mid-palatal polished surface. The FEA results of the present study similarly indicated that UCD was more susceptible to fracture at the mid-palatal area of the polished surface when opposing the LCD model. During mastication, the maxillary CD is bent at the mid-palatal line as the fulcrum axis and thus, the denture fracture is more likely to initiate from this area (Anusavice et al., 2013). A recent FEA study has also reported a similar area as the fracture initiation zone. However, the maximum tensile strain measured at tip of the incisal notch was higher (1917 µε) than that obtained in our study (1254 µε). This difference could be due to application of a bilateral 230 N load onto the posterior region in the previous study, while in our work a load of 150 N was heterogeneously distributed at anterior and posterior areas (Cheng et al., 2010).

When the UCD model opposed the LID-L and LID-T models, a different strain distribution scenario was observed, where the fracture initiation areas were found to be more palatal to the anterior teeth position, incisal notch, and the mid-posterior palatal area. The varied strain distribution patterns observed in the UCD models when opposing LCD or LID models could be due to the different occlusal force distributions in these prostheses. The occlusal force was relatively more homogeneous in the LCD model, while relatively higher occlusal forces were applied in the posterior quadrants of the LID-T and LID-L models compared to the anterior counterparts.

Investigation of the strain distribution in the LCD model indicated a higher tensile strain at the incisal notch of the lower incisors and

Table 4
Mean percentages of occlusal force distribution at each quadrants of the jaw in patients wearing CD or IOD dentures. The data are provided as Mean (standard deviation).

<table>
<thead>
<tr>
<th>Mean percentage of occlusal force</th>
<th>Anterior</th>
<th>Posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>UCD/LCD</td>
<td>16.86</td>
<td>19.69</td>
</tr>
<tr>
<td>UCD/LID (with either telescopic or Locator attachments)</td>
<td>8.20</td>
<td>7.53</td>
</tr>
</tbody>
</table>

vertical occlusal force at the anterior compared to posterior quadrants could be more clinically relevant when the maxillary and mandibular complete dentures simultaneously come into contact.
canine. This was in agreement with the results of a previous research, which investigated the fracture phenomena using scanning electron microscope (Vallittu, 1996; Lamb et al., 1985). The initiation of crack growth in the anterior zone is probably attributed to continual flexing of dentures from the lateral extension of their posterior part during force application (Vallittu, 1996).

The FEA results indicated generation of different tensile and compressive strain distributions in the mandibular IODs compared to the mandibular CD prostheses, probably due to their different rotation axes around the intercepted areas between the attachments and the acrylic denture base (Payne and Solomons, 2000). The strain concentration around the acrylic/attachment interface may consequently lead to fracture especially when self-cure resin materials are used in the attachment pick-up procedures, which generally result in a weak mechanical bonding. This was in agreement with previous studies where cast metal frameworks were used to minimize denture base fracture in the root-retained overdentures and implant-supported prostheses (Walton and MacEntee, 1994; Langer and Langer, 1991).

In relation to the attachment design, it was found that the Locator

![Table 5]

Strain (με) distribution on polished and impression surfaces of UCD opposing LCD and LID.

<table>
<thead>
<tr>
<th></th>
<th>LCD</th>
<th>LID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polished surface Impression surface</td>
<td>Polished surface Impression surface</td>
</tr>
<tr>
<td>Incisal notch</td>
<td>+1254</td>
<td>NA</td>
</tr>
<tr>
<td>Labial Frenal notch</td>
<td>-1250</td>
<td>NA</td>
</tr>
<tr>
<td>Mid-Anterior palate</td>
<td>+988</td>
<td>-559</td>
</tr>
<tr>
<td>Mid-posterior palate</td>
<td>+883</td>
<td>-186</td>
</tr>
</tbody>
</table>

* The values were independent of the attachment type.

* Positive values indicate tensile strain.

* Not applicable.

* Negative values represent compression.

![Table 6]

Strain (με) distribution around midline area on polished and impression surfaces of LCD and LID models.

<table>
<thead>
<tr>
<th></th>
<th>LCD</th>
<th>LID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polished surface Impression surface</td>
<td>Polished surface Impression surface</td>
</tr>
<tr>
<td>Incisal notch</td>
<td>+135</td>
<td>NA</td>
</tr>
<tr>
<td>Lingual flange</td>
<td>-68</td>
<td>NA</td>
</tr>
<tr>
<td>Labial flange</td>
<td>-28</td>
<td>NA</td>
</tr>
<tr>
<td>Labial frenum</td>
<td>-17d</td>
<td>NA</td>
</tr>
<tr>
<td>Lower sulcus border of lingual flange</td>
<td>+32</td>
<td>NA</td>
</tr>
<tr>
<td>Denture base</td>
<td>NA</td>
<td>-309</td>
</tr>
<tr>
<td>Locator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polished surface Impression surface</td>
<td>Polished surface Impression surface</td>
<td></td>
</tr>
<tr>
<td>Incisal notch</td>
<td>+91</td>
<td>NA</td>
</tr>
<tr>
<td>Lingual flange</td>
<td>+87</td>
<td>NA</td>
</tr>
<tr>
<td>Labial flange</td>
<td>+3</td>
<td>NA</td>
</tr>
<tr>
<td>Labial frenum</td>
<td>-116</td>
<td>NA</td>
</tr>
<tr>
<td>Lower sulcus border of lingual flange</td>
<td>-90</td>
<td>NA</td>
</tr>
<tr>
<td>Denture base</td>
<td>NA</td>
<td>-309</td>
</tr>
</tbody>
</table>

* The values were independent of the attachment type.

* Positive values indicate tensile strain.

* Not applicable.

* Negative values represent compression.
and telescopic attachments possess their own unique mechanism to retain the prostheses. When the Locator attachment was used, the maximum tensile strain was observed in the interface area with acrylic denture base, followed by the lower sulcus border of the lingual and labial flange areas. The telescopic attachment similarly concentrated the tensile strain around the acrylic/attachment interface, while it was followed by top of the telescopic attachment. This indicated the likelihood of fracture initiation from the acrylic/attachment area regardless of the attachment type used.

In this study, both attachments presented approximately similar strain distributions in the anterior midline area and smaller than that of LCD. These findings contradict the results of a previous study (Dong et al., 2006) which reported that the highest tensile strain was on top of the overdenture copings regardless of their height. This could be again due to the differed loading condition defined in the previous study, where a vertical force of 49 N was applied individually onto the first premolar, first molar, and second molar areas.

From the clinical point of view, retention of mandibular IODs using telescopic attachments resulted in a significantly higher complication frequency (100%) compared to the Locator attachment (40%), most probably due to a higher height of the telescopic attachment (5 mm) in contrast to that of Locator attachment (2.3 mm). Besides, rigidity of the telescopic attachment is relatively high, while the Locator attachment allows some degrees of resilience in both vertical and horizontal directions (Evtimovska et al., 2009).

Comparison of the maximum tensile strain values in all the studied models indicated that UCD had higher tensile strain than the opposing LCD, LID-L and LID-T models, thus the fracture was more likely to occur in this denture. This was in agreement with a previous survey on the clinical denture repair, which found a two-fold higher fracture incidence of maxillary to mandibular dentures (Beyli and Fraunhofer, 1981). Future study would investigate the stress distribution within the supporting tissues and their surrounding dental implants in mandibular IOD retained by telescopic or Locator attachments opposing conventional maxillary CD based to their occlusal force distribution.

5. Conclusion

Inequality in the number of Locator and telescopic attachments was one of the limitations of this work (8 and 15 patients with telescopic and Locator attachments, respectively). Therefore, the mean force distribution in the IOD group was calculated by combining the obtained data of both telescopic and Locator attachments. Moreover, as the main objective of this study was to analyze the distributed strain in the acrylic denture base and its interface with the attachments, the implant fixture was simulated without threads in order to reduce the analysis time and model complexity.

The thickness of masticatory mucosal tissue differs in the maxillary and mandibular arches, which could affect the stain distribution. In this study, the mucosal thicknesses were respectively assumed 2 mm and 1.5 mm for maxilla and mandible, according to the ultrasonic measurements by Uchida, Kobayashi (Uchida et al., 1989). The bite force of 150 N used in the simulations might not present the actual force applied on CD and IOD as it is slightly higher in the latter group (Ahmad et al., 2014). However, our pilot study showed a non-significant difference.
between the bite forces measured in two studied groups and thus, the higher measured mean force (150 N) was applied for load simulation.

Within the limitations of this study, we concluded that the risk of fracture incidence in the maxillary conventional complete denture was higher than those of mandibular conventional complete dentures and mandibular implant overdentures especially at the anterior palatal area of the polished surface of the acrylic denture base. On the other hand, mandibular conventional complete denture showed higher strain values at the midline area of the polished surface in contrast to the mandibular implant overdentures with either Locator or telescopic attachments.

Moreover, the Locator attachment showed lower fracture susceptibility and clinical complications compared to the telescopic attachment in the denture/attachment interface at the impression surface.

Table 8
Comparison of the complication percentages observed in the IOD prostheses with either telescopic or Locator attachments, using Chi-square test (P < 0.05).

<table>
<thead>
<tr>
<th>Attachment</th>
<th>No. of patients</th>
<th>Complication (%)</th>
<th>No Complication (%)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescopic</td>
<td>8</td>
<td>100</td>
<td>0</td>
<td>0.005*</td>
</tr>
<tr>
<td>Locator</td>
<td>15</td>
<td>40</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

* Statistically significant difference.

Fig. 5. Strain distribution in acrylic denture base interface area with (a) telescopic and (b) Locator attachments within mandibular IOD.

Fig. 6. Intraoral view of the (a) Locator, and (b) telescopic abutments. (c) The impression surface of a mandibular IOD with telescopic attachment. (d) A denture fracture incidence around the telescopic attachment.
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