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Evaluation of a framework for the co-registration of intravascular ultrasound and optical coherence tomography coronary artery pullbacks

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ABSTRACT

A growing number of studies have used a combination of intravascular ultrasound (IVUS) and optical coherence tomography (OCT) for the assessment of atherosclerotic plaques. Given their respective strengths these imaging modalities highly complement each other. Correlations of hemodynamics and coronary artery disease (CAD) have been extensively investigated with both modalities separately, though not concurrently due to challenges in image registration. Manual co-registration of these modalities is a time expensive task subject to human error, and the development of an automatic method has not been previously addressed. We developed a framework that uses dynamic time warping for the longitudinal co-registration and dynamic programming for the circumferential co-registration of images and evaluated the methodology in a cohort ($n = 12$) of patients with moderate CAD. Excellent correlation was seen between the algorithm and two expert readers for longitudinal co-registration (CCC = 0.9964, CCC = 0.9959) and circumferential co-registration (CCC = 0.9688, CCC = 0.9598). The mean error of the circumferential co-registration angle was found to be within 10%. A framework for the co-registration of IVUS and OCT pullbacks has been developed which provides a foundation for comprehensive studies of CAD biomechanics.

1. Introduction

Post-mortem studies in human coronary arteries have shown that ruptured plaques are predominantly characterized by a thin fibrous cap overlying a large necrotic core (Virmani et al., 2000). These plaques, termed vulnerable plaques or thin capped fibroatheromas (TCFAs), are characterized by a fibrous cap thickness < 65 μm. Intravascular ultrasound (IVUS) can visualize deep inside the arterial wall, providing a measurement of plaque burden, and identify plaque constituents such as necrotic core through virtual histology IVUS (VH-IVUS); however, the ability of IVUS to identify true vulnerable plaques is questionable due to its limited resolution (150–200 μm) as it cannot accurately resolve thin fibrous caps. Optical coherence tomography (OCT) is a higher resolution (10 μm) imaging modality allowing for the accurate measurement of fibrous cap thickness, providing higher sensitivity for detecting TCFAs than IVUS (Fujii et al., 2015), but the limited penetration depth of OCT does not allow for complete plaque characterization.

Wall shear stress (WSS) is understood to play a role in both plaque formation (low WSS) and plaque destabilization (high WSS) (Gijsen et al., 2013). The relationship between hemodynamics and coronary artery disease (CAD) has been separately investigated using both IVUS and OCT. Low WSS has been shown to correlate with OCT defined thinner fibrous caps (Vergallo et al., 2014), increased VH-IVUS defined necrotic core (Samady et al., 2011) and increased IVUS derived plaque burden (Stone et al., 2012). A comprehensive biomechanics based study would ideally include both modalities given their respective strengths, though in order to achieve this a robust method is required to co-register both modalities. Several clinical studies of CAD have used this dual imaging approach, assessing both plaque burden and fibrous cap thickness (Alfonso et al., 2012; Taniwaki et al., 2015; Fujii et al., 2015; Brown et al., 2015).

Achieving one to one image correspondence between the modalities is a time consuming and difficult process. Even after identifying matching images in pullbacks (longitudinal co-registration) the images must also be rotated to the correct orientation

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(circumferential co-registration). Given these challenges an automatic method for co-registering these modalities is of great interest. Previous work on the co-registration of IVUS/VH-IVUS and OCT has primarily focused on the fusion of the modalities into a single image. These prior methods are either completely manual (Raber et al., 2012) (using common landmarks such as side-branches or large calcifications) and/or require manual longitudinal matching of corresponding frames (Unal et al., 2006). Another study matches IVUS and OCT images by incorporating knowledge of the longitudinal position of images but does not extend the method to the co-registration of whole pullbacks (Pauly et al., 2008).

In this study we develop and implement a framework for the co-registration of IVUS and OCT images through dynamic time warping and dynamic programming algorithms. We compare the output of the algorithm to two expert readers in a cohort of mildly diseased patients. To the best of the authors' knowledge this is the first work to automatically co-register full IVUS and OCT pullbacks.

2. Methods

2.1. Patient data acquisition

Twelve patients that underwent VH-IVUS (20 MHz Eagle Eye Gold catheter, Volcano Corp.) and OCT (DragonFly C7 catheter, St. Jude) imaging were selected from our database. Patients had mild coronary artery disease with plaque burden (measured by IVUS) ranging from 18% to 53% (mean $\pm$ stdev = 30 $\pm$ 11.5%). All imaging data were acquired during the same cardiac catheterization procedure. The IVUS pullback speed was 0.5 mm/s ($\sim$0.5 mm image spacing) and the OCT pullback speed was 20–25 mm/s (0.2–0.25 mm image spacing) with a frame rate of 100 fps. Overall there were 1680 (140 $\pm$ 45.7) VH-IVUS and 3313 (276 $\pm$ 81) OCT images. Eligible patients provided written informed consent and the Emory University Institution Review Board approved the study.

2.2. Feature selection

In order to co-register a set of images from two different modalities common features between both image sets must be identified. As outlined in Section 1 this presents a challenge for the co-registration of IVUS and OCT images given the complementary nature of these tools. The first feature we use to co-register both modalities is the lumen area. Due to the natural tapering of the vessel and presence of side-branches lumen area varies along the length of the vessel and is a good indicator of axial position. The second feature we select is the lumen eccentricity, which is measured as the distance from the lumen centroid to the artery wall at equidistant points around the circumference. Given the limited penetration depth of OCT, comparing plaque area or thickness between both modalities is not feasible. Instead, calcifications and specifically calcification arc angle are relatively straightforward to identify in both modalities and we select this as one of our features (Fig. 1). In order to enhance these features both lumen area and lumen eccentricity include side-branches contiguous with the main vessel. Finally, under the assumption that the catheter will seek a position of minimum energy (Ellwein et al., 2011), we determined the catheter angle, as the clockwise angle between a vector from the lumen centroid to the catheter centroid and a horizontal vector at the lumen centroid (Fig. 1). As this feature is more reliable in areas of higher curvature, where the catheter is in contact with the lumen wall, the value was weighted based on the distance ratio of the catheter centroid between the lumen centroid and the lumen wall. Co-registration of the modalities must be done both longitudinally (axial direction) and circumferentially, and we address these problems separately in order to reduce computational cost.

2.3. Longitudinal co-registration

Since the IVUS and OCT pullbacks speeds are very different the regions of interest are unevenly sampled. In order to reduce computational expense we downsampled the OCT data (reduced from 3313 (276 $\pm$ 81) to 1338 (111 $\pm$ 44) images) to equal the axial resolution of the ECG-gated (automatically at the R-wave peak) IVUS data. Even after this the pullbacks are not equally sampled, due to cardiac motion. Dynamic time warping is a technique used to find an optimal alignment between two time-dependent structures $X=[x_1,x_2,\ldots x_n]$ and $Y=[y_1, y_2, \ldots y_n]$, and has previously been successfully applied for the longitudinal alignment of serial IVUS pullbacks (Alberti et al., 2013). The similarity between features is calculated by the Euclidean distance $d(i,j)$ and for the alignment of structures with m features is given as

$$d(i,j)=\sqrt{\sum_{f=1}^{m}(x_i^f-y_j^f)^2+n\bullet|i-j|} \quad (1)$$

where n is a weight that penalizes non-diagonal movements, i is the ith IVUS frame and j is the jth OCT frame. The features used for longitudinal co-registration are the normalized lumen area (normalized to the maximum area of both pullbacks combined) and calcification arc length. The calcification arc length is defined as

$$calcification\quad arc\quad length=\left(\sum_{i=1}^{360}Calc\_arc\right)/360 \quad (2)$$

where Calc_arc is a binary vector indicating whether a calcification is present at each point around the lumen circumference (Fig. 1). Due to observed differences in lumen area measurement between IVUS and OCT, possibly due to incorrect OCT calibration, we apply a correction factor (with values 0.9, 1 and 1.1) to the OCT area measurement, though this could also be equally applied to the IVUS area.

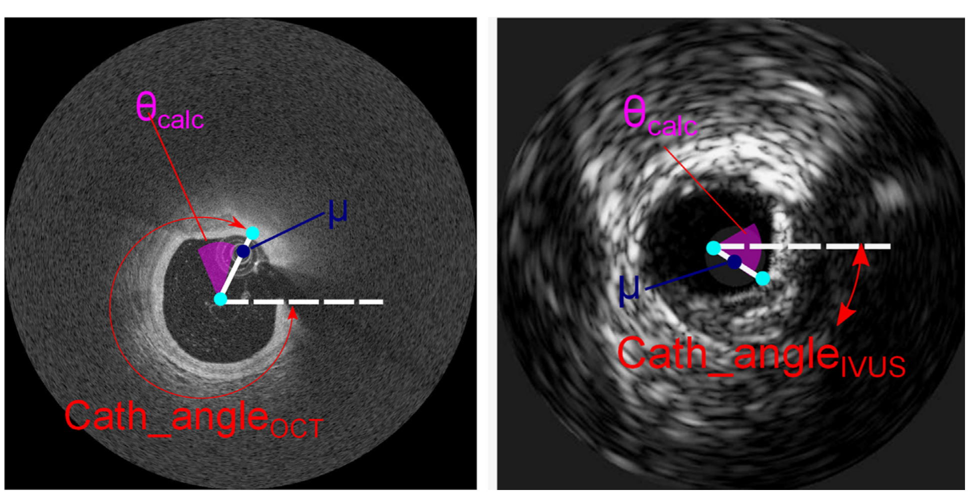

Fig. 1. Description of features used for co-registration. The blue marker indicates the position of the catheter relative to the distance between the lumen centroid and lumen wall (cyan markers) and this gives the weight μ. The value for μ in the OCT and the IVUS image are 0.8 and 0.3 respectively. Magenta indicates the calcification arc angle θ_{calc}. The catheter angles $Cath\_angle_{IVUS}$ and $Cath\_angle_{OCT}$ are measured clockwise from a horizontal line drawn from the lumen centroid. θ_{cath} the angle between the two catheters is given as $Cath\_angle_{IVUS}-Cath\_angle_{OCT}$. In the images shown $Cath\_angle_{OCT}$ is 280°, $Cath\_angle_{IVUS}$ is 25° while θ_{cath} is $-255°$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)