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Workflow for 3D printing of medical models – phases, timeline and costs

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Summary

The aim of this study is to describe the steps needed for producing medical models by 3D printing. Further, the timeline for various 3D printing processes and related process steps and their estimated cost structure will be discussed. Computed tomography images were used as a starting point for the present case and a 3D model of skull and jaw was reconstructed using Osirix software. 3D printing with material extrusion, binder jetting and material jetting processes with pre- and post-processing were explored and a model for the costs and timeline were formed. The results of this study show that, (1) binder jetting clearly is the fastest technique to produce medical models. The total process time varied from 2 h 51 min to 10 h 28 min for the jaw model and from 10 h 24 min to 66 h 13 min for the skull model. Regarding costs, (2) material extrusion is a little more affordable to produce a jaw model followed by binder jetting. To produce a skull model, binder jetting seems more affordable than material extrusion or material jetting. Material jetting is much more expensive than the two other techniques but it is also much more accurate based on the published reports. In binder and material jetting adding more parts in the same 3D printing instance will reduce the cost remarkably.

Keywords: Additive manufacturing, preoperative models, 3D Printing

1. Introduction

Medical imaging has undergone a significant development during the past decades. With the aid of modern digital technology, also medical imaging can now use digital data format such as Digital Imaging and Communications in Medicine (DICOM). Since the DICOM files are a stack of layer images of the patient, computer algorithms allow to calculate and estimate a three-dimensional (3D) form of the imaged subject. The basic concept of this field was described already in early 1990's when 3D printing was known as rapid prototyping [1]. Stereolithography as the first commercial process had been invented a few years earlier. 3D printing allows to build complex parts based on a 3D model without molds or tooling. By combining these characteristics, it is now possible to 3D print patient specific anatomical objects. These models can be utilized in making preoperative physical models or even 3D-printed individualized implants [2]. Therefore, medical applications of 3D printing vary from medical models and implants to different tools and instruments and even patient specific [3] guides, splints and prostheses or scaffolds for bio-manufacturing [4] [5].

3D-printed medical models are quite often utilized to assist during various pre-operative clinical assessments as they enable physicians to maintain better visuospatial understanding of even complex anatomical structures. There are many examples of these models used in cranio-maxillofacial surgery and they can also be utilized for other bony structures such as knee, ankle, pelvis, spine or for soft tissues such as heart or liver [6][7]. Photographing has recently been used to capture patient-specific geometry and to compute 3D models, but this is limited to superficial contours and structures [8]. Other methods for recording patient-specific geometries can include laser or structured light scanners. The last-mentioned technologies have been often used to capture dental geometries [9].

The time line and costs of 3D printing depend on the used type of technology, material, orientation and packing of the parts in the building chamber [10]. In medical applications, different models can have variable requirements based on accuracy, biocompatibility and haptic response. Previous research has shown a three-step scale description of variation in cost and accuracy of different 3D-printing processes but not a detailed cost structure [11]. McMenamin et al. [12] compared costs of binder jetting versus plastination and listed some example costs but they did not compare them between different 3D-printing processes.

The aim of this study is to describe in detail the phases needed to produce preoperative medical models by 3D printing. Two cranio-maxillofacial surgery exemplary medical models were utilized (i.e. jaw model and skull model) to present all the required steps, time line for different 3D-printing processes and overall costs. 3D-printing processes are categorized in seven different categories (i.e. Vat photopolymerization, material jetting, binder jetting, material extrusion, powderbed fusion, sheet lamination and direct energy deposition). However, the present research only presents experiments with 3D-printing machines that are office and/or hospital friendly and have good potential to produce preoperative anatomical structures (i.e. material jetting, material extrusion and binder jetting). The rest of the processes have not been considered suitable for these settings, since they will warrant intensive post processing or industrial type of an environment.

2. Materials & Methods

Figure 1 shows the phases required to transform patient medical data to a physical object using 3D printing technologies. The process is divided into three main phases (i.e. medical imaging, 3D printing and medical model preparation or post-processing). Each of the phases requires different sub-phases that add time and cost to the process to obtain physical models for pre-operatory planning.
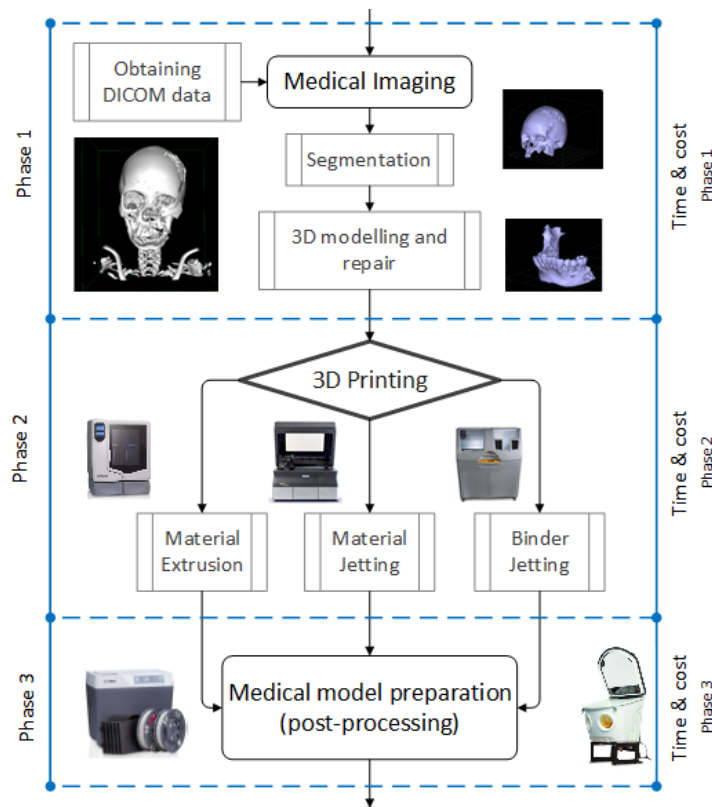
Figure 1. Process diagram to create medical models. Summary of phases and steps required.

2.1. Medical imaging

The DICOM data for the skull model for this study were obtained from an OsiriX (Pixmeo SARL, Switzerland) DICOM sample image set (Alias name: Phenix, http://www.osirix-viewer.com/resources/dicom-image-library/). The corresponding imaging unit was Philips Mx8000 IDT 16 computed tomography with slice thickness of 1.5 mm and 120 kV for the peak kilo voltage output of the x-ray generator. The x-ray tube current was 411 µA and the image size 512 x 512.

2.1.1. Segmentation

The DICOM data set were imported to OsiriX MD 8.0.2 (Pixmeo SARL, Switzerland) and segmented using 500 Hounsfield unit (HU) to add bone and more dense materials to the 3D model.

Decimate – resolution was set to 0.5 and smooth – iterations to 20. STL-format 3D file was exported from the software to obtain both the jaw and skull geometry as show in Figure 2.

Figure 2. A segmented 3D model calculated from the DICOM images.

2.1.2. 3D modeling and repair of 3D models

The STL file was first imported to DeskArtes 3D Data Export 10.3. The shells were verified to separate volumes, which are not in contact with each other. The other shells except the jaw and skull were then removed. The models were repaired using automatic repairing tools. The jaw model was then ready and exported as a separate STL (Stereolithography, Standard Tessellation Language) file. The skull model required one more repairing round by first removing all error triangles and triangles next to the error triangles and further running an automatic repairing for a second time. The skull models were also exported as a separate STL file. After that both models were repaired and ready for the 3D-printing phase.

2.2. 3D printing

2.2.1. Material extrusion

The used 3D printer was uPrint SE Plus (Stratasys Inc, US) with Catalyst EX 4.4 (Stratasys Inc, US) software. The selected layer resolution was 0.2540 mm and model infill was set to 'sparse'

with high density. Auto orientation was applied for the skull and jaw, as it tries to minimize both building time and material consumption. Support fill was generated using the Smart command. The material was ABS Plus (Stratasys Inc, US) and SR-30 Soluble Support Material (Stratasys Inc, US). The price for the machine is approximately 16 000 € and the price for both the material and the support material was 200 € per kilogram. The skull model consumed 253.16 cm3 basic material and 223.21 cm3 support material. The jaw model consumed 25 cm3 basic material and 11.78 cm3 support material. The support material can be automatically dissolved away using Wave wash cleaner (Stratasys Inc, US) unit with Ecoworks (Stratasys Inc, US) cleaning agent bags and water. The print orientation is shown in Figure 3.
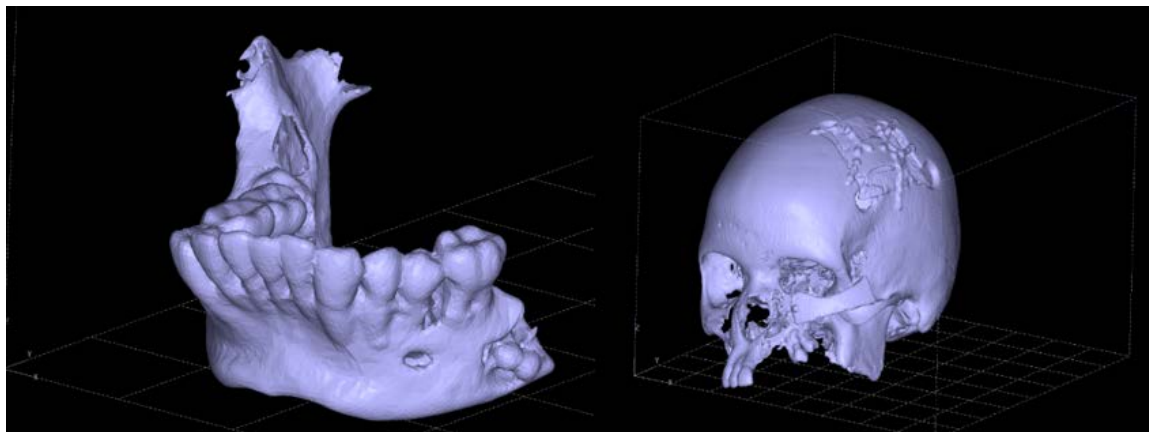

Figure 3. Building orientations in material extrusion.

2.2.2. Material jetting

In material jetting the 3D printer was Objet30 Scholar 3D printer (Stratasys Inc, US) using Objet Studio version 9.2.8.3 (Stratasys Inc, US) software. The part was auto orientated in the printer. The material was Verowhite (Stratasys Inc, US) and the support material was SUP705 (Stratasys Inc, US), a gel-like photopolymer. The price for the machine is about 35 000 €, the material price is 280 € per litre, and the support material is priced at 140 € per litre. The simulated thickness was 28 µm with matte finishing. The process requires support material to hold overhanging features,

and supports are manually washed away with pressurized water with specified washer. The skull model consumed 1402 ml Verowhite material and 2536 ml support material. The jaw model consumed 80 ml Verowhite material and 83 ml support material. The print orientation is shown in Figure 4.
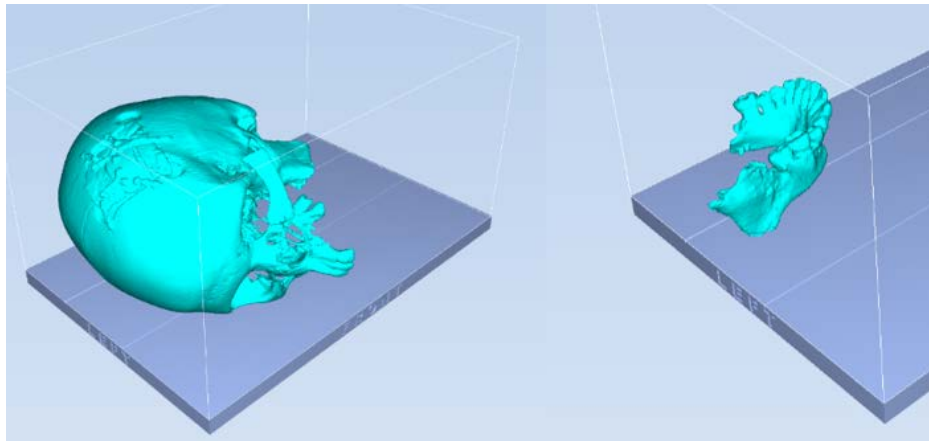

Figure 4. Building orientations in material jetting.

2.2.3. Binder jetting

In the binder jetting process the software was 3D Print 1.03 (3D Systems Inc, US) and the printer was Zprinter 450 (3D Systems Inc, US). The material was ZP151 (3D Systems Inc, US) with a layer thickness of 0.1 mm. The orientation was selected to minimize the height of the part, which then results to the fastest building time. Monochrome mode was selected for the printer. The price for the machine is approximately 35 000 €, the material price is 190 € per litre, and unbound material served as a support and can be recycled to make new parts. The print orientation is shown in Figure 5.

Supports were removed manually by detaching unbound powder with pressurized air and after that the parts were strengthened by for example dipping them in cyanoacrylate or covering them with two-component epoxies.
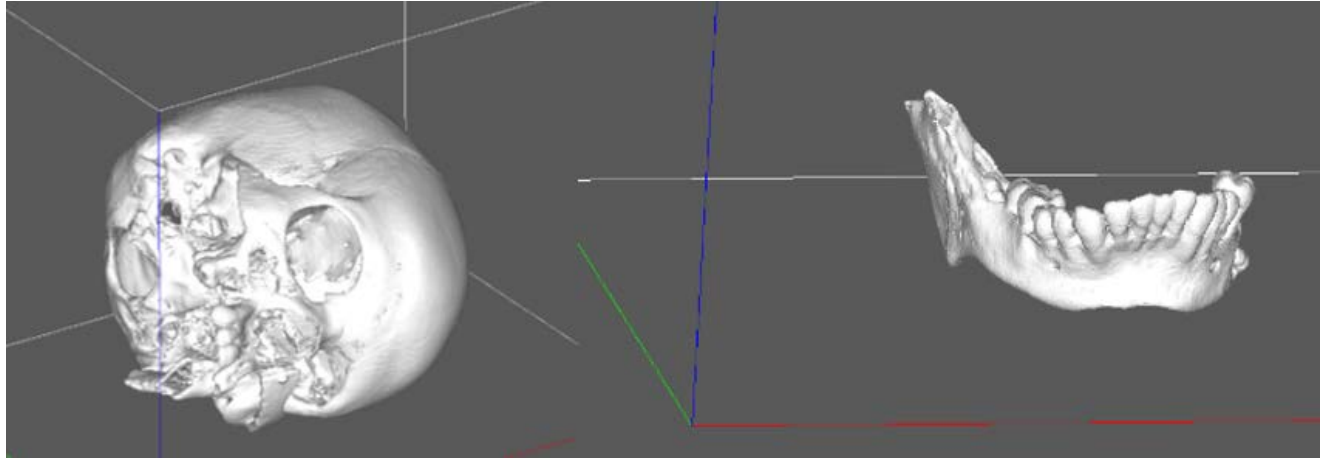
Figure 5. Building orientations in binder jetting.

2.3. Costs of 3D printed medical models

The process times in each step were measured during the process and the material and support consumptions were tracked. For the cost model in each process the annual use of a 3D printer was estimated to be 1500 h / year. A three-year period was considered as a payback time for a 3D printer, since no maintenance cost was taken account. Segmentation, creating a 3D model from DICOM and 3D modeling and repair were estimated to cost 100 € / h. Postprocessing was estimated to cost 5 €/ h for material extrusion since it is an automatic device and 80 €/ h for binder jetting and material jetting since these require manual work.

The price of the parts was calculated with Formula 1.

$$Price = Segmentation\ rate\ x\ Segmenation\ time + 3D\ modeling\ \&\ repair\ rate \times$$
$$3D\ modeling\ \&\ repair\ time + \frac{3D\ printer\ price}{3\ years \times Annual\ use} 3D\ printing\ time + material\ price \times$$
$$material\ consumption + support\ price\ \times support\ consumption +$$
$$postprocessing\ rate\ \times postprocessing\ time \quad (1)$$

3. Results

Used process times measured in different steps are presented in Table 1. The fastest process was binder jetting with a total process time of 2 h 51 min for the jaw model and 10 h 24 min for the skull model. For the jaw model material extrusion (8 h 44 min) was faster compared with material jetting (10 h 28 min) but for a bigger skull model material jetting (44 h 1 min) was faster than material extrusion (66 h 13 min). Formula 1 and the costs of different steps were used to calculate the total cost of certain parts. Different costs related to different steps of the process and their total costs are shown in Table 2. The most affordable process for the jaw model was material extrusion (75.6 €) but there was no remarkable difference with binder jetting (78.9 €). For the jaw model material jetting was clearly more expensive (147.6 €). For a bigger skull model binder jetting was the cheapest (237.2 €) but material extrusion was only slightly more expensive with a cost of 278.4 € For the skull model material jetting was remarkably more expensive (1015.3 €) than others.

Table 1. Time estimates

	Segmentation (h:min)	3D modeling and repair. 3D printing file processing (h:min)	3D printing (h:min)	Post-processing (h:min)	Total time (h:min)
Jaw, Material Extrusion	0:10	0:10	5:34	3:00	8:44
Jaw, Material Jetting		0:10	9:53	0:15	10:28
Jaw, Binder jetting		0:10	2:11	00:30	2:51
Skull, Material Extrusion		0:25	53:48	12:00	66:13
Skull, Material Jetting		0:15	42:46	1:00	44:01
Skull, Binder Jetting		0:10	9:14	1:00	10:24

Table 2. Total cost estimates for the jaw and the skull model.

	Segmentation (€) 100 €/ h	3D modeling and repair. 3D printing file processing (€) 100 €/ h	3D printing (€)	Post-processing (€) FDM 5€/ h Polyjet & CJP 80€/ h	Total cost: (€)
Jaw, Material Extrusion	16.7	16.7	27.2	15	75.6
Jaw, Material Jetting			110.9	20	147.6
Jaw, Binder Jetting			22.2	40	78.9
Skull, Material Extrusion		41.7	160	60	278.4
Skull, Material Jetting		25	893.6	80	1015.3
Skull, Binder Jetting		16.7	123.8	80	237.2

4. Conclusions and discussion

Novel additive manufacturing technologies have been developed during the past two to three decades to enable 3D printing of complex geometries and structures. This study describes the various steps and allocated time and cost structure needed to produce physical models for medical applications. This research provides a perspective to the phases required to produce two cranio-maxillo-facial objects for pre-operative planning and to study the cost and time implications.

Material jetting benefits from high geometrical accuracy compared with material extrusion or binder jetting [13][14]. However, there is trade-off between accuracy and costs, since material jetting can double the costs in small models and more than triple them in big models. When comparing binder jetting and material extrusion it is obvious that binder jetting has the advantage

of being able to 3D print different colors in medical models [6]. This can be used to identify specific structures of anatomy or metallic parts or to mark added structures that support the anatomical model for example by holding the bones together.

Regarding the manufacturing time of medical models, if the manufacturing build volume can be filled (i.e. producing multiple medical models in the same build) this can reduce the 3D printing time per part object from 9 h 53 min to 3 h 40 min. At the same time, binder jetting can benefit from the same phenomena reducing the build time from 2 h 4 min to 1 h 1 min. However, in material extrusion the 3D printing time per part will remain constant.

Costs of 3D printing will be reduced in the future as the technology and the used materials will be further developed. More importantly, this will subsequently create new applications areas. Even quite high costs for 3D-printed medical models can be acceptable if their use will save time in operation and lead to better operation outcomes. When comparing prices of the 3D-printed models none of them seems to be relatively expensive compared with what is the cost of an operation or standard medical implants. Current researches have shown only quite simple cost models in terms of expensive, middle priced or cheap [15], or alternatively similar non-quantitative values [11]. The present research shows cost structure for multiple processes not limited to only one process such as binder jetting [12]. The cost structures are important when companies or hospitals plan to invest or outsource medical models made by 3D printing. A cost analysis can be used to estimate the value of a certain investment in terms of what kind of different material and process options can be obtained.

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