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On the Use of Modeling, 3D Reconstruction, and 3D Printing Methods to Improve Simulation-Based Training in Cardiology

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***Abstract*—Simulation in healthcare originates from risky intervention. This training method is nowadays essential and aims to help medical students master medical and surgical gestures. Also, it reduces and limits medical error frequency. Cardiac catheterization allows doctors to place a stent inside a blocked artery in order to hold it open and prevent it from blocking again. This technique remains both frequent and delicate. Therefore, the use of a simulator before practicing it on real patients will allow doctors to acquire good gestural techniques. From this perspective, this paper deals with the creation of a stenting simulator called "Sim-Heart Abulcasis". Therefore, it is a two-part project, the first one consists of reconstructing a heart volume based on CT scans and then printing it in PLA material. The second is modeling a stent using SolidWorks software and then printing it in resin material. Finally, both printed pieces were fused to create a simulator prototype.**

***Index Terms*—Medical Simulation, Cardiac Catheterization, 3D Reconstruction, 3D modeling, 3D Printing, Stent, Heart, Heart-Sim Abulcasis, CT Images**

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I. Introduction

Coronary Artery Disease (CAD) is the most frequent cardiovascular (CV) disease worldwide. It is caused by the development of a plaque, essentially made of cholesterol, in the walls of coronary arteries, which results in a narrowing of the artery lumen and decreases myocardial perfusion [1]. The global prevalence of CAD was 154 million in 2016, representing 32.7% of the global burden of CV disease and 2.2% of the overall global burden of disease [2]. It is the third leading cause of mortality worldwide and is associated with 17.8 million deaths annually [3]. In addition to pharmacological treatment, the management of CAD mainly relies on cardiac catheterization, known as stenting, especially in acute occlusion of the coronary arteries known as an acute coronary syndrome. The costs of the intervention are not neglectable as the patients have to pay hundreds of dollars for a single stent. Moreover, the procedure of stenting needs long training to insure the patient maximum safety and efficient results. For example, training a physician on a specific part of coronary stenting, which is the use of radial artery access, would cost over 11,000$ according to a recent study in the United States [4]. For more than 20 years now, simulation-based training has emerged as the cornerstone of medical education, allowing quality training in complete safety for patients. Cardiology in general is described as an ideal field for the use of simulation techniques to teach both technical and communication skills [5]. To this effect, simulation is an imitation of how a real-world process or system works over time. It refers to the process of creating a virtual or physical representation of a system in order to investigate its behavior and analyze its performance [1]. Simulation training has been known for improving quality and safety in a variety of sectors, including the military, aerospace, and health care. In the particular case of health care, a simulation is an alternate approach to education that mimics real clinical practice contexts. Using realistic equipment such as manikins, procedural simulators, virtual environments, or software, students can experience rare or high-risk scenarios and acquire cognitive, emotional, and psychomotor skills in a safe practice environment [2], [3]. In addition, simulation can also be used as an alternative to issues such as students' lack of confidence in delivering real-world patient care [4]. Angélique du Coudray's delivery manikin was born in 1759 in order to train many midwives and doctors [6]. In 1960 Resusci Annie was designed in order to practice rescue techniques, in memory of a French drowning victim from the River Seine [5]. Thus, it was originally conceived for the practice of mouth-to-mouth breathing, cardiopulmonary resuscitation, and chest compressions. In 1968, Dr.Harvey designed the first model that uses the modern concept of task simulator, hence arterial pressure and cardiac auscultation, to determine heart abnormalities [7]. Meanwhile, Doctors Judson Denson and Stephen Abrahamson created a computer-controlled manikin called Sim One [8]. The first immersive operating room was developed in 1987 by Dr. David Gaba using computer software. It was first dedicated to Continuing Medical Education and then to Initial Medical Training in 1992 [6]. As a result of the development of computing and video games by the late 1990s, the provision of training in medical simulation has been reinforced with the emergence of task simulators, 3D printing, and the creation of virtual environments [9]. Therefore, the creation of a stent implantation simulator through 3D modeling and printing techniques will allow students to better master this intervention, and thus reduce x-ray exposure time [10]. The rest of the paper is organized as follows. Section 2 reviews the recent works of stent modeling. Section 3 depicts materials and methods. Section 4 is devoted to the results. Section 5 depicts the discussion. Finally, conclusions are mentioned in Section 6.

II. State-of-the-Art

Stent modeling is an important tool for medical device design, testing, and simulation. It can help medical professionals optimize stent design and placement, and improve patient outcomes by reducing the risk of stent failure and complications.

Recently, many researchers have been interested in stent modeling and printing. Boyer et al. [9] described the fabrication of biliary stents using 3D printing technology and a biocompatible synthetic polymer. They coupled collagen injection molding with XL-PVA 3D printing to create hepatobiliary stents. Finally, the authors found that the 3D-printed stents could maintain shape and function over time. Zhao et al. [11] explored the use of a homemade 3D printing system to fabricate polymeric stents. The authors found that the stents could maintain their shape and mechanical properties, and could potentially be used as vascular stents in the future. Thomas et al. [12] introduced the use of 3D printing to create a model of the extrahepatic biliary ducts, which can be used to test the performance of biliary stents. The authors found that the 3D printed model was able to accurately simulate the in vivo environment of the biliary ducts. Wu et al. [13] explored the use of 3D printing to fabricate polylactic acid (PLA) vascular stents with a negative Poisson's ratio structure. The authors found that the 3D-printed PLA stents exhibited improved mechanical properties compared to traditional PLA stents. Singh et al. [14] proposed the fabrication of polymeric stents reinforced with carbonyl iron powder using 3D printing technology. The authors found that the 3D-printed stents named ABBOTT BVS1.1, PALMAZ-SCHATZ, and ART18Z had improved mechanical properties compared to traditional polymeric stents. Also, the in vitro biological characterization showed that the printed stents showed effective hemocompatibility and thromboresistance. Xu et al. [15] proposed a new stent based on three-dimensional printing and molding equipment with the independent intellectual property of polylactic acid (PLA). The mechanical properties of the stent have been analyzed by the finite element method. Also, the authors studied the effects of mechanical, geometry, temperature, and printing speed properties. They found that the 3D-printed blood vessel exhibited good biocompatibility and mechanical properties. Lin et al [16] introduced the use of 3D printing to fabricate flexible polymer stents that can be customized to the patient's anatomy. Also, it permits handling the problem of its migration into the stomach. The authors found that the 3D-printed stents had good mechanical properties and could potentially be used in clinical applications. Lee et al. [17] proposed the use of 3D printing to fabricate biodegradable cardiovascular stents using poly (l-lactic acid). For this reason, they designed a manufacturing platform and improved the blood compatibility and anticoagulation activity of the stent. Finally, the authors argued that the 3D-printed stents exhibited good mechanical properties and biocompatibility. Guerra and

Ciurana [18] described the use of 3D printing to fabricate bioabsorbable stents that can degrade over time. The authors argued that printing speed, nozzle temperature, and path are the most important factors for dimensional accuracy. Also, they found that the 3D-printed stents had good mechanical properties and biocompatibility. Table I summarizes the existing stents.

III. MATERIALS AND METHODS

In this section, an overview of heart anatomy and the most frequent cardiovascular pathologies are described. Then, 3D modeling and reconstruction software are introduced. Finally, 3D printers used for both heart and stent printing are presented.

A. Heart Anatomy and Pathologies

The heart is a muscular organ, located in the thoracic cage behind the sternum, and shifted slightly to the left in most individuals. The heart functions as a pump that, through its regular contractions, propels blood throughout the body and thus ensures the supply of oxygen to the entire body. Every day, the heart pumps about 8,000 liters of blood, and the contractility of the heart consumes a lot of oxygen. In fact, 5% of the cardiac output is dedicated to the perfusion of the myocardium, through the coronary network [19].

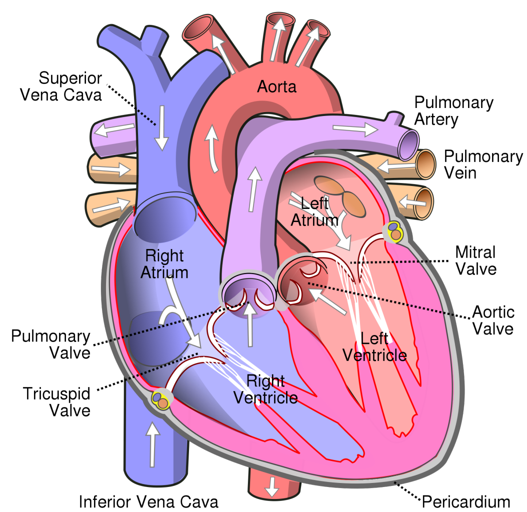

Fig. 1. Heart anatomy

The coronary arteries are a vital component of the circulatory system that supplies blood to the heart muscle. These arteries come from the aorta, which is the largest artery of the body and are responsible for supplying oxygen and nutrients to the heart. The right coronary artery originates from the right aortic sinus and divides into the marginal and posterior interventricular branches. The left coronary artery arises from the left aortic sinus and further divides into the left anterior descending and circumflex branches 1. The left anterior descending branch supplies blood to the anterior wall of the left ventricle and the interventricular septum, while the circumflex branch supplies blood to the lateral and posterior walls of the left ventricle. Coronary arteries have a unique anatomical structure that enables them to resist the high pressure and pulsatile flow of blood from the heart. [20]. When coronary circulation is interrupted or reduced by the presence of atherosclerotic plaque, coronary angioplasty comes as an effective solution in the treatment of coronary stenoses through the deployment of a metallic stent that insure compression and dissection of atherosclerotic plaque in the diseased vessel wall [21].

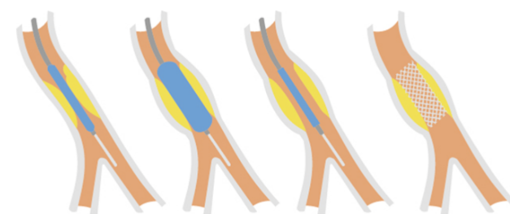

Fig. 2. Schematic deployment of a coronary stent

Nowadays, angioplasty treatment using stents is not without danger and complications. The post-procedure outcome varies depending on the characteristics of the stenosis, the patient, the practitioner, and the choice of the stent [22]. The most commonly used stents today are Drug-Eluting Stents (DES), but they have several shortcomings, including inhibition of normal late-stage coronary vasomotion and induction of long-term inflammatory responses (Fig. 2). A new generation of Bioresorbable Stents (BRS) is being developed, and expected to overcome the limitations of DES. During degradation, the absorption of BRS potentially helps improve the positive remodeling of coronary arteries, preserve vasoreactivity, reduce the incidence of stent thrombosis due to the absence of foreign materials, and inhibit edge vascular response [23]. This news has inspired our team to work on modelization and 3D printing, having as a future perspective to work on BRS.

B. 3D Reconstruction Software

1) 3D Slicer: is a free, open-source, flexible, and modular software platform with an active and large user community. It allows the use of medical image analysis, processing, registration, segmentation, and visualization techniques. Also, it ensures navigating and planning image-guided systems. The software has a complete interface with a broad range of functions, as well as free online videos and documentation. Moreover, it supports multi-modality imaging including, MRI, CT scan, ultrasound, microscopy, and nuclear medicine. This software offers advantages such as performing 3D reconstructions from 2D images taken by different modalities of medical imaging, as well as segmenting images using different tools.

2) Meshmixer: is a 3D modeling software developed by Autodesk that enables users to create, edit, and manipulate 3D meshes. Meshmixer disposes of a wide range of features such as hole filling, mesh smoothing, boundary zippering, auto-repair, plane cuts, mirroring, and boolean functions, making it useful for a wide range of applications, including product

TABLE I
COMPARISON OF THE EXISTING STENTS.

Stent	Material	Method
Boyer et al. [9]	Polycaprolactone (PCL)	SolidWorks
	Chitosan	3D printer (resin-SLA)
3D modeling		
Zhao et al. [11]	Polylactic Acid (PLA)	3D modeling
	Homemade 3D printer	
Thomas et al. [12]	3D printer (Elastic resin-SLA)	3D modeling
	Autocad Fusion360	
Wu et al. [13]	Polylactic Acid (FDM-PLA)	3D modeling
	(AutoCAD)	Negative Poisson's Ratio (NPR)
Singh et al. [14]	Carbonyl Iron Powder (CIP)	Solvent Cast Three-dimensional
	Reinforced Polycaprolactone	Printing (SCTP)
	Private 3D printer	
Xu et al. [15]	Polylactic Acid (PLA)	Finite Element Method (FEA)
		SolidWorks
Lin et al [16]	Polylactic Acid-Thermoplastic	3D modeling
	Polyurethane (PLA-TPU)	
	COMSOL	
Lee et al. [17]	Polylactic Acid (FDM-PLA)	3D modeling
Guerra and Ciurana [18]	Polycaprolactone (PCL)	3D modeling
	Private 3D tubular printer	

design, 3D printing, and digital sculpting. Also, Meshmixer enables users to both import and export different file formats, such as OBJ, PLY, and STL, and mix multiple templates to generate complex designs.

C. 3D Modeling Software

SolidWorks is a computer-aided design software that is used by a large community, including designers, product engineers, architects, construction planners, and mechanical engineers. It aims to create, edit, and design 3D models using a variety of tools, such as sketching, extruding, revolving, lofting, or sweeping. Also, the software provides a range of simulation and analysis tools that allow users to test, validate, and visualize their designs before they are manufactured.

D. 3D Printers

1) Volumic Stream 30 Ultra 3D PLA printer: In order to print the patient's heart 3D volume, Volumic Stream 30 Ultra 3D printer was used (Figure 3. It is a fused deposition modeling (FDM) printer that uses a 1.75 mm filament. It achieved a printing precision X/Y of 15µ and a precision Z of 1µ and a print resolution: from 1 micron to 275 microns. It supports different materials such as PLA, ABS, NINJAFLEX, NYLON, PETG, etc and It has a Large print volume of $295 \times 200 \times 300$ mm.

2) NextDent 5100 3D printer: NextDent 5100 is a 3D printer developed by 3D Systems. It uses stereolithography (SLA) technology to produce high-quality, accurate 3D volumes. SLA stands for stereolithography which represents a 3D printing technology using laser technology to cure a liquid resin. In photopolymerization, a liquid resin is exposed to light in a specific pattern, causing it to harden and form a solid object layer by layer. The build platform is then lifted slightly, and the process is repeated, layer by layer until the entire object is formed.

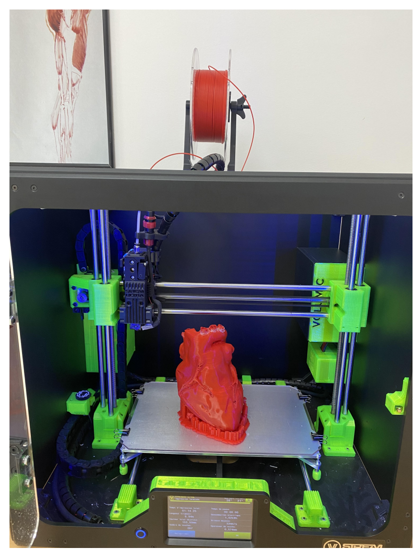

Fig. 3. Volumic Stream 30 Ultra 3D PLA printer

IV. EXPERIMENTS AND RESULTS

In this section, we deploy the results of the 3D reconstruction of a real patient's heart as well as stent modelization and simulation.

Fig. 4. NextDent 5100 3D printer

A. 3D Reconstruction of a Real Patient's Heart

To create a 3D reconstruction of a real patient's heart, medical imaging techniques such as CT scans or Magnetic Resonance Imaging (MRI) are typically used. These scans produce a series of 2D images that can be processed using specialized software to create a 3D model of the heart.

As shown in Figure 5, the process of creating our "Sim-Heart Abulcasis" typically involves the following steps: 2D image acquisition, image segmentation, 3D reconstruction, and finally 3D printing. Once the 3D model is printed, it can be used for a variety of purposes, such as surgical planning, medical education, or research.

1) 3D Slicer Software: In order to generate a real Cheikh Zaïd international hospital patient's heart 3D volume on 3D slicer software, DICOM CT scans (Digital Imaging and Communications in Medicine) were used. The " Crop Volume " tool was first used to target the heart on the image. Then " Segment Editor " functions were used to identify the contrast between different parts of the image and highlight the heart in a green color. A 3D volume of the segmented structures was finally created using the "Volume rendering tool" as shown in Figure 6.

2) Meshmixer Software: After creating a 3D volume filled inside using 3D Slicer software, a hollow aspect of the heart and arteries was reproduced using the shell function on Meshmixer Software (Figure 7). After sectioning the heart, many residues were presented inside the cavity. Therefore, the "select-del" function was used to remove them. The shell function did not allow the pulmonary arteries, the aorta, and the arteries of the pulmonary trunk to be pierced, so they had to be cut using the "Extrude" tool.

Nevertheless, 3D Slicer failed to recognize the vena cava, brachiocephalic trunk, common carotid and left subclavian artery. They, therefore, were modeled by hand as depicted in Figure 8. This is necessary in order to be able to attach the pipes to them during the manufacture of the simulation device.

3) 3D Printing: The 3D-created volume of the patient's heart was printed using Volumic Stream 30 Ultra 3D PLA printer. The general properties of PLA are mentioned in Table II. Pipes were fixed at the level of the inferior vena cava and the left subclavian artery to make the simulator base more realistic. Figure 9 shows our simulator named "Sim-Heart Abulcasis".

TABLE II
PLA PROPERTIES

Property	**Value**
Fiber diameter (mm)	1.75
Transition temperature of the Glass (°C)	55-65
Melting point (°C)	150-165

B. 3D Modeling of the Stent

In this paper, the stent was modeled using two main phases: 3D modeling using SolidWorks software, and 3D printing using NextDent 5100 which ensures high accuracy and precision. Figure 10 summarizes the following steps.

1) Stent Design: In order to create a 3D volume of a 30 mm stent, SolidWorks software was used. A cylinder with a diameter of 3 mm and a thickness of 0.4 mm (i.e., based on the plane of the propeller scan) located at the end of the two propellers was created. As shown in Figure 11, ten repetitions were done, at 360 degrees of the helices by selecting the section of the cylinder. This allowed to have the repetition of the propellers in a cylindrical shape.

The dimensions of a stent can vary depending on the specific type and intended use of the stent. Stents are small, flexible tubes or mesh-like structures that are typically used to support or widen narrow or weakened blood vessels, airways, or other hollow organs in the body. Figure 12 shows a computer-aided design model of the stent that is created with a thickness of 0.4 mm, a diameter of 3mm, and a helix of 30mm long based on average anatomical dimensions in SolidWorks software.

2) Liquid Flow Simulation: Furthermore, a simulation in terms of blood flow and blood pressure was done on SolidWorks software. Blood flow pressure simulation was simulated in order to identify the capacity of the proposed stent to bear the passage of the liquid that will simulate blood. Figure 13 depicts the plot of the pressure in the stent cavity and runner domains at the end of the filling phase. The pressure at the regions that fill last (End of Fill) is close to zero.

Moreover, liquid velocity magnitudes in different points of the proposed stent were also represented on SolidWorks. It indicates the liquid flow speed in a specific direction. Figure 14 plots the velocity vectors (i.e., direction and magnitude) of the moving melt front at each location as it passes through the stent cavity during filling. This shows that the maximum velocity occurs at the center of the stent and the minimum velocity at the stent walls.

Figure 15 shows the relationship between the velocity and static pressure of liquid flowing through a cylinder. The y-axis represents the normalized scale from 0 to 1, and the x-axis represents the iterations. The plot shows that as the velocity of the liquid increases, the pressure decreases, following a negative correlation between the two variables. This suggests

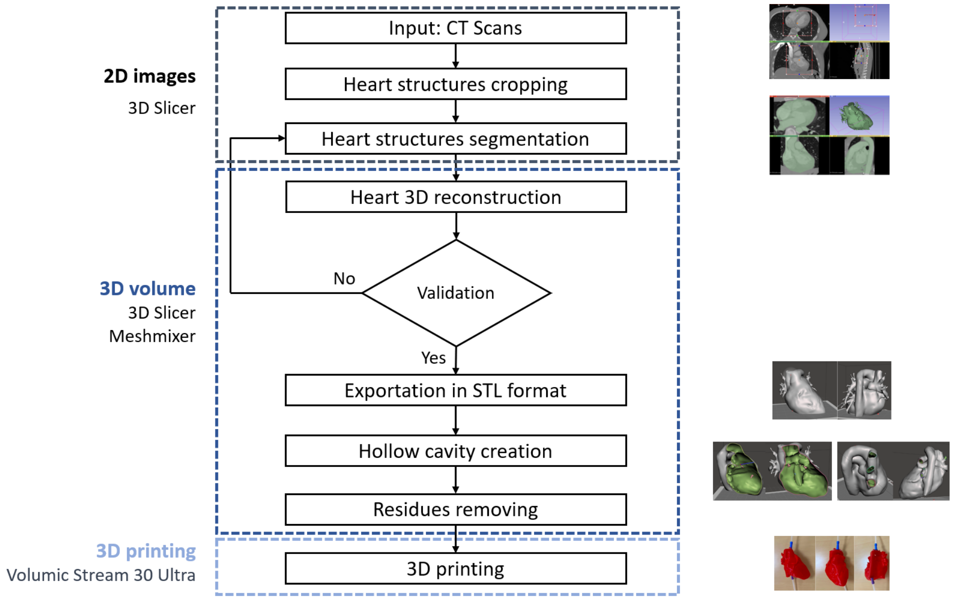

Fig. 5. Overview of the creation steps of "Sim-Heart Abulcasis" simulator

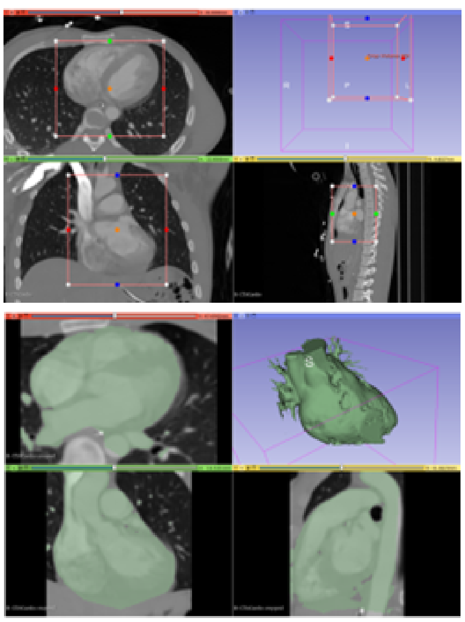

Fig. 6. Heart scan reconstructed on 3D Slicer

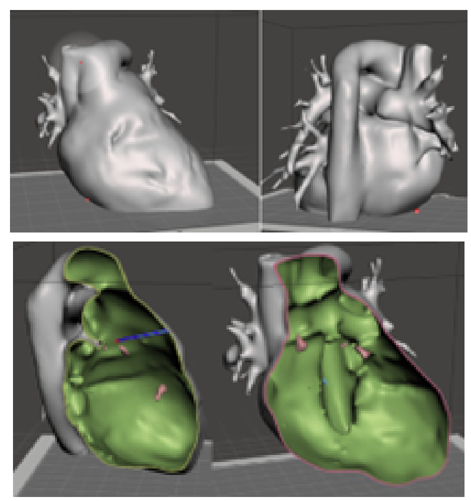

Fig. 7. STL file uploaded on Meshmixer

that at higher velocities, the pressure drop in the cylinder is more significant.

3) 3D Printing: After evaluating these simulations, the analysis of the results proved that the stent does not negatively impact blood pressure and flow when placed in an artery. Moreover, This size correlates with the diameter of conventional stents when folded. Finally, The model was exported as a ". STL" file and printed in resin in order to have better precision. Figure 16 depicts our 3D-printed stent.

V. Discussion

It is not obvious for a simulation center to set up a simulation of coronary angioplasty with normal stents because it would be too expensive. Indeed, a stent can cost up to 800$ and once it is unfolded, it cannot be folded up to be used again. A new stent must therefore be used for each simulation. For this reason, it is very interesting to print a stent in 3D to allow an unlimited number of training sessions on the procedural simulator. The proposed simulator called "Sim-Heart Abulcasis" proved to be quite realistic. Thus, this simulator can be used to help medical students master stent implantation in patients' 3D-printed hearts, and therefore make them avoid any complications due to mishandling. In addition, better training on the proposed simulator will reduce

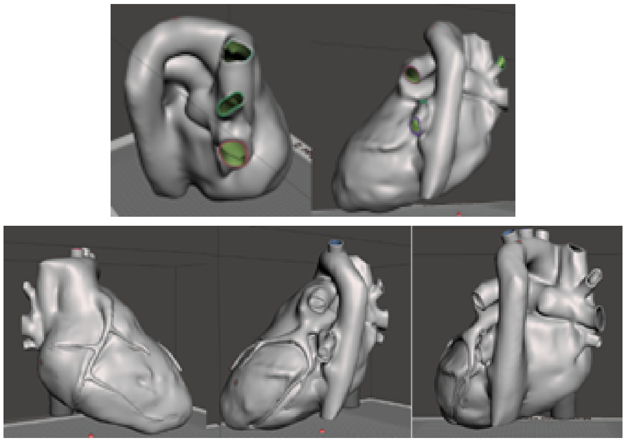

Fig. 8. Coronary artery reconstruction

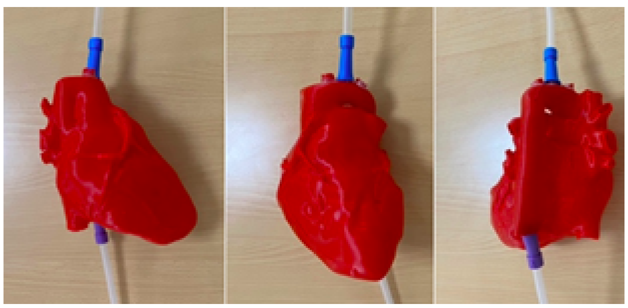

Fig. 9. 3D printed ”Sim-Heart Abulcasis”

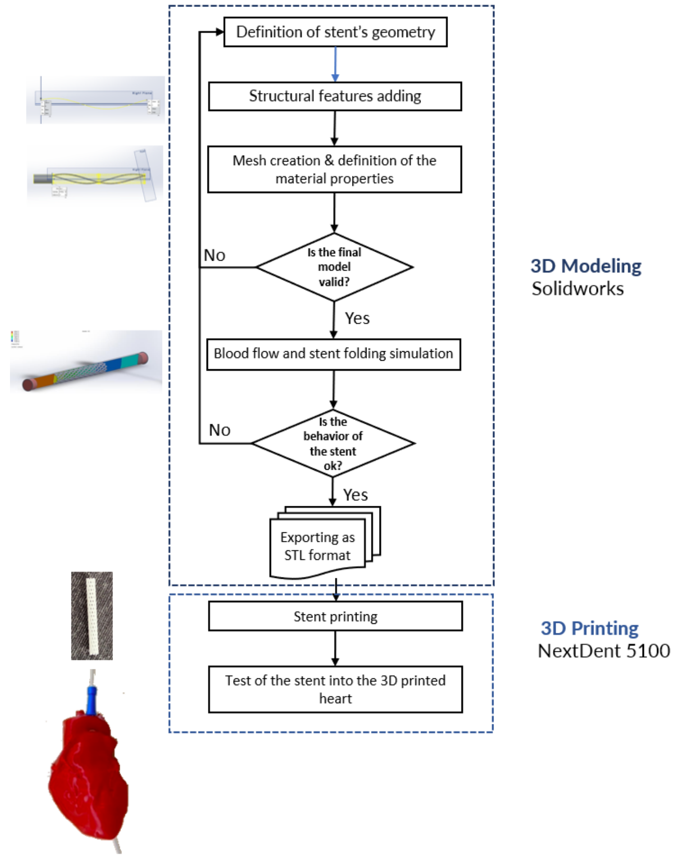

Fig. 10. Overview of the creation steps of the stent

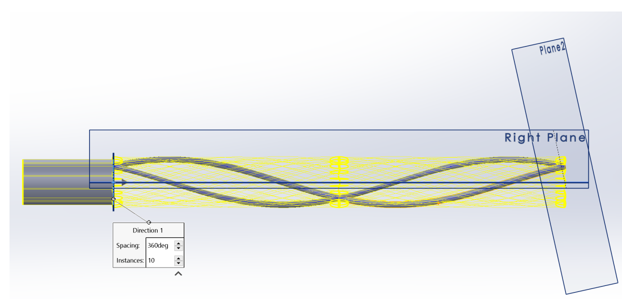

Fig. 11. Extruding a cylinder and repeating helices

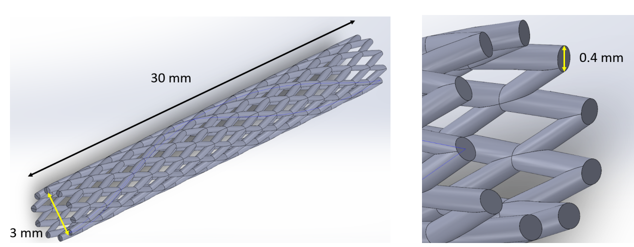

Fig. 12. Modeled stent dimensions

the surgery duration by enabling doctors to better manage their time. Consequently, this will allow students to better manage this intervention, and thus reduce x-ray exposure time.

VI. Conclusion

In conclusion, the objective of this paper is to set up a simulator, allowing students to reproduce gestures that can be delectable or difficult. The work was split into two parts. On one hand the 3D reconstruction of the heart that is the base of all simulations. In the other hand, the 3D modeling of the stent that will be introduced into the printed heart and as a prospect, we can imagine other seats and improve other functionality on the same simulator and seek to develop numerical models to simulate the behavior of stents. All of these factors are part of the new ability of 3D printing to promote teaching and training methods. The proposed simulator ”Sim-Heart Abulcasis” can be adapted to different heart diseases.

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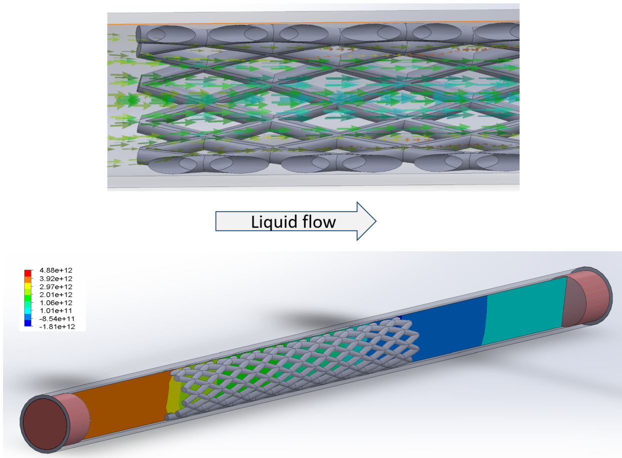

Fig. 13. Top: A liquid flow direction. Down: A static pressure simulation at iteration=56 (in Pa)

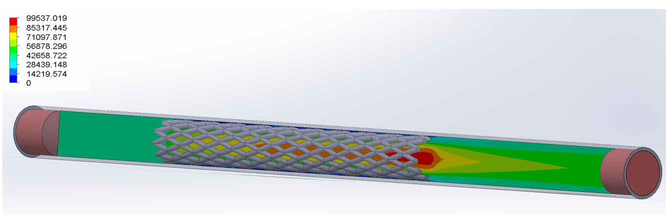

Fig. 14. Velocity simulation at iteration=56 (in m/s)

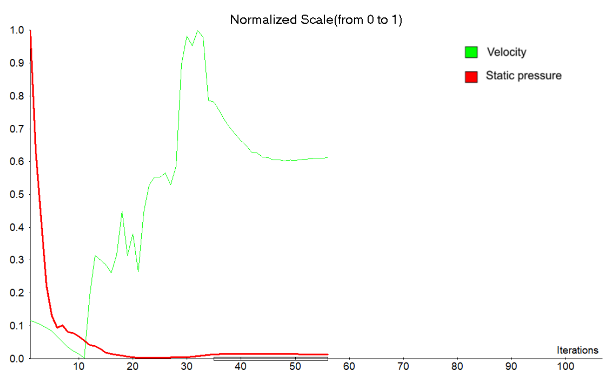

Fig. 15. The relationship between the velocity and static pressure

Fig. 16. Printed stent

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