

3D printing of liver models to assist difficult surgical operations

I. A. Karolos^{1*}, V. Tsioukas², and C. Pikridas³

¹ School of Rural and Surveying Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

* Corresponding author, email: ikarolos@topo.auth.gr

Abstract: In the effort of a surgeon to overcome in the best possible way a difficult surgical event such as the removal of tumors from liver, it is required the use of all possible imaging-diagnostic tools to familiarize the doctor with the current patient's situation. Even though tomography images are implying the 3D geometry of the human body they are not providing in a manageable way specific 3D model structures of separate organs. The present work concerns the use of 3D modeling techniques to produce 3D physical model of both liver and its internal geometry (vessels, tumor) using a 3D printer.

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I. Introduction

Liver surgeries that involve the removal of tumors are often a complicated procedure for the surgeon [1]. In this anatomically complex human organ, the diagnosis of a lesion is made by obtaining a variety of imaging data through appropriate Computed Tomography (CT) and/or Magnetic Resonance Imaging (MRI) [2]. These tomographs provide two-dimensional information to the surgeon, which in many cases is difficult to use during surgery as the surgeon is asked to assess the three-dimensional morphology of the tumor to be removed and the adjacent critical branches of the veins and arteries. In this case a three-dimensional model that optimally determines the geometry of the liver would assist in preoperative planning, increasing the success of the operation, reducing side effects for the patient, such as increased bleeding and partial removal of the tumor [3]. This paper describes all the stages of the liver 3D modeling and printing protocol, developed by our research team, suitable for optimizing presurgical planning and training of qualified physicians.

II. Triple-phase CT scan process

In the first stage of the protocol, an appropriate triple-phase CT scan is performed on the patient using a Philips iCT 256 multislice CT scanner. A vasodilator is used to obtain the data for the imaging of the final vascular branches (glyceryl trinitrate, 1-2 sublingual sprays, one spray equals 300 - 400 micrograms). At the same time, a contrast agent is administered orally, for the sketching of the gastrointestinal tract and its separation from the structures of the liver, with the aim of the precise segmentation of the liver parenchyma. In addition, a high contrast agent (370 mg I/ml) is administered intravenously for optimal delineation of anatomical structures. Cross sections of very thin thickness (1 mm) are obtained with 50% coating and pitch 1, elements necessary for the subsequent reconstruction of the imaging data in 3D models. The scan is performed in three different phases of perfusion of the liver, Arterial,

Portal and Delayed phase (Fig 1), for the emergence and subsequent segmentation of the arterial and venous network but also for the segmentation of lesions which, depending on the type of lesion, may show different enrichment over time. Regarding the infusion protocol, the volume of the administered contrast agent was set at 140 ml with an infusion rate of 7 ml/sec.



Figure 1: Triple-phase CT scan suitable for liver anatomy reconstruction. On the left, the Arterial phase, on the middle, the Portal phase and on the right the Delayed phase.

III. Segmentation process of parenchyma and internal structure of the liver

In the next phase of the protocol, follows the three-dimensional segmentation of the individual structures of the liver (liver parenchyma, tumors, vascular branches of the hepatic artery, portal, and hepatic vein). The above segmentation process is accomplished with the help of appropriate software developed by our research team. The software is using the © NVIDIA Clara's Artificial Intelligence (AI) assisted annotation tool [4] to simplify and automate the export process of the liver's parenchyma and tumor as much as possible. The Digital Imaging and Communications in Medicine (DICOM) CT images of the Portal phase are first imported to the software. Then, the user selects at least six points between the CT cross sections, on the outline of the liver. This procedure is repeated by the user, this time describing the tumor outline using points. Then, our software is communicating with the Clara © annotation tool, and with the help of specific pre-trained models, the artificial intelligence algorithm describes with two-dimensional closed polygons the liver

parenchyma and tumor as they are depicted along all sections of the portal phase (Fig 2).

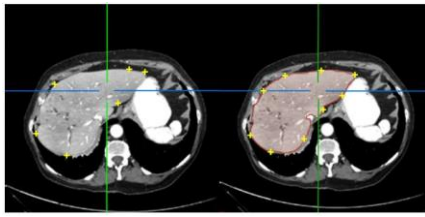


Figure 2: On the left, the selection of the points on the liver outline and on the right the final polygon that describes the liver parenchyma, after the application of the deep learning algorithm.

Based on the points from which the polygons with known X, Y, Z coordinates are defined on the DICOM images, the three-dimensional model of the liver and the tumor (s) is created in .stl (Standard Tessellation Language) format. The .stl file describes the model by approximating its surface with triangles in the three-dimensional space (mesh triangles). For the three-dimensional display of the remaining internal structure of the liver, the software uses appropriated thresholding algorithms which are applied by the type of examination (Arterial, Portal, and Delayed phase) in the areas of enhancement of the contrast agent (hepatic artery, portal, and hepatic vein). Veins and arteries are also described automatically with polygons of known coordinates which in turn become .stl files. Eventually, five .stl files are extracted from the software, one for each distinct structure of the liver (liver parenchyma, tumor, hepatic artery, portal vein and hepatic vein) whose surfaces are smoothed with appropriate smoothing algorithms. Fig 3 shows a relevant result.

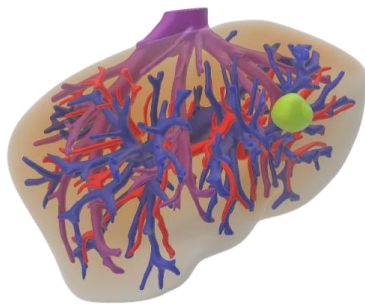


Figure 3: 3D reconstruction of a liver model. With light brown color is the liver parenchyma, with blue color is the portal vein, with magenta color is the hepatic vein, with red color is the hepatic artery, and with green color is the tumor.

IV. 3D Printing process

After the final export of the liver 3D model, the process of its 3D printing, with the method of extrusion of thermoplastic material (FDM - Fused Deposition Modeling), takes place in the protocol. This additive manufacturing technology is widespread and is characterized by simplicity, efficiency, and reduced cost of consumables. The main parts of a 3D FDM printer are the heated construction bed, the extruding of thermoplastic material which is fed to it in a filament form, and the moving X, Y, Z axes. For the printing session the © Prusa i3 MK3S [5] is used with the © Mosaic Palette 2S [6] for up to four different color and filament material

combination. The process of printing the liver model involves printing the parenchyma, veins, arteries, and tumor in different colors and integrating them into a common reference system based on the exact anatomy of the model (Fig 4). For printing, Polylactic Acid (PLA) thermoplastic filament in red, blue, and purple color is used. Due to the complex anatomy of the veins-arteries, for their support on the construction bed is used in conjunction with the PLA, the water-soluble thermoplastic Polyvinyl Alcohol PVA which is removed from the main model using water, after the printing session.



Figure 4: The final 3D printed liver model. With red color, the half of the liver parenchyma (the other half with transparent as removable part) and the hepatic arteries, with blue color the portal veins, and with purple color the hepatic veins and tumor.

V. Conclusions

3D printing of patients' liver (or any other internal organ) 3D models, is an interdisciplinary and innovative process, which ensures better pre-surgical planning and control of a surgery. In addition, additive manufacturing helps training surgeons as they can experiment with the printed model before moving on the actual surgical process. It also helps the patients to understand a lot better and with more valid information, the nature of their lesion and to inform them about the actual processes that will take place in the surgical operating room.

ACKNOWLEDGMENTS

Co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH – CREATE - INNOVATE (project code: T1EDK-03599).

AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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