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OPTIMIZING FDM 3D PRINTING OF MEDICAL MODELS

Gabriela STRNAD

George Emil Palade University of Medicine, Pharmacy, Science, and Technology of Targu Mures
Faculty of Engineering and Information Technology
N. Iorga, 1, Targu Mureş, 540139, Romania
gabriela.strnad@umfst.ro

Abstract

Present paper presents the results on four cases of optimization of FDM 3D printing of medical models used for training on specific medical issues (2 cases) and of personalized patient-specific models used for complex Trauma and Orthopedic surgical procedures planning (2 cases). Depending on optimization criteria (proper combination of model splitting – minimum need of supports/or no supports – minimization of printing time and material consumption, facile support removal and good surface quality), the modification of the Cura slicer recommended settings related to layer thickness and support pattern, support Z distance, support X/Y distance, support overhang angle, and minimum support area, allowed the reduction of 3D printing time with 24% and 33%, very easy support removal, and an assessment of surface accuracy and quality as very good for the purpose, made by end users.

Key words: medical models, 3D printing, fused deposition modeling, surgical planning

1. Introduction

Additive manufacturing is used today in medical field for rapid fabrication of 3D printed models for training of medical students and young doctors, providing a more hands-on learning experience [1, 2]. 3D printing allows the creation of patient-specific models based on CT scans or MRI data, models which can be used for surgical planning and simulation giving the surgeons a better understanding of complex anatomical structures and supporting the rehearsal of difficult surgical procedures, thereby reducing the risk of complications during actual surgery [3-6]. Personalized models can also serve for doctor- patient communication to explain the details of the surgical procedure, alleviating patient anxiety and improving their understanding of the treatment plan.

For 3D printing of medical models made of polymers the most used manufacturing processes are Fused deposition modeling (FDM) – which involves heating a thermoplastic material and extruding it layer by layer to build the model [7-10], stereolithography (SLA) – where liquid photopolymer resin is cured by a light source, typically a laser, to create solid 3D objects [11-13], and selective laser sintering (SLS) – that uses a high power laser to sinter polymer powder into a solid structure [14, 15]. As FDM is the most affordable in terms of equipment and materials cost, and offers a great variety of materials to be used, allows a great degree of customization and tool-less manufacturing, this process is a great choice for medical models manufacturing. The FDM drawback related to necessity of supporting of complex overhanging surfaces of medical models by using supplementary 3D printed structures called supports, which leads to long printing time and rough surface finish after supports detachment, can be alleviated by optimizing process parameters.

The objective of present research paper was to optimize the FDM 3D printing process parameters for manufacturing of two medical training models (femur bone model and lumbar spine model) and two complex patient-specific models based on CT scans, models that were used for thorough and careful planning of two very difficult trauma and orthopedics surgical interventions performed at County Emergency Clinical Hospital of Targu-Mures.

2. Materials and methods

Four medical models were 3D printed on FDM UM3 and UM3Ext (Ultimaker) machines, equipped with 0.4 mm AA printing nozzles, using 2.85 mm PLA filament (BASF). The 3D printing workflow started with 3D models described as .stl or .obj files. These files were then imported into Cura slicing software were different settings for process parameters were made, and .gcode files were saved and transferred to 3D printers instructing them how to build models layer by layer.

Models made for training purposes (femur bone and lumbar spine) were downloaded from Thingiverse design community (thingiverse.com), from where everyone can download files and build them with their 3D printer, and can use and alter any design. Femur bone model was developed starting from .obj file downloaded from https://www.thingiverse.com/thing:3295652/files. Lumbar spine model was made by extracting L1-L5 vertebrae and Pelvic base .stl files from https://www.thingiverse.com/thing:4868387/files.

Personalized models for surgical procedures planning were prepared starting from patient anonymized CT scans and DICOM files (Digital Imaging and COmmunication in Medicine) consisting on stacks of 2D tissue image sections which, when combined, can be used to generate 3D models. The utilized DICOM files were read and segmented using open source 3D Slicer software (www.slicer.org). After cropping the region of interest in each case, the segmentation was made applying threshold function to exclude all irrelevant tissue regions in order to only highlight bone tissue. The results from these segmentations were then converted to personalized 3D models by using the option of Export/Models and saving .vtk files as .stl.

The .stl files of each of four models were consequently opened in Cura where the process parameters were studied and fine tuned for optimized results to respond to the specific criterion of best combination of printing time - material consumption - surface quality. The printing time and materials consumption were objectively assessed using the data from Cura and time and weight measuring. The surface quality was evaluated by subjective assessment made by the models end users (medical doctors and surgeons).

3. Results and discussion

The first medical FDM 3D printed model (case 1) presented here was a human femur that was used for training of medical resident doctors and students on a specialty workshop having the subject “Femoral osteosynthesis with external fixator – DHs and DCS”. The number of pieces that were fabricated was 20. Figure 1.a presents images taken during the workshop.

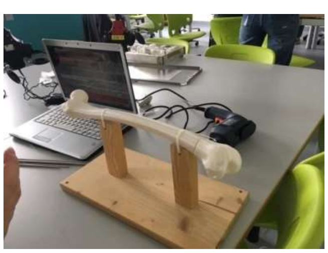
The model’s height of 454 mm did not fit inside of building volume of UM 3Ext 3D printing machine (Fig. 1.b), as a consequence the model had to be split in several pieces. In these conditions *the optimization for this specific case aimed to find a proper combination of model splitting – minimum need of supports/or no supports – minimization of printing time and material consumption*.

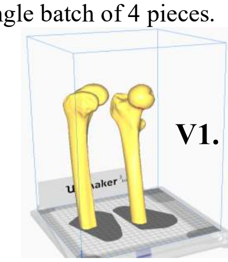
Fig. 1.c presents the two versions that were adopted for model splitting analysis:

• version 1 – V1, in two pieces: 1 - head, neck, greater and lesser trochanter and half of body of femur, and 2 – patella and half of body of femur;

• version 2 – V2, in three pieces: 1 – body of femur, 2 - head, neck, greater and lesser trochanter, and 3 - patella.

As the number of complete models that had to be fabricated was 20, the split models V1 and V2 were prepared for simultaneous 3D printing of 4 of each split piece, these batches being then printed 5 times. The following results are discussed referring to one single batch of 4 pieces.





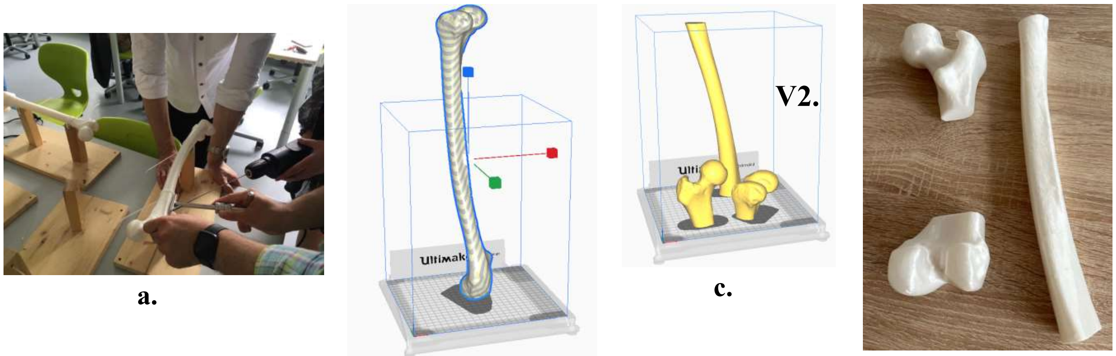


Fig. 1. Femur 3D medical model used for training; a – images during the workshop training , b – Cura slicer view of the model, c – V1 and V2 versions for model splitting, d – 3D printed model split in three pieces (V2)

Figure 2.a presents the preview of 3D printing of V1, where the print settings were: layer height – 0.2 mm, infill - 20% grid, adhesion layer - raft, use of supports. The end users (workshop coordinators) validated that the quality of surface printed with 0.2 mm layer height was good enough for the models, so this was the value adopted, leading to the decreasing of printing time. In FDM 3D printing if the overhangs are greater than 45°, with respect to the vertical, they will need support, so each of two V1 split models were prepared to be printed with supports. Table 1 presents the results in terms of printing time and material consumption of V1: 3228 min (53 h and 48 min) and 805 g – for the fabrication of 4 complete femur bone models.

For the print settings of V2 version, it is clear that split 1 – body of femur does not need supports. For splits 2 and 3, the settings were optimized using a support overhang angle of 90° and a minimum support area of 25 mm^2, as a results, the preview of printing process showed that the split parts 2 and 3 will be printed with no supports (Fig. 2.b), even if there are overhangs angles way greater that 45°. The trial of printing with no supports was successful in terms of effectiveness and surface quality, as figure 1.d shows, validating the optimization of printing with no supports. By this, the printing time and material consumption of V2 for the fabrication of 4 complete femur bone models (Fig. 2.c, d, e) was 2443 min (40 h and 43 min), and 672 g (Table 1). This optimization led to a 24% reduction of printing time compared with V1, and a 17% decrease of material consumption (Table 1), supporting the decision of models making using this combination of splitting – printing parameters.

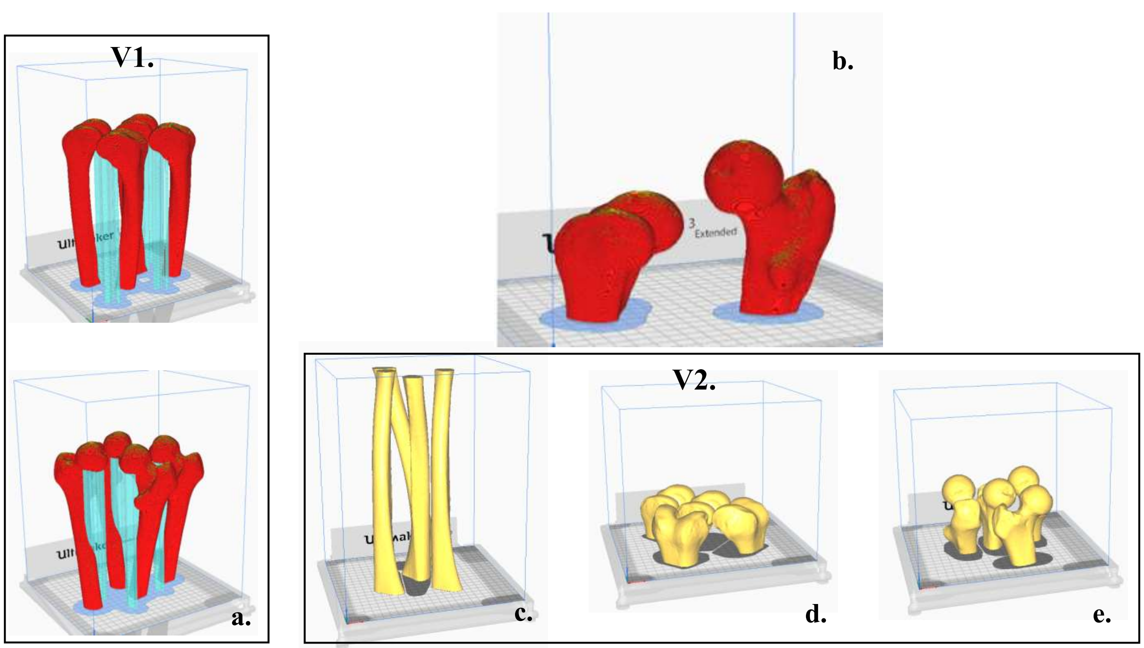


Fig. 2. V1 and V2 versions of model splitting for the simultaneous fabrication of 4 split pieces; a – Cura preview of 3D printing of V1version, requesting support structure, b – Cura simulation of printing 2 and 3 pieces of V2 with no support structure; c, d, e – Cura prepare views of 3D printing of V2 version, requesting no support structure

Table 1. Printing time and material consumption dependence on model splitting choice and 3D printing settings

Version	Print settings	Printing time	Material consumption	Optimization
V1 splits: 1 and 2	Layer height: 0.2 mm Infill 20%, grid Adhesion layer: raft Support: on, overhang angle 60°	1 - 29 h 16 min 2 - 24 h 32 min **Total: 53 h 48 min** **3228 min**	1 - 434 g 2 - 371 g **Total: 805 g**	
V2 splits: 1, 2, and 3	Layer height: 0.2 mm Infill 20%, grid Adhesion layer: raft Support: off – no support	1 - 17 h 15 min 2 - 11 h 48 min 3 - 11 h 40 min **Total: 40 h 43 min** **2443 min**	1 - 284 g 2 - 193 g 3 - 195 g **Total: 672 g**	-785 min (13 h 5 min); – **24,32%** -133 g; **- 16,52%**

The second medical FDM 3D printed training model was a lumbar vertebrae spine one, containing also the pelvic base (case 2). After fabrication the models are actually used for medical resident doctors and students training at ATI Clinic (Anesthesiology and Intensive Care Clinic) at County Emergency Clinical Hospital of Targu-Mures (Fig. 3 a, b, c). Two complete training models were printed with initial dimensions (Fig. 3.a, b), and end users required one more model with dimensions increased by 25% (Fig. 3.c). As the quality of the models printed with a layer height of 0.2 mm was validated as good enough by the users, after printing only one vertebra as a test one, the complete models were printed with this main setting. For this case the *optimization criterion was the ease of support removal*.

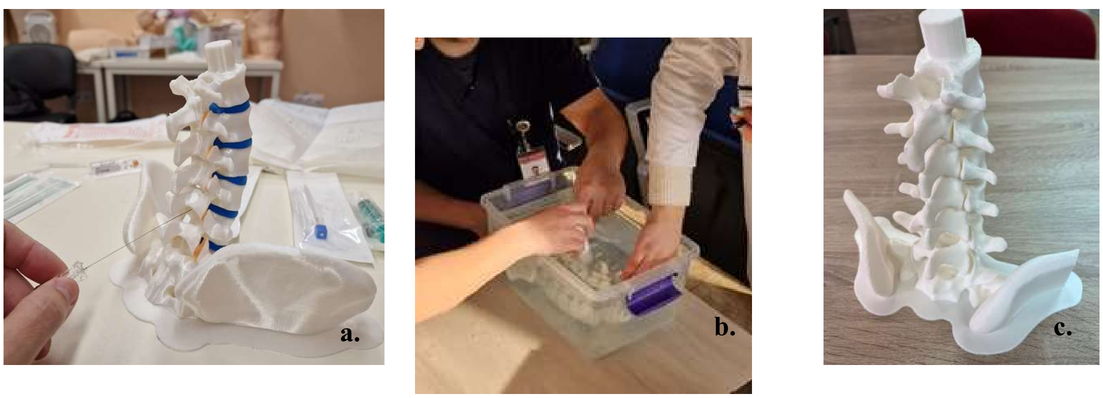
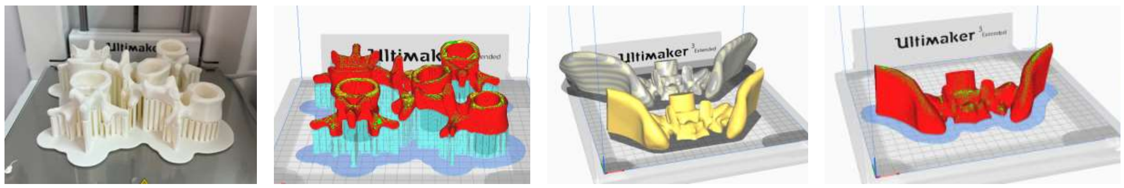


Fig. 3. Lumbar spine 3D medical model used for training; a, b – images during the trainings; c – 3D printed model with increased dimensions

As the vertebrae present complicated shapes and surfaces it is impossible to be printed without supports. The optimization of the models was made related to following process parameters: support pattern, support overhang angles, support Z, and X/Y distances. The most used patterns for supports are grid and triangles, allowing the achievement of sturdy supports and resiliency against vibrations, but having the drawbacks of increasing printing time, and presenting more contact with the supported areas of the model, which leads to more difficult post processing and a lower surface quality after supports detachment. As a consequence, these patterns were avoided and Zig Zag pattern was chosen, being fast, simple and easy to remove. Even recommended Support overhang angle is 60°, the setting used was 80°. Important change was made to Support Z distance, which defines the distance from the model to the top and bottom of the support. A high value for these distances creates a bigger gap between the model and support, meaning easier post-processing, and creates a smoother model surface due to the reduced number of contact points. A low value is useful when is supporting complex overhangs that require high detail, but makes supports harder to remove. The Support Z distance need to be a multiple of layer height, and recommended value is 2 x layer height. The setting was increased at 3 x layer height, resulting a Support Z distance of 0.6 mm, instead of 0.4 mm. Support X/Y distance adjusts the horizontal distance between a model and its support, and larger distance eases the removal process, meaning better surface finishes on vertical sections. Usually the recommended value for support X/Y distance when working with a 0.4 printing nozzle is 0.7 mm, but the value was increased to 1 mm. With these optimized settings, L1-L5 vertebrae were printed simultaneously (Fig. 4.a, b), with a printing time of 16 h 7 min, a material consumption of 192 g, and the support removal process was subjectively assessed as very facile, compared to other models were the recommended settings described above were used.

Pelvic base model, on which the L1-L5 vertebrae are placed, has a shape that allowed printing without supports, the only change needed was its trimming, for the model with 25% increased dimensions, in order to fit into the UM3Ext printing machine X/Y working space (Fig. 4. c, d). The resulting printing time was 5 h 31 min, and material consumption was 82 g.

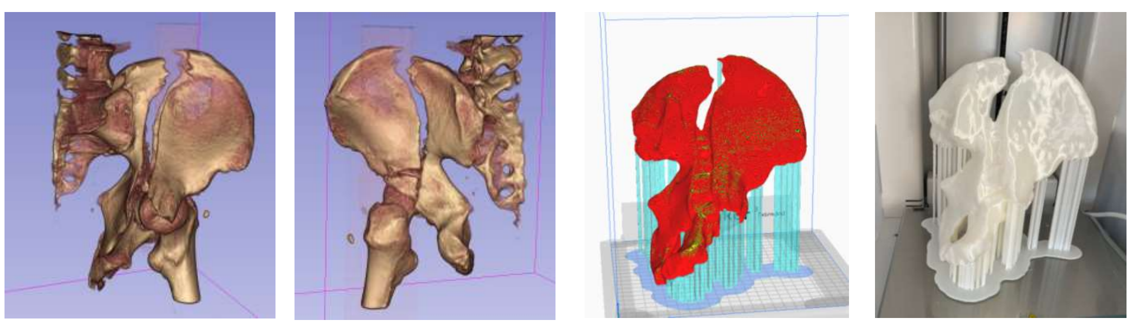


a. **b.** **c.** **d.**

Fig. 4. 3D printing of lumbar spine model components; a, b – 3D printed L1-L5 vertebrae and Cura preview showing the support structure; c, d – Cura prepare and preview of trimmed pelvic base 3D printing with no support structure

The third model (case 3) was fabricated prior to a very complex surgical intervention performed at Trauma and Orthopedics Clinic at County Emergency Clinical Hospital of Targu-Mures, this being the very first surgery of this hospital planned with the support of a patient-specific 3D printed model [16].

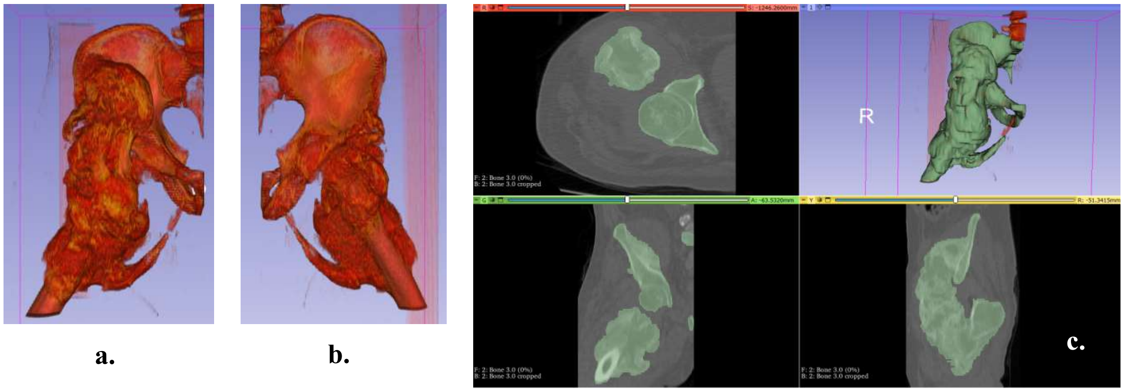
Figures 5.a and 5.b present the anterior and posterior views volume rendering of region of interest, showing the severe trauma of pelvic region that had to be corrected by surgery. By using patient anonymized CT scans and open source 3D Slicer software, the segmentation performed trimmed away sacrum and femoral bone, retaining only the pelvic hip bone, with its ilium, ischium and pubis components. The hip bone segment was exported as .stl file, prepared in Cura for FDM 3D printing (Fig.5.c), and the model was printed on UM3Ext (Fig. 5.d). In this case the *optimization criterion was the good quality of model surface*. Consequently, the 3D printed model was prepared with a layer thickness of 0.2 mm, and, as supports are mandatory for printing this complex shape, the setting for supports were: support pattern Zig Zag, support Z distance 0.6 mm, support X/Y distance 1 mm, support overhang angle 60°. Printing time was 21 h 40 min, and material consumption was 320 g. By using these modified settings the model's post-processing by support removal and surface finishing was assessed as very facile, and the quality of the surface was evaluated as very good by the surgical team that used the model.



a. **b.** **c.** **d.**

Fig. 5. Personalized 3D printed model for surgical planning; a, b – 3D Slicer anterior and posterior view of region of interest; c – Cura preview of 3D model printing with support structure; d – FDM 3D printed model with supports

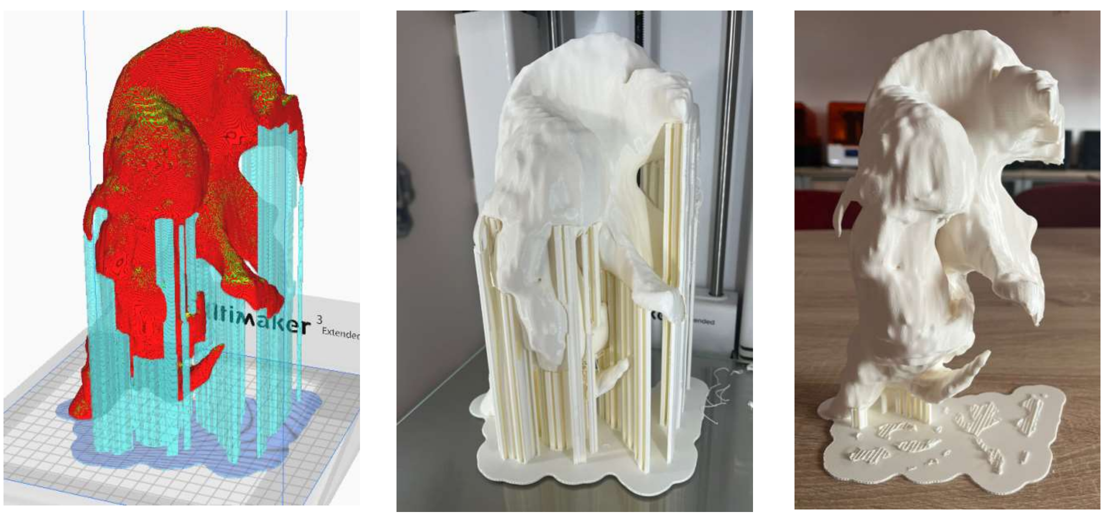
The fourth model (case 4) was also a personalized one, used very recently at Trauma and Orthopedics Clinic to carefully plan a demanding case of resection of a bone bridge formed in the hip joint of the patient [17]. The complexity of surgical procedure was high and it was performed by a team of trauma surgeons completed with general surgeons from General Surgery II Clinic. The bone bridge formed is showed in anterior and posterior presentations in Fig. 6.a and b. Figure 6. c presents the conventional four-up view of 3D Slicer segment editor module, with axial, sagital, coronal, and 3D views, where the thorough thresholding and editing of the slices in the region of interest was done, resulting the exported .stl for 3D model. In this case the *optimization criteria were the good quality of model surface combined with a short delivery time of the printed model to medical team*.



a. b.

Fig. 6. Complex medical case of a pathological bone bridge formed on hip joint; a, b – 3D Slicer anterior and posterior view of region of interest; c – 3D Slicer segmentation and 3D model that was generated

3D model that was generated had a large and complex shape, requesting the printing with supports. Initial simulation of the printing was done with following settings: layer thickness of 0.2 mm, support Z distance 0.4 mm, support X/Y distance 0.7 mm, support overhang angle 60°, resulting a printing time of 33 h 16 min, which did not met the criterion of short as possible delivery time to operating room. As a consequence, based on previously good results obtained using modified and optimized settings, the model was 3D printed with layer thickness of 0.25 mm, support pattern Zig Zag, support Z distance 0.6 mm, support X/Y distance 1 mm, support overhang angle 80°. Printing time was 22 h 26 min, reduced with 33% compared to initial simulation, and material consumption was 414 g. Even the support structure was intricate (fig. 7.a and b), its removal was done with great ease and the surface quality of the model (Fig. 7. c) was assessed by the surgical team as very good for the purpose.



a. b. c.

Fig. 7. Personalized 3D printed model for surgical planning; a – Cura preview; b – FDM 3D printed model with support structure; c - FDM 3D printed model after the removal of supports

4. Conclusions

Present paper presents the results on optimization of FDM 3D printing of medical models used for training on specific medical issues and of personalized models used for complex surgical procedures planning.

The optimization criteria were different, based on the specific request of each particular case:

- when the models were large, did not fit in the building space of the 3D printing machines, and had to be fabricated in a large number, the optimization targeted proper combination of model splitting – minimum need of supports/or no supports – minimization of printing time and material consumption, and was done by a good choice of complete model splitting in several pieces that were printed with no supports;

- when the models could not be fabricated without supports, the optimization criteria were the ease of their removal and good surface quality resulting after post-processing. This was done by modifying the Cura slicer recommended settings for support pattern, support Z distance, support X/Y distance, support overhang angle, and minimum support area, in the sense of choosing Zig Zag pattern, increasing support Z, X/Y distance, increasing overhang angle, and decreasing minimum support area.

The results show optimizations in terms of:

- reduced printing times, by 24% - model 1, and by 33% - model 4, where the time was important;
- reduced material consumption, by 16% - case 1, where the material cost was important;
- facile support removal combined with a good surface quality, cases 2, 3, and 4, where the accuracy and the quality of the surface was important, and was assessed by the end users of our 3D printed models: Anesthesiology and Intensive Care medical doctors and Trauma and Orthopedic surgeons.

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