Title:
Segmentation Strategy and 3D Printing of a Patient-specific Heart Model

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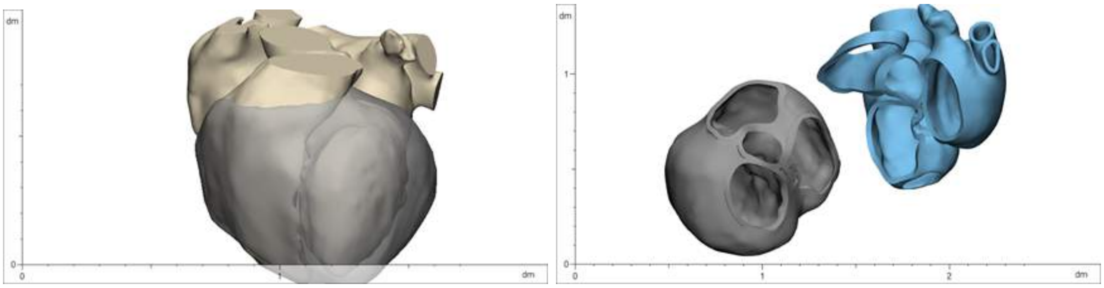
Introduction

Three-dimensional printing (3DP) is a process of additive manufacturing by which a 3D object is built layer-by-layer. Over the last 10 years, 3DP has become an affordable means for producing bespoke solutions quickly [9]. In the medical field, this technology has gained popularity for creating customized prosthesis, implants, fixtures, surgical tools, as well as reproducing patient-specific 3D anatomical models [5]. The starting point, in this case, is given by a set of 2D images of the interior of the body acquired by medical imaging techniques, such as computer tomography (CT) or magnetic resonance (MR). From them, through a process known as segmentation, anatomical structures of interest are isolated and then exported as faceted geometries, almost ready to be printed.

The great advantage of this technology is the possibility of customizing those geometries to obtain patient-specific models that can be exploited for personalized cares. For example, physical prints draw their competitive advantage in the haptic perception they guarantee, being therefore complementary to the visual assessment provided by 2D imaging or other 3D visualization techniques, such as virtual reality and augmented reality [9]. This potentiality turned out to be very useful also in the cardiovascular field: through 3D printing, for example, accurate educational tools able to illustrate complex cardiovascular anatomy and pathology can be created [6]. Compared to 2D images, 3D renderings guarantee a better understanding of the human body, also of fine but fundamental anatomical details [8]. This aspect also turned out to be helpful for improving communication between surgeons and patients [3]. Above all, this technology can be used to create and analyze 3D model before starting actual surgery on the patient [3]. In this scenario, the decision-making process, considered complex and non-routine, can benefit from the availability of physical 3D models allowing for an effective replication of the surgical procedure such as dissections, suturing or devices placement, thus reducing operative risks [10]. Moreover, patient-specific implants and custom-made devices could be designed and tested, opening new clinical possibilities [10]. This could be extremely useful for example for congenital heart diseases [5].

In this context, the aim of this work is to realize a compliant patient-specific heart model, a sort of template, endowed with mechanical properties that could get close to those ones of the biological tissue. This can be considered a sturdy base for potential applications in a clinical environment, as just now discussed. In another perspective, the paper basically aims at providing medical investigators with key information on how a patient-specific multi-material heart model should be built from CT or MRI datasets.



(a) (b)

Fig. 1: **(a)** A step in the workflow to obtain the digital heart model. The blood pool is colored in light brown, while the myocardium is gray and semi-transparent. **(b)** Splitting of the STL model into two parts, to which different printing materials are assigned.

Main Idea

The starting point for this manufacturing process is segmentation. by which the anatomical structures of interest can be isolated, generating a 3D model. This step has been conducted exploiting Mimics software (version 21), starting from a stack of high-resolution Computed Tomography (CT) scans. It consisted of 393 slices in the axial plane, with a resolution of 512x512 pixels. The dimension of each pixel was 0.35 mm, while the distance between two subsequent slices was 0.75 mm.

The process was performed manually to obtain the "blood pool" volume: thresholding algorithm was firstly applied, followed by meticulous fixing operations on the obtained mask, in order to remove over-segmented details in between heart chambers and mitigate the influence of *trabeculae carnee* presence on the surface of the ventricles. Moreover, some shells had to be removed and the mesh fixed. All these operations were performed through 3-Matic software (Materialise, Belgium, version 13), in order to be sure of obtaining a watertight mesh.

The final model consisted of the 2 ventricles, the 2 atria and the first tract of the aorta, while other vessels have been neglected for simplicity. At this point, the blood pool - i.e. the interior volume of the heart filled with blood - is obtained. A strategy to obtain the surrounding tissues is to create a shell, starting from the segmented model. Despite the thickness of the shell can be specified as variable, most of the work in the literature assign constant values, thus not reproducing the realistic thickness variation ([12], to cite an example): this would affect the mechanical properties of the final print, resulting in an unrealistic uniform behavior. To solve the problem, the following strategy has been implemented: the myocardium was segmented aside, from the same stack of images, and only in a second step, through boolean operators, it was properly merged with the shell derived from the blood pool. A graphical illustration of a step of the process can be found in Fig. 1a, where the blood pool model has a light brown color, while the myocardium is gray and semi-transparent. In this way, the wall thickness map has been replicated as faithfully as possible. For example, the atria have an average thickness of about 2.5 mm, as it can be derived from the literature for an adult healthy subject (see, for example [11]). Globally, the wall thickness ranges from 1 to more than 10 mm, in correspondence with the left ventricle [1]. The final STL file consisted of 103076 triangles, with a surface area about 829 cm^2 and a volume of about 122 cm^3.

A Stratasys Connex Object260 (Stratasys, USA) printer was employed. It implements the material jetting technology, allowing to reach a resolution of the building layer up to 16 μm. Differently from other printing technologies, the material jetting can easily create multi-material objects, also realizing polymeric blends whose mechanical properties and compliance can be finely tuned. Moreover, with respect to the other 3DP technology, prints are relatively fast, with the printable volume slightly above average

	Agilus30	***Blend***
Tensile strength [MPa]	2.4 - 3.1	0.5 - 1-5
Elongation at Break [%]	220 - 240	130 - 150
Shore (Scale A)	30 - 35	36 - 50

Table 1: Mechanical properties of Agilus and the blend of Agilus and VeroWhite.

(255x252x200 mm). The employed software for preparing the job was GrabCAD Print (Stratasys, USA, version 1.49). The position and orientation of the model on the printing platform were properly set, to minimize the printing time, followed by material assignment.

The *VeroWhitePlus* and *Agilus30Clear* are the materials selected for this work. The former is a rigid and opaque resin, with good mechanical properties, while the latter is rubber-like, characterized by elongation at break equal to 220-240%, as declared by the producer. As support, SUP706 has been selected: it dissolves in a solution of caustic soda and sodium metasilicate. Preliminary tests were conducted exploiting a single material: a blend between *VeroWhite* and *Agilus* was adopted, varying the relative proportion and so the global shore hardness: in this way, however, we had always to keep a balance between the resulting properties of thin atrial wall and the thicker ventricle one. The results was not satisfactory, hence the model has been divided into two parts: to guarantee the possibility of a differentiated material assignment, the STL model has been split into two parts, exploiting Boolean functions applied to the model. The process was always performed in 3-Matic environment and the result is shown in Fig. 1b. In this way, the materials assignment was easier: for the thin atria walls a blend of 60% VeroWhite and 40% Agilus, with a final shore hardness equal to 50 A, was chosen, while for the thicker ventricles pure Agilus, whose shore A hardness is 30, was thought to be the best choice. The mechanical properties of the two materials, as declared by the supplier, are summarized in the Tab. 1.

The overall printing time was about 14 hours. At the end, the model was soaked in soda solution for about 2 hours, then support structure was manually removed, with the help of water jet. After the final washing, the model was ready, as can be seen in Fig. 2. The print is translucent, with a very smooth surface, characterized by excellent finishing and reproduction of anatomical details. The distensibility was qualitatively assessed: the behavior of the portion made with the blended material is very good, characterized by high deformability and elastic recovery. On the contrary, the portion made of pure Agilus has a different behavior: in correspondence with the right ventricle, where the wall is not so thick, properties are satisfactory, while at the left ventricle location, where the wall is much thicker, the model results to be a bit too stiff and not adequately deformable. As regards the transition from a material to the other, no clear distinction is perceptible both from a visual and a tactile point, suggesting excellent integration between parts.

Conclusions

With this first phase of the work we were able to produce a realistic compliant patient-specific heart model. However, the make it effectively useful in clinical practice, some improvements are needed. First of all, the mechanical behavior should be fine tuned, in order to reach a better agreement between the printed model and its biological counterpart. We understood how, if we want a fully complaint model printed with this kind of technology, the wall thickness must be not to exceed a certain threshold: indeed, even if the softest available material was chosen, the walls with a thickness close to 10 mm end up to be rigid eventually. A solution could be artificially tuning the wall thickness and the material blend, in a way that the final behavior of the printed object is consistent with our expectations. Preliminary, a methodology for mapping and rescaling the mechanical properties of the heart on the set of materials available for the printer would be desirable, too. In this way, acting on the thickness of the walls and the material blend, an optimization procedure whose objective would be to confer at the printed heart similar

Fig. 2: Print result, after supports removal and washing.

stiffness of the real one could be possible. To this end, a deeper understanding of the biomechanics of the heart and the capability of predicting the behavior of the printed materials are needed. To the best of authors' knowledge, such knowledge is not available in the literature.

Experimental tests both on the materials themselves and on the printed model would be useful to acquire that information. Static and cyclic loads conditions should be conducted, comparing obtained data with those ones that can be found in the literature, also to enlarge the range of potential applications for our model.

Besides the qualitative evaluation, the dimensional accuracy of the print, with reference to the original STL models, could be evaluated. Here, the NextEngine Ultra HD laser scanner had been used. It is a multi-stripe triangulation-based laser scanner, equipped with a rotating table. In this way the acquisition, exported as a point cloud, can be compared with the original STL file. It is a very important question, if we want to understand how our replica is faithful to the original, by a dimensional point of view.

Another key point is related to the heart valves in the printed models. From CT images that were available, these structures cannot be effectively isolated: for this reason, they are not present in our model. The combination of the CT images with ad-hoc imaging techniques, such as 3D echocardiography, would be able to capture valves leaflets, allowing us to enrich the model in sense. Even the introduction of an accurate replica of *chordae tendineae*, cords of connective tissue that connect the papillary muscles to atrioventricular valves, would be a very demanding challenge. Another goal is related to the possibility of speeding up and automating the segmentation procedure, in order to make this technology more suitable for operative environments. Segmentation is a very time-consuming and tedious activity, subject to intra- and inter-observer variability and requires dedicated expert operators [2], especially in case of very complex anatomies. For example, the process to obtain our hollow heart model, from the raw images to the final smoothed model, without considering the printing phase, took the operator a few tens of hours. In order to implement an effective technology transfer to an operating environment, one week-person to provide clinicians with a patient's model could be in many cases excessive. Novel techniques that allow automatic segmentation of complex cardiac and extracardiac structures (e.g. atlas-based segmentation) are gradually taking place, making 3DP easier to be effectively operated in clinical contexts [7], but we are still far away from accessible and robust tools.

To conclude, a simple cost analysis can be done. In general, 3DP technology has now reached a cost that is not prohibitive [3]. Indeed, prices of 3DP printers for this kind of application have noticeably decreased in recent years, giving the possibility to multiple subjects to access them. This is especially true for Fused Deposition Modelling (FDM) or Stereolithography (SLA) printers, while for printers as employed in this work costs are still a bit higher. Excluding the cost of the machine itself, the price for the raw material is affordable (excluding the support, the weight of our model is about 500g, with a cost per kg of resins of about 300€). We have also to consider that in many cases just specific portions of the heart can be printed, according to the particular needs: in this way, costs further reduce. The other potential cost item is given by segmentation software license: even if nowadays valid open-source segmentation solutions are available, they are oftentimes limited to research activities and not mature for a real operative environment. Even if with some limitations, open-source solutions anyway can guarantee accurate segmentation results in most of the cases. The need for well-trained personnel, with competencies ranging from Medicine to Engineering, is however a must to get successful results.

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