Vessel Structures Alignment by Spectral Analysis of IVUS Sequences

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Abstract. IntraVascular UltraSound is an imaging technique very helpful for the diagnosis and treatment of cardiac diseases, since it allows the visualization of vessel morphology together with vessel geometry and dynamics induced by heart motion. Non rigid arterial deformation is of clinical interest, since it serves to measure vessel wall stiffness and, through elastographic analysis, to determine vessel plaque nature. However, rigid arterial displacement is a main artifact in any study involving geometric measurements (segmentation, elastography, etc). In this paper, we present a novel method based on spectral analysis which removes rigid cardiac dynamics and preserves the vessel geometry. Results on invivo sequences show that the proposed strategy aligns vessel structures regardless of the acquisition device characteristics.

1 Introduction

IntraVascular UltraSound (IVUS) is a catheter based technique which outputs cross sectional images along the vessel. A single image plane allows the visualization of 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. It provides a uniform sampling of the vessel that allows the analysis of vessel geometry. Besides, non-ECG gating pullbacks capture dynamics induced by heart motion.

Global vessel dynamics mainly consist of a radial dilation, a translation and a rotation of the vessel. On one hand, artery radial dilation due to blood flow is of clinical interest 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 which makes difficult the main structures visualization in an appropriate orientation and alignment. Such image and structure misalignments hinder extraction of plaque, vessel geometric measurements and any analysis at corresponding regions.

The impact of cardiac cyclic movements artifacts might be minimized by means of ECG-gated techniques ([4], [5]). 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.

Automatic registration of consecutive IVUS frames is an alternative way of reducing the impact of cardiac movement, which does not require special devices nor increases the acquisition time ([7], [8]). The low signal to noise ratio of ultrasonic images make standard image alignment algorithms ([9], [10]) fail to achieve the expected results. It follows that there are few techniques addressing registration of IVUS planes ([11], [12], [13]).

In this work, we develop a novel approach for image sequence and arterial structures alignment based on spectral analysis [14], which removes rigid motion, but preserves the vessel geometry at the same time. The method removes motion in two steps. 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 ([15], [16]) of two consecutive polar images. We estimate the phase by adjusting a regression plane to the phases of the principal frequencies.

The method has been validated on 12 vessel segments, of 300 frames each one, extracted from two different IVUS devices: a Clear View and a Galaxy. We have assessed the reduction of cardiac dynamics both in quantitative and qualitative terms. The quantitative validation bases on the reduction of cardiac motion in the correlation between a given image and a first reference frame and, also, on calcium alignment. The method has also been qualitatively validated in terms of user time saving in manually analyzing and processing sequences.

The paper is structured as follows. In section 2 a detailed description of the method is presented. In section 3 the most relevant results for this method are showed. Finally, in section 4 the conclusions and main further lines are described.

2 Methodology

Rigid vessel displacement in IVUS can be modeled as a translation followed by a rotation around the new translated origin. We compute first the translation and then the angle of the rotation.

IVUS images are captured by a radio frequency transducer, so the reference system of the reconstructed image has the origin of coordinates at the center of the catheter. It follows that, along the sequence, the catheter is a fixed structure, meanwhile the vessel presents a translation, mainly induced by heart motion, from one frame to the next one. In order to suppress this dynamic displacement 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 has n rows and m columns, then

the coordinates of CM are given by:

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

In this new reference system, the catheter appears along the sequence as a translated structure, but not the vessel. For a detailed explanation we refer to [17].

We take the center of mass of the image as center of rotation. A rotation in Cartesian coordinates converts into a horizontal displacement in polar coordinates provided that the origin is placed at the center of rotation. Therefore, we transform each frame into polar coordinates with the center of mass as origin. The horizontal angular shift representing the rotation is computed using Fourier analysis [14] 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 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:

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

with $\xi = (\xi_1, \xi_2)$ the frequency and $\langle \xi, \tau \rangle = \xi_1\tau_1 + \xi_2\tau_2$ the Euclidean scalar product. Therefore, if we consider the phase (complex argument), $\rho(\xi)$, of the ratio between the two Fourier developments ([15], [16]), 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:

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

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

In practice, we do not consider all frequencies but only the principal (greater amplitude) ones common to two consecutive frames. Their values and their phase-shift yield a point cloud like the one shown in fig.1(left). 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(center). The cumulative sum of the rotation pattern (fig.1(right)) serves us to correct the cardiac frequency along the sequence.

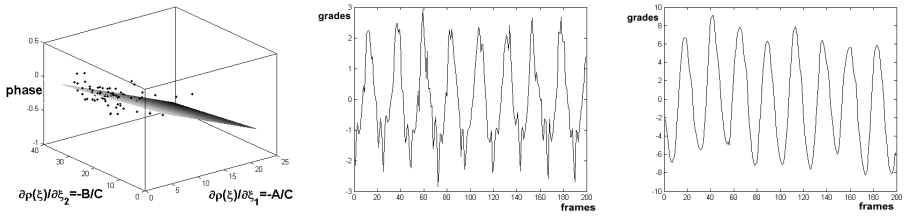

Fig. 1. Adjustment of a regression plane (left), rotation pattern from the first slope of the plane (center) and the corresponding cumulative sum (right).

3 Validation

3.1 Experimental Setting

The method has been validated on coronary vessels of 12 different patients from two different devices, 6 from Clear View and 6 from Galaxy. 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. We have analyzed calcified (8) and non-calcified (4) vessel segments, of 300 frames each one, with a length ranging from 5 to 6 mm.

Suppression of cardiac dynamics has been assessed in, both, quantitative and qualitative terms by the following measures:

Quantitative Measures

- **Suppression of cardiac frequency.** The normalized correlation between two images, I and I_0, is given by:

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

  The correlation between each frame of the sequence and the first one is a similarity measure which detects changes in morphology and position. Since we only are interested in detecting position changes rather than different morphologies, we only take into account those frames with stable plaque. The impact of noise in gray-values is reduced by correlating mask images corresponding to vessel structures and tissue.
- **Vessel Structures Alignment.** We use the calcium alignment along the sequence as validation criteria. The angular position of the bisectrix of calcium sectors reflects the calcium positions along the considered segment.

The Fourier coefficients corresponding to the cardiac frequencies give the amount of cardiac movement existent in the quantitative measures. The ratio between the principal cardiac amplitudes for the measurements before and after correction indicates the reduction in cardiac dynamics.

Qualitative Measures.

– **User Time Saving in Processing the Sequence.** The qualitative measure we propose is the reduction in the time needed for manually segmenting vessel walls. The relevance of the issue lies on the fact that whenever one validates any IVUS segmentation algorithm, a compulsory step is to manually segment the target structures. The assessment protocol is as follows. The expert uses the segmentation application [18] to trace the adventitia border in sequences before and after dynamics suppression. Vessel borders are depicted by adjusting a spline on the first frame of a sequence and correcting it, if necessary, on the next frames by moving the control points that define the first spline. The number of movements in control points that the expert needs to correct the spline along the sequence is our measure of time-saving.

3.2 Results

Figure 2 shows longitudinal cuts before (fig.2(left)) and after (fig.2(right)) image alignment since they are the usual way to visually assess vessel structures alignment and the amount of cardiac movement. 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.2(left)), 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 (fig.2(left)), the lumen and the fibrotic tissue are hardly distinguished, while, afterwards (fig.2(right)), fibrotic plaque appears as a bright line and lumen is distinguished near the plaque.

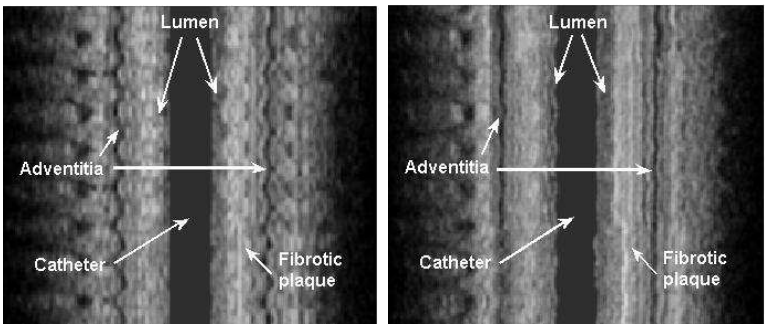

Fig. 2. Longitudinal cuts before (left) and after (right) the rotation correction.

Figure 3 shows the reduction of rigid motion in terms of the correlation plot (left) and its Fourier development (right). Solid line graphics were computed on

the original sequence and dotted line ones after dynamics suppression. Although both correlations are high due to the way of its computation, note the reduction of cardiac frequency, which is better captured in terms of amplitude in the Fourier development (right). Cardiac frequency corresponds to the peak at 67 freq/min in the Fourier development (right) of the original sequence correlation (left).

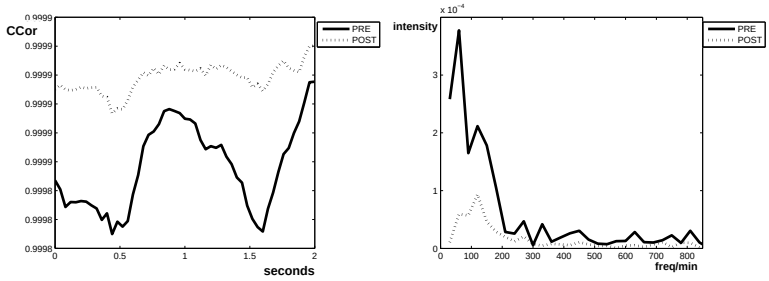

Fig. 3. Correlation before (solid line) and after (dotted line) correcting the sequence (left) and their corresponding Fourier developments (right).

Table 1 shows the percentage of cardiac frequency suppressed for each of the 12 patients and the mean for each device. The reduction percentages range from 66.99% to 88.65% with an average of 72.27% for the Galaxy and 82.12% for the Clear view. The differences between devices are due to the sensitivity of the 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 77.20%.

Table 1. Percentage of Cardiac frequency effect reduction in IVUS images

Galaxy							Clear View						
P1	P2	P3	P4	P5	P6	TOT	P7	P8	P9	P10	P11	P12	TOT
66.99	68.85	73.31	77.37	77.51	69.60	**72.27**	82.32	88.65	84.36	72.08	77.14	88.16	**82.12**

Table 2. Percentage of Calcium Alignment

Galaxy					Clear View				
P1	P2	P3	P4	TOTAL	P5	P6	P7	P8	TOTAL
81.24	69.94	67.02	76.58	**73.70**	86.37	68.31	73.87	79.03	**76.90**

Table 2 summarizes the statistics for the calcium alignment (8 cases) in percentages. The figures reported are as in Table 1. In this case, there is no

significative difference between the two devices, with a mean reduction of 73.70% for the Galaxy and 76.90% for the Clear View.

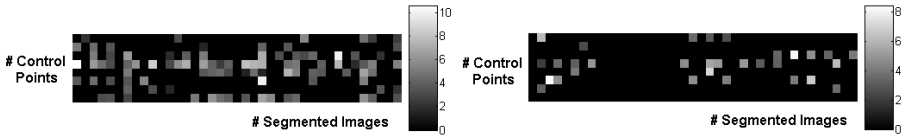

Fig. 4. Distances of control points (rows) between two consecutive manually segmented frames (columns) before (left) and after correction (right).

Figure 4 illustrates the qualitative time-saving in terms of the number of movements in control points needed to segment a sequence, before (fig.4(left)) and after (fig.4(right)) dynamics suppression. Each row stores, for a given control point, the distance between its position in two consecutive frames (columns). The colorbar beside each image gives the range of distances, so that, the darker the pixel is, the less the control point has been modified. Since a black pixel implies that the control point has not been modified at all, the number of non-black pixels indicates the number of movements. Table 3 summarizes the results obtained for two experts and four patients. The total percentage (bold face figure in last column) shows a reduction of 58.05%. This means that an expert spends an average of 4 minutes to manually segment a sequence of 200 frames after the alignment, which takes a minute to carry out the process.

Table 3. Control Points Movements

	Patient 1		Patient 2		Patient 3		Patient 4		Mean
	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2	Exp 1	Exp 2	
# Pre Movements	133	129	75	73	93	66	83	82	91.75
# Post Movements	79	85	2	7	36	37	27	58	41.38
Percentage (%)	40.60	34.11	97.33	90.41	61.29	43.94	67.47	29.27	**58.05**

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 method based on spectral analysis to suppress rigid motion induced by cardiac dynamics. We assessed this reduction in quantitative (structure alignment) and qualitative (time-saving in manually processing the sequence) terms for two different acquisition devices. The statistics presented validate the method for clinical use and for approaching elastographic plaque characterization.

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