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A comparative study on complete and implant retained denture treatments – A biomechanics perspective

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ABSTRACT

Although implant-retained overdenture allows edentulous patients to take higher occlusal forces than the conventional complete dentures, the biomechanical influences have not been explored yet. Clinically, there is limited knowledge and means for predicting localized bone remodelling after denture treatment with and without implant support. By using finite element (FE) analysis, this article provides an *in-silico* approach to exploring the treatment effects on the oral mucosa and potential resorption of residual ridge under three different denture configurations in a patient-specific manner. Based on cone beam computerized tomography (CBCT) scans, a 3D heterogeneous FE model was created; and the supportive tissue, mucosa, was characterized as a hyperelastic material. A measured occlusal load (63N) was applied onto three virtual models, namely complete denture, two and four implant-retained overdentures. Clinically, the bone resorption was measured after one year in the two implant-retained overdenture treatment. Despite the improved stability and enhanced masticatory function, the implant-retained overdentures demonstrated higher hydrostatic stress in mucosa (43.6 kPa and 39.9 kPa for two and four implants) at the posterior ends of the mandible due to the cantilever effect, than the complete denture (33.4 kPa). Hydrostatic pressure in the mucosa signifies a critical indicator and can be correlated with clinically measured bone resorption, pointing to severer mandibular ridge resorption posteriorly with implant-retained overdentures. This study provides a biomechanical basis for denture treatment planning to improve long-term outcomes with minimal residual ridge resorption.
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1. Introduction

Residual ridge resorption is a progressive phenomenon harmful to patient's oral health, and has been reported to continue even after 25 year's post-extraction of teeth, which severely compromises prosthetic support and retention for satisfactory functioning of conventional complete dentures (Atwood, 1971, Tallgren, 1972). To overcome these problems, implants have been increasingly used to retain complete dentures and have demonstrated to be a successful treatment alternative for edentulous patients with mandibular denture predicament (Fueki et al., 2007, Rashid et al., 2011, Barao et al., 2013). Despite these clear benefits, there have been reports concerning severe residual ridge resorption associated with implant-retained overdentures (Jacobs et al., 1992, Blum and McCord, 2004). The biomechanical differences of these different configurations have not yet been clearly addressed in their association to possible clinical outcomes.

The functional pressure, namely interstitial fluid pressure or hydrostatic pressure, in oral mucosa has been indicated one of the most important etiological factors accounting for the residual ridge resorption (Mori et al., 1997, Blum and McCord, 2004). Such highly vascularized soft tissue plays a critical role in distributing masticatory force from the dentures to underlying bony ridge (Mori et al., 1997, Sawada et al., 2011, Ahmad et al., 2013) over a larger denture-supporting tissue interface, thereby alleviating stress concentration. An aging edentulous mandible is mainly supported by the periosteal plexus of blood vessels and is therefore very susceptible to diminished circulation under denture-induced contact pressure, which reduces nutrient supply and metabolite removal in the supporting bone (Bradley, 1981). The resultant hydrostatic pressure may exceed the systolic pressure and disturb local circulation in surrounding periosteal tissue, potentially causing bone resorption (Maruo et al., 2010).

Clinically, limited in vivo techniques exist for evaluating the disturbance induced by denture insertion to mucosa. Despite recent

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finding in correlating hydrostatic pressure to soft-tissue induced bone resorption, the biomechanical effects of a denture pressing on the mucosa still remains poorly understood (Aspenberg and van der Vis, 1998, Kim et al., 2010). This prevents effective prediction of possible bone remodelling post-insertion as there have been few adequate clinical methods for examining the associated biomechanics. Finite element (FE) methods have exhibited compelling advantages in biomechanical analysis. With advanced clinical computerized tomography (CT), sophisticated 3D FE models allow precisely capturing anatomical and biomaterial features of an individual patient, thereby faithfully reflecting a case-specific bone profile and density distribution (Field et al., 2010). Complex soft-tissue responses can be modelled in a nonlinear manner to more realistically reflect biomechanical behaviours (Kanbara et al., 2012).

This study aims to evaluate the differences in mucosal hydrostatic pressure of these three different (namely, complete, two and four implant-retained) denture treatments in a patient-specific setting. A 3D heterogeneous FE model was created based on clinical CT scans. The mucosa is characterized as a nonlinear (hyperelastic) material derived from clinical data. Visual insertion of the prostheses was tested under a clinically measured occlusal load (63N). The simulated treatment results with two implant-retained overdentures were validated clinically against a one year follow-up study for this specific patient. Furthermore, increased occlusal forces reported in literature were also attempted on these models to examine their consequences. The FE analysis (FEA) procedure allows comparing different treatment options by correlating the biomechanical responses to possible clinical outcomes, thereby establishing an *in-silico* approach to evaluating different denture designs for reducing risk of residual ridge resorption.

2. Materials and methods

2.1. Patient data acquisition and modelling

An i-CAT CBCT (Imaging Sciences International, Hatfield, Pa) was utilized to obtain the anatomical data from the patient's mandible with a duplicate denture containing barium sulphate to provide sufficient X-ray opacity, which mixed the cold-curing acrylic polymethyl methacrylate (PMMA) (Vertex-Dental, The Netherlands) with 15% barium sulphate powder (SIGMA-ALDRICH, St. Louis MO, USA). The scans were performed at 120 kVp, 18.45 mAs, and 20 s exposure, with a resolution of 0.30 mm per slice. The image was stored in DICOM format (Fig. 1a) and imported into ScanIP Ver. 4.3 (Simpleware Ltd, Exeter, UK) for segmentation. Three segmented masks (bone, mucosa, and denture) were further processed in 3D parametric modelling software Rhinoceros 4.0 (Robert McNeel & Associates, Seattle USA) to create geometric models with non-uniform rational B-spline (NURBS) (Fig. 1b).

In order to enable meaningful comparison, the same denture profile is considered here for all three different configurations. For the implant-retained overdentures, the two implants were placed in the vicinity of canine (Fig. 1c); and the four implants were placed equidistant within the interforamina region (Fig. 1d) (Clelland et al., 1995, Ahmad et al., 2013). The final assemblies were exported to ABAQUS 6.9.2 (Dassault Systèmes, Tokyo Japan) for FE meshing (Fig. 1e). To ensure the numerical accuracy, adaptive mesh was employed and a mesh convergence test was carried out, as (Li et al., 2004, 2005). For these different cases, the final meshes contain 2,614,854 (complete), 2,864,871 (two implants), and 3,188, 247 (four implants) degrees of freedom using quadratic tetrahedral elements with hybrid formulation (C3D10H) to ensure smoothness of contact interfaces for the nonlinear analyses.

Clinical treatment was conducted independently to FEA here; and the subject chose the two-implant retained overdenture treatment. A follow-up CBCT scan was performed under the same condition one year after the overdenture insertion. The second image stack was processed in the same manner as the initial one, by registering their isosurfaces. Differences between these two sets of measurement data allowed us to determine bone remodelling (Ahmad et al., 2013) and correlate the outcomes with the FEA results.

The bone remodelling was measured using the CBCT images data to reconstruct 3D models in Mimics Ver. 14.1 (Materialise NV, Leuven Belgium). Superimposition of pre- and post-treatment models was done initially by manual registration to approximate the surfaces. Subsequently, refinement of superimposition was undertaken using the Standard Tessellation Language (STL) registration method by automatically registering the stack of STL slices on the stack of pre-treatment mask slices. Once the models were optimally superimposed, resorption and apposition were quantified by measuring the changes in bone volume.

2.2. Material property

Although linear elastic and homogenous material models have been widely assumed in most previous FE studies (Li et al., 2010, Rungsiyakull et al., 2010), such assumptions may not adequately replicate complex tissue responses or interaction (Kanbara et al., 2012). In this study, the jaw bone was characterized with heterogeneous material properties as per Hounsfield Unit (HU) to more precisely reflect the anatomical variation in density and modulus, which could potentially affect load-deformation responses. In the CT image, the jaw HU values vary from −300 to 1500. The associated mineral densities of 0.72 g/cm^3 and 1.86 g/cm^3 were adopted from literature for cancellous and cortical bones, corresponding to the maximum (HU_{max}) and minimum (HU_{max}) values (Zaw et al., 2009). The apparent mineral density ρ_{app} is interpolated linearly against the HU value as,

$$\rho_{\text{app}} = \rho_{\min} + \rho_{\text{diff}} \times \frac{(HU - HU_{\min})}{(HU_{\max} - HU_{\min})} \tag{1}$$

where $\rho_{\min}$ denotes the minimum density and ρ_{diff} indicates the difference between the maximum and minimum densities.

To correlate Young's modulus E to ρ_{app}, Eq. (2) was adopted (Carter and Hayes, 1977) by considering the jaw bone as a two-phase porous material (Rho et al., 1993) at a low strain rate $\dot{\varepsilon}_e$. The determined heterogeneous material properties were assigned to the Gaussian point in each element (Fig. 1f).

$$E = 3790\dot{\varepsilon}_e^{0.06}\rho_{\text{app}}^3 \tag{2}$$

The mucosa has been known to behave nonlinearly under mechanical loading (Kishi, 1972, Kydd and Daly, 1982, Sawada et al., 2011). The hyperelastic constitutive material model was adopted herein, which defines strain energy (U_ε) per unit volume as a function of local strain. This strain energy driven behaviour was derived from a least-square fitting of the clinical data (Kishi, 1972) (dashed curve in Fig. 2); and a third order ($N=3$) Ogden strain energy equation (Bergomi et al., 2011) provides the closest match (Eq. 3, a solid curve in Fig. 2). The material parameters are summarized in Table 1. Other materials adopt linear elastic and homogeneous properties from previous studies (Sato et al., 2000, O'Brien, 2008).

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3) + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i} \tag{3}$$

2.3. Mastication scenario

For the implant retained overdentures, the screw threads were assumed to be fully locked with surrounding bone through proper osseointegration (Lin et al., 2010, Rungsiyakull et al., 2010, Chen et al., 2013). The augmented Lagrangian algorithm was adopted to simulate the denture-mucosa contact, with a low frictional coefficient assumed as 0.1 to mimic proper lubrication in the oral environment (Prinz et al., 2007). A pair of localized masticatory loads was applied to both sides of the denture around the first molar in vertical direction. This loading scenario has been referred to as isometric bilateral biting in literature (Hart et al., 1992), which bears a nearly symmetric loading condition to maintain a proper balance for stabilizing denture (Katayoun et al., 2012, Yamashita et al., 2000). In this study, the average voluntary biting force was clinically measured (63N) and applied onto the dentures; and similar magnitudes have been reported in other FE studies (Maeda and Wood, 1989, Barão et al., 2008, Chowdhary et al., 2008). The kinematic boundary conditions were prescribed to the distal ends of the condyles (Hart et al., 1992, Korioth et al., 1992).

3. Results

3.1. Hydrostatic pressure in mucosa

The hydrostatic pressure contours on the mucosa are plotted in Fig. 3, comparing all three different denture configurations, on both the external surface (between denture base and mucosa, (a)–(c)) and periosteal surface (between mucosa and bone, sectioned views through axial planes (d)–(f)). The heterogeneous residual ridge led to non-uniform distribution of hydrostatic stress for local stiffness variances, even under a well-fitted denture base to the patient. These pressure contours exhibit a bilateral profile due to the biting activity considered, but the distribution differed noticeably between the complete denture and implant retained ones, particularly in the anterior-posterior direction, where the implants generated more cantilever effects.

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