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A head-to-head comparison between CT- and IVUS-derived coronary blood flow models

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ABSTRACT

The goal of this work is to compare coronary hemodynamics as predicted by computational blood flow models derived from two imaging modalities: coronary computed tomography angiography (CCTA) and intravascular ultrasound integrated with angiography (IVUS). Criteria to define boundary conditions are proposed to overcome the dissimilar anatomical definition delivered by both modalities. The strategy to define boundary conditions is novel in the present context, and naturally accounts for the flow redistribution induced by the resistance of coronary vessels. Hyperemic conditions are assumed to assess model predictions under stressed hemodynamic environments similar to those encountered in Fractional Flow Reserve (FFR) calculations. As results, it was found that CCTA models predict larger pressure drops, higher average blood velocity and smaller FFR. Concerning the flow rate at distal locations in the major vessels of interest, it was found that CCTA predicted smaller flow than IVUS, which is a consequence of a larger sensitivity of CCTA models to coronary steal phenomena. Comparisons to in-vivo measurements of FFR are shown.

1. Introduction

Coronary blood flow simulations have played a major role in the understanding of hemodynamic mechanisms involved in the onset and progression of atherosclerotic disease (Chatzizisis et al., 2007, 2008; Coskun et al., 2006; Koskinas et al., 2010; Stone et al., 2003), characterization of plaque location (Rikhtegar et al., 2012), plaque erosion (Campbell et al., 2013) and plaque rupture (Choi et al., 2015). Moreover, there is an increasing interest from the medical community in the use of such computational tools to aid decision making process due to feasible estimation of Fractional Flow Reserve (FFR) non-invasively (Taylor et al., 2013; Yoon et al., 2012).

Patient specific hemodynamic simulations rely on two fundamental issues: (i) computational domains and (ii) boundary conditions. Vascular geometries are obtained using imaging methods: coronary computed tomography angiography (CCTA) (Choi et al., 2015; Rikhtegar et al., 2012; Taylor et al., 2013; Yoon et al., 2012) or angiograms (AX), which can be utilized alone (Campbell et al., 2013; Morris et al., 2013), or in combination with either intra vascular ultrasound (IVUS) (Chatzizisis et al., 2008; Koskinas et al., 2010; Stone et al., 2003) or optical coherence tomography (OCT) (Ellwein et al., 2011). In turn, definition of boundary condition requires knowledge of global and local hemodynamic information, i.e. systemic pressure, heart rate and blood flow distribution.

Most of computational hemodynamic studies are performed using CCTA and IVUS.[1] Although there have been studies addressing the consistency between these two image modalities concerning the overall decision-making process (Fischer et al., 2013), it has been largely acknowledged that these modalities feature several differences ranging from the economic cost and patient risk to the resulting anatomical definition (Kruk et al., 2014; Leber et al., 2005).

Regarding the definition of boundary conditions, estimation of total coronary flow and flow distribution among branches is crucial to set reliable patient-specific simulations, and the impact on hemodynamics simulations has been analyzed elsewhere (Molony et al., 2015; van der Giessen et al., 2011). This is of the utmost importance for clinical applications either in the estimation of FFR or wall shear stress (WSS).

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[1] Also, the use of OCT images to construct computational domains for blood flow simulations is gaining popularity (Ellwein et al., 2011).

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Previous works merged IVUS data into CCTA models (Gijsen et al., 2014; Ryou et al., 2012), and recently, the differences of FFR estimated by CCTA and by quantitative coronary angiography were studied in Liu et al. (2016). A comparison between CCTA and IVUS in terms of hemodynamic variables predicted by computational fluid dynamic models could help to better understand the implications of modeling choices, and gain insight about the sensitivity to imaging modality.

The goal of the present work is to compare the hemodynamic variables in coronary vessels when the geometric models are constructed from CCTA and from IVUS. A strategy to define boundary conditions in the CCTA model is proposed, and then the boundary conditions for the IVUS model are derived such that both geometric models feature the same blood inflow at the main vessel of interest. Maximum hyperemic conditions are assumed, targeting physiological conditions of FFR procedures.

2. Material and methods

Fig. 1 summarizes the methodology explained in this section.

2.1. Study sample

The study sample consisted of 11 patients (16 arteries) who were indicated to both CCTA and IVUS protocols for diagnostic or therapeutic percutaneous coronary procedure at Sírio-Libanês Hospital, São Paulo, Brazil. The time span between both medical studies was 3.4 ± 4.9 days, and the CCTA was always performed first. This study was approved by the local ethics committee and is in a accordance with the Helsinki Declaration. Patients demographics are presented in Table 1.

2.2. Imaging modalities

Geometries segmented from CCTA (Section 2.2.1) and IVUS (Section 2.2.2) are shown in Fig. 2. Clearly, anatomical definition strongly depends on image modality. These discrepancies are extensively characterized in Section 3. An illustration of the processing steps from medical image to geometry is presented in Fig. 3. Note that the same region of the vessel is analyzed for each modality. For more details see the Supplementary Material, and references (Bulant et al., 2016) (CCTA) and (Maso, 2013) (IVUS). For both geometric models, extensions at inlet/outlets were added to reduce boundary effects in the simulation (Gijsen et al., 2014).

2.2.1. CCTA image processing

All CCTA images were acquired at end-diastole. Segmentation is achieved using implicit deformable models (Antiga et al., 2008). First, a curvature anisotropic filter is applied over a region of interest (Whitaker, 2001). Initialization of the level-set method is performed in individual arteries using a colliding front algorithm (Antiga et al., 2008). The segmented lumen is defined using a marching cubes method (Lorensen and Cline, 1987). All image and mesh processing stages are performed using vmtk (The vascular modeling toolkit website,), ImageLab (Hadlich et al., 2012) and HeMoLab (Larrabide et al., 2012) softwares.

2.2.2. IVUS image processing

IVUS and AX images were acquired in synchronization with the ECG signal and end-diastolic frames are gated to reconstruct the vessel geometry using deformable models (Maso Talou, 2015). Segmented cross-sectional lumen was registered to match the AX images. Side branches from IVUS images were manually segmented.

Table 1
Baseline characteristics of the study sample (11 patients and 16 arteries). Data are represented as mean ± SD, or as number and percentages of patients.

Men, n(%)	10 (91%)
Age (years)	59 ± 12
Weight (kg)	83 ± 16
Resting mean systemic pressure (mmHg)	91 ± 6
Resting heart rate (bpm)	72 ± 9
Arteries, n(%)	
Left anterior descending (LAD)	10 (62%)
Left circumflex (LCx)	5 (31%)
Ramus intermedius (RI)	1 (7%)
Circulation dominance, n(%)	
Right	10 (91%)
Co	1 (9%)

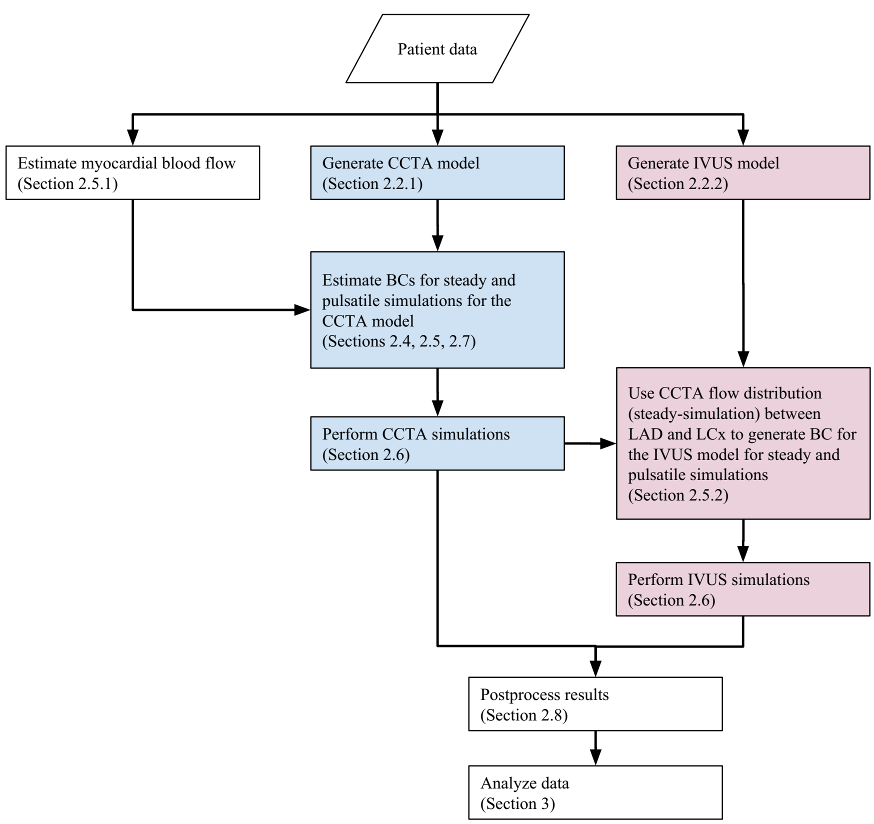

Fig. 1. Flowchart illustrating the methodology employed in this work.

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