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Advanced Auricular Prosthesis Development by 3D Modelling and Multi-material Printing

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Abstract

We investigate the use of medical imaging, digital design and 3D printing technologies as a viable means of reproducing a person's anatomy, with the intension of producing a working, patient specific prosthesis. This approach offers several advantages over traditional techniques, as data capture is non-intrusive, models can be made using quantitative methodologies, design iterations can be digitally stored for future reproduction, and additive manufacturing ensures no loss of quality when converting the digital model into a physical part. We also present a combined model segmentation with multi-material printing approach to increase the colour complexity of the final model. When combined with multi-material printing using elastic materials, our approach provides a comprehensive strategy to accurately realising mimic of both skin pigmentation and the tactile feel of human tissues. Ultimately, we believe our approach provides an innovative strategy for prosthesis production which could have considerable potential for implementation in a clinical setting.

Keywords: Prosthesis, 3D printing, Modelling, Multi-material, Auricular, Soft Tissue

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1 Introduction

Traditional methods of maxillofacial prosthetic design have proven to be highly effective means of producing a given facial prosthesis. However, the process largely remains qualitative in nature, with the artistic skill of the clinician being the most pivotal factor in the fit and final aesthetic appearance of the end prosthesis [1]. Traditional processes are also highly labour intensive, as parts are handmade, whilst the procedure to take an impression of the defective surface can be highly invasive and uncomfortable for the patient [2, 3]. In order to eliminate these disadvantages, and to potentially reduce the time and work needed to develop a prosthesis, an alternative to the traditional method is required.

Modern Computer Aided Design (CAD), patient scanning and 3D printing technology are poised to transform the way in which prosthesis devices are developed and

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realised, replacing more traditional, manual approaches [4–6]. Medical imaging data can now feasibly be used to construct patient representative models and could potentially supersede impression/cast based approaches when attempting to reconstruct a defective or uncompromised area of anatomy. The use of medical imaging data offers several advantages both in terms of resolution of topography reproduction, in addition to being minimally invasive to the patient, part of routine clinical practise, while also capturing useful information of the wider patient anatomy for model construction and virtual placement analysis [7,8]. Modern digital CAD software offers multiple advantages to the traditional design process as no model fabricating is required and designs are digitally evaluated and stored, reducing costs and readily allowing for future reproduction. Additionally, digital reproduction of surrounding anatomy can allow for virtual placement and aesthetic evaluation without the necessity for the patient to be present. Finally, 3D printing is the ideal technology for translation of digital models to working devices, owing to the high precision of modern devices and the diverse possibility of materials combination that could be employed during fabrication. Indeed, polyjet multi-material printing technology allows for not only near perfect digital reproduction, but can realise complex colour combinations, mimicking skin pigmentation, in addition to adjustable mechanical properties, to realise the tactile feel of human tissue.

In this work we propose a process using a medical imaging data to construct a virtual model of a patients uncompromised anatomy/defective area, before the captured data is conditioned to obtain a final model of the proposed prosthesis. Finally, the finished prosthesis is manufactured through high resolution, multi-material 3D printing. As a proof of principal, we examined the reproduction of a volunteer's ear and into a 3D model, before printing in a flexible material to mimicking the tactile feel of the volunteer's original anatomy. We also examine design possibilities that would allow for complex rendering of multiple colour combination on the single model, thereby mimicking more closely the complex colour attributes found on human skin tissue. Ultimately, the presented approach realises a rapid, cost-effective and anatomically precise methodology for prosthesis development, with potential for increased realism resulting from multi-material printing. We believe that such techniques would complement or potential surpass traditional techniques and practises for prosthesis development and production.

2 Experimental

2.1 CT scan data and model construction

Models of the ear were constructed directly from publically available CT scan data of anonymised patient data (http://dicom.nema.org/) in the standard Digital Imaging and Communications in Medicine (DICOM) format. The data set comprised individual slices, with an approximate thickness of 0.625mm, of a patient's head and which includes the

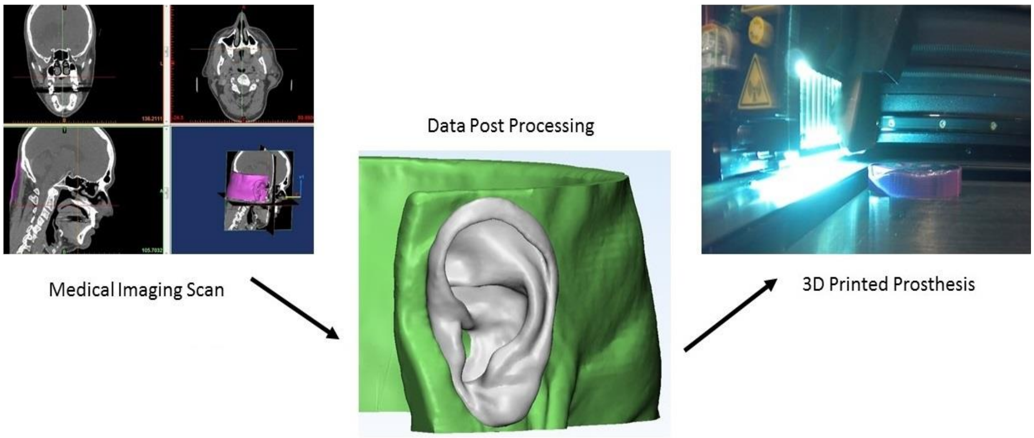

Figure 1: A summary of the process chain for the production of the ear prosthesis.

ears for prosthesis production. All DICOM data was analysed using Mimics (Materialise, Belgium).

2.2 Model construction and Post processing

Models from the scanner software were further processed using the 3-Matic software package (Materialise, Belgium), which can allow for direct STL manipulation, error checking and part thickness analysis. Data conditioning comprised smoothing of rough surfaces, removal of features that could lead to print failure, and to perform procedures such as part hollowing, to obtain the final ear model. To realise the multi-coloured prosthesis design, we examined an approach of independent material allocation to multiple segments of the complete model. To achieve this the final ear model was segmented into seven individual STL files, which, when combined to form the prosthesis. To segment the ear model, we once again used 3-Matic to perform operations such as thickness/depth analysis and slicing.

2.3 3D Printing

Once all post processing had been completed, the final model was 3D printed to produce the final prosthesis. In this study a high resolution 3D printer was used (Connex 3 500, Stratasys, USA) which can print models in up to three individual materials or blends thereof to an accuracy of 16–30μm. Materials range from coloured, hard and elastic materials, such that we are capable of reproducing a prosthesis model with a tactile feel and pigmentation more closely representing that of human tissues. The high resolution of the printer also ensures that allow the major and minor surface contours can be readily reproduced, whilst also realising a high quality surface finish to the prosthesis, similar to that obtained by traditional techniques.

Initially, a model is loaded into the printer's software as an STL file and is allocated specific material combination before being sliced into the individual printing layers. Simultaneously a water soluble support material is allocated as required to ensure the build integrity. When printing the multi-segment models, as each is created as an individual STL file, the printer software allows for independent material allocation to each of the segments. In this work the segments comprised of varying combinations of Tango plus, a clear rubber like material, with VeroMagenta, a rigid magenta coloured material. Therefore different depths of potential skin pigmentation could be achieved in the model by either increasing or decreasing the percentage content of VeroMagenta with Tango Plus.

3 Results

3.1 Scanning and model creation

The DICOM data was input into the software Mimics for 3D model construction. The software is capable of isolating specific tissue data across the three typical geometrical planes, before rendering the selected data into a digital, 3D model. The software operates using a series of threshold functions which highlight regions of a particular Hounsfield Unit (HU), allowing for the rapid differentiation of different tissue types such as bone, soft tissue, etc. For the examined data set a threshold function of -275 to 93HU was found to be optimal to fully encompass all the soft tissue information from the patient data. This threshold encompasses the entirety of the CT scan data and so cropping was required to isolate the ears, from which to make the prosthesis, and the rear circumference of the head for virtual placement analysis. Once the regions of interest had been isolated across the three geometrical planes, the Mimics software allows for the conversion of this data into a 3D representative model of the patient. Figure 2a) shows the final model, which was then exported as a STL file for post processing using more sophisticated software.

3.2 Prosthesis Modelling

The output STL model from Mimics was loaded into 3-matic and checked to remove any errors during the rendering process that would otherwise cause issues during 3D printing, such as multiple shells, inverted normal, etc. Generally, the models produced by Mimics were very close to the final printable model and only required minor post processing. To form the auricular prosthesis, the left ear was segmented from the wider patient data and the reverse side smoothed to yield a standalone ear model. A part thickness analysis of the isolated ear uncovered regions of the model that were too thin (<300μm) to be produce a robust 3D printed model using the employed system

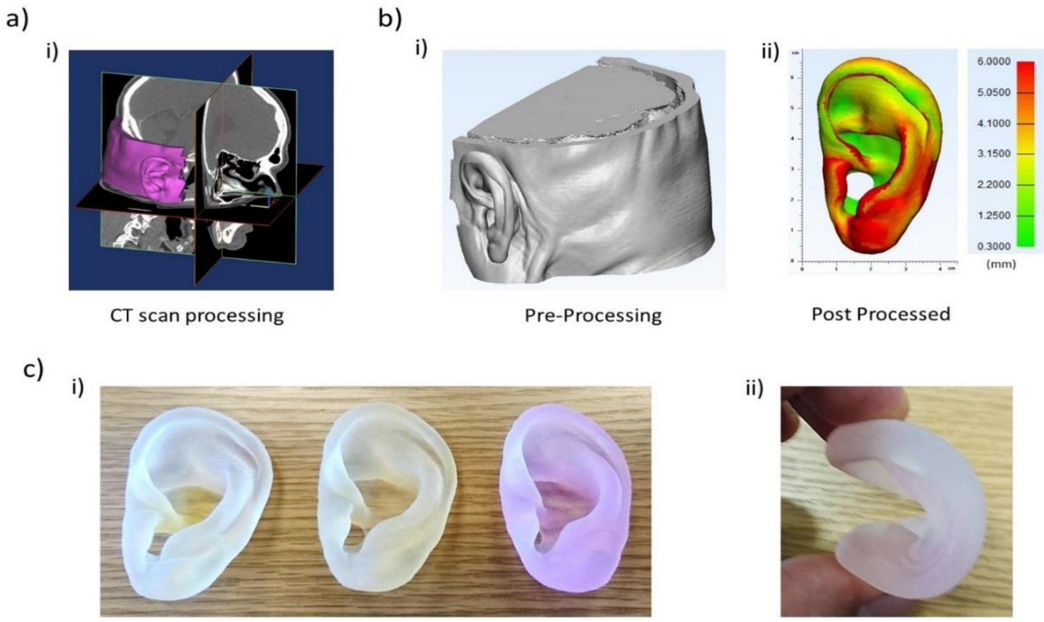

Figure 2: a) Construction of patient representative model from CT scan, b) i) Data extraction prior to CAD processing and ii) thickness analysis post processing of the CT scan data, and c)i) various 3D prints of the ear model in varying material combinations and ii) demonstration of the elastic deformation of the ear model.

(Figure 2bii). To remedy this, compromised area were reconstructed digitally, using the push-pull, extrude and smoothing functions within 3-matic to ensure the model had a minimum thickness of 1mm and that all major contours were reproduced. Figure 2b) illustrates the final model of the ear prosthesis.

3.3 Prosthesis 3D printing

Upon completion of the ear prosthesis model, 3D printing was performed using a various material combination, comprising entirely of the Tango plus material and combinations comprising various percentage additions of the VeroMagenta material. Some of the resulting models can be seen in figure 2ci) where ears 1 comprises 100% Tango Plus, ear 2 comprises 20% VeroYellow and 80% Tango Plus and ear 3 is the complex multi segment/material combination print, which will be discuss in the next section.

The tango plus material used in this study was a translucent variant, which on its own provided the softest tactile feel but was not a suitable colour for a prosthesis. It was found that a minimum of 10% Vero material was required to provide any visually noticeable pigmentation into a given prosthesis. Ultimately it was found there was significant scope to adjust the pigmentation of the models to encompass, lighter and darker skin tones and we hope to investigate further material combinations in future work. In addition to pigmentation mimicry, the tactile feel of a typical prosthesis was also reproduced, whereby the printed prosthesis could be elastically deformed. Fig-

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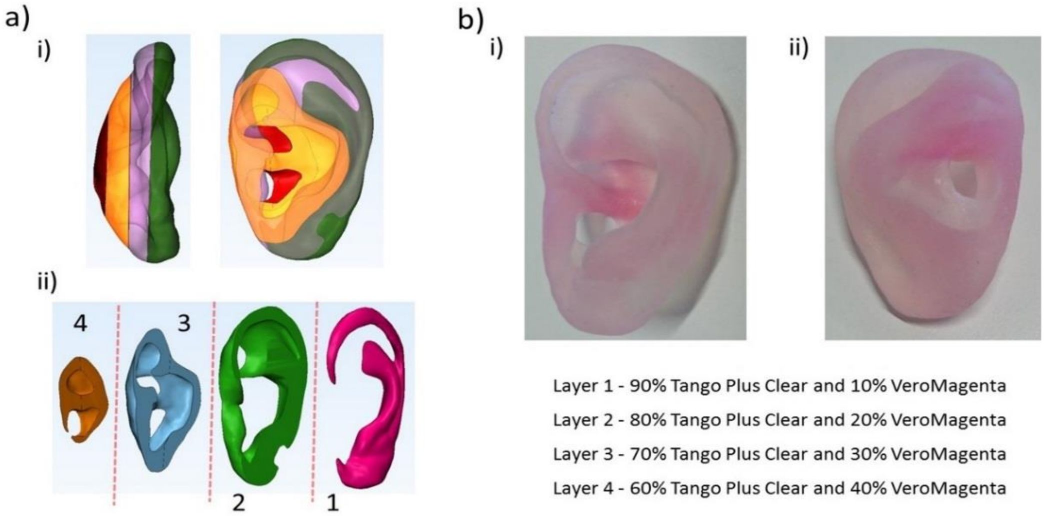

Figure 3: a) i) Front and side profiles of the segmented ear model, highlighting the orientation of the sub section in the overall model and ii) an exploded view of the separate section of the prosthesis and how they are orientated over four sublayers of the model. b) A 3D print of the final prosthesis.

ure 2c) shows a demonstration of the elastic deformation of an ear model, whereby upon relation of the compressive force, the ear would spring back to its original shape. It is noted that as the percentage blend of the VeroMagenta with the Tango plus increased beyond the threshold of 50-60% Vero material, this significantly flexibility of the printed prosthesis. We hope to more closely examine and quantify the mechanical properties in future studies.

3.4 Multi-Segment Model

Following the creation of the final digital prosthesis, the model was segmented into subsections based on the height of the ear, resulting in the ear being partitioned into six primary segments, over four layers of the model (Figure 3a). Each of these layers were allocated with individual material assignment, with varying percentage content of VeroMagenta and Tango Plus, leading to a deepening of the colour during the transition from layer 1 to 3. Additionally, a fourth layer was implemented to balance the colour tones in layers 2 and 3. A complete breakdown of the spatial orientation of the segments can be seen in Figure 3a). Preliminary findings reveal the potential of this approach to increase the colour complexity of the prosthesis, thereby increasing the potential mimicry of human skin pigmentation. We hope to develop on these findings in future work.

4 Conclusions

This study has demonstrated the potential of the 3D design and multi segment/material printing, alongside the use of medical imaging data, to produce realistic prosthetic models of the ear. The fabricated prosthesis were realised to a high degree of accuracy and surface finish, and could easily be applied to realise alternative prosthetic parts, such as the nose or orbital prosthesis. Using the multi-material printing approach we could tailor the skin pigmentation of the prosthesis to a variety of skin tones, whilst also mimicking the mechanical properties of the original anatomy. Beyond the use of a material combination, we discovered that additional colour complexity can be created by segmentation of a digital model and the assigning of unique material combination to each segment. By creating darker variations of a base colour for the prosthesis, realism such as the depth of colour perceived in shaded regions can be realised, further increasing the realism of the designed models. Currently there are limitations in the complexity of the skin tones that can be mimicked without compromising the mechanical properties, due to the percentage material combinations, but we believe as the technology matures over the coming years, these limitations will be resolved. It was found that direct prosthesis production overcomes limitations relating to the subjective nature of current prosthesis fabrication, and allows for production within a single day, which compares favourably against traditional techniques where prosthesis turnaround time takes several weeks/months. Ultimately, this technique holds considerable potential for implementation within a clinical setting, streamlining to overall process for prosthesis production and could see usefulness in other niche areas such as anatomical modelling and soft robotics.

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