

Process of Manufacturing Transparent Models of Anatomical Structures

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Abstract

In recent years, a rapid increase in the use of three-dimensional (3D) printing technologies in medicine, especially in the manufacturing of the diagnostic models, can be observed. In some cases, there is a need to fabricate transparent models that allow visualization of internal structures of the object. Unfortunately, techniques used to manufacture such models are often very expensive and time-consuming. The above-mentioned issues were the motivation for developing a new method of fabrication transparent models for visualization of internal structures for planning surgical treatments. This paper presents the process of making transparent models using the newly developed method – the stacked layers method. In order to compare this new method and one of the most common 3D printing technologies – fused deposition modeling (FDM) – the models for two medical cases using both of these methods were fabricated. As a result of this work, it can be concluded that the stacked layers method provides faster and cheaper way of making transparent medical models. The main features of fabrication process that have a huge impact on quality of the models made by new method were pointed. The results of this study suggest that models fabricated with the use of this method can be useful as a diagnostic tool in medical applications for planning surgical treatments.

Keywords

3D printing, medical applications, additive manufacturing

1. Introduction

Doctors are expected to prepare for every surgical procedure. This is particularly important in the case of procedures which interfere with the bone tissue. Such surgical interventions require that the physician becomes very thoroughly acquainted with the case and patient history so that the procedure can be carefully planned. For this, doctors use diagnostic imaging, so that preoperative information can be derived from images acquired by computed tomography (CT) or magnetic resonance imaging (MRI).

The development of the three-dimensional (3D) printing technology led to its increasing applications in medicine. 3D models of anatomical structures generated on the basis of CT or MRI have attracted considerable interest. Due to suitable software, a possibility has gradually opened up to create models reflecting the actual bone structures. The accuracy of such models allowed operations to be carefully planned and the duration of procedures to be shortened, as the surgeon was able to study the specific case longer than ever before [1]. However, in some cases models whose internal structure can be examined prove much more practical. 3D SLA printing enables us to fabricate transparent models from photocurable

resins. Still, the cost of material required to make models in this method is definitely higher than in FDM printing. For this reason, alternative solutions are sought: ones that would offer not only accurate reproduction but also relatively low cost of fabrication. One of the methods under consideration is based on the models made by cutting individual layers from acrylic glass by a laser plotter and gluing them together. The purpose of this study is to compare the methods whereby such models are made and highlight difficulties and problems which can be encountered in the process.

2. Stacked layers method

Two anatomical structures were used to make models according to the selected method: the proximal end of the femur together with a fragment of the femoral shaft after hip joint replacement and the fragment of the mandible which normally contains the trigeminal nerve.

Both cases require that the physician can see the interior of the model. A re-operation is sometimes necessary after hip joint

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replacement. In such case a transparent model of the femur may prove very helpful for the physician, allowing them to insert the ready-made prosthesis through the opening. The transparency of the model enables the doctor to verify if the endoprosthesis has been correctly selected, for example, by seeing how it adheres to the walls of the bone. If the endoprosthesis is too large or too small, the correct size can be selected before the operation, which helps prevent the procedure from unnecessarily protraction.

As for the size of the mandible, when titanium implants are used, the location of the trigeminal nerve could present an issue. Placing the implant too deep may exert mechanical pressure on the nerve, leading to a sensory loss in the lower lip and mouth corner, numbness, prickling or burning sensation, and chronic pain [2-3]. Visualization of the course of the nerve in a model will allow the physician to study a specific medical case more carefully. If the trigeminal nerve passes through a problematic location, the physician will be aware of this fact well in advance and thus able to make an appropriate decision on the necessity to modify the course of the nerve. As a result of these precautions, potential complications for the patient could be avoided.

2.1. Data preparation

A stacked layers model made of sheets of selected material must be based on relevant medical data and suitably prepared (Figure 1). In the case of anatomical structures, model data can be obtained by two different methods: (1) with the help of an optical or contact measurement system and (2) through imaging techniques such as CT or MRI [4]. The latter method is used for diagnostic purposes, as it is the only way to visualize anatomical structures inside a living organism.

The stacked layers method will be presented using the example of a diagnostic model of the femur. Two-dimensional (2D) images were obtained by CT scanning and saved in the Digital Imaging and Communications in Medicine (DICOM)

standard. The DICOM standard enables images to be archived, processed, and managed. DICOM data conversion in specialist software allows us to perform reconstruction of a 3D image of anatomical structures. Software most commonly used for this purpose includes Mimics, 3D-Doctor, and 3D Slicer [5]. The software generates a fully functional (i.e., subsequently modifiable) 3D model of selected tissues. In this study, 3D Slicer, an open-source software, was used. The desired type of tissue was isolated by segmentation, which means that only voxels from a specific range on the Hounsfield scale were selected for the reconstruction process. In certain cases, manual editing is required to remove interference. A model obtained in this manner was saved in the STL format (Figure 2).

The 3D surface model generated in the process was imported into the Slicer For Fusion software by Autodesk. Slicer For Fusion includes the feature of slicing a model into layers. It is important that real dimensions of a specific structure should be preserved after the model has been imported into the application. The next step involved defining the parameters of the material selected for model manufacturing. Although in this study models were made of acrylic glass, the use of other materials is possible, provided that they are capable of forming transparent models (e.g., polycarbonate panels). Designing a layered model requires the application of StackedSlices, a technique which slices the model with the XY plane. The selected slicing method offers optimum model accuracy when the model imported is positioned in the Z axis (Figure 3). In the model of mandible fragment, the cutting plane (XY plane) should be parallel to the frontal plane of the human body. This setting of slicing plane will minimize the stair-step effect on the physical model.

The software also offers the possibility of setting the position of dowel pinholes, which allows setting the relative position of consecutive layers of the material. The process of making models of anatomical structures is characterized by difficulties

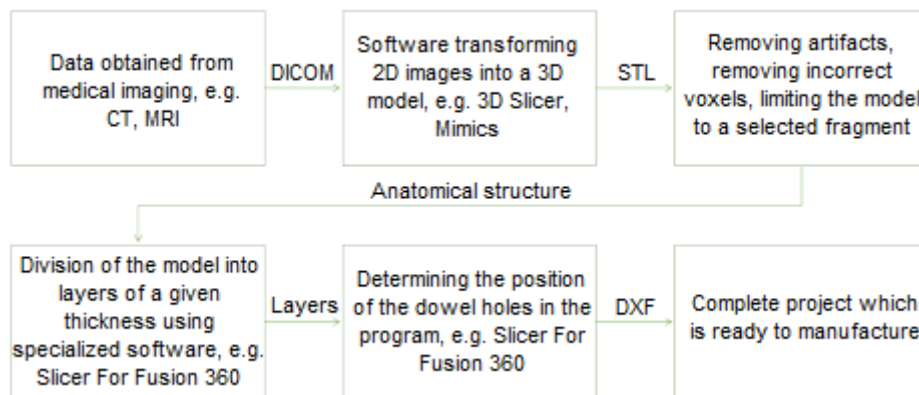


Figure 1. Data preparation procedure.

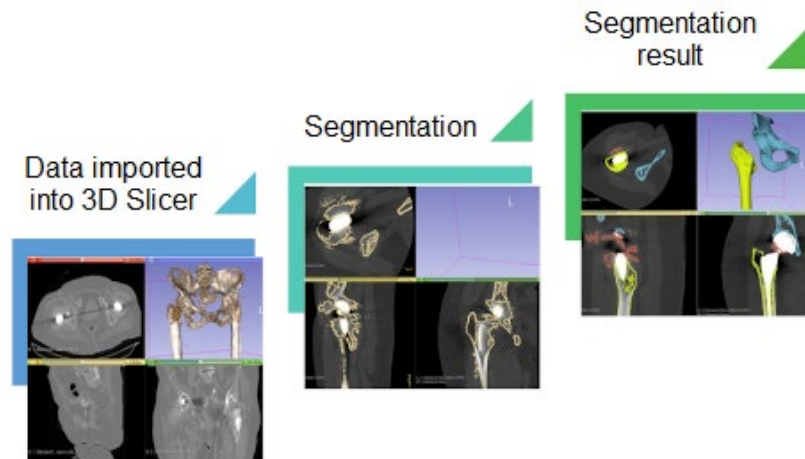


Figure 2. Reconstruction process of 3D geometry of the femur in the 3D Slicer software.

in appropriately defining the location of the holes because such structures are often very irregularly shaped. The above operations result in a model that is ready for manufacturing (Figure 4).

After the location of holes was set, the layered model was saved in the DXF format. It is also possible to create a template featuring the locations of individual layers in a sheet together with their numbering. The template is very helpful during the assembly of the model because it provides for a quick identification of individual layers. Consequently, it reduces the risk of a mistake in the assembly of consecutive layers.

2.2. Making physical prototypes

The process of cutting layer contours from polymethyl methacrylate (PMMA) sheets was performed by means of the ATMS CO₂ laser plotter. Its CO₂ laser resonator has 120 W power and a work area of 1,300 × 90 mm, which is completely sufficient for making models using the present method. Consecutive stages of model manufacturing are shown in Figure 5.

The first step in the model manufacturing process was to import project files saved in the DXF format into RDCAM software controlling the laser plotter. The next phase involved positioning a PMMA sheet in the X and Y axes of the work area. Thickness of material sheets should be the same as the slice thickness set during the CT scan on the basis of which the models are prepared. Otherwise, the physical model may be less accurate. An important part of the process was the verification of the calibration of optical path and focal length of the laser beam. Consecutive layer contours were cut out after the selection of correct processing parameters was completed. The preprocessing and the proper cutting lasted about 30 min for the femur and about 15 min for the fragment of the mandible.

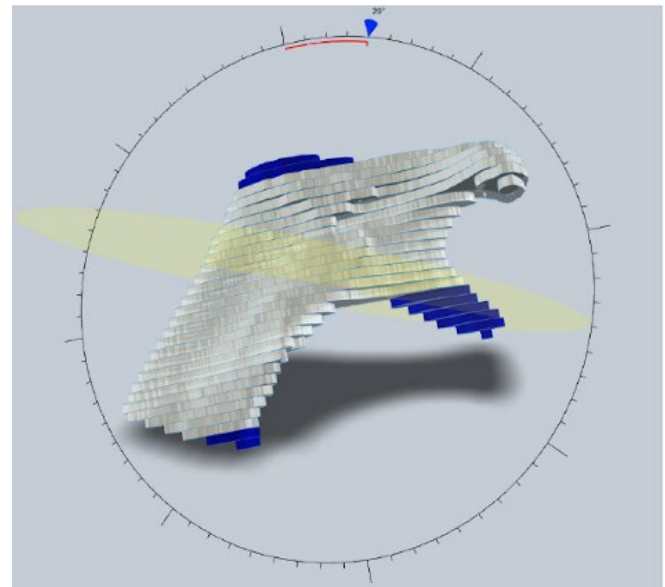


Figure 3. Positioning model slicing planes.

The above operations generated a set of components that had to be correctly connected. For this purpose, we used Pattex, a colorless and fast-drying cyanoacrylate-based adhesive that does not damage the acrylic glass.

3. Results

The procedure led to the construction of two layered models: a model of a fragment of the femur (Figure 6A) and a model of the fragment of the mandible (Figure 7A). For the purpose of comparative analysis, the same models were made using

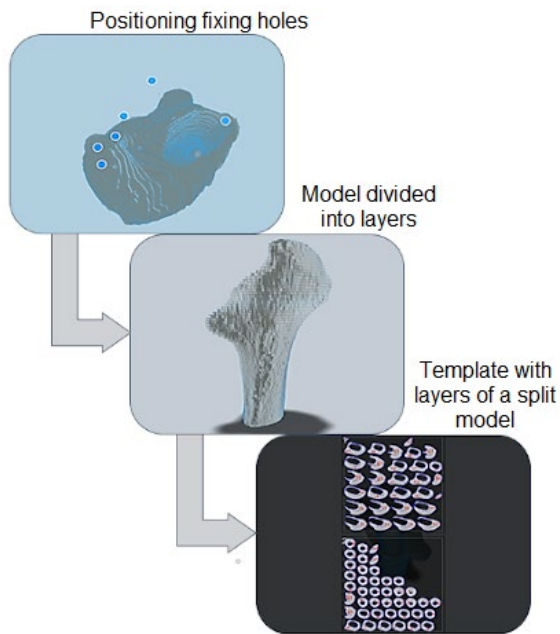


Figure 4. Preparation of the layered model's design data.

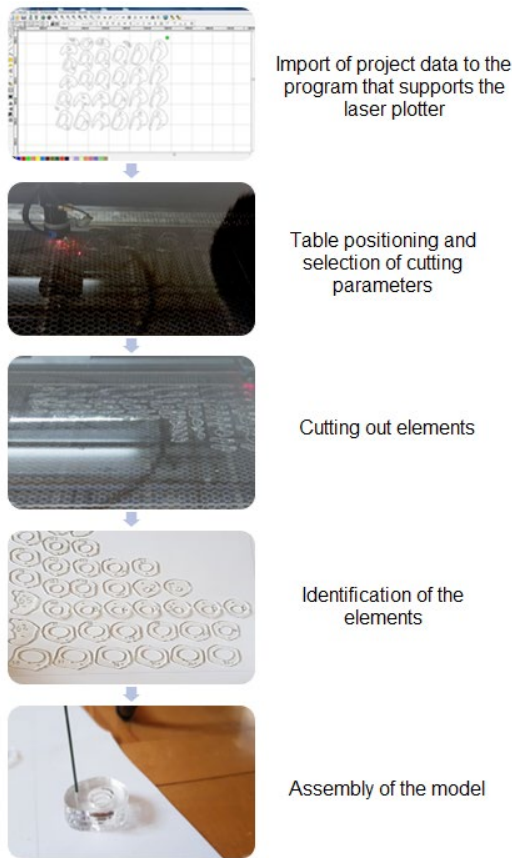


Figure 5. Stages of making models using the stacked layers method.

FDM 3D printing (Figures 6B and 7B) from blue ABS on the UP Plus 2 printer.



Figure 6. A physical model of the fragment of the femur made using (A) stacked layers method and (B) 3D printing.

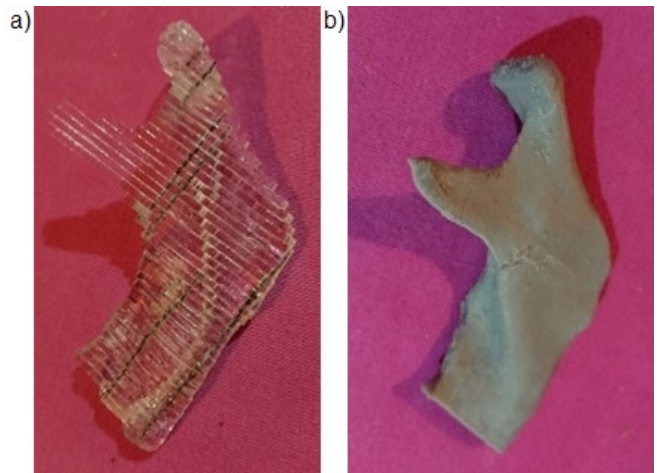


Figure 7. A physical model of the fragment of the mandible made using (A) stacked layers method and (B) 3D printing.

On both models, which were made by stacked layers method, the stair-step effect is visible. Impact of this effect on the accuracy of these models has been minimized due to the setting of slicing planes parallel to proper planes of models which are adequate to planes of human body.

A comparison of models reveals that the stacked layers method offers better visualization of internal structures. In addition, the method allows us to make models faster than 3D printing (Table 1).

Table 1. A comparison of the time required to make models using each method

Type of reconstructed anatomical structure	Method of making the model	Time to make
Fragment of the mandible	Stacked layers	~2 h
	FDM printing	3 h 40 min
Fragment of the femur	Stacked layers	~3 h
	FDM printing	8 h

Printing time is of particular importance in the case of large-sized models such as the pelvis.

4. Conclusions

In this article, the process of manufacturing layered PMMA models designed for planning surgical and alloplastic procedures was presented. The effect of this study was the construction of physical models of a fragment of the femur and a section of the mandible, which can be used as an auxiliary tool in the diagnostic process. The main advantage of the PMMA layered model is its transparency, which in combination with easy access to each layer by the physician due to nonadhesive assembly provides a new visualization method for medical data. Low cost of manufacturing layered acrylic glass models is their significant advantage. Layered model construction techniques may help improve the quality of imaging of internal structure and facilitate planning of surgical treatment.

On the basis of the performed work, it can be concluded that: The stacked layers method provides a faster way to make models than 3D printing.

The developed method offers better visualization of internal structures because of the PMMA transparency.

In the process of making models by stacked layers method, there are number of important elements that have an impact on quality of these models. They are as follows:

- selection of material parameters
- correct configuration of machine parameters
- selection of the layered model assembly method.

In order to obtain accurate transfer of all medical data to the physical model, it is important to use sheets of material with thickness equal to layers acquired by the diagnostic devices on the basis of which the input model was reconstructed.

The slicing plane should be parallel to one of the planes of the human body. This position of the slicing plane of consecutive layers should help reduce the impact of the stair-step effect on model geometry and quality.

Acknowledgments

The authors would like to thank the personnel of the Laboratory of RP Techniques and Laboratory of Laser Techniques at Rzeszow University of Technology for their help. The research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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