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Durable phantoms of atherosclerotic arteries for optical coherence tomography

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We previously reported a method to fabricate phantoms of coronary arteries. This method allows the deposition of multiple layers on a tubular structure, each layer replicating optical and mechanical properties of coronary artery layers. We now report further improvements to this method to produce phantoms of arteries affected by atherosclerosis. Different strategies used to add features such as intimal thickening, lipid pools, calcifications, and thin cap fibroatheroma to multilayered coronary artery phantoms will be presented. The phantoms can be used in training personnel to use OCT systems and to diagnose different conditions. They can also be used to develop and test procedures without requiring human or biological samples. Since they are highly durable, they can also serve as a reference for comparing results between different systems, or one system over time.

Durable phantoms of atherosclerotic arteries for optical coherence tomography

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ABSTRACT

We previously presented a method to fabricate phantoms of normal coronary arteries. This method allows the deposition of multiple layers on a tubular structure, each layer replicating optical and mechanical properties of coronary artery layers. We now present an improved method to produce phantoms of arteries affected by atherosclerosis. The method now includes techniques to introduce structures that mimics the OCT signature of a calcification and of a lipid pool.

Keywords: Optical Coherence Tomography, phantoms, atherosclerosis, arteries

1. INTRODUCTION

Intravascular optical coherence tomography (IV-OCT) has now reached a stage close to widespread clinical use. A review of the recent technology and applications of OCT in cardiology can be found in Ref. [1]. Tremendous progress has been made on the technical side and assessment of IV-OCT as a diagnostic tool in cardiology has been convincingly demonstrated. A few companies are now working towards the commercialization of the technology. Acceptance in the clinical world is under way since IV-OCT is already approved in a few countries. The field is nevertheless still missing diseased artery phantoms. These are essential to ease further development of the technology, to insure training of personnel, and to serve as calibration and validation targets. In the current paper, we present a method to produce artery phantoms containing diseased structures. We first recall our previously described method to fabricate phantoms of normal arteries. We then describe how the fabrication process is modified to introduce structures that provide the OCT signatures of a calcification and of a lipid pool. We finally present OCT images of diseased artery phantoms that were fabricated with the proposed method.

2. PHANTOMS OF NORMAL ARTERIES

In a previous communication,² we described a method to fabricate phantoms of normal arteries. These phantoms are fabricated by the successive deposition of three different layers: intima, media, and adventitia. The material for each layer is deposited on a rotating shaft while being continuously wiped to control the thickness. The setup is illustrated in Fig. 1. The material used for each layer mimics the OCT signature of a corresponding artery layer in terms of backscattering amplitude and attenuation. The material is a silicone matrix containing aluminum oxyde to provide the backscattered OCT amplitude. Aluminum oxyde also provides a certain level of attenuation that is further increased when needed by the addition of carbon black. Figure 2(a) shows a normal artery phantom. The intima and adventitia layers are white since only aluminum oxyde is used for these layers. Carbon black is introduced in the media material resulting in a black layer. Figure 2(b) shows an OCT image of the phantom with its three well defined layers. The optical properties of the layers were chosen to mimic those measured on a porcine coronary artery. Theses phantoms also mimic the mechanical properties of arteries in the low deformation regime.

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Figure 1. Setup used to fabricate multilayer tubular phantoms. The material is deposited on a rotating shaft and continuously wiped by a blade to control the thickness. The blade is inclined in the figure to show that tapered layers can be fabricated.

Figure 2. (a) Photography and (b) OCT image of a normal artery phantom.

3. PHANTOMS OF DISEASED ARTERIES

Calcifications and lipid pools provide very clear signatures in IV-OCT images.³ A calcification is characterized by low backscattering and low attenuation and provides a signal-poor region with defined boundaries. A lipid pool is characterized by high backscattering and large attenuation and provides a signal-poor region with diffused boundaries. The OCT signatures of such structures can be mimicked with inclusions made of the same material used to fabricate the normal artery layers, but with different concentrations of aluminum oxide and/or carbon black. As a first step towards phantoms of diseased arteries, we modify our fabrication method to introduce such structures in a thickened intimal layer.

The various steps of the fabrication process are illustrated in Fig. 3. We begin in Fig. 3(a) with a grooved shaft that serves as a mold for an asymmetric D-shaped lumen over a delimited length of the phantom. In Fig. 3(b), a thin layer of intima material is deposited, it covers the inclusion from a lumen point of view. In Fig. 3(c),

an inclusion is fabricated and then deposited over the intima material. Additional intima material is added in Fig. 3(d) to cover the inclusion and to fill the groove. The remaining of the fabrication process is similar to that of a normal artery. The intima layer is completed in Fig. 3(e), the media layer is deposited in Fig. 3(f), followed by the adventitia layer in Fig. 3(g). Since the phantom is made of elastic material, it is stretched to be removed from the shaft. The completed phantom is illustrated in Fig. 3(h).

Figure 3. Steps in the fabrication process of a diseased artery phantom. See text for the detailed description.

4. OCT IMAGING

Measurements were performed with a custom-built Mach-Zehnder SS-OCT interferometer using a Santec swept source with a repetition rate of 30 kHz, a bandwidth of 110 nm, and a center wavelength of 1310 nm. Images are extracted from pullbacks made with custom-built pullback unit and intravascular probe.

The OCT image of an artery phantom with a calcification is presented in Fig. 4(a). The lumen is asymmetric due to the D-shaped thickened intimal layer. The three layers are visible with the transition from the media to the adventitia being very well defined. The inclusion is made of silicone with a small content of aluminum oxide leading to small backscattering with low attenuation. Thereby, the clear OCT signature of a calcification is obtained: a signal-poor region with defined boundaries. The inclusion was made with a regular rectangular shape to enhance the clear definition of the boundaries.

Figure 4(b) presents a phantom with a lipid pool. The inclusion is made of silicone with high concentrations of aluminum oxide and of carbon black leading to high backscattering and high attenuation. Thereby, the clear OCT signature of a lipid pool is obtained: a signal-poor region with diffused boundaries.

5. CONCLUSION

We have presented a method to include diseased structures in artery phantoms. The resulting phantoms do provide OCT signatures similar to what is observed in clinical measurements. Since the material used to fabricate these phantoms is silicone, they are durable. Future work will aim at obtaining inclusions with optical properties that match more closely those of the true diseased structures. This will be possible when the needed data

Figure 4. OCT images of an artery with (a) a calcification and (b) a lipid pool.

will be more widely available in the literature. Up to now, only a few papers have addressed the quantitative measurement of the optical properties of atherosclerotic structures. Future work will also consider inclusions that are different from silicone. This will provide mechanical properties more representative of atherosclerotic structures. Future work also includes the fabrication of more complex structures, like the thin-cap fibroatheroma.

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