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A pilot study to assess the accuracy of capturing oncology facial defects with multimodal image fusion versus laser scanning

ABSTRACT

Statement of problem. Fabrication of conventional facial prostheses is a labor-intensive process which traditionally requires an impression of the facial defect and surrounding tissues. Inaccuracies occur during facial impressions due to soft tissue compression, the patient's reflex movements or the lack of support of the impression material. A variety of three-dimensional (3D) imaging techniques have been introduced during the production of facial prostheses however there has been little evaluation of the accuracy of the different imaging techniques in this clinical context.

Purpose. Compare the difference in accuracy of capturing oncology facial defects with multimodal image fusion and laser scanning against a cone beam computed tomography (CBCT) reference scan.

Material and methods. Ten casts of oncology facial defects were acquired. To produce reference models, a 3D volumetric scan was obtained with a CBCT scanner (NewTomVG; Sefla S.C.) and converted into surface data using open-source medical segmentation software (ITK-SNAP; http://www.itksnap.org/). This model was cropped to produce a CBCT mask using an open-source system for editing meshes (MeshLab; http://www.meshlab.net/). The multimodal image fusion model was created using stereophotogrammetry (DI3D; Dimensional Imaging Ltd DI4D) to capture the external facial features and a custom optical structured light scanner to record the defect. The casts were also scanned with a commercial 3D laser scanner (3D Scanner Ultra HD; NextEngine Inc) to create the laser scanned model. Analysis of the best fit of each

experimental model to the CBCT mask was performed in MeshLab. The unsigned mean distance was used to measure the absolute deviation of each model from the CBCT mask. A paired-samples t-test was conducted to compare the mean global deviation of the two imaging modalities from the CBCT masks.

Results. There was a statistically significant difference in the mean global deviation between the multimodal imaging model (mean= 220µm, SD=50µm) and laser scanned model (mean = 170 µm, SD 70µm); t(9)= 2.56, P= 0.03). The color error maps illustrated that the greatest error was located at sites distant to the prosthesis margins.

Conclusions. The laser scanned models were more accurate; however, the mean difference of 50µm is unlikely to be clinically significant. The laser scanner had limited viewing angles and a longer scan time which may limit its transferability to the clinical environment in this context.

CLINICAL IMPLICATIONS

Multimodal image fusion shows potential as a true and precise method of capturing oncology facial defects based on previous in-vitro research and compares well to a commercially available laser scanner. The approach combines the initial short capture time of stereophotogrammetry with the ability of the structured light scanner to process into deeper defects. This makes the multimodal imaging technique a practical option to introduce in the clinical environment and further research is planned to appraise its clinical use.

INTRODUCTION

The fabrication of conventional facial prostheses is a labor-intensive process comprising multiple clinical and laboratory stages.[1] These include obtaining an impression of the defect as well as the

unaffected side for unilateral defects e.g. the contralateral ear.[1] Inaccuracies during impression taking can occur due to soft tissue compression, the patient's reflex movements or by the lack of support of the impression material.[2] Following the impression a plaster model is poured and a wax pattern of the future prosthesis is produced. A negative mold is then fabricated and used to produce the silicone prosthesis.[1] Achieving a satisfactory end result that will mask the missing facial tissue is highly dependent on the skills of the maxillofacial prosthetist.[3]

Three-dimensional (3D) imaging and computer-aided design and computer-aided manufacturing (CAD/CAM) technologies are more commonplace within the hospital setting and have many applications within dentistry and oral and maxillofacial surgery.[4] A variety of 3D imaging techniques have been introduced for the production of facial prostheses in an attempt to overcome some of the limitations of conventional impressions. Potential benefits include improved patient comfort, reduced invasiveness and efficiency of data collection.[2, 5] Computer-aided design processes may also reduce dependence on the artistic skills of the maxillofacial prosthetist.[6] Additionally, application of additive manufacturing processes could significantly reduce the time taken and number of clinical stages for facial prosthesis production.[1]

Data from medical computed tomography imaging systems have been successfully used in the production of facial prostheses e.g. during the manufacture of orbital or nasal prostheses.[7, 8] There are a number of potential limitations in using 3D models derived from computed tomography data. These include the need for volume rendering to obtain a 3D representation of the anatomical structures.[6] This process can be influenced by various factors leading to a change in dimensions when compared to the original anatomy.[9] In addition, there may be concerns associated with exposure to radiation and costs.[1, 6]

Non-invasive systems including stereophotogrammetry can produce a 3D surface model from multiple viewpoints in a synchronized manner with a short capture time and clinically acceptable accuracy.[10] Various reports have illustrated the successful use of stereophotogrammetry to produce facial prostheses on superficial defects.[1] However this imaging modality has difficulty recording deep defects because the baseline separation of the cameras does not usually permit binocular vision in such regions. In order to overcome this the use of optical scanning to supplement the missing data from the deeper defect area based on a multimodal imaging technique has been suggested.[11]

Laser surface scanning is an alternative technique to stereophotogrammetry and has been successfully introduced into the workflow for producing facial prostheses.[6, 12] As with stereophotogrammetry, laser scanning of deeper regions and undercuts is limited by the separation of the laser line generator and the receptor camera.[6] Additionally, some systems will require the patient to remain still for a prolonged time which could further limit data acquisition.[1]

Digital data acquisition and rapid prototyping has the potential to assist the manufacturing process in a variety of ways. Firstly, stereolithic models of the defect can be produced, duplicated and used by the maxillofacial prosthetist to produce a wax pattern of the prosthesis in the usual way.[10] Secondly, positive replicas of the actual prostheses can be created in wax, trialed on the patient and processed through flasking and investment.[13] Additionally, negative molds for casting the prosthesis can be produced which would eliminate the need for conventional flasking and investment procedures.[6, 14] More recently, color 3D printing and infiltration with medical-grade silicone has been reported.[15]

Despite the vast number of case reports exploring the use of 3D imaging and CAD/CAM in the production of facial prostheses, there has been little evaluation of the accuracy of different

imaging techniques for this clinical context. Therefore, this in-vitro study aimed to compare the difference in accuracy between multimodal image fusion (stereophotogrammetry plus structured light optical scanning) and laser scanning, for capturing oncology facial defects, against a cone beam computed tomography (CBCT) scanned model. A CBCT scan was selected as the reference scan due to the accuracy and reliability of its measurements.[16] The null hypothesis was that there was no statistically significant difference in the unsigned mean global deviation between the multimodal imaging models, the laser scanned models and the reference CBCT scan.

MATERIAL AND METHODS

This in-vitro study compared the difference in accuracy between multimodal image fusion (stereophotogrammetry plus structured light optical scanning) and laser scanning against a CBCT scanned model. Ethical approval was obtained and a sample of 10 historical casts of various oncology facial defects were acquired from the maxillofacial laboratories within Leeds Teaching Hospitals and Bradford Teaching Hospitals. To the best of the authors' knowledge, the difference in accuracy deemed to be clinically important in this context has not yet been formally defined. Therefore, the sample size for this pilot study was determined by the number of relevant casts available within the two units. The sample included four nasal defects, five orbital defects and one combined defect. Images of the meshes obtained of the sample have been included in a previous article.[11]

Reference CBCT scan

A 3D volumetric scan of each cast was taken with CBCT scanner (NewTomVG; Sefla S.C.). This was converted into surface data using open-source medical segmentation software (ITK-SNAP; http://www.itksnap.org/) and the data was cropped to produce a CBCT mask using an

open-source system for editing meshes (MeshLab; http://www.meshlab.net/). The CBCT masks formed the reference scan for comparing the other imaging modalities.

Multimodal image fusion model

3D models were produced for each cast using multimodal image fusion and the method has been documented in a previous article.[11] Prior to scanning the casts, the stereophotogrammetry and optical structured light scanner were calibrated utilizing calibration targets. The external facial features were then captured using stereophotogrammetry (DI3D; Dimensional Imaging Ltd DI4D) (Fig. 1). This obtained four photographs of the cast in a synchronized manner. The two stereo pairs of images were then processed using passive stereophotogrammetry software to generate a 3D surface image. The defect was then independently imaged with a custom optical structured light scanner (comprising two off-the-shelf cameras (IDS uEye LE monochrome 1MP cameras; IDS Imaging Development Systems GmbH) and a digital light processing projector (Optoma PK201; Optoma Europe Ltd)) (Fig. 2). Depending upon the complexity of the defect, up to 10 images were taken with the custom optical structured light scanner. The models were aligned, merged and resurfaced using MeshLab to produce a single fused model of the external facial features and defect. In the previous study, the precision (intra-operator repeatability) of the multimodal image fusion technique was also evaluated by repeating the process of aligning the model of the defect to the external facial features.[11]

Laser scanned model

Each cast was captured using a commercial 3D laser scanner (3D Scanner Ultra HD; NextEngine Inc) (Fig. 3). The scanner was calibrated utilizing the manufacturer's reference object prior to scanning the casts. Alignment marks were made on each cast in accordance with the manufacturer's instructions. The autodrive along with the bracket scanning setting were used to

enable the cast to be scanned in three consecutive angles. Where there were visible areas of data missing from the 3D model (e.g. the presence of competing undercuts) the cast was repositioned on the autodrive at up to three different inclinations and a new scan was obtained. Each individual mesh was aligned using alignment pins, trimmed to remove unwanted data and then fused using software (ScanStudio; NextEngine Inc) to produce a single fused model comprising surface data.

Analysis

Analysis of the best fit of each experimental model to the CBCT mask was performed in MeshLab. The multimodal image fusion model and laser scanned model were independently aligned to the CBCT mask based on the iterative closest point algorithm.[17] The unsigned mean distance between all the 3D points of the experimental model and CBCT mask was used to calculate the global absolute deviation of each model from the CBCT mask. This is important because following alignment, some parts of the experimental model will lie behind the CBCT mask whilst other parts will lie in front of it resulting in both positive and negative distance values. The unsigned mean distance prevents the positive and negative distance values from cancelling each other out and underestimating the magnitude of the difference.[18] Color error maps were also produced for each CBCT mask to highlight points on both experimental models which deviated from the CBCT mask under different distance parameters.

Two of the casts had missing data due to extreme undercuts. As the subsequent prostheses would not extend into this area, the corresponding casts were marked by a maxillofacial prosthetist to identify the clinically relevant areas. The unsigned mean distance was reassessed excluding those data points within the defect border which lay several millimetres

from the clinically relevant area. A paired-samples t-test (P=0.05) was conducted to compare the overall unsigned mean global deviation of the two imaging modalities from the CBCT masks.

RESULTS

The unsigned mean global absolute deviation of the imaging modalities from the CBCT masks are outlined in Table 1. There was a significant difference in the unsigned mean global deviation between the multimodal imaging models (mean= 220µm, SD= 50µm) and laser scanned models (mean= 170µm, SD 70µm); t(9)= 2.56, P= 0.03).

Color error maps were produced for each CBCT mask to demonstrate points on each model which were within different parameters for unsigned distance (Fig. 4a and 4b). The color error maps for the multimodal image fusion models illustrated the greatest error was located at sites distant to the prosthesis margins (i.e. within the base of the defect or along the facial contours). In comparison, the laser scanned models appeared to have a generalized reduction in the greatest error category (>500µm) compared to the multimodal image fusion models. A few laser scanned models had more holes within the mesh as a consequence of the limited viewing angles.

DISCUSSION

The results of the present study support the rejection of the null hypothesis. Both the multimodal imaging models and laser scanned models had a mean global absolute deviation of under 250µm from the CBCT masks. Whilst thresholds for clinically relevant differences in accuracy do not yet appear to have been formally defined in this context, the authors feel that a mean global absolute deviation of under 250µm is likely to clinically acceptable. The laser scanner produced 3D models which deviated to a statistically significant lesser degree from the reference CBCT scan compared to the multimodal image fusion models. The overall difference in the mean global

deviation between the two imaging modalities was 50µm. Whilst statistically significant, the difference between the two modalities is unlikely to be clinically significant with respect to the fit of the subsequent prostheses as the color error maps showed the greatest error was usually located at sites distant to the potential prosthesis margins. However, it is also important consider the impact of the location of these distant errors which could impair prostheses design particularly for unilateral defects e.g. where the position of the orbit needs to be carefully reproduced.

One of the difficulties presented in the present study was selecting an appropriate model to use as a reference or gold standard. As previously discussed, there are potential limitations in using 3D models derived from CBCT data. Volume rendering, which is performed to produce a 3D representation of the object, can be influenced by a variety of factors including the isovalue used to extract the surface. This could change the anatomical dimensions in real patients; however, it is unlikely to have a major impact in this study as the casts are of uniform density. Furthermore, the CBCT scan had a voxel size of 300µm and therefore may lose fine detail consequently decreasing its precision in small volumes. Additionally, it is important to note that the alignment process itself is likely to introduce a degree of error due to the nature of the iterative closest point algorithm.[17]

The laser scanner was able to capture fine detail and produced models which more accurately matched the CBCT models. Only Cast G demonstrated a greater mean global absolute deviation with the laser scanner than with multimodal image fusion. This cast had extreme undercuts which had been poorly captured by the laser scanner, resulting in a much higher maximum deviation value and consequently a greater mean global absolute deviation. This relates to one of the limitations of the laser scanner which has limited viewing angles (due to the

size of the stereo baseline) which meant that some areas of undercut were poorly captured resulting in holes within the model. Each cast was therefore repositioned and scanned up to 3 times at different inclinations to maximize data acquisition**.** Stitching together multiple scans in this manner has the potential to introduce errors within the final model.[17] Additionally, each scan took several minutes to complete based upon the manufactures recommended settings. This may limit the scanner's applications in the clinical environment as patients may not be able to remain still for this prolonged time.

The method of multimodal image fusion has previously been shown to have potential as a true and precise method of capturing facial defects based on in-vitro data.[11] This approach combines the initial short capture time of stereophotogrammetry with the ability of the structured light scanner to capture the internal surfaces of the defect. Whilst multimodal image fusion had a greater mean global absolute deviation than the laser scanner, this appeared to be within clinically acceptable limits. The stereophotogrammetry software had some difficulties in aligning the left and right pairs of scans in this study. This is likely to be due to inadequate features on the cast compared with the characterization real facial tissues. Therefore, this particular source of error may be reduced in the clinical environment.

The time invested for multimodal image fusion included both the initial data acquisition time and the post-processing time. Data acquisition first involved stereophotogrammetry to capture the external facial features and this has the efficiency of a single photographic exposure. The custom structured light scanner then captured the internal surfaces of the defect and required approximately one second per 3D image (up to 10 images were taken depending upon the complexity of the defect). Post-processing alignment and surfacing was performed using an open source software for editing meshes (MeshLab; http://www.meshlab.net/). The post-

processing time would be dependent upon operator experience whereby an experienced user could align and surface a set of scans in a few minutes, whilst an unskilled user may take up to 30 minutes. Recent improvements in automatic registration would be a useful addition, and freely available source code can be downloaded in this regard although this was not utilized in the present study.[19]

The short acquisition time and recent improvements in automatic registration may make multimodal image fusion a more practical solution to introduce in the clinical environment. The laser scanner had a prolonged scan time, and whilst accurate and useful for comparison in this study, its clinical application would be limited. It is important to note that the custom structured light scanner used in this study required a laptop and Universal Serial Bus cable connection. A scanner with a wireless connection may be better suited to clinical applications. Commercial scanners (e.g. Artec Space Spider; Artec 3D) are available with a similar field of view and reported resolution which are fully ergonomic and run at 7.5 frames per second.

For analysis, deviation was assessed across the entire surface of the CBCT mask and therefore there is a risk that the results could have underestimated errors at clinically important areas such as the prosthesis margins.[11] However, it was also important to not only capture the defect but also take sufficient accurate data on the surrounding facial features so that the contours of a prosthesis could be made in harmony with the surrounding tissues. The color error maps did indicate that this was not the case as the greatest error was usually located away from clinically important areas. A complete set of color error maps can be found online enabling a judgment to be made regarding the clinical relevance of the error patterns. An alternative approach could have been to perform regional analysis on the most clinically important areas and this is a potential consideration for future development.[18] Further research is also planned to

evaluate what difference in accuracy would be clinically important in this context and to determine what factors would impact on prosthesis fit (e.g. error location).

Finally, there are also limitations relating to the in-vitro nature of this study. The casts have artificially trimmed edges, smooth featureless surfaces and are produced in type III yellow stone. These factors may have impeded precise alignment with the any of the different imaging modalities. Further research is therefore needed to evaluate their performance in the clinical environment.

CONCLUSIONS

Both methods captured the defect and external facial features to an acceptable level of accuracy. Although the laser scanner had a statistically significant lower mean global deviation than the multimodal imaging method, the mean difference of 50µm is unlikely to have a clinical impact. The short capture time and ability to process into deeper defects makes the multimodal imaging technique a more practical option to introduce in the clinical environment. Further research is planned to appraise its clinical use.

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TABLES

Table 1: global deviation (standard deviation) µm of the different imaging modalities from the CBCT mask

Cast	Average global deviation (standard deviation) µm	
	Multimodal image fusion[1]	Laser scanning
A	140 (130)	90 (80)
B	150 (130)	120 (150)
C	190 (150)	150 (130)
D	210 (210)	150 (250)
E	230 (260)	230 (280)
F	230 (230)	180 (330)
G	250 (320)	320 (810)
H	250 (210)	170 (310)
I	260 (200)	150 (180)
J	310 (290)	120 (170)
Overall	220 (50)	170 (70)

[1] Jablonski RY, Osnes CA, Khambay BS, Nattress BR, Keeling AJ. An in-vitro study to assess the feasibility, validity and precision of capturing oncology facial defects with multimodal image fusion. Surgeon. 2017.doi: 10.1016/j.surge.2017.11.002.

FIGURES

Fig. 1. Stereophotogrammetry (DI3D; Dimensional Imaging Ltd DI4D) was used to capture the external facial features during the multimodal imaging technique.

Fig 2. Custom optical structured light scanner used to capture the defect during the multimodal imaging technique. This small scanner comprised two off-the-shelf cameras each measuring 34x32x41.3mm (HWD) (IDS uEye LE monochrome 1MP cameras; IDS Imaging Development Systems GmbH) and a digital light processing projector of similar size to a smartphone (Optoma PK201; Optoma Europe Ltd)).

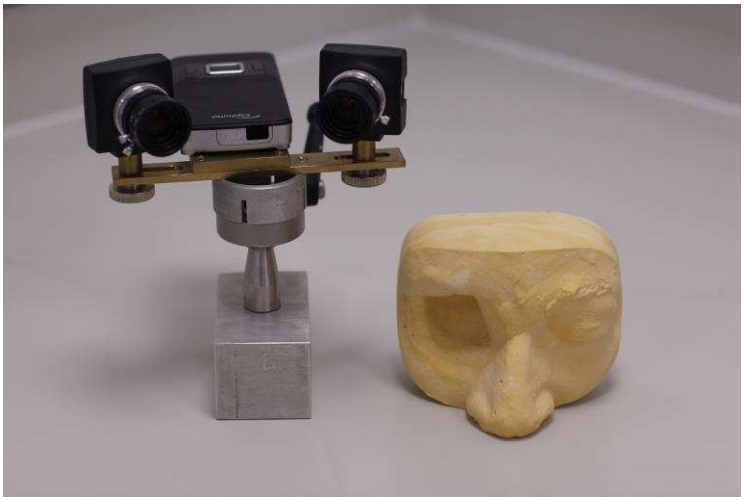
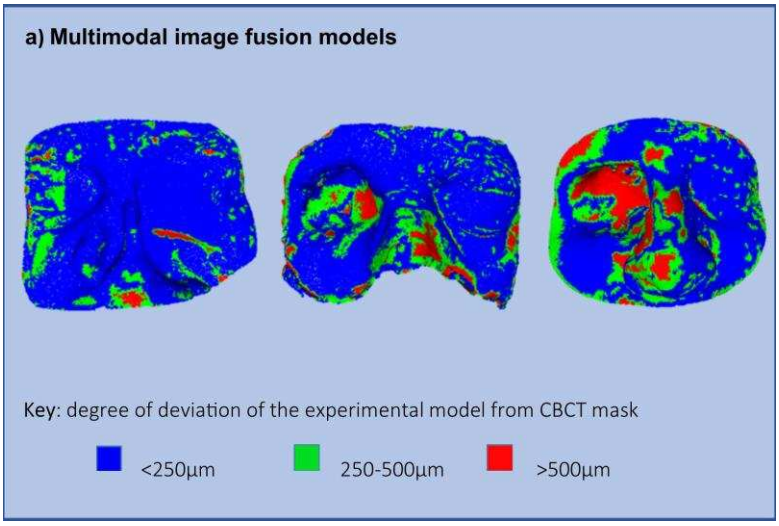
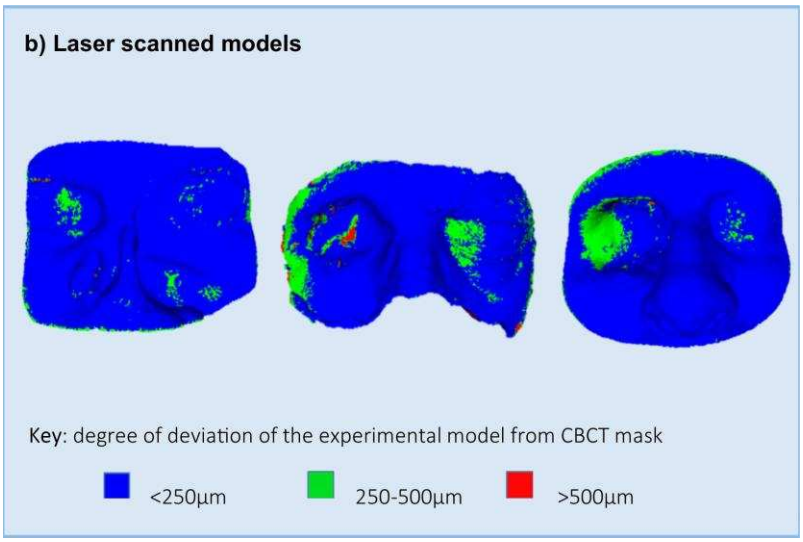


Fig. 3. Commercial 3D laser scanner used to produce the laser scanned models (3D Scanner Ultra HD; NextEngine Inc).

Fig. 4. example color error maps (left = Cast A, middle = Cast F, right = Cast J)

A, Multimodal image fusion models: note the greater error is located at sites distant to the prosthesis margins. B, Laser scanned models: Note there appears to be generalized reduction in the greater error (red) compared to the multimodal image fusion models.




b) Laser scanned models
Key: degree of deviation of the experimental model from CBCT mask
<250µm
250-500µm
>500µm