Visualization of blood flow in carotid artery stenting with endovascular Doppler optical coherence tomography imaging and computational fluid dynamic modeling

Barry Vuong[1], Helen Genis[1], Ronnie Wong[1], Joel Ramjist[1], Jamil Jivraj[1], Carry Sun[1], Victor X.D. Yang[1,2,3,4,*]

[1]Biophotonics and Biomedical Engineering Laboratory, Department of Electrical & Computer Engineering, Ryerson University, Toronto, Canada
[2]Physical Science - Brain Sciences Research Program, Sunnybrook Research Institute, Toronto, Canada
[3]Division of Neurosurgery, Sunnybrook Health Sciences Centre, Toronto, Canada
[4]Division of Neurosurgery, Faculty of Medicine, University of Toronto, Toronto, Canada
[*]corresponding author: yangv@ee.ryerson.ca

Abstract Carotid artery stenting (CAS) is currently the standard of care for carotid atherosclerotic lesions. The goal of CAS is to provide support for the arterial wall and attempt to restore normal blood flow; however, placement of a stent causes significant alterations to the treated artery's vascular morphology and hemodynamics. The presence of stagnant or recirculation zones around the stent struts could promote thrombogenesis, leading to post-procedural complications such as stroke. The risk of post-procedural complications can further be increased when the stent is malappositioned. Alternatively, the treated arterial wall could revert back to its narrower state (restenosis). Currently, the factors that cause post-procedural complications are not well understood. Furthermore, clinical imaging modalities lack the resolution to measure the local hemodynamics in diseased arteries. In this study, we utilized an emerging high resolution (1 to 10 μm) and minimally invasive optical imaging system known as endovascular optical coherence tomography (EV-OCT). EV-OCT imaging is analogous to ultrasound; however backscattered light is measured instead of sound. Fiber optic catheters were inserted into the subclavian artery (SA) and common carotid artery (CCA) of porcine models following carotid stent deployment. Cross-sectional velocity profiles were acquired through a function variant of EV-OCT termed endovascular Doppler optical coherence tomography (EV-DOCT). EV-DOCT images visualized velocity contours around the stent struts within the SA or CCA. Computational fluid dynamic (CFD) models were employed to provide further insight into the local hemodynamics. The dimensions of the artery and virtual stent CFD model were measured and constructed based on EV-OCT images. A time-dependent velocity profile of a human internal carotid artery was used as the inlet parameter. Correlation between hemodynamic events from EV-DOCT images and CFD models were observed. More specifically, low to stagnant regions of flow were resolved around stent struts. These regions have been suggested to promote thrombogenesis. EV-DOCT has the potential to provide real-time monitoring of the stent placement, as well as to determine improper stent placement and malapposition more accurately than carotid angiography. Characterization of hemodynamic events could provide insight into the cause of post-procedural complications.
Keywords: Optical Coherence Tomography, Doppler Imaging, Computational Fluid Dynamic modeling, Medical Imaging

1 Introduction

Carotid atherosclerotic lesions in the arteries are a key factor in the cause of ischemic stroke [1]. These lesions are generally characterized by a narrowing of the artery restricting blood to the brain. A minimally invasive technique to widen the artery and restore blood flow is the deployment of a Nitinol stent. Studies have shown that carotid artery stenting (CAS) is an effective method of treatment for high-risk patients [1]; however there are complications such as the development of micro-emboli or the re-narrowing of the artery (restenosis). Unfortunately the mechanism behind the formation of micro-emboli and restenosis is still unclear. Studies have suggested that the interaction between the blood flow, stent placement, and arterial wall plays a critical role [2]. The presences of stagnant or recirculation zones around the stent struts could promote thrombogenesis, leading to post-procedural complications such as stroke. The risk of post-procedural complications can further be increased when the stent is malappositioned. Furthermore, stagnate regions lead to increase platelet aggregation, which in turn stimulates the migration of smooth muscle cells (SMC) to the lumen. This process is the beginning of the vascular remodeling process and could lead to restenosis.

Currently, clinical imaging modalities lack the resolution to measure the local hemodynamics within arteries after stent placement. In this study, we utilized an emerging high resolution (1 to 10 μm) and minimally invasive optical imaging system known as endovascular optical coherence tomography (EV-OCT). EV-OCT imaging is analogous to ultrasound; however backscattered light is measured instead of sound. The depth penetration of the light can range from 1 to 3 mm and is tissue dependent. The creation of fiber optic catheters with miniaturized focusing optics has provided a way to overcome the shallow depth limitations of OCT. Cross-sectional velocity profiles can be acquired through the function variant of EV-OCT termed endovascular Doppler optical coherence tomography (EV-DOCT) [3, 4, 5]. In this study we demonstrate that EV-DOCT has the capability to estimate of velocity profile within the carotid artery. Comparison of the EV-DOCT image and computation fluid dynamic models show good correlation.

2 Methods

2.1 Endovascular Doppler optical coherence tomography system

A commercially available endovascular optical coherence tomography system was utilized (C7-XR, LightLab Imaging, St. Jude Medical Inc., USA). This system only provided structural OCT images of the arterial wall. To estimate velocity, an in-house custom data acquisition system was coupled to capture the OCT interferogram signal, k-clock and laser trigger [3, 4, 5, 6]. After the OCT interferogram signal was acquired, a technique known as split spectrum Doppler OCT (ssDOCT) was used to estimate of the velocity [3]. This technique has shown to have higher sensitivity than the conventional DOCT velocity estimators [3].

2.2 *In vivo* model

A healthy porcine model was utilized in this study. Porcine is believed to be a suitable experimental animal model for the human common carotid bifurcation as they exhibit similarities to the diametric ratio of the human internal to common carotid artery [7]. The EV-DOCT catheter was inserted through the femoral artery and guided into the subclavian artery (SA) and common carotid artery (CCA) with fluoroscopy. After a region of interest was located, a carotid stent was deployed. The stent deployment catheter was then exchanged to the EV-OCT catheter for imaging. All imaging studies were approved by the Animal Care Committee at Sunnybrook Health Sciences Centre (Toronto, Canada).

2.3 Computational fluid dynamic modeling

Computational fluid dynamic (CFD) models (COMSOL V4.4, USA) were employed to provide further insight into the local hemodynamics. The dimensions of the artery and virtual stent CFD model were measured and constructed (Dassault Systemes SolidWorks Corp., V2014, France) based on EV-OCT images. A time-dependent velocity profile of a human internal carotid artery was used as the inlet parameter [8] with a peak velocity of 2.3 m/s [4]. Blood was assumed to be a Newtonian fluid with a viscosity of 0.004 Pa·s and density of 1060 kg/m^3.

3 Result and Discussion

Fig.1 shows both the cross-sectional structural EV-OCT image (Fig. 1a) and the corresponding ssDOCT image (Fig. 1b). The stent had been deployed across a bifurcation within the artery, as verified through volumetric EV-OCT imaging (not shown). It was observed in the structural EV-OCT image that several of the stent struts were not appositioned onto the lumen when the EV-OCT catheter was positioned near the distal carina. The ssDOCT image had resolved an eccentric laminar-like velocity profile within the parent vessel. Low velocities were observed between the malapossitioned stent struts and arterial wall. Several studies have suggested that regions of low flow have increased thrombus deposition, which could lead to stroke [2].

Fig. 2a shows CFD modeling of the artery after stent placement. Stream lines depict flow within the parent vessel, as well as jet streams flowing into the bifurcation. The cross-sectional velocity profile can be observed in Fig. 2b. An eccentric, laminar-like profile had formed within the parent vessel. The region that approximates

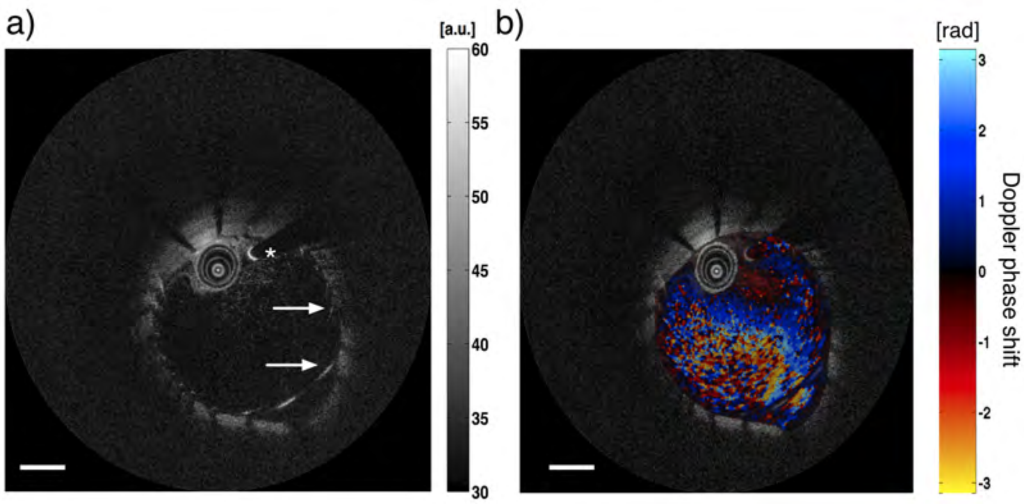

Fig. 1 a) Structural EV-OCT image of an artery after stent placement. Stent struts can be observed be appositioned on the lumen (upper arrow) and malappositioned (lower arrow). The guide wire (*) created a shadowing effect in the EV-OCT image. b) The corresponding ssDOCT image. Laminar-like flow can be seen in the parent vessel, while low velocity was observed between the stent strut and lumen. Scale bar is 1 mm.

the gap between the stent struts and lumen demonstrated a low velocity profile. It can be observed that there are similarities between CFD modeling and EV-DOCT estimation.

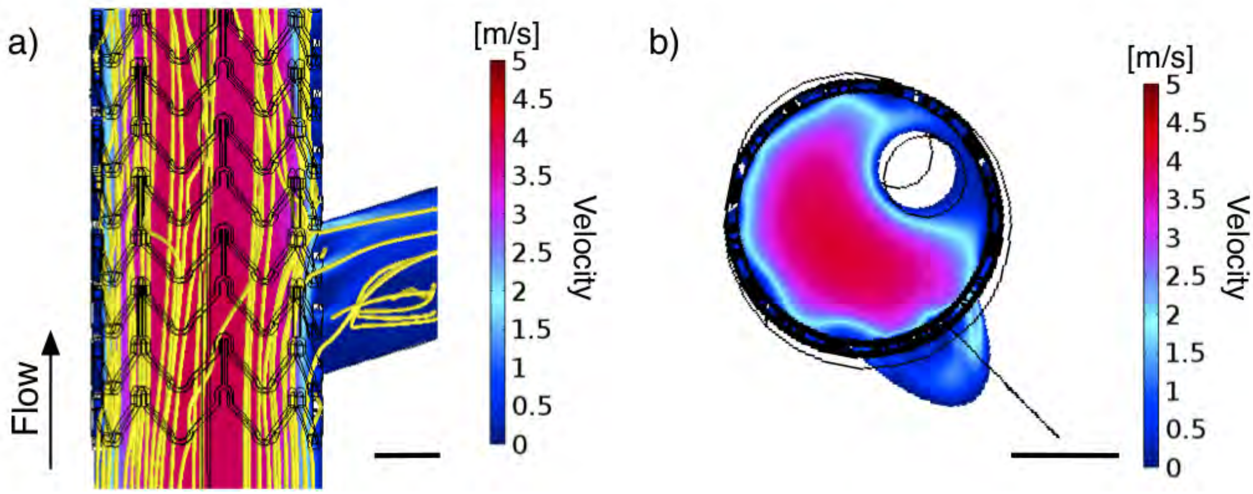

Fig. 2 The result of the CFD modeling with OCT catheter. a) Longitudinal view of the CFD model. b) Cross sectional view of the CFD model. Scale bar is 1 mm.

4 Conclusion

EV-DOCT imaging has the potential to provide *in vivo* velocity estimates of blood vessels and visualization of velocity profiles. In this study, a low velocity region had formed between the lumen wall and malappositioned stent struts, possibly leading to increased thrombus deposition. Our previous studies also demonstrated that EV-DOCT had the capability to visualize other hemodynamic events [4]. Visualization of these hemodynamic events could provide insight into the mechanism that causes post-operative complications such as stroke or restenosis.

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