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# 3D printed surgical planning prototype manufactured by a hybrid multi-material 3D printer

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**Abstract:** Surgical planning is a preoperative method of pre-visualization that is carried out before or during a surgical intervention in order to achieve the best outcome. This can be done either image-based or hands-on. Regarding the first strategy, it is based on the use of medical images. However, it has a huge limitation, which is the difficulty of identifying anatomical structures (crucial for surgeons to make correct decisions) and distances between tissues without any physical support. This problem is overcome with the use of 3D models. Despite this important development, until nowadays most of the surgical planning prototypes were 3D printed either using the moulding technique, which might take several days, or high-cost technologies as is material jetting. That is why, the present manuscript seeks to solve the problems arose by the use of a hybrid-multi material 3D printer which can not only use several materials at the time, but also two 3D printing technologies. The prototype introduced in this study is a neuroblastoma, a common cancer among children.

**Keywords:** Multi-material, 3D printing, Hybrid; Surgical planning prototypes, Neuroblastoma.

## 1. Introduction

AM technologies can be classified into seven categories according to ISO/ASTM 52900 Standard [1]: binder jetting, direct energy deposition (DED), material extrusion (includes FFF-Fused Filament Fabrication-), material jetting, powder bed fusion (includes SLS-Selective Laser Sintering- and SLM-Selective Laser Melting-), sheet lamination and vat photopolymerisation (includes SLA-stereolithography-). These technologies can be used for different applications in the medical sector, being one the manufacture of 3D printed surgical planning prototypes.

In recent years most of the surgical planning prototypes manufactured were monomaterial and monocolour, with FFF technology. Therefore, it was not easy to identify the different anatomical structures (soft and hard tissues) within the surgical planning prototype. Despite that, Krauel et al. [2] and Ranking et al. [3] manufactured surgical planning prototypes entirely in FFF since it is a cost-effective technology, but not the best for mimicking soft living tissues. Then, Krauel et al. [2] also manufactured prototypes using SLS. With this technology polyamide or polypropylene can be used. However, these two technologies only provided the opportunity to identify the different anatomical structures. This is why, Material Jetting technology 3D printers have been used in the manufacture of



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3D physical models using photopolymer resins [3,4]. For instance, Krauel et al. [3] manufactured two models using this technology and their relative soft consistency allowed the surgeons to use the same surgical instruments that would be used in the real operation. However, Material Jetting prototypes are expensive and hospitals are not able to afford them.

All in all, until now the most common limitations that these surgical planning prototypes faced are the next: (1) they were 3D printed using just one material, which limits the possibility of visualizing the different anatomical parts, (2) the materials used are too hard for mimicking the different anatomical structures and, consequently, the rehearsal experience is not the best; and (3) the use of some AM technologies, as it is Material Jetting, can be very expensive.

Next, these 3D realistic models are used in surgical planning which is a preoperative method of pre-visualization carried out before a surgical intervention in order to achieve the best outcome. This preoperative surgical planning can be done in two ways: (1) computer image-based or (2) hands-on preoperative surgical planning. The first approach was until now the most used process since it was not until the last years that the surgical cases started to be 3D printed. Image-based strategy has a huge limitation, which is the difficulty of identifying the anatomical structures (crucial for surgeons to make correct decisions) and distances between tissues without any physical support. Overall, both processes have the same step, but the latter strategy mentioned adds the opportunity of using a real 3D model. Therefore, surgical planning consists on several steps [5,6]:

- Image acquisition: for obtaining the medical images, two medical images technologies are normally used such as CT (Computer Tomography) and MRI (Magnetic Resonance Imaging). These non-invasive imaging techniques provide information about the architecture, composition and organization of the corresponding tissue. The images obtained in both medical imaging technologies are saved in DICOM (Digital Imaging and Communications in Medicine) format.
- Pre-treatment image processing: in this step, image processing techniques such as image enhancement can reduce the effects of statistical noise on most CT images [5]. Additionally, the region of interest is selected.
- Design approach: the segmentation is carried out by using different softwares, both open-source (3DSlicer) or proprietary-source (Materialise Mimics). Segmentation aim is to simplify the representation of an image into something that is easier to analyse. Once segmentation is finished, a surface mesh is extracted and, in case of artefacts, they can be eradicated either manually or automatically. Then, the data is saved in STL (Standard Tessellation Language).
- Materials selection: depending on the AM technology used for the manufacture of the 3D printed surgical planning prototype, a different material should be used.
- 3D printing: in this step, the AM technologies used for the manufacture of prototypes will depend on the application.
- Validation: once the 3D realistic models is 3D printed, it can be validated either by doctors or CT validation. The latter choice has already been used [7,8].
- Application: there are different possible uses of the realistic models. Firstly, improving the rehearsal experience, in which surgeons use the 3D prototype for practising before the operation with surgical tools; and, by this way, they do not have any surprise. Additionally, it has been demonstrated that surgeons who trained with physical models had better skills in comparison with those who did not have the same opportunity [9]. Within this use, visualization is also possible when the prototype is manufactured with hard materials such as PLA (PolyLactic Acid) using FFF. Secondly, for surgical education, since the prototypes enable future doctors training in Medical Schools, to have a better idea of the human body apart from using real human bodies. And last but not least, for patient education because 3D prototypes are useful for improving the interaction between the doctors and patients. By this way, relatives can understand what their children are suffering and see how the operation is going to be carried out as well as discuss the operation with the surgeons.

Regarding the different medical cases that have been 3D printed, CIM UPC along with Hospital Sant Joan de Déu have developed a know-how of 3D printing prototypes once the patient has been diagnosed with the disease. Most of the cases are neuroblastomas [3] and hepatectomies [8]. On the one hand, neuroblastoma is a cancer that develops from immature nerve cells found in several areas of the body such as kidneys (the most common origin), chest, abdomen, neck or near the spine. Neuroblastoma most commonly arises in and around the adrenal glands, which have similar origins to nerve cells and sit atop the kidneys. This disease commonly affects children who are 5 years old or younger. On the other hand, hepatectomies are the surgical removal of a liver part. As this hospital is focused on underage patients, it is possible to regenerate 90% of the liver. Despite this excellent work-flow, most of these prototypes were 3D printed using high-cost technologies as are the material jetting and SLS and using the moulding technique, based on 3D printing the negative of the case.

Therefore, the aim of the present study is to introduce a new methodology in 3D printing complex surgical prototypes by using low-cost technologies as are FFF and DIW (Direct Ink Writing). For that, the complete process of a neuroblastoma case will be introduced: medical acquisition, design approach, 3D printing process (G-code generation, materials selection, 3D printing and removal of PVA-polyvinyl alcohol-) and validation. Additionally, material costs are introduced.

## 2. Workflow for 3D Printing Surgical Planning Prototypes

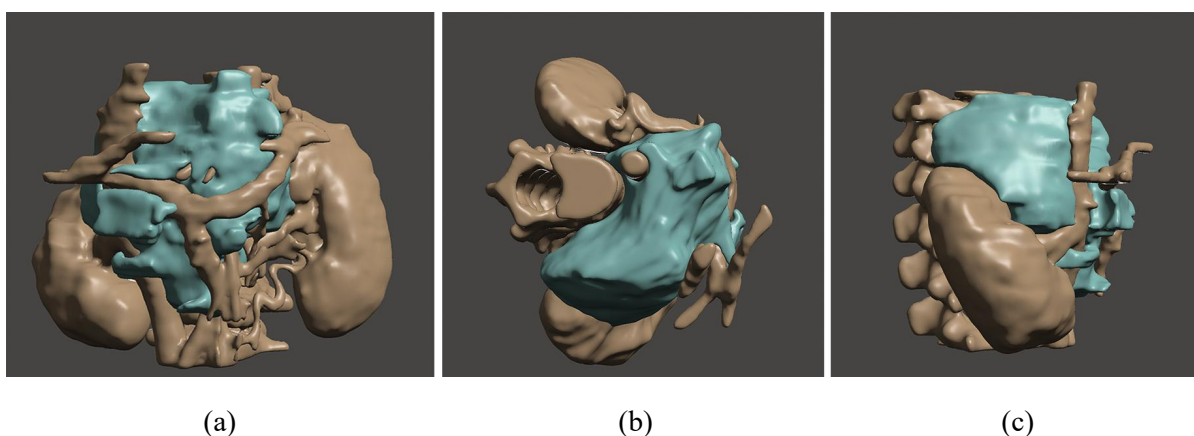
In the present section, the necessary tools, which were previously explained, for a correct 3D printing will be analysed as well as the knowledge that needs to be acquired.

### 2.1. Medical Acquisition

The DICOM images are processed at the Hospital Sant Joan de Déu using the abovementioned medical technologies. Additionally, the segmentation of the DICOM images is also carried out at the hospital. Normally, a semi-automatic segmentation is carried out using an IntelliSpace Portal from Philips.

### 2.2. Design Approach

Once the segmentation is finished, the different files are received and before the 3D printing, all the files are placed together in a 3D graphical software as can be Rhinoceros or Meshmixer for looking into the different parts and determining how to proceed with the 3D printing process, in other words, deciding the most optimal process. See Figure 1.



**Figure 1.** Design approach (a) Frontal view. (b) Superior view. (c) Side view.

### 2.3. 3D Printing Process

The main idea would have been to use the hybrid multi-material 3D printer developed by CIM UPC within the QuirofAM project, which is led by CIM UPC. The present 3D printer is based on a tool changer which takes a FFF print-head. However, in the present study, only the FFF printing parts were

used. Despite this, 3 different materials were used, which is more than usual in a conventional 3D printer that normally uses one or two different materials at the same time.

This process consists of three different steps: (1) the generation of the G-code; (2) the materials selection; and (3) the proper 3D printing process.

*2.3.1. G-code Generation.* The generation of the G-code is done by using a g-code generator software, in which different parameters are chosen such as the printing speed, layer height or infill. These parameters are needed for each STL. In the present case study, Table 1 shows the printing parameters used for this printing. In the present 3D printing procedure, there are two processes: (1) process 1, which uses T1 (PVA) and T2 (FF); and (2) process, which uses T0 (PLA) and T1 (PVA).

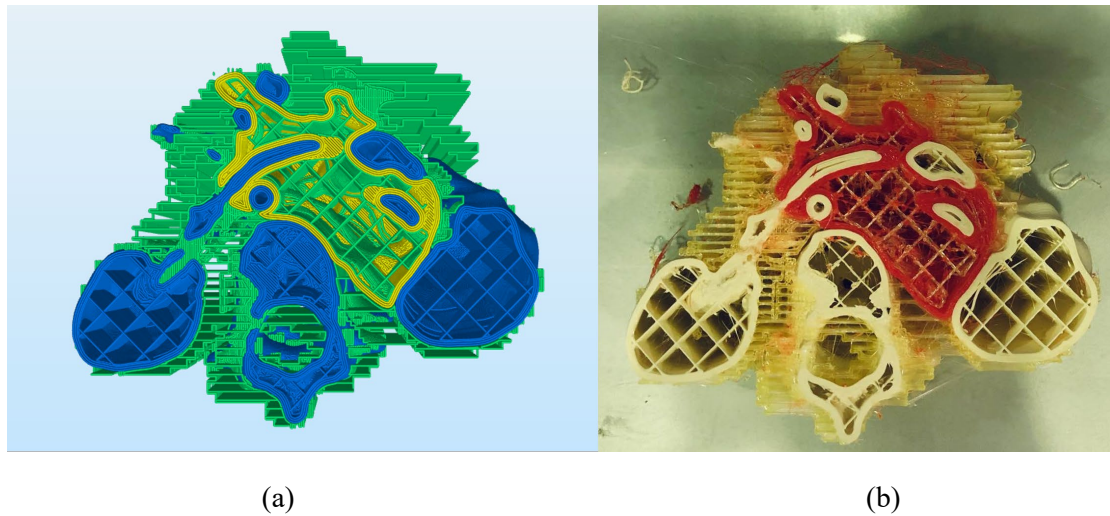
**Table 1.** Printing parameters for the 3D printing of the neuroblastoma prototype.

Parts	Parameters	Value
General Conditions	Scale [%]	80
	Filament Diameter [mm]	1.75
	# Tool Changes (T0)	607
	# Tool Changes (T1)	1113
	# Tool Changes (T2)	521
	Temperatures (T0) [°C]	205/170
	Temperatures (T1) [°C]	210/170
	Temperatures (T2) [°C]	235/170
	Nozzle Diameter (T0,T1,T2) [mm]	0.4
	Extrusion Factor (T0,T1,T2) [%]	100
Process 1 (T1/T2)	Layer Height [mm]	0.15
	# Top Solid Layers	8
	# Bottom Solid Layers	5
	# Shells	3
	Infill (FF) [%]	10
	Infill Angle [%]	45/-45
	Printing Speed [mm/min]	2000
Process 1 (T0/T1)	Layer Height [mm]	0.15
	# Top Solid Layers	6
	# Bottom Solid Layers	5
	# Shells	3
	Infill (FF) [%]	8
	Infill Angle [%]	45/-45
	Printing Speed [mm/min]	2600

Figure 2 verifies that the printing parameters applied to the 3D model are being well applied. For example, the infill used can be checked.

*2.3.2. Materials Selection.* Above, the printing parameters used for this prototype were introduced. However, these printing parameters may have small changes depending on the prototype that is going to be 3D printed. That is why, Table 2 outlines the general parameters for each material. The materials were used for the next parts (see Figure 3): (1) PVA for the support, (2) PLA for the anatomical structures (blood vessels, spinal cord and kidney); and (3) TPU (Filaflex™) for the tumor.

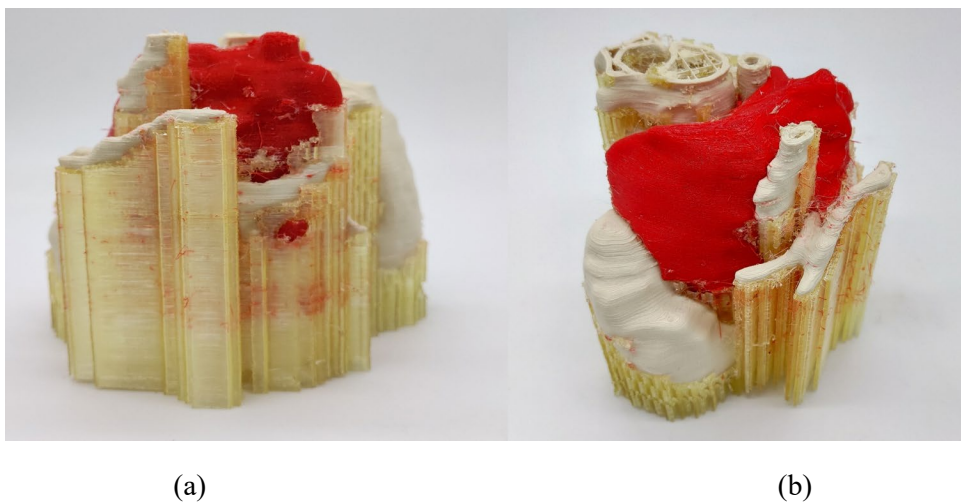
*2.3.3. 3D Printing.* Once all the printing parameters are selected and the materials are chosen, the 3D printing process starts. This process took around 48 hours to complete, less than in Witowski et al. [10]. Figure 3 shows 3D printed prototype.



**Figure 2.** 3D printing **(a)** G-code generator software view. **(b)** Real 3D printing process view.

**Table 2.** Printing parameters of the materials.

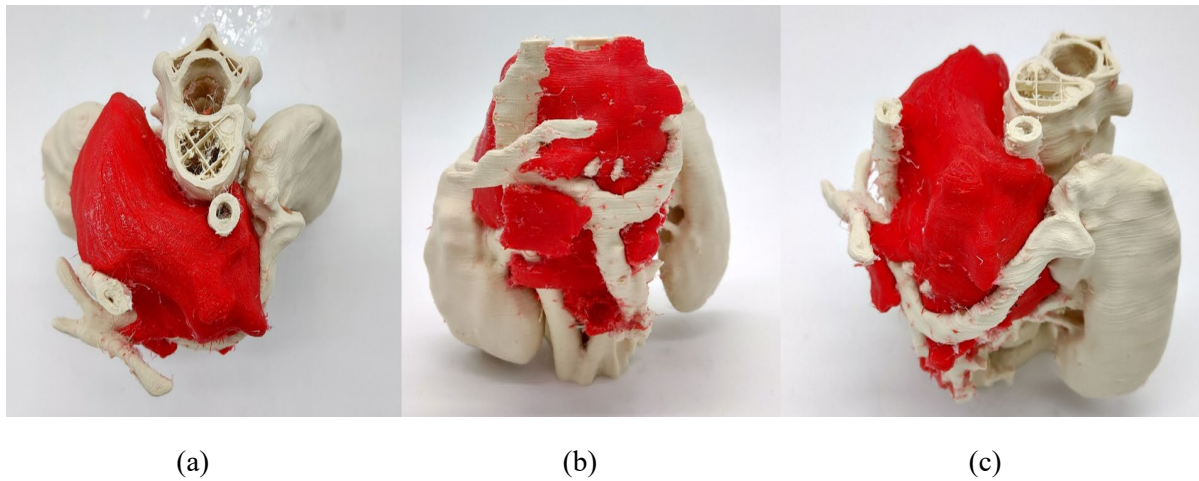
Parameters	PLA	PVA	TPU
Active/Standby Temperature [°C]	205/170	210/170	235/170
Extrusion Width [mm]	0.5	0.5	0.5
Nozzle Diameter [mm]	0.4	0.4	0.4
Default Printing Speed [mm/s]	2400-3000	1800-1900	900-1500
Primary Layer Height [mm]	0.15	0.15	0.15
Retraction Distance [mm]	5.5	5.5	10
Extra Restart Distance [mm]	0.1	0.1	0.1
Retraction Vertical Lift [mm]	1.5	1.5	1.5
Retraction Speed [mm/s]	1000	1000	720



**Figure 3.** Outcome of the 3D printing **(a)** Frontal view. **(b)** Perspective view.

**2.3.4. Removal of PVA.** The removal of PVA is done in an easy way by the immersion of the prototype in water during several hours. By this way, the prototype is finished (see Figure 4).

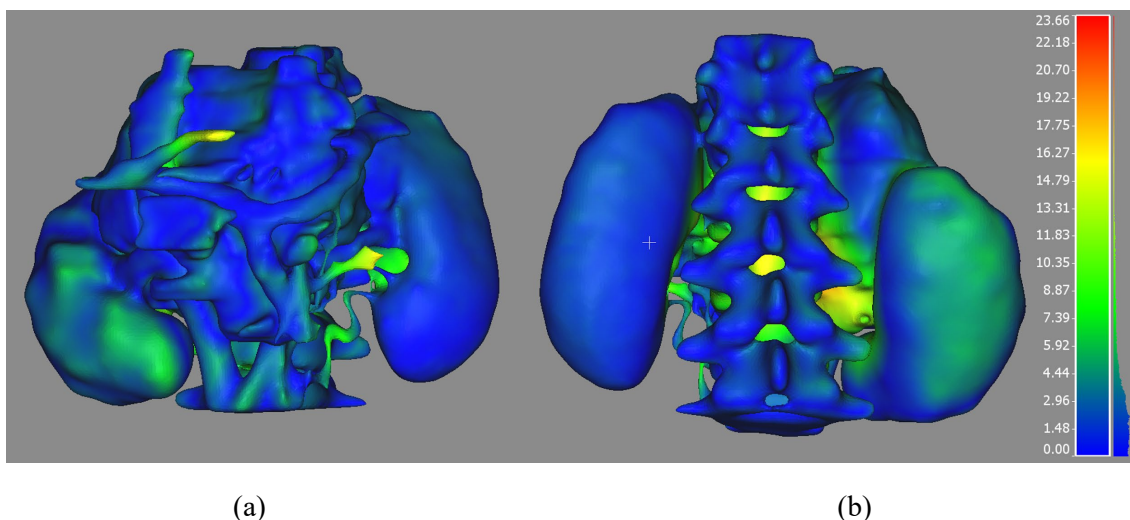




**Figure 4.** After removing the PVA **(a)** Superior view. **(b)** Frontal view. **(c)** Perspective view.

### 3. Validation

The validation of the prototypes is an important step for verifying the quality of the prototype with the original STL. For that, a 3D triangular mesh editing software (CloudCompare V2.11) was used. Firstly, the surgical printed planning prototype was scanned using a 3D scanner (Creaform Scanner 3D Academia 10 from AsorCAD®). Secondly, both STL files were manually aligned by selecting different referential points in each mesh. And finally, a detailed quantitative analysis was done so as to determine the differences between the CT scan of the patient organ and the scan of the 3D-printed prototype manufactured, using a point-based registration of the meshes. For that, the distance between the meshes was computed using the cloud-to-cloud distance (Hausdorff distance algorithm). Figure 5 shows the results of the validation. The colour bar is in mm. Related to this validation process, several parameters obtained are summarised in Table 3.



**Figure 5.** Results of the validation **(a)**Frontal view. **(b)** Back view.

The prototype closely matches the patient organ. However, there is a significant error in some regions, especially the inner parts out of reach of the 3D scanner. This is the main limitation and the fact that the average distance difference between both STL is around 4 mm. If it would have been possible

to carry out the validation by comparing two CT images, the different would have been less. For instance, Adams et al. [7] and Tejo-Otero et al. [8] had a mean error of 0.6 mm and 3.35 mm, respectively. Both validations were carried out in a CT scanner.

**Table 3.** Results of the validation.

Parameters	Values [mm]
Average Distance	4.03
Sigma	4.21
Maximum Error	0.45
Maximum Distance	23.12

#### 4. Material Costs

Another important aspect about these prototypes is the materials' cost of the prototype. In this study, only the materials cost will be taken into account. Table 4 summarises the materials' costs of the prototype. In total, 14.07€ was the cost of the prototype by adding the price of PVA, PLA and Filaflex used.

**Table 4.** Costs of the prototype.

Material	Total Weight [g]	Cost [€/750g]	Cost [€/500g]	Total Cost
PVA (Smart Materials 3D)	122.31	47.90	-	7.81
PLA(Smart Materials 3D)	90.63	18.20	-	2.19
Filaflex (Recreus)	60.30	-	33.76	4.07

#### 5. Conclusion

In the present manuscript, an improved manufacturing process of a multi-material surgical planning prototype was achieved. Since it was the first step in using a new multi-material and hybrid FFF-DIW 3D printer, limitations need to be pointed out: (1) the errors in some regions, especially the inner parts, could be solved by using a non-invasive medical technique as CT scanner; and (2) only materials cost was taken into consideration since the labour costs are included in the 3D printer maintenance. This paper represents an advance in the state-of-the-art and solves many problems such as the drawback of an only-material 3D printers. In future research works, more materials will be used, especially by 3D printing soft materials (hydrogels and silicones) using a progressive cavity pump.

#### Acknowledgements

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