State of the art in 3D printing of compliant cardiovascular models: HeartPrint

Material characterization of HeartPrint models and comparison with arterial tissue properties

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***Abstract* — Over the years, catheter-based interventions have gained popularity for the treatment of cardiovascular diseases and became daily practice. However, the errors in manual catheter-based interventions remain too high which motivates the use of precisely controlled robotic catheters. CASCADE, a recent EU-funded FP7 project has been set up to investigate autonomous catheter control for endovascular aortic valve replacement procedures. Robotic surgical skills will be learned and assessed on an artificial test-bed which should mimic the anatomy and behavior of the real vasculature. Therefore, this paper presents both the design and the material properties of the 3D printed compliant vascular model used in the test-bed setup. It was found that the HeartPrint™ flex 3D printing process was capable of creating flexible models with a Young's modulus and distensibility that are within the range of human arterial tissue properties. Thus besides the correct anatomical representation of the aorta, the designed model also mimics the material behavior of the real anatomy.**

Keywords—3D printing, cardiovascular, HeartPrint, material characterization

I. Introduction

Catheter procedures are amongst the most common medical interventions used to treat cardiovascular diseases. However, errors in manual catheter-based interventions remain too high in medical practice [1]. The use of precisely controlled robotic catheters can make an important contribution in this context. A new European research project ("CASCADE", Cognitive AutonomouS CAtheter operating in Dynamic Environments) has been set up in order to advance the treatment of cardiovascular diseases, by providing a new dexterous and intelligent (self-aware, self-exploring) robotic instrument, initially focusing on endovascular aortic valve replacement.

Robotic surgical skills will be learned and assessed on a representative artificial test-bed prior to transferring this to cadavers, animals, and ultimately to patients. The test-bed will further help in the development of techniques for real-time 3D reconstruction and finite element simulation of the vasculature, to investigate safe and reliable exploratory strategies and to validate procedure outcome in terms of successful procedure execution. This test-bed consists of a realistic cardiovascular system, i.e. the bench-top model, along with simple actuation systems to replicate physiological motion due to respiration and the cardiac cycle.

The focus of this paper will be on the design of the bench-top model and its material properties, which ought to be comparable to human artery mechanical properties.

II. Materials and Method

The bench-top model is a transparent, flexible model of the aorta, from the aortic valve to the common iliac artery, and includes the main side branches (Figure 1). Based on a CT scan, the Mimics Innovation Suite® (Materialise, Leuven, Belgium) was used to obtain the virtual 3D reconstructed aortic model and to prepare it in a printable format. Afterwards, the bench-top model is printed using the Materialise HeartPrint™ Flex technique which is capable of 3D printing the model directly from the virtual file. This 3D printing technique has several advantages compared to the traditional method for creating flexible models using the two-step approach of mold making and casting. It is less time consuming and it can go beyond the possibilities of molding for creating highly complex, patient-specific cardiovascular anatomies.

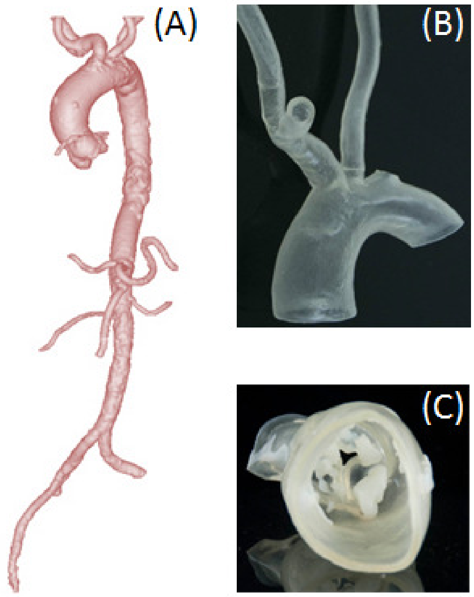

Figure 1: 3D design of the aortic bench-top model (A) and two printed segments of this model, including the aortic arch with carotids (B) as well as the valve with calcifications (C).

In order to verify whether the 3D printed aortic bench-top model mimics the behavior of the real vascular tissue, quantification of the material properties of this HeartPrint™ flex model is necessary. Therefore, based on a set of tensile and compliance tests on small samples, the material properties of the model were defined and compared with human arterial tissue properties.

Five uniaxial tensile tests, as well as 15 compliance tests, were performed to identify the ultimate strength (σ_u, ε_u), Young's modulus (E) and distensibility (D) of the material. The shape and dimensions of the samples are shown in Figure 2. For the tensile test, samples are stretched at 1mm/s and the applied force with the corresponding extension are continuously recorded. For the compliance tests, variations in internal pressure were monitored during a gradual increase and decrease of the internal volume of the samples.

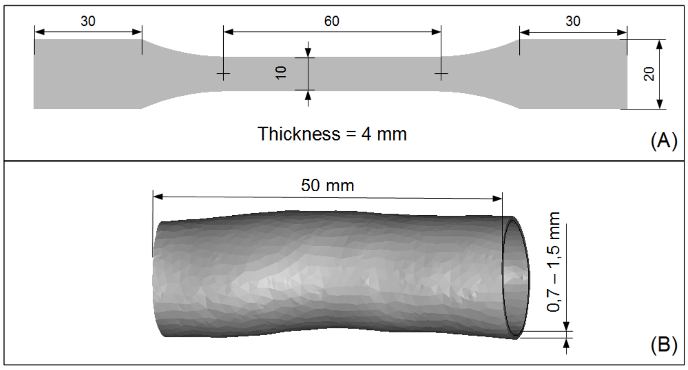

Figure 1: Schematic illustration of the samples for the uniaxial tensile test (A) and the compliance test (B). Dimensions are in mm.

III. RESULTS AND DISCUSSION

The results for the uniaxial tensile test are shown in Figure 3 with ultimate stress and strain values of 1.05 ± 0.17 MPa and 73.19 ± 6.52 % respectively. Since the stress-strain curve of this rubber-like material is highly non-linear, the Young's modulus is calculated for two different sections of the curve. A first value of E is calculated using the secant-method at the points of 5 and 25% strain resulting in an average value of E_1 = 0.91 ± 0.02 MPa. A second value of E is calculated at the point of maximum stress and has an average value of E_2 = 2.06 ± 0.23 MPa. Based on these results, it is observed that the HeartPrint™ Flex samples exhibit a stiffness which is within the range of arterial tissue. Depending on the artery (e.g. aorta, carotids, coronaries) the stiffness can vary substantially, from 0.2 MPa up to about 9 MPa [2, 3].

The results for the compliance tests are shown in Figure 4, with the distensibility of the samples varying between 1.9 – 3.7 $\times10^{-3}$ $mmHg^{-1}$ whereby a decrease in wall thickness of the samples corresponds with a decrease in distensibility. This range is comparable to the clinical range of distensibility values for various arteries, such as the ascending and descending aorta, carotid arteries and pulmonary arteries, as shown in Table 1.

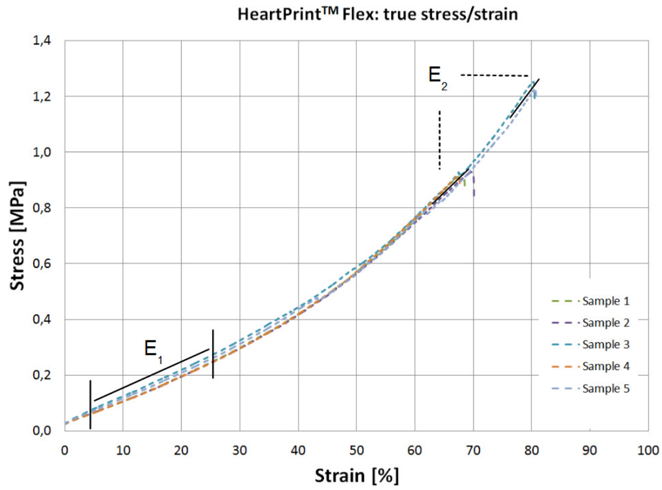

Figure 2: Stress-strain curves of the HeartPrint™ Flex samples obtained during a uniaxial tensile test.

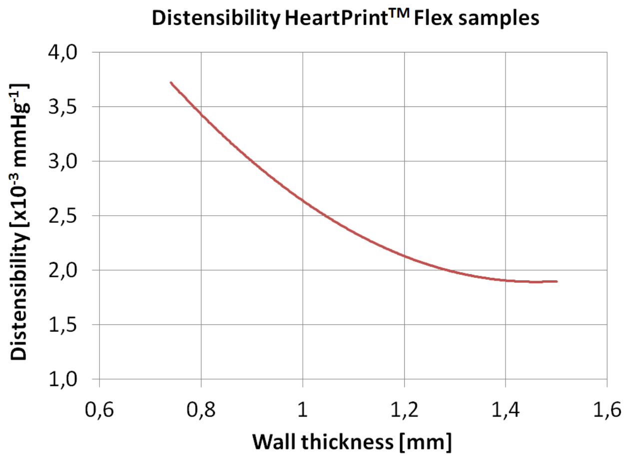

Figure 3: Distensibility of HeartPrintTM Flex samples with different wall thicknesses.

Table 1: Clinical range of distensibility values for arteries such as the ascending and descending aorta, carotids as well as pulmonary arteries, reported by various authors.

Study	Vessel	Distensibility [$\times10^{-3}$ $mmHg^{-1}$]
Chue et al. [4]	Aorta	Asc: 4.1 ± 2.1 Desc: 4.4 ± 1.7
Groenink et al. [5]	Aorta	Asc: 4.4 ± 2.2 Desc: 4.6 ± 1.5
Gan et al. [6]	Pulm. artery	4.6 ± 3.8
Lénárd et al. [7]	Carotid	3.8 ± 1.4 (static) 2.1 ± 0.9 (dynamic)

IV. CONCLUSION

The material properties of the bench-top model were determined and it was found that both Young's modulus and distensibility of the HeartPrint™ Flex model are within the range of human arterial tissue properties. The designed model does therefore not only offer the correct geometry of the aorta,

but it also mimics the material behavior of the real anatomy. These features are needed for training, accurate modeling and validation of the robotic surgical skills, all developed within the framework of the CASCADE-project.

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