Reducing Cardiac Motion in IVUS Sequences

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Abstract

Cardiac vessel displacement is a main artifact in IVUS sequences. It hinders visualization of the main structures in an appropriate orientation and alignment and affects extracting vessel measurements. In this paper, we present a novel approach for image sequence alignment based on spectral analysis, which removes rigid dynamics, preserving at the same time the vessel geometry. First, we suppress the translation by taking, for each frame, the center of mass of the image as origin of coordinates. In polar coordinates with such point as origin, the rotation appears as a horizontal displacement. The translation induces a phase shift in the Fourier coefficients of two consecutive polar images. We estimate the phase by adjusting a regression plane to the phases of the principal frequencies. Experiments show that the presented strategy suppress cardiac motion regardless of the acquisition device.

1. Introduction

IntraVascular UltraSound (IVUS) is a catheter based technique which allows vessel morphology visualization by means of cross sectional images along the vessel. A single image plane shows the principal arterial structures: lumen, plaque and vessel wall [1]. The sequence is captured by a radio frequency transducer using a constant speed motorized pullback. A uniform sampling of the vessel allows the analysis of vessel geometry and, in non-ECG gating pullbacks, captures its dynamics induced by heart motion.

Global vessel dynamics mainly consist of a radial dilation, a translation and a rotation of the vessel. On the one hand, artery radial dilation due to blood flow is of clinical interest since it serves to measure the stiffness of the artery wall and to determine plaque composition by means of elastography ([2],[3]). On the other hand, rigid motion is a main artifact since it difficulties the main structures visualization in an appropriate orientation and alignment. Extraction of plaque, vessel geometric measurements and any analysis at corresponding regions are hindered due to structure misalignments and motion.

ECG-gated techniques ([4], [5]) minimize the impact of cardiac cyclic movements artifacts. A first approach consists of synchronizing the pullback with the ECG by means of a stepping motor, so that only those frames synchronized with the cardiac pulse are captured [6]. This implies that the technique requires longer time compared to continuous pullbacks, prolonging the acquisition of the invasive procedure. This has motivated designing an image-based gating method [5], which simulates ECG-gating by re-sampling constant speed pullbacks. Although this improvement solves the time execution problem, it is prone to distort the real geometry of the vessel, since the frames discarded might skip relevant features.

An alternative way of reducing the impact of cardiac movement, is the use of automatic registration based techniques, such as, cross-correlation or mutual information ([7], [8]). Although they do not require special devices nor increase the acquisition time, the compatibility between the nature of ultrasonic images and the noise sensitiveness of the methods, make standard image alignment algorithms fail to achieve the expected results. It follows that there are few techniques addressing registration of IVUS planes ([9], [10], [11]).

In this work, we develop a novel approach for cardiac motion reduction and arterial structures alignment in image sequences of IVUS based on spectral analysis [12], which removes rigid motion, but preserves the vessel geometry at the same time. Rigid vessel displacement in IVUS can be modeled as a translation followed by a rotation. The translation is suppressed by taking, for each frame, the center of mass of the image as the origin of coordinates. We transform each image of the sequence into polar coordinates using this center as the origin of the transform. In this way, rotations are visualized as horizontal displacements, inducing a phase shift in the Fourier development ([13], [14]) of two consecutive frames. We adjust a regression plane of the phases of principal frequencies to obtain a robust estimator of the angular displacement.

The method has been validated on vessel segments extracted from two different devices. We propose a measurement based on normalized correlation and Fourier development of such correlation to assess cardiac motion reduction. Such quantitative measurement is well related to the standard technique of longitudinal cuts. The reduction obtained on 10 patient sequences resulted in an average of 81.49%.

The paper is structured as follows. In section 2, we present a detailed description of the procedure. In section 3, we show the most relevant results for this method. Finally, in section 4, we describe the conclusions.

2. Methodology

Rigid motion is given by a translation followed by a rotation around the translated origin. We compute first the translation and then the angle of the rotation.

IVUS images are processed from the caption of a radio frequency transducer. Thus, the center of the catheter acts as the origin of coordinates of the reference system to reconstruct the image. If we travel along the sequence, we can observe the catheter as a fixed structure, but the vessel presents a translation, mainly induced by heart motion, from one frame to the next one.

In order to suppress this dynamic translation we change, for each frame $I(i,j)$, the origin of the reference system to the center of mass (CM) of the image. If the IVUS image, I, has n rows and m columns, then the coordinates of CM are given by:

$$CM = \left(\frac{\sum_{i=1}^{n} i \sum_{j=1}^{m} I(i,j)}{\sum_{i=1}^{n} \sum_{j=1}^{m} I(i,j)}, \frac{\sum_{j=1}^{m} j \sum_{i=1}^{n} I(i,j)}{\sum_{i=1}^{n} \sum_{j=1}^{m} I(i,j)} \right)$$

In this new reference system, with a dynamic center of mass (one for each frame), the catheter appears along the sequence as a translated structure, but not the vessel.

In order to suppress the rotation of the sequence, we note that a rotation in Cartesian coordinates converts into a horizontal displacement in polar coordinates provided that the origin is placed at those center. We take the center of mass of the image as center of rotation and transform each frame into polar coordinates with such center as origin. After that, we compute the horizontal shift representing the rotation by means of Fourier analysis [12] as follows.

Let I_1 and I_2 be two consecutive polar frames of the sequence and $\widehat{I_1}$ and $\widehat{I_2}$ their corresponding Fourier transforms. Since there is a displacement between the two frames, namely $\tau = (\tau_1, \tau_2)$, we have that I_2 is given by:

$$I_2(i,j) = I_1(i - \tau_1, j - \tau_2)$$

and, consequently, its Fourier transform is:

$$\widehat{I_2}(\xi) = \widehat{I_1}(\xi) e^{-i\langle \xi, \tau \rangle}$$

where $\xi = (\xi_1, \xi_2)$ is the Fourier frequency and $\langle \xi, \tau \rangle = \xi_1\tau_1 + \xi_2\tau_2$ the Euclidean scalar product.

Constant displacements (translations), introduce a phase shift between Fourier developments. Thus, if we consider the phase (complex argument), $\rho(\xi)$, of the ratio between the two Fourier developments ([13], [14]), we have that:

$$\rho(\xi) = \rho \left(\frac{\widehat{I_2}}{\widehat{I_1}} \right) = \langle \xi, \tau \rangle \ = \xi_1\tau_1 + \xi_2\tau_2$$

It follows that, in a theoretic ideal situation, the points $(\xi_1, \xi_2, \rho(\xi))$ lie on a plane:

$$\pi : \rho(\xi) = A\xi_1 + B\xi_2$$

where A, B would correspond to the two components of the image translation τ_1 and τ_2, respectively.

In practice, we do not consider all frequencies but only those common to the two consecutive frames which have the greatest amplitude from a certain percentile.

Their values and their phase-shift yield a point cloud like the one shown in fig.1(a). The regression plane to the scattered points is a min-square estimator of the plane π. The first slope of the regression plane is our estimation of the angle of rotation between two consecutive frames. After the adjustment of a regression plane for each pair of frames, we obtain the rotation pattern of the whole sequence of images of the pullback, as shown in fig.1(b). The cumulative sum of the rotation pattern (fig.1(c)) serves us to correct the cardiac frequency along the sequence.

3. Validation

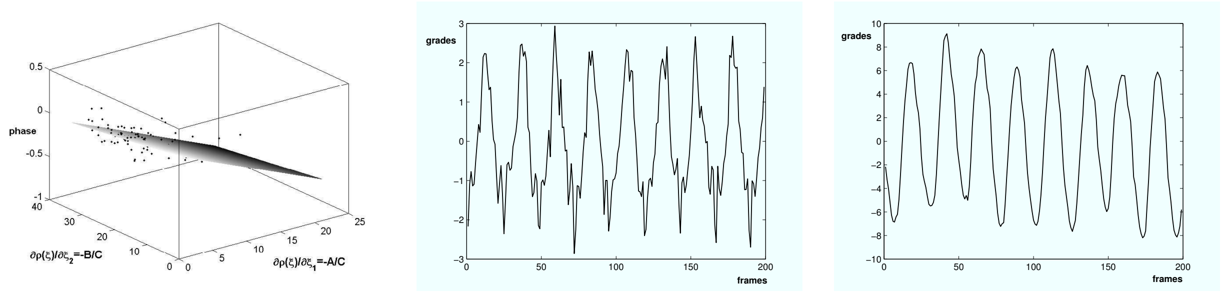
3.1. Experimental setting

The method has been validated on 10 different patients from two different devices, 5 from Clear View and 5 from Galaxy of 300 frames each one. Both devices are from Boston Scientific, at 40 Mhz with a constant pullback at 0.5 mm/s and a digitalization rate of 25 frames/s for the Clear View and 30 frames/s for the Galaxy.

Suppression of cardiac dynamics has been assessed by means of the normalized correlation between two images, I and I_0, given by:

$$CCorr = \frac{\sum_{i,j} I(i,j) I_0(i,j)}{\sqrt{\sum_{i,j} I_0(i,j)^2 \sum_{i,j} I(i,j)^2}} \qquad (1)$$

The correlation between each frame of the sequence and the first one is a similarity measure which detects changes in morphology and position. Besides, correlation values are biased in the presence of noise and texture. We minimize the impact of morphological changes and noise in (1) by applying a Gaussian filter to smooth texture and reduce the impact of noise in grey values. Then, we binarize the image by a threshold to only correlate mask images corresponding to vessel structures and tissue.



(a) (b) (c)

Figure 1. Adjustment of a regression plane (a), rotation pattern from the first slope of the plane (b) and the corresponding cumulative sum (c).

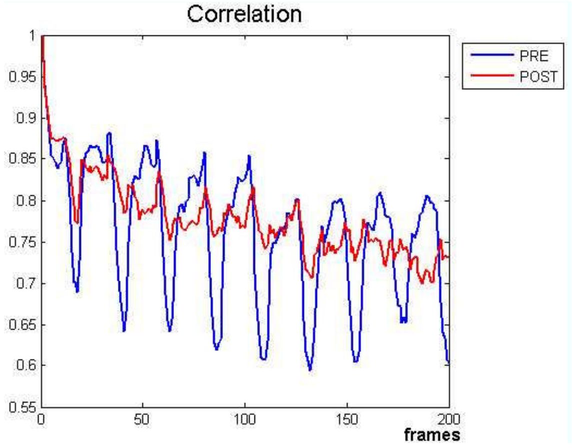


Figure 2. Correlation before (blue line) and after (red line) correcting the sequence.

Figure 2 shows the graphic for the coefficients, CCoeff(i), setting I_i and I_0 as explained in the previous paragraph for the original (blue line) and corrected (red line) sequence. Differences in vessel shape make the correlation coefficient decrease in time. Such baseline sets an upper bound for the CCoeff values obtained from the corrected images. The periodic oscillating behavior shown in the blue line is due to cardiac dynamics. It follows that the periodic component of the CCoeff is a good score for measuring cardiac movement reduction.

The Fourier development of CCoeff contains the coefficients corresponding to the previous periodic component. This component belongs to the cardiac frequencies, which give the amount of cardiac movement. The ratio between the principal cardiac amplitudes for the measurements before and after correction indicates the reduction in cardiac dynamics.

Figure 3 shows the Fourier development before (blue line) and after the correction (red line) for the correlation computed in fig.2. Cardiac frequency corresponds to the peak at 67.5 freq/min with an echo at 135 freq/min. The reduction in cardiac motion is better appreciated in the right hand-side close-up.

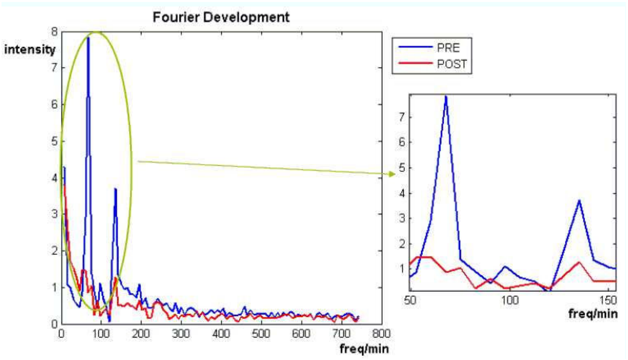
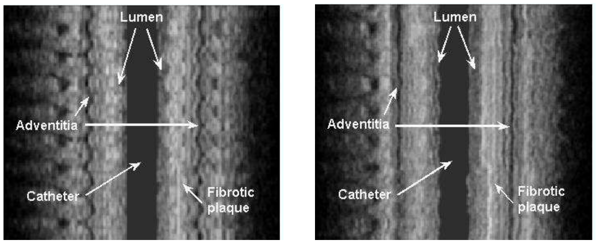


Figure 3. Fourier developments of the correlation before (blue line) and after (red line) correcting the sequence.

3.2. Results



(a) (b)

Figure 4. Longitudinal cuts before (a) and after (b) the rotation correction.

Figure 4 shows longitudinal cuts before (fig.4(a)) and after (fig.4(b)) sequence alignment since they are the usual way to visually assess the amount of cardiac movement and vessel structures alignment. The catheter (central band in grey) splits the image in two halves which correspond to radial cuts of the vessel in opposite directions. The light grey region next to the catheter is the lumen, the dark line after it, is the adventitia and the bright structure at the bottom of the cut is a fibrotic plaque. Before movement correction (fig.4(a)), the adventitia presents an undulated pattern, while the catheter is a straight band. After dynamics suppression, the adventitia has straightened and the undulation has shifted to the catheter. Besides, before correction, the lumen and the fibrotic tissue are hardly distinguished, while, afterwards fibrotic plaque appears as a bright line and lumen is distinguished near the plaque.

Table 1. Cardiac Motion Reduction in IVUS images

	P1	P2	P3	P4	P5	TOT
G	76.45	76.31	81.78	78.51	79.15	**78.44**
C	82.32	88.65	84.36	79.14	88.16	**84.53**

Table 1 shows the percentage of cardiac frequency suppressed for the 10 patients. We report the percentages for each patient and the mean for each device. The reduction percentages range from 68.85% to 88.65% with an average of 78.44% for Galaxy (G) and 84.53% for Clear View (C). The differences between devices are due to the sensitivity of correlation to textures. The more textured the image is (as it is the case for Galaxy pullbacks), the less reliable as a similarity measure the correlation is. Still, the total mean reduction of both devices is 81.49%.

4. Conclusions and further lines

The suppression of rigid arterial motion is of high interest, since it is a main artifact in any method involving vessel wall and plaque measurements. We presented a novel spectral analysis-based method to suppress rigid motion induced by cardiac dynamics. We proposed an objective index to assess cardiac dynamics reduction which correlates with standard technique of longitudinal cuts. The statistics presented validate the method for clinical use in two different acquisition devices and show the robustness of the method.

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