Three dimensional quantification of mandibular bone remodeling using standard tessellation language registration based superimposition

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Abstract
Objective: The aim of this study was to evaluate a new method to quantify longitudinal mandibular bone remodeling three-dimensionally by superimposition of cone beam computed tomography images.

Materials and Methods: This method is used to quantify the treatment effects of implant-retained overdentures in 20 patients aged 52–79 at recruitment after 1 and 2 years post treatment. Three dimensional models of pre- and post-treatment were reconstructed for each patient and superimposed using Standard Tessellation Language registration method and segmentation.

Results: Color maps of the differences generated by superimposition allow detailed examination and quantification of the progressive dimensional changes of bone in a three-dimensional manner and enable the visualization of the apical displacement and thinning of the cortical layer of bone underneath the denture base. Most of the remodeling changes took place during the first year with a mean decrease in volume of 3.7% (SD = 4.4%; range = +3.7% to −15.9%, median = −3.7%). This remodeling pattern continued during the second year, but at a reduced rate of 2.5% per year (SD = 4.2%; range = +2.1% to −11.3%, median = −3.9%).

Conclusion: Standard Tessellation Language registration based superimposition of cone beam computed tomography images may be considered an objective and reproducible method to three-dimensionally quantify mandibular bone remodeling.

Mandibular bone remodeling has been quantified in two-dimensional (2D) and in an indirect manner most commonly using serial casts (Hoad-Reddick et al. 1999; Narhi et al. 2000; Blum & McCord 2004) and 2D radiographs (Jacobs et al. 1992; Powers et al. 1994; Wright et al. 2002). These 2D techniques may not have addressed the subject of bone remodeling adequately due to the limitations of the techniques. The use of serial casts only allows external changes to be quantified and it does not provide any information on the bones response underneath the denture base to mastication pressure. Does the cortical bone become thinner or does the entire layer become displaced apically to make the bone more compact? These serial cast measurement techniques were also indirect as the measurement of bone was carried out together with the mucosa, which itself responded to denture wearing in a varied manner by increasing or decreasing its thickness by atrophy (Razek & Shaaban 1978) or increased keratinisation (Kapur & Shklar 1963; Muller & Proschel 1989). The impression made to fabricate the casts for measurement is also affected by the technique and the pressure applied by the operator (El-Khodary et al. 1985) to make the impression of the compressible mucosa (Kydd et al. 1974). Dimensional changes of the impression and plaster materials used to make the casts is another concern (Teraoka & Takahashi 2000; Petrie et al. 2003).

Although 2D imaging is a direct technique, it has been reported that mandibular angulation as a result of variable intermaxillary distance in the edentulous patient can affect the magnification factors of the radiograph produced significantly (Batenburg et al. 1997; Stellingsma et al. 2000). Unless meticulous precautions are taken to reproducibly position the edentulous patient at the exact intermaxillary distance in the X-ray apparatus during radiographic acquisition in subsequent years, 2D radiographs may not be a reliable
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quantitative technique for bone measurement. Moreover, the contrast of the bony tissue on the radiograph is affected by the volume of bone that is present in a particular image plane, which can affect the delineation of the margin of that bony structure (Batenburg et al. 1997). Hence, the conflicting results seen from these 2D imaging techniques when comparing bone resorption associated with different treatment modalities. For instance, some researchers reported more bone resorption associated with complete dentures (Sennery et al. 1988; Kordatzis et al. 2003), whereas others reported more resorption with implant-retained dentures (Finger & Guerra 1986; Jacobs et al. 1992) when comparing the two treatment modalities.

In the past, prior to the availability of cone beam computed tomography (CBCT), the use of 3-dimensional (3D) imaging with medical CT to address the issues associated with 2D studies would be considered unethical due to its associated high dosage of radiation. However, with the advent of CBCT in 1999, which allows the acquisition of 3D images at a much lower radiation dose (Ludlow & Ivanovic 2008), the repetition of its use over time has been a common practice in studies comparing different treatment effects on bone structure (Carvalho et al. 2010; Lagravere et al. 2010; Kaner & Friedmann 2011).

Acquisition of an image of the mandible up to the condylar area will expose patients to an effective radiation dose of about 100 μSv depending on the CBCT machine and scanning parameters used (Palomo et al. 2008). To put this figure in perspective, the average normal background radiation, we are all constantly exposed to per year from cosmic, terrestrial, air, water and food is about 3100 μSv (UNSCEAR 2000) and to add another 100 μSv (3% or 12 days of background radiation) to this figure in a year can be considered a small fraction. The annual effective dose limit for infrquent exposure has been recommended at 5 mSv (White & Pharaoh 2004).

Although the image quality of CBCT is not as good as that of CT scan due to errors in the reconstruction algorithm and other inherent artifacts (Schulze et al. 2011), many scientific studies have validated the accuracy of 2D and 3D linear and angular measurement from bony maxillofacial structures (Moreira et al. 2009; Damstra et al. 2010; Griebel et al. 2011; Timcock et al. 2011) and 3D reconstructions (Marec et al. 2010) based on CBCT. The use of post-processing algorithms like the commercial medical imaging program Mimics (Materialise NV, Leuven, Belgium) also help to reduce some of these artifacts related to CBCT. In Mimics, the conversion into 3D surface model uses an adapted marching cubes algorithm that takes the partial volume effect into account leading to accurate 3D models with mean absolute accuracies up to one-fifth of the voxel size (Gelaude et al. 2008).

Several techniques of superimposition of 3D images from CBCT have been used in various disciplines of dentistry to evaluate treatment outcomes over a passage of time. Superimposition based on a series of anatomical landmarks and voxel values have been commonly used and reported to give accurate and reproducible results (Cevidan et al. 2006, 2007, 2009; Carvalho et al. 2010; Tai et al. 2010). One major advantage of working with 3D CBCT images is that the images taken with CBCT are not affected by the change in head position during image acquisition at various time points (Hassan et al. 2009; El-Beialy et al. 2011), hence, making superimposition of these series of images possible.

For the abovementioned reasons, this study aims to take advantage of the availability of 3D CBCT imaging and superimposition technique of medical imaging program to develop a method to directly quantify bone remodeling in a 3D manner. The ability of this method to clearly identify the treatment effects of wearing implant-retained overdentures on mandibular bone with the passage of time will be investigated. The knowledge of how bone remodels over time is a very important issue in Removable Prosthodontics as it would help in the treatment planning of a suitable prosthesis that minimizes bone resorption in edentulous patients and its associated effect on oral health related quality of life.

Material and methods

Patient recruitment

Ethics approvals to carry out this study have been obtained from the Ethics Committee of Universiti Teknologi MARA (UiTM), Malaysia (600-RMI [5/1/6] 20th April 2009 and 600-RMI [5/1/6/01] 6th December 2011). Patients were recruited through the UiTM email network. Most responses were from staff and students who referred their parents or elderly relatives to participate in this study. The exclusion criteria of patients for this study were diabetes, irradiation of the jaws, serious or debilitating systemic disease, those undergoing psychiatric treatment, heavy smoking, history of substance abuse and medical conditions that may contraindicate surgical procedure. Local exclusion criteria were any active pathology affecting the jaws or mucosa or abnormalities that will prevent the construction of satisfactory conventional or implant-retained denture. All participants were informed of the protocol of the study, including the procedures of making new dentures, implant surgery, yearly recalls, three exposures to CBCT at three time points, T1 before treatment, T2 and T3 at 1-year and 2-year post treatment, respectively, and gave their written consent to participate. The first CBCT was for accurate assessment of bone height and thickness for implant placement and served as the baseline measurement of bone level, and the second and third imaging for the evaluation of bony changes. More than 30 patients were recruited for this study, but only 25 patients underwent the complete treatment protocol. Out of the 25 patients with implants, two did not come for follow-up due to death and illness and three had to be excluded because of poor quality radiographs. Their age ranged from 52 to 79 years old at recruitment, average age was 67 years old. They were 8 male patients and 12 female patients and have been edentulous in the mandible for at least 5 years.

Clinical protocol

All patients had new conventional complete dentures made with balanced occlusion by one clinician (RA) and all laboratory work was carried out by one dental technologist. Patients were asked to wear these dentures for at least a month to ensure they are completely satisfied with the denture before implants were placed.

All CBCT images were taken from one machine (i-CAT; Imaging Sciences International, Hatfield, PA, USA). The machine was set at 120 kVp, 18.45 mAs, 20-s acquisition time, 13 cm field of view and a voxel size of 0.30 mm. The effective radiation dose the patient received was 101.5 μSv. To help these edentulous patients to remain stationary during scanning, they were asked to wear their dentures and bite gently in occlusion, and had their head strapped to the head positioner in the X-ray machine. The DICOM files of the images were acquired and stored to a portable hard drive.

The 3D images were processed and analyzed using the Simplant program (Materialise, Leuven, Belgium) for accurate placement of implants in the two canine regions. All patients received Ankylos® implants (Dentsply, Friadent, Germany). The implants
remain uncovered surgically after a healing period of 2–3 months and Ankylos® Syn-Cone® abutments were attached to the implants. The overdenture was made such that it was mainly mucosa-borne by maximizing the coverage of the denture bearing area. The patients were then placed on an annual maintenance recall program.

**Reconstruction and superimposition of 3-dimensional models**

CBCT images were reconstructed into 3D models using Mimics program version 14.1. For each patient, a threshold value was selected that would produce as complete a structure of the mandible as possible without too many holes or artifacts. The program also gives predefined threshold sets for bone that could be selected or alternatively a profile line could be drawn on the region of interest and the program will calculate the threshold. Crucially important, was that a similar threshold value for each patient was applied to reconstruct the three mandibles at three time points. This ensured that the reconstructed mandibles are of the same dimension, and any changes in dimension between the three bones would be the result of bone remodeling and not the effect of thresholding. A pilot study was conducted to examine the effect of using different threshold values on the dimensional changes of the reconstructed models. It was found that if the threshold values chosen were within 20% of the recommended value, there was no difference in the dimensional changes observed. If values larger or smaller than the 20% were chosen, the models appeared fragmented/eroded or noisy/bulky, respectively, which an experienced Mimics user will not have selected.

The thresholding values selected was varied between patients as their bone differs in density. Every model was segmented manually and no filtering, wrapping or smoothing function was used as these procedures would affect the dimension of the bone. All 3D models were reconstructed using the ‘optimal’ quality setting provided by the program. These tedious and time-consuming segmentation procedures were performed by the first author only to ensure maximum consistency.

Superimposition of the three mandibles was performed initially by manual registration to approximate the surfaces as much as possible. Subsequently, superimposition was refined using the Standard Tessellation Language (STL) registration method. The transformation matrix of this method, which runs automatically, registers the stack of slices of the STL models on the stack of slices of the mask of the pretreatment model. This transformation usually takes about 3–5 min to complete.

A good superimposition is achieved when maximum overlapping of colors of these three models can be visualized in the 3D window and their respective color-coded bony contours are maximally overlapped in the 2-D axial, sagittal and coronal views of the masks (Fig. 1). This calls for thorough observation in the stack of slices and if it is found not satisfactory, this method allows further minor adjustment either by a technique called local registration or by manually offsetting the model in the three planes x, y and z by 0.01 mm movement intervals. If gross differences were detected, the models

![Fig. 1. Superimposition of 3D models. (a) 3D models of pretreatment (red), 1-year post treatment (yellow) and 2-year post treatment (green) used for superimposition. (b) superimposition achieved and viewed in 3D window. Overlapping of bone outline contours of the superimposed models viewed in 2D sagittal (c), coronal (d) and axial (e) windows. (f and g) are enlarged images of the coronal section of bone showing the changes in bone contour by thinning of the cortical layer and displacement of the entire cortical layer, respectively.](image)
could be distorted and most likely due to patient motion artifacts. To check for accuracy and reproducibility of the superimposition, instead of using the mask of pretreatment model, the mask of 1 or 2 years model can be used. The respective STL models can then be exported into the 1 or 2 years project file. The superimposition in all three project files based on three different masks should appear the same. Once the models were optimally superimposed, they were exported to 3-matics program (Materialise NV) for further segmentation to produce color maps that reveal the differences from which the depth of bone resorption and/or deposition may be seen (Fig. 2). This 3-matics software also allows local measurement of bone depth change in mm at any one point on the model. A negative value would indicate bone resorption and a positive value, bone deposition.

The external remodeling changes were quantified by measuring the changes in bone area and volume for pre- and post-treatment models. These values for area and volume were generated automatically using the program. The area of interest is from about 5 mm distal to the implants up to the retromolar area just anterior to the ascending ramus. The area immediately around the implants were excluded to avoid artifacts from beam hardening and the anterior part of the ridge in between implants were excluded because the bone in this area may have been deliberately altered during placement of implants. Prior to measurement, these segments of bone were turned into solid models by mask cavity fill operation so that the dimensional changes observed in area and volume would reflect the external cortical changes only. Trabecular changes will be analyzed using fractal analysis and will be the subject of a separate study.

Results

This STL registration superimposition technique based on masks yielded consistent results as evidenced by the close overlapping of the bone contours of the three models. It clearly shows where remodeling predominantly took place, the extension of the remodeling and how the bone contour changes in response to load. Remodeling occurred predominantly on the denture bearing areas; occlusally in the molar region and more lingually in the premolar area. In some areas, thinning of the cortical bone seems to have occurred (Fig. 1f), whereas in other areas, the entire thickness of cortical bone appeared to be displaced apically away from the loading force (Fig. 1g). Most of the remodeling changes took place during the first year with a mean decrease in volume of 3.7% (standard deviation, SD = 4.4%; range = +3.7% to −15.9%, median = −3.7%). A positive value indicates a net increase in bone volume and a negative value, a net decrease in bone volume. This remodeling pattern continued during the second year, but at a reduced rate of 2.5% per year (SD = 4.2%; range = +2.1% to −11.3%, median = −3.9%). This phenomenon is obvious from the color maps of the bone dimensional changes that took place during the first year (Fig. 2b) in comparison with that of the second year (Fig. 2c). The extent of bone remodeling is highly variable between patients, but for most of them, the depth of bone resorption and deposition is within −2–2 mm. In terms of reduction in surface area, the mean decrease was 3.3% after the first year (SD = 2.9%; range = +3.1% to −7.4%, median = −1.7%) and 1% after the second year (SD = 1.9%; range = +2.9% to −4.7%, median = −1.3%).

Discussion

Many aspects of this research ranging from the prosthodontic treatment provided, prosthesis fabrication, image acquisition, segmentation and superimposition performed, was controlled and standardized by engaging only one clinician (who is also an experienced Mimics user), one dental technologist and one radiographer. These efforts were made to ensure for the most part the dimensional changes observed in the images with the passage of time are a genuine treatment effect. All scans were also made from one CBCT machine to achieve accurate superimposition as a previous study has shown that measurements on 3D models of human skulls taken from different CBCT scanners produced statistically significant and clinically relevant differences [van Vlijmen et al. 2011].

The validity and reproducibility of the results of this study depends on several factors. First, the quality of the CBCT images itself. Machine parameters used in this study; such as, the power setting, voxel size, acquisition time and field of view, were similar to other published studies that reported high accuracy using similar i-CAT machines [Ballrick et al. 2008; Nada et al. 2011]. Obtaining a high quality image has been one of the major challenges of this 3D study. The 20-s acquisition time appeared to be too long for some of these edentulous elderly patients to remain stationary. Problems were also
accounted with male patients having broad shoulders. During rotation, the scanner tends to hit the shoulder and resulted in patient’s movement. The resultant distorted images remained unusable. Three patients’ data had to be excluded due to these motion artifacts. This forms a major loss to this study as recruiting suitable, healthy edentulous patients who were willing to participate in the implant surgery was difficult.

The second factor is the validity of the segmentation. All models were manually segmented by the first author who is a Prosthodontist with prior knowledge of mandibular anatomy and has been using Mimics program for more than 3 years. This is to ensure consistency in the visual perception of what is bone and what is soft tissue or artifacts, which in turn influences the decision of the threshold value chosen. Segmentation of the three models at the same time helped in defining the threshold value and in deciding whether to include or exclude certain voxels from the images. If the voxels were artifacts, they usually only appeared in one scan and not in the other two and this helped making the decision to remove them easier. The same parameters were used to reconstruct 3D models from these segmented images and therefore the models should be of the same dimension. The researchers are interested in measuring the differences in dimensions between these three models and not in making absolute measurements in dimension of any models. Hence, even if the 3D models reconstructed from this CBCT machine are not absolutely accurate because of the errors in the reconstruction algorithm and other inherent artifacts, it should not affect the differences in dimensions seen between the three models because all three models inherited this systematic error.

The third factor is the reproducibility of the superimposition. A combination of manual and automatic [STL registration method] superimposition was performed to improve accuracy and calculation time using the software. Other methods of superimposition are available in Mimics – point, image and global registrations. Point and image based registration are superimposition based on chosen anatomical landmarks based on the 3D and 2D images, respectively. Global registration is completely automatic. When superimposition is performed based on chosen landmarks on the 3D image (point registration), difficulty was encountered in locating a landmark accurately on a curved surface of the 3D image that could be relocated exactly on the other two models. Locating a landmark on a 2D image requires that the gantry tilt of the three models are exactly the same, otherwise it will be challenging to place the same landmark on three different images. Reslicing of the models is required to achieve similar gantry tilt and this is a very time-consuming procedure as it requires resegmentation of the images. A pilot study was performed to compare the superimposition results of these four methods and STL registration gave the most satisfactory result. This is possibly because the STL registration technique superimposes the STL model on the complete stack of slices, whereas using the point or image registration method, superimposition is performed based on only a few chosen anatomical landmarks.

This study was initially planned for the treatment effect to be analyzed after 1 year only. Hence, only two CBCTs corresponding to before and 1 year after treatment were requested in the first ethics application. However, following analysis of the results after a year, it was found that the remodeling change in the bones was very small with a mean reduction in volume of 3.7% and a mean reduction in area of 3.3% a year. This value is much lower compared to what has been reported in the 2D studies of up to 33% reduction in surface area after a year (Blum & McCord 2004). There was also a huge variation between patients. Some patients even demonstrated a net increase in volume after the first year. Hence, further investigation was required to verify that the dimensional changes observed after the first year were not a chance finding due to inaccuracies of the 3D reconstruction, superimposition or the partial volume effects. Therefore, a second ethics approval was obtained to record another CBCT after 2 years of treatment for reanalysis of the bone dimensional changes.

The second year superimposition results confirmed that the dimensional changes observed were a genuine change in the bone as the bone contour of the second year model closely followed the contour of the first and pretreatment models. In most cases, the first and second year bone contours were closer than between the pre and first year bone contours. It shows that bone remodeling is a progressive phenomenon, but the rate was slower during the second year. This observation that more rapid remodeling took place during the first year of wearing the overdenture is consistent with the findings of other studies (Carlsson & Persson 1967, Tallgren 1972). The superimposition result also very clearly shows how the bone contours underneath the denture base change in response to loading. Some areas exhibited displacement of the entire thickness of the cortical layer, whereas some other areas demonstrated thinning of the cortical bone. The results of bone remodeling rate, pattern and behavior observed in this study will be discussed in a separate study.

The main weakness of this study is that the quality of superimposition was based on subjective visual assessment. Superimposition error could not be objectively calculated. However, as visual assessment can be performed in both 3D and 2D views in all the stack of slices, the errors would have been minimized. The three exposures to CBCT taken at 1 year intervals is another weakness of this study. As responsible clinicians, we should not expose patients to unnecessary radiation. However, we feel that the diagnostic benefits of CBCT in this study far outweighed the risks associated with the increased radiation.

In summary, this 3D study has been able to address the issues related with the limitations of 2D mandibular bone remodeling studies, namely, it has been able to, [1] directly quantify bone remodeling in a 3D manner, [2] precisely locate areas of bone remodeling and [3] visually demonstrate the changes in bone contour in response to load. On the basis of this study, STL registration based superimposition of CBCT images may be considered an objective and reproducible method to three-dimensionally quantify mandibular bone remodeling.

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