Busuttil Naudi, K., Benramadan, R., Brocklebank, L. , Ayoub, A. , Ju, X. , and Khambay, B. (2012) *The virtual human face – superimposing the simultaneously captured 3D photorealistic skin surface of the face on the untextured skin image of the CBCT Scan.* International Journal of Oral and Maxillofacial Surgery . ISSN 0901-5027

http://eprints.gla.ac.uk/62871/

Deposited on: 30th April 2012

The Virtual Human Face – Superimposing the simultaneously captured 3D photorealistic skin surface of the face on the untextured skin image of the CBCT Scan

Kurt Busuttil Naudi, Rehab Benramadan, Laetitia Brocklebank, Ashraf Ayoub*, Xiangyang Ju, Balvinder Khambay.

*Corresponding author address & address where work can be attributed:

Biotechnology and Craniofacial Sciences (BACS) Research Group

Glasgow University, College of Medicine, Veterinary and Life Sciences

378 Sauchiehall Street, Glasgow, G2 3JZ, United Kingdom

Telephone: +441412119600

Fax: +441412119601

E-mail: ashraf.ayoub@glasgow.ac.uk.

Key Words: Virtual human face

Cone Beam CT

Stereophotogrammetry

Orthognathic surgery

Simultaneous capture

Title for running heads:

The Virtual Human Face

ABSTRACT

The aim of this study was to evaluate the impact of simultaneous capture of the three-dimensional (3D) surface of the face and cone beam computed tomography (CBCT) scan of the skull on the accuracy of their registration and superimposition. 3D facial images were acquired in 14 patients using the Di3d (Dimensional Imaging, UK) imaging system and i-CAT CBCT scanner. One stereophotogrammetry image was captured at the same time as the CBCT and another one hour later. The two stereophotographs were then individually superimposed over the CBCT using VRmesh. Seven patches were isolated on the final merged surfaces. For the whole face and each individual patch; maximum and minimum range of deviation between surfaces, absolute average distance between surfaces, and standard deviation for the 90th percentile of the distance errors were calculated. The superimposition errors of the whole face for both captures revealed statistically significant differences (P=0.00081). The absolute average distances in both separate and simultaneous captures were 0.47mm and 0.27mm, respectively. The level of superimposition accuracy in patches from separate captures ranged between 0.3 and 0.9mm, while that of simultaneous captures was 0.4mm. Simultaneous capture of Di3d and CBCT images significantly improved the accuracy of superimposition of these image modalities.

INTRODUCTION

Currently, the interest in utilizing three dimensional (3D) images in the planning for orthognathic surgery is significantly increasing; this is because they are considered the ideal methods for representing the face. Creating a precise three dimensional replica of the head including both hard and soft photorealistic tissue structures has been the target of several researchers. One of the most promising methods that have been proposed is the registration of skin surface images acquired by both stereophotogrammetry and cone beam computed tomography (CBCT).

It is generally agreed that creating 2D models is of limited significance, being applicable only in profile prediction planning. In everyday life patients do not look at themselves in profile. The complexity of some of the suggested registration methods is also viewed as a serious shortcoming. In addition, relying on laser scanners as a source for the soft tissue data has a number of limitations. The capture is slow; therefore image distortion caused by movement of the subject or change in facial animation is a potential source of errors. In addition, the developed skin surface image lacks the photorealistic appearance and the characteristic surface texture[1,2].

Stereophotogrammetry, first suggested for use in dentistry by Mannsbach in 1922[3], makes use of two of more images of an object that are taken from different viewpoints. A 3D image of the object is then built using the concept of triangulation to recover the third dimension, thus providing the illusion of depth in the created 3D image[4]. Over the past decades the technique has undergone significant development. The introduction of high resolution digital cameras has allowed the resolution of even the finest detail of the skin surface of the subjects[5]. Stereophotogrammetry has now developed into a relatively simple, safe, non-invasive, extremely rapid (<1ms) and highly accurate image capture technique.

The CBCT was introduced in 1982 by Robb[6]. It provides high image accuracy with shorter scanning times and lower radiation doses compared to conventional computed tomography (CT)[7]. Although the CBCT is used in the maxillofacial region primarily to obtain images of the hard tissues of the face, the image editing software used to manipulate the data obtained from the scan is capable of extracting the soft tissue image of the face of the subject. Unfortunately the created image lacks the lifelike photographic texture of the facial soft tissues.

The superimposition of the two images obtained from the above methods would allow the placement of a high resolution 3D facial photograph onto the untextured image of the face obtained from the CBCT image. The difficulty would be ensuring that the facial expression is exactly the same for both image captures. Differences in facial expression could be minimised if the two images were captured at the same time.

The aim of this study is to evaluate the impact of the simultaneous capture of stereophotographs and CBCT images on the accuracy of their registration and superimposition.

MATERIALS AND METHODS

The study was carried out on fourteen patients who were being referred for the management of their dentofacial problems. Male patients with facial hair were excluded to avoid artefacts in the created image. Three dimensional facial images for these patients were acquired using the Di3d imaging system and i-CAT CBCT scan, which is the normal practice for our orthognathic surgery patients. For each patient, two stereophotogrammetry images were captured, one at the same time of the CBCT scanning, this will be referred to as the simultaneous image, and the other delayed image, was captured 30 minutes later in a separate room. The image for the first stereophotograph was taken of the patient while they were sitting in the i-CAT scanner just before the CBCT scan was acquired (Figure 1). Before capturing the images the patients were asked to remove spectacles and jewellery, to keep all hair off the face, to keep both eyes open, bring their teeth in contact and relax their lips.

Stereophotogrammetry

The Di3D imaging system (Dimensional Imaging, Hillington Park, Glasgow, UK) is based on the stereophotogrammetry concept and is able to capture high resolution, full-colour 3D models of the face (180°, ear to ear view). The system consists of two camera stations which are connected to each other. Each station contains a pair of high-resolution (14 Megapixel, 50mm focal length) digital cameras (Canon, (UK) Ltd). Two white-light studio flash units (Esprit Digital DX1000, Bowens, UK) are placed alongside the camera stations to illuminate the subjects (Figure 1). The system is calibrated before each use using a fully automated method with a calibration target (Figure 2).

Cone Beam Computed Tomography

The i-CAT (Imaging Sciences International, Hatfield, USA) is a CBCT imaging tool which is now routinely used in many maxillofacial units. Apart from hard tissue information, the image created by the i-CAT can also be manipulated to show the soft tissues of the face of the patient. All the cases were scanned using an extended height field of view option (22cm), 0.4 voxels, with two 20 second scans to capture the complete dataset.

Data processing

DI3Dcapture™ software was used to process the captured stereo pairs of images and create the 3D facial models, as described in Khambay et al[1]. DI3Dview™ software was used to view the created high resolution 3D models and the images were stored as wavefront object files (*.obj).

The CBCT data was imported into Maxilim software (Medicim NV, Mechelen, Belgium) as Digital Images and Communications in Medicine (DICOM) files. This allowed manipulation of the image and segmentation of the hard and soft tissues by thresholding. The untextured soft tissue surface of the CBCT scans was then exported as a stereolithography file (*.stl) (Figure 3). Maxilim was also used to convert the wavefront object files of the stereophotograph images into stereolithography files to allow superimposition of these images on those obtained from the CBCT. This was done for each individual stereophotograph image using VRmesh (VirtualGrid, Bellevue, WA) software.

Superimposition

For each case, superimposition was carried out for the simultaneous soft tissue image onto the CBCT model and for the delayed soft tissue image on the same CBCT model. Four landmarks were digitized manually in the same sequence on the Di3d models and the CBCT models; Left external canthus, right external canthus, left cheilion and right cheilion (Figure 3). These were utilised for the initial rigid registration process. Areas of no clinical relevance (head hair, ears and neck) were excluded to improve the accuracy of the superimposition, as suggested by Maal et al[8]. Data artefacts associated with the CBCT model in the inner surface of the nose, possibly due to the presence of surgical plates, were also deleted. Iterative Closest Point (ICP) registration was then applied to register the textured (Di3d) and untextured (CBCT) surfaces to the best fit. The superimposed images were saved as a VRMesh files (*.vrg). Surface differences were automatically computed and displayed as colour coded surface error maps (Figure 4). To quantify the magnitude of mismatch between the superimposed images, seven areas were selected and isolated as patches; forehead, nose, right cheek, left cheek, upper lip, lower lip and chin (Figure 5). The patches were exported as Virtual Reality Modelling Language (VRML) files (*.wrl). Since VRMesh can only provide a visual image of the differences between the two surfaces, specialised software was developed in-house to measure the absolute distances between the two surfaces and to provide simple statistical analysis of the results.

Statistical analysis

Quantitative measurements of the superimposition errors of each superimposed model for both simultaneously captured images and the delayed images were calculated. The maximum and minimum range of surface deviation (Euclidean distances), the absolute average distance between the two surfaces and the standard deviation were computed for the 90^{th} percentile of the distance errors.

For each patient, the measurements were collected for the whole face and for the selected patches. A Student *t*-test was applied to analyse the difference between the two sets of data obtained from the separate image captures. *P* values of less than 0.05 were considered significant.

RESULTS

Table 1 shows the results of the absolute average distances, and the standard deviations (SD) between the two registered surfaces of the complete faces for the 90^{th} percentile of the distance errors of both separate and simultaneous captures. The results reveal a statistically significant difference between the two occasions of image capture (*P*=0.00081). The absolute average distances in both simultaneous and separate image captures were 0.27mm and 0.47mm, respectively.

Table 2 similarly shows the absolute average distances and the standard deviations between the two registered surfaces of the seven patches for the 90th percentile of the distance errors in both the delayed and simultaneous captures. There was a statistically significant difference between the two image capture occasions in all the patches. The most significant statistical difference was recorded in the chin patch (*P*=0.000069). The level of superimposition accuracy in the patches from the delayed captures ranged between 0.3 and 0.9mm, while the superimposition accuracy for the simultaneous capture images was 0.4mm or less.

DISCUSSION

Visualizing a precise preoperative 3D prediction of the possible appearance of the face following the correction of a maxillo-mandibular deformity is not only of prime importance for the surgeon, but also for the patient. Prediction planning would ease some of the psychological impacts of the surgery on the patient by eliminating the uncertainty aspect of the surgical correction of the facial bones. This can only be achieved with an accurate 3D model of both the soft tissue of the face and the underlying skeletal structures.

Various methods have been published on the building of an integrated digital facial model that overlaid both the soft tissues and the skeletal structure of the face. 3D laser scanning, video imaging, 3D Metrics stereo cameras, and digital colour portraits have been utilized as sources for soft tissue data. Data concerning the facial skeleton have been collected by plain radiographs, and CT scanning. The resultant composite models were either displayed in 2D or 3D[9-13].

Stereophotogrammetry is a more promising soft tissue imaging modality. It is a simple, fast and accurate method which captures the face shape and texture in 3D[1, 14-17]. Recently, several studies have adopted similar approaches in building their 3D facial models as they implemented stereophotogrammetry and computed tomography concepts[8]. Different stereophotogrammetry based imaging systems have been used, including the C3D system, the Di3D system, and the 3dMD system.

In 2007, Ayoub et al[2] applied the same registration method for building a digital virtual human face. They examined the feasibility of the registration method on human subjects. The study concluded that in most of the surfaces the errors were within ± 1.5mm. These errors have been attributed to facial expression and spatial soft tissue changes caused by nonsimultaneous capture of the stereophotogrammetry and CT facial images and differences in the patient positioning during the capture; the Di3D system images the patient in the sitting position, while the spiral CT scanner (used in this study) required the patient to be in the supine position.

Maal et al[8] replaced the conventional spiral CT scans with CBCT scans which were taken with the patient in an upright position. Three registration methods were assessed. The study found that excluding error regions before finalizing the registration by the ICP algorithm improved the accuracy of the matching process. However, the results were similar to those presented by Ayoub et al[2]. In addition, the author acknowledged that the use of non rigid registration is not favourable as it provides the best fit between the two surfaces by allowing deformational changes of these surfaces rather than passive superimposition.

On reviewing the available literature, it is clear that the simultaneous acquisition of both the stereophotogrammetry based photorealistic 3D skin surface and the CBCT scan skin surface has not been addressed fully.

Previous work has validated the reliability of the Di3d system in recording 3D facial images[1,18]. The CBCT scan is preferred over the conventional CT scan as it exposes the patient to less radiation, and scans the patient in the sitting position[19].

Since the coordinate data for both the soft tissue CBCT model and the underlying CBCT skeletal model were the same, only one model was used for the registration process. Considering that the preliminary superimposition process requires the identification of identical landmarks on the two surfaces, both surfaces should be structurally similar For this reason the soft tissue CBCT model was chosen for registration with the Di3d soft tissue model.

The initial stage of the registration process required manual identification of similar landmarks on the both models. According to Khambay et al[20], registration of the facial stereophotogrammetry image and CT skin image using anatomical landmarks was much more accurate than using artificial landmarks. The distribution of the landmarks used in this study was selected to cover a wide area of the face in order to enhance the initial matching process. As the 3D CBCT model is untextured, one might assume that some degree of difficulty might be encountered during this step. However, precise identification of these landmarks did not have a significant impact on the accuracy of the matching process. The landmarks were only required to assist the software in bringing the two surfaces into an approximate initial match.

Regions that normally would not be included in the planning for orthognathic surgery, such as the hair, the ears, and the neck, were deleted from the initially matched surfaces. Besides being unimportant in the planning process, they would increase the errors of the method due to the known limitations of the Di3d and the CBCT scan in capturing these structures.
It is recognized that reconstructed 3D-CBCT soft tissue models might show unexplainable defects at the tip of the nose, and streak artefacts extending from the inner aspect of the nose[2,20]. Despite that, the nose region should not be removed as it could be affected by some orthognathic surgical procedures. Hence, its assessment should be an integral part of the treatment planning.

The superimposition of the surfaces was refined to the best fit by applying the ICP rigid registration algorithm. The algorithm attempts to match surfaces by iteratively computing the closest point on a surface to a given point on another surface[21]. The algorithm utilizes the full geometry of both surfaces instead of depending only on landmarks; hence a more accurate final alignment can be achieved.

Previous studies have been limited to the analysis of the accuracy of superimposition of the whole face[2,8,20], which is misleading since some regions of the face are associated with higher errors in superimposition than others. That is why in this study specific regions (patches) in each model were also examined individually. These regions may respond differently to orthognathic surgery. Therefore, calculating and recognising the errors in each patch separately will ensure more precise prediction planning in the future. The forehead region is not affected by basic orthognathic surgery and was therefore used as a reference point in comparing the separately captured models.

The use of the 90th percentile points in the calculation of the superimposition errors is generally agreed to represent the level of error more efficiently. In most of the patients and for the two capture methods, the computed maximum range of surface differences of the 90th percentile decreased dramatically in comparison to the 100th percentile (e.g. surface deviations range for the separate capture of the complete face; 100th percentile points mean = 4.84, 90th percentile points mean = 1.32). The findings indicated that distances between the superimposed surfaces were high for 10% of the points due to possible artefacts. Discarding these erroneous data was performed in order to achieve an authentic picture representing the level of superimposition errors. However, there is always the risk that some of these points are crucial landmarks for orthognathic surgery planning and comprehensive facial analysis.

A study conducted by Kau et al.[22] using a 3-dimensional laser scanning system concluded that capturing the soft tissue morphology of the face with this technique was clinically reproducible both at 3 minutes as well as at 3 days time intervals. It could be argued that the same concept can be applied as another scenario for testing the impact of the time on the reproducibility of facial expression when Di3d images are captured. In this study, this scenario cannot be applied, as standardization of facial expression may not be fully achieved when both Di3d and CBCT images are acquired separately due to the fact that patients are usually more relaxed when being photographed than when being placed in the i-CAT machine for scanning.

On examining the total face in all the patients, the simultaneous capture showed lower errors in superimposition than the separate capture (Table 1). The remaining errors found in the superimposition of the simultaneous Di3d-CBCT model could be attributed to the differences in the physical properties between the registered skin surfaces with each method (Figure 6), and to the artefacts caused by the CBCT scan (Figure 7). This was represented mostly around the eye regions and at the tip of the nose, the regions with the highest errors both in the delayed Di3d-CBCT model and simultaneous Di3d-CBCT model (Figure 8). The simultaneous capture yielded a relatively considerable improvement in the accuracy of superimposition as the absolute error dropped from 0.47mm, recorded with separate capture, to 0.27mm. The results showed significant differences between the two occasions of image capture ($P<0.05$). This could indicate that changes in the soft tissue shape could possibly occur if Di3d and CBCT images are taken at separate times.

With regards to the seven selected patches, the most significant difference in the accuracy of superimposition was recorded in the chin patch (P=0.000069). The mobile nature of the mandible could possibly be the contributing factor. All the patients were asked to relax and bring their teeth in contact during image capture. However, with the relaxing atmosphere of the Di3d image capture room, patients could bring their teeth slightly apart leading to changes in the chin position accompanied with a degree of mouth opening. In contrast, being in a CBCT scanner could be a relatively stressful experience for some patients, and these could over close their lips. Such alteration in the chin position during Di3d and CBCT capture could be too subtle for the operator's eye to recognize, yet it could result in spatial changes in the related soft tissue.

The second most significant differences were found in the right and left cheek patches with *P* values of 0.00029 and 0.0042 respectively. This significant improvement in the registration accuracy of the cheek areas could be attributed to the simultaneous capture of the both Di3d and CBCT images.

P values for the differences in the superimposition accuracy at the nose, the forehead, the upper lip and the lower lip patches were 0.0055, 0.0115, 0.0164, 0.0149 respectively. These regions showed less improvement with the simultaneous capture when compared to the chin and cheeks. With regards to the forehead, we suggest that the use of the head strap during the CBCT scan could cause a degree of deformation in the soft tissues as no head strap was required for the separate Di3d image capture.

In spite of the reduction noticed in the absolute mean superimposition errors of the simultaneously captured facial images, this may not be perceived as clinically significant. The highest error in the separate capture among the overall means of the total face and the seven patches was 0.9mm. A pilot study by Jones et al.[23] investigated the magnitude of change in a two-dimensional profile prediction that was required to be clinically significant and concluded that a 2mm change in the horizontal position on the maxillary and mandibular soft tissues was considered to be necessary before an expert or lay person could notice the change. Hence, it could be argued that the differences between both timings of image capture are too small to have an impact on the perceived clinical changes. On the other hand, implementing 3D images as one of the armamentaria for planning orthognathic surgeries urges the need for increased accuracy. Currently, the trend is towards 3D virtual prediction planning of orthognathic surgery. Any errors in the integration of the 3D soft tissues and skull models could increase the cumulative errors of the prediction planning method and finally could transfer to errors in the surgery.

The impracticality of capturing both the Di3d and CBCT images simultaneously is another issue which should be acknowledged. Adjusting the Di3d equipment in front of the CBCT machine is time and space consuming (Figure 1). But since providing highly accurate virtual models is the ultimate goal, building equipment which incorporates both the Di3d and the CBCT imaging modalities would be useful.

In conclusion, this study found that the improvement in the accuracy of superimposing simultaneously captured Di3d-CBCT models was statistically significant. The findings demonstrate the effect of the separate capture as a potential source for registration errors. There was a remarkable improvement in the integration accuracy of separately captured Di3d-CBCT models in comparison with previous studies. The main reason was the sitting position during the CBCT scanning which had the most crucial impact on maintaining the shape of the soft tissues and subsequently on the accuracy of registration.

AKNOWLEDGEMENTS

The authors would like to thank the superintendent and specialist radiographers in the oral and maxillofacial radiology unit at Glasgow Dental Hospital & School for their support and advice during the project.

Competing interests: None declared

Funding: None

Ethical approval: Approval was obtained from the local ethics committee of the University of Glasgow, UK

REFERENCES

1. Khambay B, Nairn N, Bell A, Miller J, Bowman A, Ayoub AF. Validation and reproducibility of a high-resolution three-dimensional facial imaging system. Br J Oral Maxillofac Surg 2008: 46: 27-32.

2. Ayoub AF, Xiao Y, Khambay B, Siebert JP, Hadley D. Towards building a photo-realistic virtual human face for craniomaxillofacial diagnosis and treatment planning. Int J Oral Maxillofac Surg 2007: 36: 423-8.

3. Mannsbach M. Die Stereophotogrammetrie als helfsmittel in der Orthodontie. Zahnartzl. Orthop. 1922: 4: 106.

4. Adams LP, Spirakis A. Stereo Photogrammetry. In: Shelton JC, Orr JF, ed.: Optical measurement methods in biomechanics. London: Chapman & Hall, 1997: 17-38.

5. Lane C, Harrell W Jr. Completing the 3-dimensional picture. Am J Orthod Dentofacial Orthop 2008: 133: 612-20.

6. Robb RA. The Dynamic Spatial Reconstructor: An X-Ray Video-Fluoroscopic CT Scanner for Dynamic Volume Imaging of Moving Organs. IEEE Trans Med Imaging 1982: 1: 22-33.

7. Sukovic P. Cone beam computed tomography in craniofacial imaging. Orthod Craniofac Res 2003: 6 Suppl 1: 31-6; discussion 179-82.

8. Maal TJ, Plooij JM, Rangel FA, Mollemans W, Schutyser FA, Bergé SJ. The accuracy of matching three-dimensional photographs with skin surfaces derived from cone-beam computed tomography. Int J Oral Maxillofac Surg 2008: 37: 641-6.

9. Sarver DM, Johnston MW. Video imaging: techniques for superimposition of cephalometric radiography and profile images. Int J Adult Orthodon Orthognath Surg 1990: 5: 241-8.

10. Girod S, Keeve E, Girod B. Advances in interactive craniofacial surgery planning by 3D simulation and visualization. Int J Oral Maxillofac Surg 1995: 24: 120-5.

11. Chen LH, Chen WH. Three-dimensional computer-assisted simulation combining facial skeleton with facial morphology for orthognathic surgery. Int J Adult Orthodon Orthognath Surg 1999: 14: 140-5.

12. Xia J, Wang D, Samman N, Yeung RW, Tideman H. Computer-assisted three-dimensional surgical planning and simulation: 3D color facial model generation. Int J Oral Maxillofac Surg 2000: 29: 2-10.

13. Curry S, Baumrind S, Carlson S, Beers A, Boyd R. Integrated three-dimensional ciraniofacial mapping at the Craniofacial Research Instrumentation Laboratory/University of the Pacific. Semin Orthod 2001: 7: 258-65.

14. Ayoub AF, Wray D, Moos KF, Siebert P, Jin J, Niblett TB, Urquhart C, Mowforth R. Three dimensional modelling for modern diagnosis and planning in maxillofacial surgery. Int J Adult Orthodon Orthognath Surg 1996: 11: 225-33.

15. Ayoub AF, Siebert P, Moos KF, Wray D, Urquhart C, Niblett TB. A vision-based three-dimensional capture system for maxillofacial assessment and surgical planning. Br J Oral Maxillofac Surg 1998: 36: 353-7.

16. Honrado CP, Larrabee WF. Update in three-dimensional imaging in facial plastic surgery. Curr Opin Otolaryngol Head Neck Surg 2004: 12: 327-331.

17. Heike CL, Cunningham ML, Hing AV, Stuhaug E, Starr JR. Picture perfect? Reliability of craniofacial anthropometry using three-dimensional digital stereophotogrammetry. Plast Reconstr Surg 2009: 124: 1261-72.

18. Winder RJ, Darvann TA, McKnight W, Magee JD, Ramsay-Baggs P. Technical validation of the Di3D stereophotogrammetry surface imaging system. Br J Oral Maxillofac Surg. 2008: 46: 33-7.

19. Kau CH, Richmond S, Palomo JM, Hans MG. Three-dimensional cone beam computerized tomography in orthodontics. J Orthod. 2005: 32: 282-93.

20. Khambay B, Nebel JC, Bowman J, Walker F, Hadley DM, Ayoub A. 3D stereophotogrammetric image superimposition onto 3D CT scan images: the future of

orthognathic surgery. A pilot study. Int J Adult Orthodon Orthognath Surg. 2002: 17: 331-41.

21. Besl PJ, McKay ND. A method for registration of 3-D shapes IEEE Trans. Pattern Anal. Mach. Intell. 1992: 14: 239-56.

22. Kau CH, Richmond S, Zhurov AI, Knox J, Chestnutt I, Hartles F, Playle R. Reliability of measuring facial morphology with a 3-dimensional laser scanning system. Am J Orthod Dentofacial Orthop. 2005: 128: 424-30.

23. Jones RM, Khambay BS, McHugh S, Ayoub AF. The validity of a computer-assisted simulation system for orthognathic surgery (CASSOS) for planning the surgical correction of class III skeletal deformities: single-jaw versus bimaxillary surgery. Int J Oral Maxillofac Surg. 2007: 36: 900-8.

Table 1. Means and standard deviations for the 90th percentile of distance errors for the complete face in the both simultaneous and separate image captures for all the cases (SD = Standard deviation).

Complete face	Separate capture		Simultaneous capture	
	90th percentile		90th percentile	
	mean(mm)	SD(mm)	mean(mm)	SD(mm)
Patient 1	0.31	0.22	0.27	0.21
Patient 2	0.40	0.28	0.25	0.17
Patient 3	0.49	0.35	0.25	0.18
Patient 4	0.47	0.31	0.35	0.23
Patient 5	0.41	0.26	0.27	0.19
Patient 6	0.41	0.31	0.24	0.16
Patient 7	0.99	0.84	0.27	0.20
Patient 8	0.41	0.31	0.32	0.25
Patient 9	0.55	0.41	0.27	0.18
Patient 10	0.58	0.40	0.22	0.16
Patient 11	0.33	0.22	0.33	0.22
Patient 12	0.38	0.28	0.22	0.17
Patient 13	0.54	0.33	0.28	0.21
Patient 14	0.33	0.25	0.25	0.18
Overall mean	0.47		0.27	
SD	0.17		0.03	
t-test value	4.246			
P value	0.000814			

Table 2. Overall means and standard deviations for the 90th percentile of distance errors for the seven separate face patches in the both separate and simultaneous image captures, all differences were found to be statistically significant (SD = Standard deviation).

	Separate capture		Simultaneous capture			
	Mean (mm)	SD (mm)	Mean (mm)	SD (mm)	t-test value	*P*-value
Forehead	0.34	0.17	0.20	0.07	2.82	0.0115
Nose	0.53	0.15	0.37	0.09	3.17	0.0055
Right cheek	0.35	0.09	0.21	0.06	4.52	0.0002
Left cheek	0.39	0.13	0.25	0.06	3.29	0.0042
Upper lip	0.47	0.23	0.29	0.08	2.66	0.0164
Lower lip	0.61	0.28	0.40	0.09	2.62	0.0149
Chin	0.83	0.36	0.30	0.09	5.21	0.00006

CAPTIONS TO ILLUSTRATIONS

Figure 1. The patient in position in the i-CAT machine with the Di3D system positioned in front of the i-CAT ready for image capture.

Figure 2. Schematic illustrating the calibration target for the Di3D imaging system.

Figure 3. Image of the untextured soft tissue surface of the CBCT scan exported as a stereolithography file.

Figure 4. Image of a colour-coded surface mismatch error map for one of the cases following superimposition of the CBCT and Di3D images.

Figure 5. Illustration of the seven patches selected for individual superimposition.

Figure 6. Image illustrating the differences in the physical properties of the skin surfaces obtained from the CBCT and Di3D systems. In the CBCT model (left) the skin is smooth and devoid of any facial hair. In the Di3D model (right) the skin is textured and eyebrows and eyelashes are visible.

Figure 7. Image illustrating the artefacts that occur in the image acquisition of the CBCT model. A defect is visible at tip of the nose (left) and streak artefacts extend from internal aspect of nose (right).

Figure 8. Images showing that both the separate Di3D-CBCT model (left) and the simultaneous Di3d-CBCT model (right) shared errors in the eye and nose regions. (Red = highest error, blue = lowest error).