Design of Coronary artery phantom using polyvinyl alcohol cryogel for Optical Coherence Tomography imaging in Kawasaki Disease

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ABSTRACT

Kawasaki disease, a childhood pathology, is marked by the potential for coronary artery complications, which can lead to the dilation or inflammation of the blood vessel wall if left untreated. Intravascular Optical coherence tomography (IV-OCT) was introduced for intravascular imaging of coronary arteries to provide valuable navigation guidance information to cardiologists. It requires a skilled operator, and the acquisition protocol is complex. The goal of this study is to present a framework to reproduce patient specific coronary OCT phantoms using polyvinyl alcohol cryogel (PVA-c), which can be used for training cardiologists and for better understanding of the OCT image formation process. This innovative approach enables us to produce phantoms with both mechanical and optical properties very similar to human tissue. To produce these phantoms, we design and print in 3D modular cylindrical molds from real OCT arterial images. A mixture of PVA is poured into the molds and submitted to three thaw and freeze cycles to create soft tissue that represent coronary arteries affected by Kawasaki disease. Once the phantoms have been created, OCT pull-back sequences are acquired and compared to the original images. We acknowledged that our PVA-c phantoms reproduces morphological shape and visual appearance on OCT very similar to human tissue. This holds true even when applied to extremely small morphologies.

Keywords: Optical Coherence Tomography, Polyvinyl Alcohol Cryogel, Coronary artery, Kawasaki Disease, Image-guided interventions

1. DESCRIPTION OF PURPOSE

Kawasaki disease (KD) is a childhood illness that presents with several characteristic symptoms, including fever, rash, bilateral nonexudative conjunctivitis, redness of the lips and oral mucosa, changes in the extremities, and swelling of cervical lymph nodes [1]. If left untreated, approximately 15% to 25% of affected children are at risk of developing coronary artery aneurysms or ectasia. These conditions involve abnormal dilation or enlargement of the coronary arteries. Subsequent complications may include intimal thickening, thrombi, stenosis, and even the disappearance of the media border. Importantly, these changes and the subsequent scarring mechanisms can significantly stiffen the arterial wall. Failure to diagnose and treat these arterial complications promptly can lead to myocardial infarction. Therefore, early detection and appropriate management of Kawasaki disease are important steps to prevent potential long-term complications. The light-based IV-OCT imaging demonstrates great promise in assessing the inner structures of coronary arteries. It utilizes near-infrared light to generate high-resolution intracoronary images ranging from 10 to 20 µm. This imaging technique allows the detection and evaluation of various properties of the arterial wall, including its biophysical and dynamic characteristics, coronary artery layer thickness, and the presence of thrombi and calcifications. However, mastering OCT to diagnose Kawasaki disease requires years of experience; training with realistic simulators could speed up the learning process bridging the gap between theory and clinical practice.

The goal of this work is to present a framework for creating patient-specific coronary artery phantoms using PVA-c. Our approach is based on the 3D modeling of the segmented OCT patient datasets. This work is organized as follows: Section 2 presents the steps of the OCT phantom development. Section 3 reports the results obtained on coronary artery phantom study using OCT imaging. Section 4 discusses the results and concludes by outlining the novelty of our approach and future works.

Medical Imaging 2024: Image-Guided Procedures, Robotic Interventions, and Modeling,
edited by Jeffrey H. Siewerdsen, Maryam E. Rettmann, Proc. of SPIE Vol. 12928,
1292808 · © 2024 SPIE · 1605-7422 · doi: 10.1117/12.3006698

2. METHODS

2.1 Design of modular molds and 3D printing

Modular molds were designed using MeshMixer software. These molds are composed of two parts, each divided into three sections to facilitate demolding. The chosen mold consists of an outer casing and an inner stem rod (Figure 1a and 1b). Common geometric shapes such as cylinders and right-angled blocks were used to design the housings. These parts were printed on a 3D printer (Prusa i3 MK3S) using polylactic acid (PLA) filament. The molds were printed to an accuracy of 0.15 millimeters. The challenges of this molding process are to accurately model the structure of the artery and its lumen, scaled 1:1, and to demold the parts without damaging the morphology of the internal walls. The stem rods were printed in resin using a 3D printer (Formlab Form3) which offers a higher precision of 0.025 millimeters. To avoid the use of supports, the parts have no hanging arms. As a result, the printed parts have holes but no assembly pins, 1/8" stainless steel pins are used instead. These cylindrical pins offer greater mechanical strength than the printed parts.

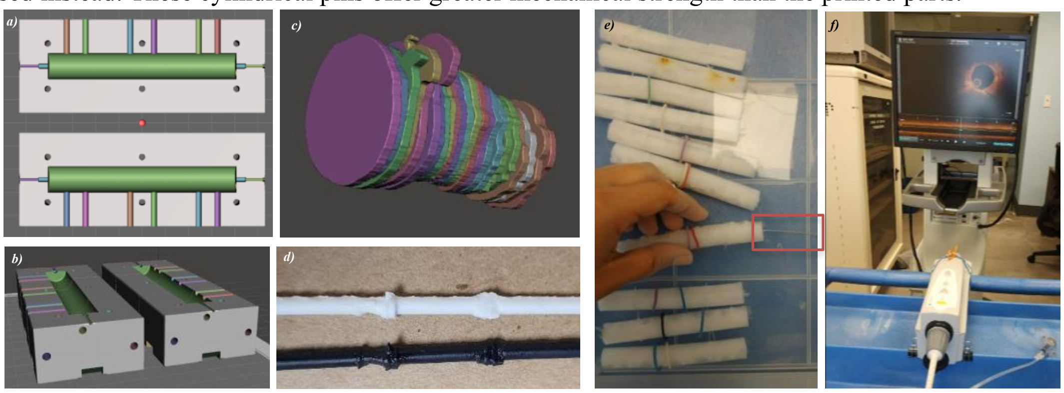

Figure 1: Design and printing of the coronary artery OCT phantom. a)b) Modular molds were designed using MeshMixer CAD software. c) 3D cross-sections (the exemple corresponds to figure 2) are manually segmented from the patient OCT images and d) modeled on a cylindrical stem rod . The stem rod is installed into a small enclosure in the mold to create the patient's anatomy. e) The red square shows the optical probe inserted in the phantom to acquire the OCT sequences f) and visualized it on the screen device.

2.2 Modelisation of coronary artery from OCT images

Two artery sections from two different acquisitions were selected for modelling. Once the artery sections have been selected, the OCT images are manually segmented. The first OCT sequence features thrombosis and is made up of 14 cross-sectional images for a total section length of 2.8 millimeters and the second OCT sequence shows a good combination of the various features and is made up of 22 cross-sectional images giving a total section length of 4.4 millimeters. From our design, the inner rod stem must be 100 millimeters long to be suspended in the outer casing of the mold. Since these coronary cross-sections are very short, the inner rod stem is formed by a cylinder with a diameter of 2.5 mm, in between these two sections of artery.

2.3 PVA-c OCT phantom

PVA-c phantoms were created from a mixture composed by 85% distilled water and 15% polyvinyl alcohol as presented in Tibamoso et al. [5]. The mixture is transparent, has a higher viscosity than water but remains in liquid form and is easy to handle. Wide opening for pouring the PVA mixture were incorporated in the 3D design of the molds. These openings are arranged in pairs to facilitate the evacuation of air from the molds and limit the formation of air bubbles. The stem rod was coated with the thinnest possible layer of petroleum jelly to facilitate the de-molding process of the phantom. Then, the phantom was submitted to a series of three freeze-thaw cycles in a custom controlled freezer. Once all cycles completed, the phantom can be demolded and immersed in distilled water to remain hydrated and retain their good mechanical properties. To image the lumen using the developed coronary artery phantom, we used Abbott ILUMIEN OPTIS Imaging System with resolution of 10 µm. The optical probe was inserted into the coronary artery phantom, and the images of the PVA-c phantom were acquired using both OCT pullback and stationary OCT. The first method involves inserting an OCT catheter into a vessel and gradually pulling it back while emitting and collecting light, in contrast in the second method the catheter remains still inside the vessel. MicroDicom was used to measure and analyze the acquired phantom images. An image editor (Gimp) was used to compare morphologies and differences observed between the clinical real images and the phantoms images.

3. RESULTS

3.1 Qualitative analysis

The lumen of the phantom was clearly recognizable in the proposed OCT phantoms, as illustrated in Figure 2. Moreover, as we increased the precision of the print of the stem, the resemblance of the imaged phantom lumen became more and more like the original image. All the OCT images presented here are the outcome of pullback acquisition.

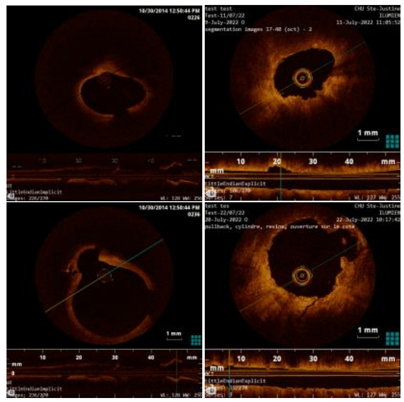

Figure 2: Comparison between original OCT images of patient (left) and the corresponding PVA-c phantom (right)

These figures have the particularity of having more pronounced morphologies than others, which facilitates their recognition in the series. Upon comparing original OCT images of patient and PVA-c phantom OCT images, a distinct resemblance in the optical response to the original artery tissue becomes evident. Notably, the morphological shape of the two images presented is readily recognizable in the phantom, considering the object's size imaged, which falls within the order of a millimeter. The increased contrast observed in the phantom images can be attributed to the presence of petroleum jelly. To preserve the morphological resemblances accurately, the most effective approach involved making a longitudinal cut in the phantom, when performed well. This step was necessary to remove the inner stem, which played a crucial role in the molding process.

3.2 Quantitative analysis

The OCT sequences of the phantoms' imaging were manually segmented and measured using the surface area of each cross-section. The resulting surface values of phantoms with the resin inner stem are generally more similar.

We utilized the MicroDicom software, making use of the available measurement tools, to assess both the PVA-c phantom and the reference OCT sequences. Additionally, we ensured uniformity by measuring the original OCT image and its corresponding phantom image aiming to minimize potential sources of errors. The measurement technique remained consistent for both cases. To be precise, our evaluation focused on the diameters along both the larger and smaller axes—this technique mirrors the approach used by cardiologists to measure real clinical cases. We have employed the same technique to assess the coronary artery's lumen in our comparative analysis. Subsequently, we determined the corresponding area and computed the percentage difference in diameters.

		Diameter in mm (Area in mm²)			
		Patient #1.		*Patient #2.*	
		OCT image 1	*OCT image 2*	*OCT image 1*	*OCT image 2*
Larger axis	*PVA-c phantom*	2.39 (4.47)	2.71 (5.75)	2.56 (5.16)	2.67 (5.60)
	Reference OCT sequence	3.13 (7.67)	3.50 (9.65)	3.79 (11.27)	3.45 (9.35)
	Difference (%)	**26.81 %**	**25.44 %**	**38.74 %**	**25.49 %**
Smaller axis	*PVA-c phantom*	1.76 (2.44)	2.45 (4.70)	1.83 (2.63)	1.47 (1.70)
	Reference OCT sequence	1.91 (2.86)	3.23 (8.17)	2.22 (3.88)	1.81 (2.58)
	Difference (%)	**8.17 %**	**27.47 %**	**17.33 %**	**20.73 %**

Table 1. Diameter measurements, Area estimations, and diameter Differences (%) of the lumen were compared between the PVA-c phantom and reference measurements from patients' OCT images. Two diameter measurements were taken along both the larger and smaller axes.

It should be noted that the size of the artery images presented an additional challenge in this study. The maximum difference in surface area compared with the reference image was around 1 square millimeter, which may seem significant given the size of the images observed. The differences are below 40% in all cases and mostly below 25%. However, this difference can be explained by several sources of error, such as distance and area measurements, segmentations, and phantom creation, internal stem extraction. Results can be improved by increasing the number of phantoms created, or by modifying the internal stem extraction method. Resin-printed internal stem offers sufficient accuracy to differentiate the different strata, and the use of metal printing could potentially further improve results, although this may not be necessary.

4. NEW WORK TO BE PRESENTED

This study presents a new approach for modelling patient-specific OCT phantoms of coronary arteries. Our phantoms are modelled using two-part process. First, modular custom-made molds were designed and printed in 3D using a PLA 3D printer. Second, resin 3D printer was used for printing the patient-specific geometry of coronary artery from OCT sequence. PVA-c was found to be a promising material for OCT imaging. While this study was validated using the intracoronary OCT images of pediatric patients affected by Kawasaki Disease, it can be extended for modeling different pathologies of coronary artery. Incorporating the automatically acquired reconstructed 3D representations, as demonstrated in the study by Abdolmanafi et al. [4], could provide a broader range of different clinical cases.

5. CONCLUSION

This study demonstrated the feasibility of creating coronary artery phantoms using PVA-c based on OCT images at small scales. The results obtained in this study showed that the coronary artery phantoms created using 3D printing with resin stem show strong resemblance to the original coronary artery images obtained from real patients. Both qualitative and quantitative measurements showcase the accuracy and similarity of the phantoms' surfaces when compared to the reference image, with minor variations. Designed PVA-c phantoms reproduce both mechanical and optical properties very similar to human tissue. Only two artery sections might not adequately represent the diverse range of coronary lesions observed in the OCT images of patients with Kawasaki disease. By incorporating a broader variety of images, the representativeness of the phantoms created could be substantially improved. This will be considered in our future study. These patient-specific phantoms offer valuable tools for training of cardiologists and for research purposes, providing new opportunities for better understanding the image formation process in OCT imaging. Future work will involve modelling of different tissue layers.

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