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Replacement of the distorted dentition of the Cone Beam Computed Tomography (CBCT) scans for orthognathic surgery planning

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Abstract

Purpose: CBCT imaging does not record dental morphology accurately due to the scattering produced by metallic restorations and the reported magnification. The aim of this study was the development and the evaluation of a new method for the replacement of the distorted dentition of CBCT scans with 3D dental image captured by a digital intraoral camera.

Materials and Method: Six dried skulls with orthodontics brackets fixed on the teeth were used in this study. Three intra-oral markers made of dental stone were constructed and attached to orthodontics brackets. The skulls were CBCT scanned and occlusal surfaces were captured using TRIOS[®] 3D intraoral scanner. The digital intra-oral scan (IOS) was fused into the CBCT models. This produced a new composite digital model of the skull and dentition. The skulls were scanned again using the commercially accurate Laser Faro[®] arm to produce the 3D model “gold standard” for the assessment of the accuracy of the developed method. This was assessed by measuring the distance between the occlusal surfaces of the new composite model and the “gold standard” 3D laser scanned model

Results: The results showed the errors related to the superimposition of the intra-oral image on the CBCT to replace the distorted dentition were between 0.11 and 0.20 mm.

Conclusion: The results of this study suggests that the dentition in the CBCT can be accurately replaced with the digital IOS captured by an intra-oral scanner to create a composite model which will improve the accuracy of the digital orthognathic surgical planning and the fabrication of an occlusal wafer.

Introduction

Cone-beam computed tomography (CBCT) is widely considered the gold standard for obtaining images of hard tissue and is becoming a routine dental imaging modality specifically designed for maxillofacial surgery. However, for orthognathic surgery planning the accurate recording of the dental occlusion is necessary. In CBCT imaging, visualization of the dentition is compromised due to streak artifacts caused by metal dental restorations and orthodontic brackets. (1-2)

The possibility of taking a CBCT scan without streak artefacts can be achieved if all metallic objects within the oral cavity are eliminated. Removal of metallic restorations as well as orthodontic brackets, would be time consuming and has financial implications (3).

Metal artefact reduction (MAR) algorithms reduce the severity of artefacts by adjusting mathematical calculations of the CBCT to replace the distortion areas. However, until now, no MAR algorithm has been developed to a level of accuracy that could produce images with adequate precision (4).

The process of spatially superimposing 3D images of accurate dental occlusion will facilitate the broad application of CBCT scan for orthognathic surgery planning (5).

Gateno et al. (6) reported the first clinically applicable method to combine an accurate dentition image of the dentition into the computerized 3D skull image with the use of extra-oral fiducial markers. Subsequently, Swennen et al. (7) developed a triple CBCT scan, they used voxel-based registration to create a composite model of jaw bones and dentition with accurate dental anatomy. The registrations were based on the maximization of mutual information registration algorithm reported by Maes et al (8). The technique proved to be highly accurate and convenient for patients. The disadvantage of this method is that the triple CBCT scan requires scanning the patient twice, which is associated with an increase in exposure to radiation.

The aim of the study was to develop and evaluate a new method for the replacement of the distorted dentition of CBCT scans with 3D dental image captured by the digital intraoral camera.

Materials and Methods

Six dried skulls with orthodontics brackets fixed on the teeth were used in this study. The skulls were available among our historical archive, so no approval was required to utilise them for the study. Three intra-oral markers made of dental stone were constructed, one on the central incisor, one on the right second premolar and the other on the left second premolar of the maxilla. These were constructed using a die stone class IV (Sherahard-rock, John Winter &Co LTD, Halifax, England). Stainless steel wire, 0.5mm (K.C. Smith Ortho Ltd, Hertfordshire) was used to create a cross-wire appearance by soldering a horizontal and vertical wire to be easily adapted to the orthodontic brackets. The cross wires were attached to the markers using a specific glue. The markers were installed onto the brackets with the help of the cross wires. The markers were secured onto the brackets with the use of orthodontic elastics (Figure 1).

Each skull was positioned in the middle of the field of view and CBCT scanned using i-CAT scanner (Imaging Sciences International, Warple Way, London) with 0.4mm voxel size. A 13-cm field of view (FOV) was used, which took 20 seconds to complete. The images were then exported as a Digital Communication in Medicine (DICOM) file. The CBCT volumetric data of the skull hard tissue (DICOM format) were converted into stereolithography (STL) format using Maxilim software (Medicim- Medical Image Computing, Belgium).

The dentition was scanned, with the markers in place, using a TRIOS 3D intraoral scanner (3Shape A/S, Copenhagen, Denmark). Each CBCT maxilla image and the corresponding digital 3D dental image with the markers in place were imported into VRMesh software, (VirtualGrid, Seattle City, Washington) (Figure 2). The two images were then manually aligned using the markers, and six points were selected in the corners of each marker. A total of 18 reference points were placed in the CBCT image (source) and IOS image (target) for manual registration, this was followed by fine alignment iterative closest point (ICP) between the surfaces. This allowed the occlusal surface of the dentition of the maxilla to be replaced with the 3D image of the occlusal surfaces captured by the intraoral scanner. This method is summarised in (Figure 3).

To measure the accuracy of the proposed method of superimposing the intra-oral dental image on the CBCT, the skulls were laser scanned using the industrial Faro 3D laser scanner (Figure 4) (Scantec, Coventry, UK), which allowed 3D surface capture with an accuracy of 25 µm according to the manufacturer's terms. The superior quality of the recorded images can not be obtained with any other imaging modality; this would not be achieved clinically as the scanner is not designed for applications on patients. Therefore, this laser produced image was considered the gold standard for the comparison with the digitally assembled 3D model of the teeth and jaw bones.

The composite model and the corresponding laser-scanned skull were imported into the VRMesh software (Figure 5). The dentition of the composite model and laser model were isolated from

the rest of models. Manual registration was performed by using anatomic corresponding points in the two images. Surface-based registration was then applied ensuring that the composite model image of the maxilla was the source and the image of the laser scanned model was the target. The occlusal surfaces of the dentition on both images were isolated, the discrepancies between the two were measured and displayed in the histogram chart (Figure 6). The absolute distances between the corresponding surfaces determined the errors associated with the fusion of the digital 3D image of the dental arch with the CBCT. To assess the statistical significance of the measured differences Wilcoxon signed rank test was applied at $p < 0.05$.

To assess the errors of capturing the teeth using intra-oral scanners, the dentition and markers of the composite model and laser model were isolated from the rest of models (Figure 7). The two images were then manually aligned using the markers, with six points selected in the corners of each marker, followed by fine alignment (ICP) between the surfaces. The discrepancies between the two images were measured and displayed in the histogram chart (Figure 8).

Results

No statistical significant differences between measurements on the first and second occasion of superimposition IOS model into CBCT skull at $P < 0.05$ (Table 1).

The absolute mean distance between the maxillary occlusal surface meshes for the IOS dentitions and laser model dentitions, when registered on intra-oral markers, ranged from 0.13 to 19mm, whereas when registered on the skulls surfaces, ranged from 0.11 to 0.20mm (Table 2). The overall results showed high accuracy of the developed superimposing method. The differences between the occlusal surfaces are shown in the histograms in (Figure 6, 8), most of the occlusal areas showed light green to orange colour, indicating a good fit of the superimposed dental image on the CBCT scan.

Discussion

At present, CBCT imaging does not record the occlusal surfaces accurately due to the scattering produced by metallic restorations, orthodontic brackets and the low- resolution of the CBCT scan. This is a major obstacle for occlusal registration which interferes with orthognathic wafer fabrication to guide the surgical correction of dentofacial deformities ⁽⁹⁾.

In an attempt to solve this problem, several authors have used simple image fusion techniques by applying the best-fit algorithm between teeth surfaces ⁽¹⁰⁻¹¹⁾. The technique is straightforward but has some limitations, as using the teeth surfaces of the CBCT as registration references is an unreliable method, this has been well investigated and reported by Nairn et. al, due to the magnification that occurs during radiographic scanning of the dentition ⁽¹²⁾. Therefore, there are inherent inaccuracies with the use 3D image produced from the direct radiographic scanning of the dentition for the virtual planning of orthognathic surgery.

Other studies explored the extra oral fiducial markers to replace a defective dentition ^(6,13-15). The disadvantage of using extra-oral fiducial markers was the resultant significant change in the facial soft tissues. This could interfere with soft tissue prediction planning for orthognathic surgery.

In this study, the rational behind using the orthodontic brackets to hold the reference markers was to decrease the laboratory time for construction of new appliances. Most of the previous studies have used dental casts to fabricate a template or a device that can hold the fiducial markers in place ^(12,16). The proposed method does not require construction of lingual or palatal plates to guide the superimposition of the dental image on the CBCT scan, which reduces the cost and the laboratory time ⁽¹⁶⁾.

The developed markers can be easily located above the level of the clinical crowns on the labial and buccal aspects of the teeth of the upper jaw, this prevents the markers from being distorted by streak artefacts.⁽¹⁾ The design also prevents the undesired distortion of the soft tissues that had been reported in previous methods^(6,13-14).

The marker and cross wire were designed to be non-invasive, comfortable and securely positioned on the labial and buccal aspects of the maxilla using 0.5mm stainless steel wire was fitted perfectly into the horizontal slot of the brackets and the 1mm wire was found to be suitable for the vertical slot.

One of the main advantages of the intraoral scanner is the possibility of capturing the teeth and brackets with the markers in place directly, which eliminates the need of dental impression which reduces the total processing time and minimise patient's inconvenience.

According to Yang et al.⁽¹⁶⁾ 20 minutes are required for taking dental impression and 45 minutes are required for the stone model to set. In our study, it took less than 10 minutes to apply the markers on the orthodontic brackets and obtain a digital dental image.

The mean absolute superimposition error in this study ranged from 0.13 to 0.19 mm. This is similar to the previous study where the mean registration error ranged from 0.13 to 0.26 mm ⁽¹⁾.

Uechi et al. ⁽¹⁴⁾ used a references splint with three ceramic balls and reported on the root mean square errors (RMSE) for the accuracy of superimposition of dental image on the CBCT between 0.025 mm to 0.21 mm, which is similar to our finding. Yang et al. ⁽¹⁶⁾ used a palatal plate with four spherical fiducial markers and found RMSE less than 0.2 mm. The mean distance between the two occlusal surfaces on the maxillary was 0.20 to 0.03 mm.

de Waard et al.⁽¹⁷⁾ used a wax bite containing markers to replace the distorted dentition by the IOS dental model. The mean registration errors between the IOS model and augmented model ranged from 0.12 to 0.45 mm.

Nairn et al.⁽¹²⁾ investigated the amount of magnification of the dentition of the CBCT of the skull. The absolute mean difference between the occlusal surfaces of the CBCT and laser image ranged from 0.53 to 0.14mm.

Most of the previous methods explained that intra-oral fiducial markers can be distorted during CBCT scanning images due to the streak artefacts^(1,15). However, in our method, the markers were above the occlusion level which overcame the errors in image acquisition due to the streak artifacts. The size of the fiducial marker plays an important role in the registration process. Based on the trial we conducted before but not reported in this study, the smaller markers failed to facilitate the accurate registration process.

Based on the findings of this study we recommend a follow up investigation to compare the accuracy of the presented technique with the existing orthognathic planning methods to identify the magnitude of the discrepancy and investigate its clinical implications. The presented method is a step in the right direction to improve the virtual prediction of the surgical correction of dentofacial deformities.

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Legend of the figures:

Figure 1. The maxillary teeth with three markers attached to orthodontic brackets, the markers secured onto the brackets with orthodontic elastics.

Figure 2. The CBCT maxilla image and corresponding digital 3D dental image with the markers in place imported into VRMesh.

Figure 3. Flowchart demonstrating how the composite virtual image was created.

Figure 4. The faro laser arm scanning one of the skull and the dentition to produce the “gold standard” model for comparison.

Figure 5. Laser scan skull (left) and composite skull & dentition (right) were imported into VRMesh.

Figure 6. Colour error map showing discrepancies between in the position of the dentition of developed composite model.

Figure 7. The dentition and markers of the composite model and laser model were isolated.

Figure 8. Colour error map showing discrepancies between the positions of the superimposed dentitions.

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Table 1. The average difference between the first and second superimposition of IOS model into CBCT skull, $p=0.2557(>0.05)$

Model	Average (mm)
1	-0.02685
2	-0.01407
3	0.04754
4	0.07291
5	0.02607
6	0.01209

Table 2. The average difference between the dentition surfaces of laser model and the IOS model when aligned (a) on the bone surface and when aligned (b) on the intra-oral markers.

Model	(a) Bone surface	(b) Marker surface
	Absolute mean distance(mm)	Absolute mean distance(mm)
1	0.20	0.19
2	0.20	0.15
3	0.11	0.14
4	0.17	0.13
5	0.18	0.19
6	0.11	0.15















