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An in-vitro study to assess the feasibility, validity and precision of capturing oncology facial defects with multimodal image fusion

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ABSTRACT

Aim: Assess the feasibility, validity and precision of multimodal image fusion to capture oncology facial defects based on plaster casts.

Methods: Ten casts of oncology facial defects were acquired. To create gold standard models, a 3D volumetric scan of each cast was obtained with a cone beam computed tomography (CBCT) scanner (NewTomVG). This was converted into surface data using open-source medical segmentation software and cropped to produce a CBCT mask using an open-source system for editing meshes. For the experimental model, the external facial features were captured using stereophotogrammetry (DI4D) and the defect was recorded with a custom optical structured light scanner. The two meshes were aligned, merged and resurfaced using MeshLab to produce a fused model. Analysis was performed in MeshLab on the best fit of the fused model to the CBCT mask. The unsigned mean distance was used to measure the absolute deviation of each model from the CBCT mask. To assess the precision of the technique, the process of producing the fused model was repeated to create five models each for the casts representing the best, middle and worst results.

Results: Global mean deviation was 0.22 mm (standard deviation 0.05 mm). The precision of the method appeared to be acceptable although there was variability in the location of the error for the worst cast.

Conclusion: This method for merging two independent scans to produce a fused model shows strong potential as an accurate and repeatable method of capturing facial defects. Further research is required to explore its clinical use.

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Introduction

A diagnosis of head and neck cancer has a major psychological and physical impact on patients. In 2014, over 11,000 new cases of head and neck cancer were reported in the United Kingdom.[1] Approximately half of head and neck cancer patients will undergo major surgical resection.[2] This radical surgery can prolong survival time but will also result in a substantial loss in quality of life due to deformity or disability.[3] The resulting defects may be reconstructed with surgery or rehabilitated with removable prostheses.

Conventional facial prostheses are fabricated on plaster casts formed from an impression of the defect which captures both the facial border and the depth of the defect. Conventional impressions have multiple disadvantages including inaccuracies due to soft tissue deformation under the weight of the material or due the patient's reflex movements.[4] Patient anxiety or discomfort may result from covering the face or restricting the airway during the impression procedure.[5] Additionally, rehabilitating orbital defects can be challenging when matching the unaffected side because eyes must be closed to take the impression.[4]

Facial prostheses require multiple replacements during a patient's lifetime for various reasons including colour deterioration, poor maintenance, degradation of the materials or poor fit.[6] Additionally, longevity of facial prostheses will vary depending on the retention method. Reported serviceability is often within the range of 6–18 months however implant retained prostheses typically remain in service for longer than those adhesively retained.[6] A UK based survey of maxillofacial laboratory staff in 2002 estimated over 2000 patients required facial prostheses annually.[7] Therefore, there is a clinical need to devise an accurate, easily reproducible and less invasive method of recording facial defects.

Various studies have employed a variety of different three-dimensional (3D) imaging techniques in attempt to overcome the disadvantages of conventional impressions through optical,[4] laser,[5] and stereophotogrammetry systems.[8] These reports allude to the significant potential benefits of using 3D facial imaging as an alternative to conventional impressions through improved patient comfort, reduced invasiveness, efficiency of data collection, and enabling of computer aided design and computer aided manufacturing (CAD/CAM) processes.[4,5] They also overcome the limitations associated with the use of computed tomography or magnetic resonance imaging such as patient radiation exposure or artefacts related to metal objects e.g. implants.[9] A survey of UK maxillofacial prosthetists and technologists in 2007 found that 31% of the respondents were employing digital technologies during the design or manufacture of maxillofacial silicone prostheses.[6] Their positive reflections included the perceived accuracy of these procedures and avoidance of patient impressions.[6]

Stereophotogrammetry systems are becoming more commonplace within the hospital setting. These take images of objects from multiple viewpoints in a synchronised manner and have the benefits of a short capture time and clinically acceptable accuracy.[8] However, as they are unable to capture deep defects this method is not optimised for use with oncology patients. Structured light 3D scanners work by projecting a dense pattern onto a target, and viewing the data using calibrated cameras. In contrast to stereophotogrammetry, this technique is robust to less textured regions and is also more accurate in selecting corresponding points in the stereo image-pairs. This in turn allows a narrower baseline separation between the cameras with no loss in precision. Consequently, a hybrid technique using an inexpensive structured light scanner to supplement the data acquired by stereophotogrammetry may facilitate the capture of sufficient accurate data for prosthetic rehabilitation.

Therefore, this *in vitro* study aimed to assess the feasibility, validity and precision of using multimodal image fusion to capture oncology facial defects based on plaster casts. The external facial features would be captured with stereophotogrammetry and fused with the internal defect imaged through optical scanning.

Materials and methods

Ethical approval was obtained from the Dental Research Ethics Committee at the University of Leeds. Ten historical plaster casts of a variety of oncology facial defects were acquired from the maxillofacial laboratories within Leeds Teaching Hospitals and Bradford Teaching Hospitals. The samples varied in size and degree of undercut and included four nasal defects, five orbital defects and one combined defect.

To create the gold standard models, a 3D volumetric scan of each cast was taken with a cone beam computed tomography (CBCT) scanner (NewTom VG, NewTom, Verona, Italy) (0.3 mm voxel size). This was converted into surface data using open-source medical segmentation software (ITK Snap, http://www.itksnap.org/) and cropped to produce a CBCT mask using an open-source system for editing meshes (MeshLab, http://meshlab.sourceforge.net/).

To create the experimental model, the external facial features were first captured using stereophotogrammetry (DI4D, Hillington, Glasgow.). Subsequently, the defect was imaged with a custom optical structured light scanner comprising two off-the-shelf IDS uEye LE monochrome 1 MP cameras (IDS, Obersulm, Germany) and a digital light processing projector Optoma PK201 (Optoma Europe Ltd, Watford, UK). This was then aligned to the external facial features, merged and resurfaced using MeshLab to produce a single fused model of the external facial features and defect (Fig. 1).

Analysis was performed on the best fit of the experimental model to the CBCT mask. The two meshes were aligned based on the iterative closest point (ICP) algorithm and assessed for global absolute deviation.[10] The unsigned mean distance between the meshes was used to measure the absolute deviation of each fused model from the CBCT mask. Colour error maps were also produced for each CBCT mask to demonstrate points on the fused model which were within different distance parameters.

Two fused models had missing data due to extreme undercuts. As the subsequent prostheses would not need to obturate this area, the corresponding casts were marked by a maxillofacial prosthetist to identify the prosthesis margins. The unsigned mean distance was reassessed excluding data

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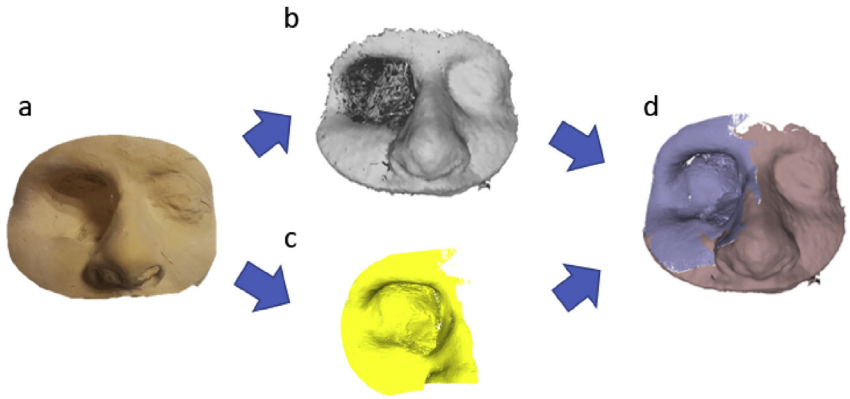

Fig. 1 – Summary of the method for creating the experimental model. a) Original plaster cast. b) External facial features recorded with stereophotogrammetry. Note the defect is poorly defined. c) Defect recorded with bespoke structured light scanner. Note the difference in resolutions between the two systems. d) Aligned, cropped and merged experimental model prior to resurfacing.

points within the defect border which lay several millimetres from the clinically relevant area.

The precision (intra-operator repeatability) of the multimodal image fusion was also evaluated. The process of aligning the model of the defect to the external facial features was repeated to create five models each for three casts and the mean global absolute deviation was calculated. The casts with the best, middle and worst results were selected for this purpose.

Results

The overall mean global deviation of the 10 fused models from the CBCT masks was 0.22 mm (standard deviation 0.05 mm) (Table 1). Colour error maps were produced for each CBCT mask to demonstrate points on the fused model which were within different parameters for distance (Fig. 2). These colour error maps illustrated that the greatest error was usually focused within the deepest part of the defect or located at a site distant to the prosthesis margins.

The results for repeatability indicated the precision of the method (Table 2). The colour error maps for the best and middle casts had a low degree of variability in the distribution of the error (Fig. 3). However, the colour error maps for the worst cast indicated some variability in the alignment process and subsequent location of the error (Fig. 3).

Table 1 – Global deviation (standard deviation) (mm) of the 10 fused models from the CBCT masks.

Cast	Defect description	Average deviation (SD) mm
A	Superficial nasal defect	0.14 (0.13)
B	Superficial nasal defect	0.15 (0.13)
C	Superficial nasal defect	0.19 (0.15)
D	Deep right orbital defect	0.21 (0.21)
E	Combined orbital and nasal defect	0.23 (0.26)
F	Deep right orbital defect	0.23 (0.23)
G	Deep nasal defect	0.25 (0.32)
H	Superficial right orbital defect	0.25 (0.21)
I	Deep orbital defect	0.26 (0.20)
J	Deep orbital defect	0.31 (0.29)
Overall mean		**0.22 (0.05)**

Discussion

Multimodal image fusion shows potential as a valid and precise alternative method of capturing facial defects. Our technique used stereophotogrammetry to record the external facial features and a relatively inexpensive structured light scanner to supplement data from the defect area. This combined the benefits of the initial short capture time from stereophotogrammetry with the abilities of the structured light scanner to capture the internal surfaces of the defect and allowed sufficient accurate data capture to enable prosthetic rehabilitation.

3D facial scanning has been shown to have multiple advantages including improved patient comfort, reduced invasiveness, efficient data collection and facilitation of CAD/CAM processes.[4,5] A variety of rapid prototyping techniques have been demonstrated for producing baseplates, wax patterns for investment, or negative moulds of facial prostheses.[4,11,12] These CAD/CAM processes may decrease the laboratory time required to produce prostheses, facilitate transfer of information between clinicians and enable digital data storage for subsequent reuse.

During our study, it was noted that models for two of the casts were missing data from the depth of the defect. This was the result of limited viewing angles due to the size of the stereo baseline of the two imaging modalities. The structured light scanner deliberately had a smaller baseline, allowing deeper viewing into defects however it was unable to capture data from the depth of two defects due to the presence of extreme undercuts. These areas were not judged to be clinically important as the prostheses would lie distant from these areas. To overcome this, either new data could have been created to close the holes in the base of the mesh, or alternatively the meshes could have been analysed according to

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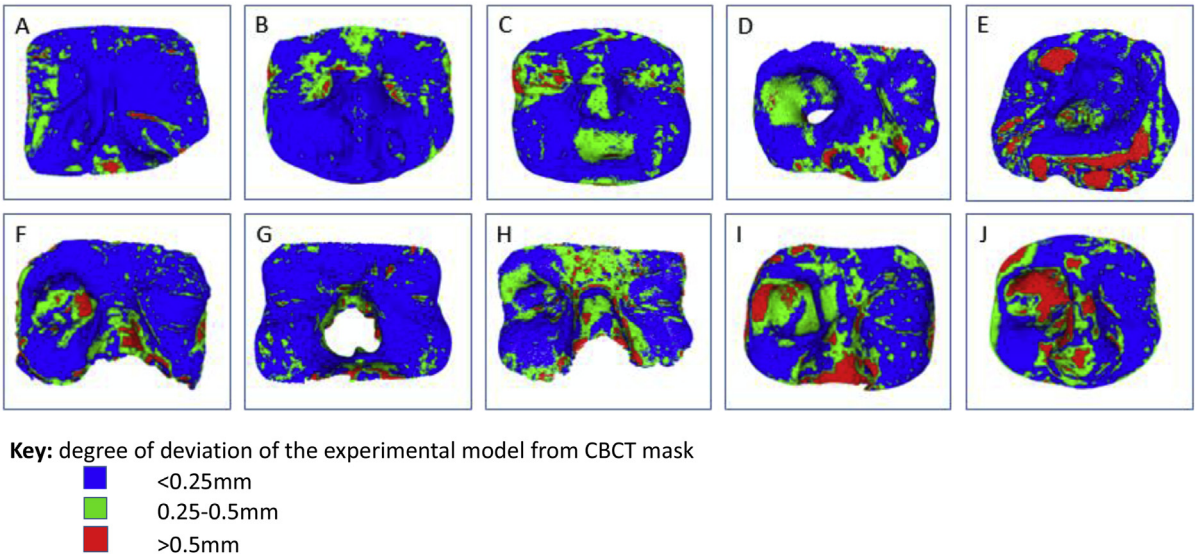

Fig. 2 – A-J: colour error maps for the 10 casts. Note how the greatest error was located at sites distant to the prosthesis margins or within the deepest part of the defect. Casts A, E and J represent the best, middle and worst result respectively. Casts D and G had extreme undercuts and therefore the corresponding CBCT masks had been trimmed to exclude data points which lay several millimetres for the clinically relevant area.

Table 2 – Precision for repeated reconstruction of the casts with the best, middle and worst result.

	Average global deviation (SD) mm					
	Original	Repeat 1	Repeat 2	Repeat 3	Repeat 4	Mean result SD mm
Best cast (Cast A)	0.14 (0.13)	0.14 (0.13)	0.23 (0.19)	0.14 (0.12)	0.14 (0.13)	0.16 (0.04)
Middle cast (Cast E)	0.23 (0.26)	0.23 (0.25)	0.22 (0.25)	0.22 (0.26)	0.22 (0.25)	0.23 (0.002)
Worst cast (Cast J)	0.31 (0.29)	0.33 (0.32)	0.29 (0.26)	0.31 (0.30)	0.31 (0.30)	0.31 (0.02)

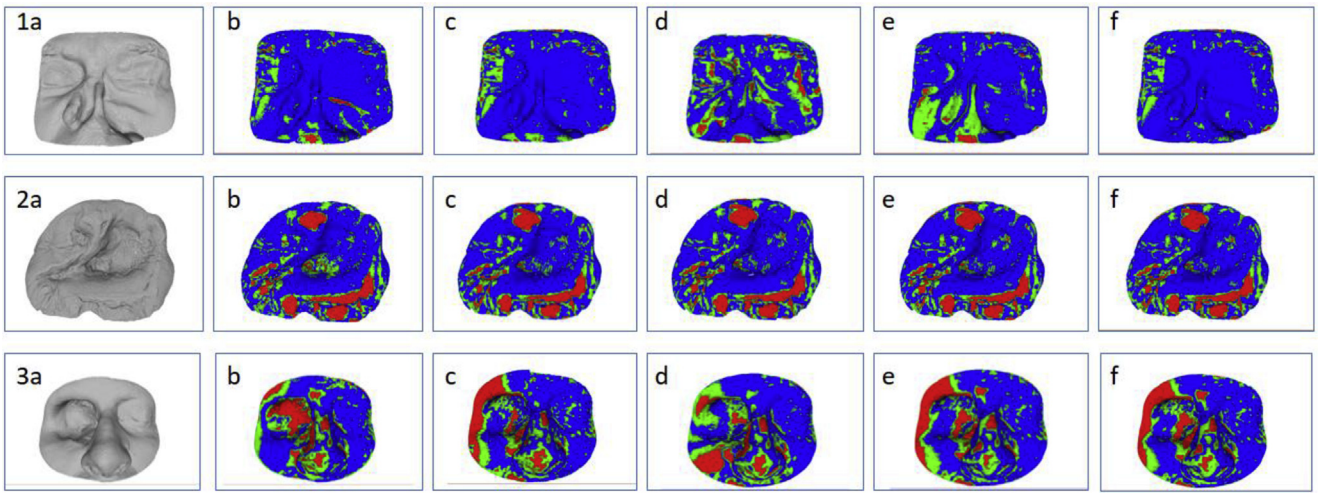

Fig. 3 – Colour error maps for repeatability to illustrate variability of error for the best middle and worst casts. 1a) Best cast. 1b-f) Colour error maps for the five repeats illustrate minor variability in the location of error. 2a) Middle cast. 2b-f) Colour error maps illustrate the location of error has a consistent distribution across all repeats and lies distant to the prosthesis margins. 3a) Worst cast (Cast J). 3b-f) Colour error maps illustrate greater variability in the location of error for the worst cast. Errors located within the base of the defect or along the contours of the nose may not be clinically relevant. However, some repeats show greater deviation along right prosthesis margin and it is likely the resulting baseplates would need to be adjusted to ensure an acceptable fit of the prosthesis margins.

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clinically relevant areas. The latter was performed as it was considered inappropriate to create new data for the purpose of the study.

When resurfacing the meshes to create a single fused model, a clinically insignificant join was created along the boundary of the two meshes because of the differences in the resolution between the two imaging modalities. The resurfacing process also smoothed and blurred the surface of the fused model. An alternative to resurfacing might be to use a mesh zippering technique to blend the two meshes without the need to create a new surface.[13] This is an area for future development.

The unsigned mean distance of the fused model from the CBCT mask was calculated for analysis as opposed to the signed mean. This ensured that the magnitude of the error would not be cancelled out by the direction, and consequently prevented the creation of artificially favourable results. The result for mean global deviation (0.22 mm) is likely to be clinically acceptable especially as the greatest error was usually located at a site distant to the prosthesis margins. This value does however lie close to the values for resolution of the CBCT scanner (0.3 mm). Therefore, within the limitations of our method it is unclear if our result was closer to or further from the true value and this will be addressed in a future study.

One of the limitations of the present study was that global analysis was performed across the entire surface of the CBCT mask. There is a risk that any significant error at clinically important areas (e.g. the prosthesis margins) would be underestimated as this would have been diluted by the large number of points across the rest of the mask with a low degree of deviation. However, the colour error maps did illustrate that the greatest error was usually focused at areas unlikely to be clinically important e.g. the depth of the defect or along the contours of the nose. An alternative approach would have been to perform regional analysis and analyse the areas relevant to the prosthesis margins. Similar methods have been proposed in assessing facial images during orthognathic surgery prediction.[14] However, as CBCT scans are unable to capture texture (such as a pre-marked outline of the prosthesis) it would be difficult to reliably transfer this across to the CBCT mask.

A further limitation in our analysis was that the mean distance between the two meshes was used. Distances were measured between the closest points on the two meshes instead of using correspondences between anatomical points. As a consequence of this technique and the nature of the alignment algorithm, the meshes may have been considered to be well-aligned (based on a low distance deviation) despite the true anatomical points potentially being offset.[15] This may have led to slight overestimations in our values for accuracy.

The precision (intra-operator repeatability) of the multimodal image fusion method was also evaluated and the results indicated a high degree of repeatability (Table 2). The colour error maps for the worst cast illustrated there was greater variability in the alignment. This may be a consequence of false edges on the plaster models which had been trimmed to facilitate prosthetic work. Additionally, insufficient definition of the smooth, featureless surface of the cast may have made impaired stereophotogrammetric reconstruction, or subsequently impeded precise alignment. Therefore, using the optical scanner with an adjusted focal distance, to capture a larger region of the defect in each scan, may have improved our ability to align the meshes for this cast. The assessment of textured 3D facial scanning methods will be a focus of future clinical research.

Finally, further research is required to investigate its use in the clinical environment. For example, the shape of the eye would not be captured optically due to its reflective surface and as a result would be portrayed as concave. Therefore, our method would not fully overcome the limitation of closing the eyes during conventional impressions.

Conclusions

In summary, this method of multimodal image fusion shows potential as an accurate and repeatable method of capturing facial defects. The benefits of stereophotogrammetry's short capture time coupled with the accuracy of the structured light scanner makes this both an interesting and viable approach to overcome the limitations of conventional impressions. Further research is required to investigate its use in the clinical environment.

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Conflicts of interest

None.

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