Accurate Volumetric Quantification of Coronary Lesions by Fusion between Intravascular Ultrasound and Biplane Angiography

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1. INTRODUCTION

Intravascular ultrasound of the coronary arteries (IVUS) has become a well-established complementary method to angiography for cardiovascular diagnosis and supervision of coronary interventions [1, 2]. The vessel cross-sections can be imaged, accurately depicting the lumen as well as the vessel wall, including the composition and location of the plaque [3]. This information is essential for both planning the intervention (e.g. for stenting or angioplasty) as well as for validation of the results [4]. A major drawback of IVUS is its inability to consider the vessel curvature and the orientation of the imaging catheter when assigning the detected plaque to specific locations. Any quantifications performed on these data are inevitably distorted, since the vessel curvature remains unconsidered. Especially, conventional 3-D reconstruction techniques may overestimate the volume of a vessel or any part thereof when the catheter is not oriented in parallel to the vessel centerline (Fig. 1). Merging of IVUS frames acquired during different heart phases further distorts volumetric quantification [1, 4]. This paper presents an approach to estimate the volume by geometrically correct 3-D reconstruction of the IVUS data, followed by accurate quantification of the volumes between adjacent frames, considering the spatial orientation of the catheter as well as the vessel geometry.

2. THE FUSION APPROACH

To obtain a geometrically correct 3-D reconstruction of the IVUS data, fusion with angiography is performed (Fig. 2). The image data acquired from biplane angiography, and usually needed for catheter guidance, can be utilized to accurately reconstruct the path and orientation of the IVUS catheter. We have developed a comprehensive system to determine the relative changes from frame to frame during the IVUS pullback, as well as to calculate the absolute orientation of the entire frame set [5, 6]. The biplane angiograms are taken immediately at pullback start and cover at least one heart cycle. They are used to extract the catheter path as well as an outline of the contrast-dye filled vessel. An optimized semi-automated dynamic

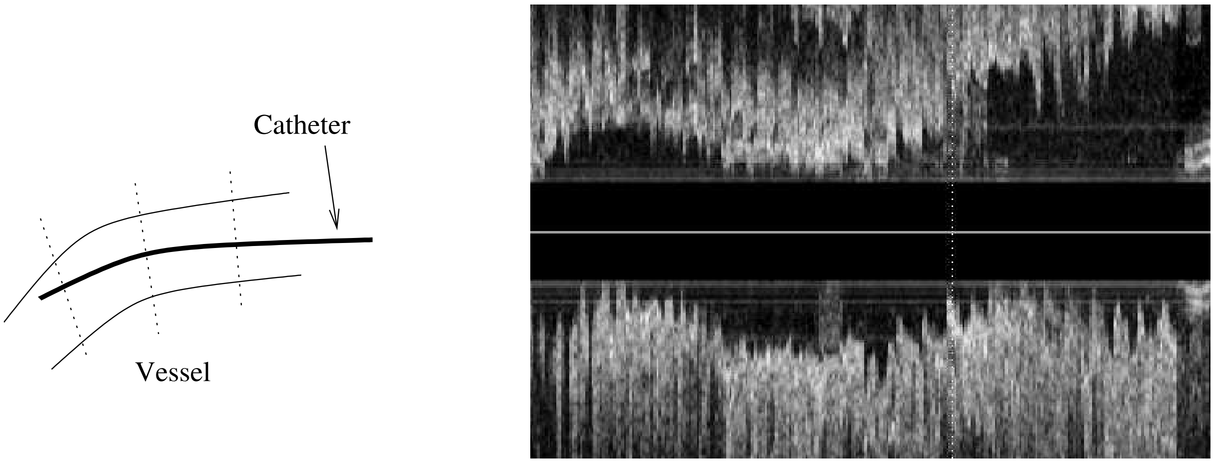
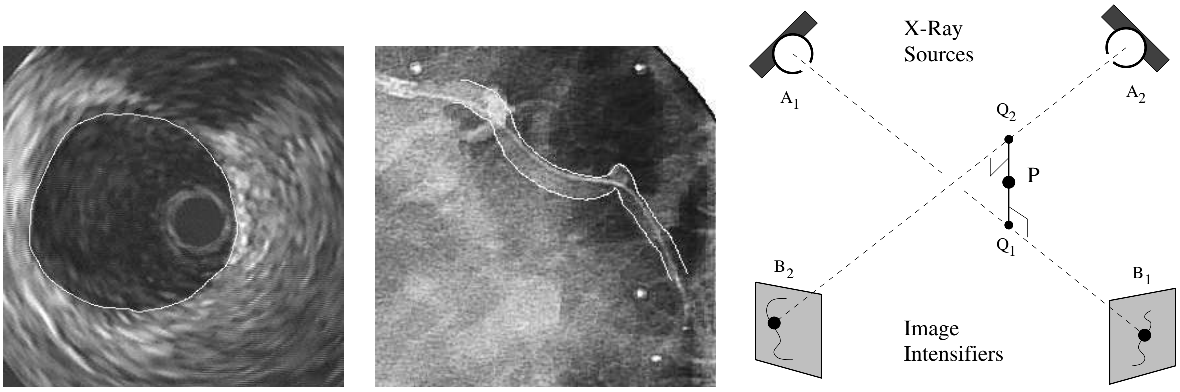


Figure 1: Conventional, not ECG-gated, longitudinal reconstruction of IVUS pullback data; the dotted line indicates a cross-section for which the area would be overestimated substantially due to the tilted angle of the catheter with respect to the vessel course.

programming approach extracts the 2-D data along the expected pullback trajectory. User interaction is required only to mark the start and end points, as well as some intermediate guide points, to define the region of interest. From the known imaging geometry, an accurate 3-D model of the catheter path within the respective vessel segment is generated (Fig. 2c, and [5]). For IVUS acquisition, motorized pullback ensures a constant pullback speed, thus allowing to associate each image with a specific location on the 3-D catheter model. In-vivo, the ECG signal is used to select a subset of IVUS frames corresponding to a single heart phase. The relative and absolute orientations of the IVUS frames are determined using our previously reported system for establishing the absolute orientation in 3-D [6, 7]. The relative orientation changes between adjacent frames are calculated analytically from the catheter path based upon a discrete approximation of the Frenet–Serret formulas. Afterwards, the absolute orientation of the frame set is determined by applying statistical optimization on the overall match of the segmented 3-D IVUS frames with the vessel outline as reconstructed from the angiograms. These methods have been validated successfully in several in-vitro and in-vivo studies. The system outputs the 3-D coordinates of each contour in their correct spatial locations. This set of data serves as input for the following volumetric quantification.

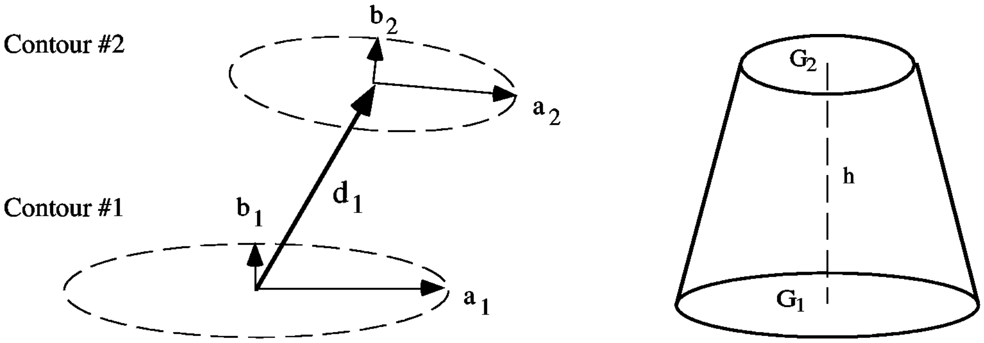
3. VOLUMETRIC MEASUREMENTS

Several methods have been presented previously for volumetric analyses on angiographic data using generalized cylinders or generalized conic sections [8, 9]. As Figure 3 shows, the usually elliptical cross-sections derived from angiographic profiles were transformed into a conic section with base areas G_1 and G_2. No further information is available if geometric reconstruction from biplane angiography is used without IVUS. However, the fusion with IVUS data results in a much more complex model for volumetric quantification, thus requiring new methods. The surfaces of individual structures are represented by spatial contours, which are positioned at arbitrary planes (corresponding to the IVUS frames) as acquired during the automated catheter pullback. Therefore, any applicable volume-measurement method must be



(a) (b) (c)

Figure 2: (a) single IVUS frame, with inner lumen detected; (b) corresponding angiographic image in LAO view, with lumen borders outlined; (c) principle of the catheter path reconstruction.



(a) $\Longrightarrow$ (b)

Figure 3: (a) volume between two adjacent cross-sections after elliptical reconstruction; (b) conventional approximation as a generalized conic section.

able to estimate the volume from a set of contours randomly positioned in space. Our algorithm integrates the volume over the individual areas of the contours within each frame, and is based on previous work of Watanabe *et al.* [10] for volumetric measurements in large organs. The general idea of compensating local volumes between two adjacent contours until a geometrically trivial object is reached [9] is adhered to in this development as well. Considering two adjacent frames a and b, the in-plane areas enclosed by contours $\mathrm{S}a$ and $\mathrm{S}b$ can be calculated, but need to be corrected for the overestimation introduced by the tilting. Therefore, the contour centroids $\mathrm{W}a$ and $\mathrm{W}b$ have to be determined. Our initial algorithm presented in [5,6] assumed a homogeneous distribution of the contour points, which cannot be ensured in complex shapes, and was replaced by the algorithm in [10]. After the centroids are known, the mean direction between a and b is the vector from $\mathrm{W}a$ to $\mathrm{W}b$, and furthermore equals the height h in the generalized conic section model (Figs. 3b, 4). In the next step, the areas are corrected by the tilted angle relative to the mean direction. The normals $\mathrm{N}a$ and $\mathrm{N}b$ of the contours are calculated, with their magnitudes set to the enclosed in-plane areas of the corresponding contours, as proposed in [10].

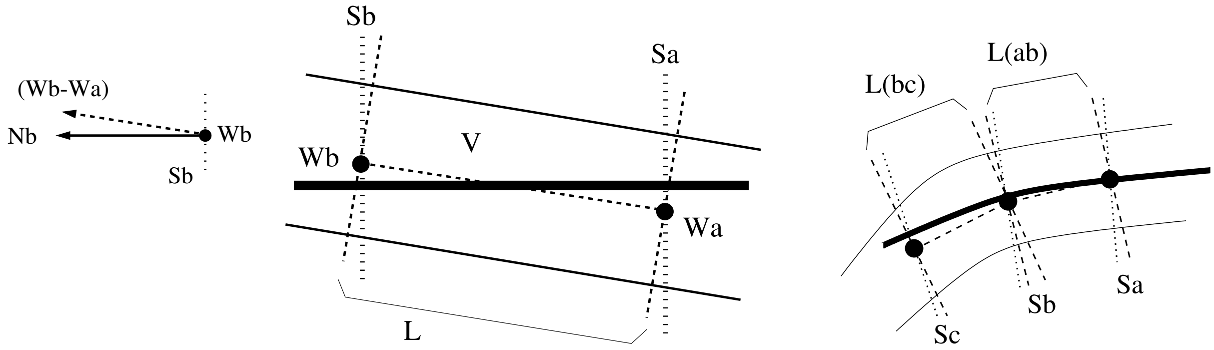


Figure 4: Determination of the volume V between frames a and b; $\mathrm{W}a$ and $\mathrm{W}b$ are the centroids, $\mathrm{N}b$ is a normal on b where its magnitude corresponds to the area of $\mathrm{S}b$; volumes are compensated by orthogonal projection of $\mathrm{S}a$ and $\mathrm{S}b$; right hand side shows two volume elements in an arc.

Applying the scalar products

$$\mathrm{G}a = (\mathrm{N}a \cdot (\mathrm{W}b - \mathrm{W}a)) \; / \; \mathrm{L} \tag{1}$$

$$\mathrm{G}b = (\mathrm{N}b \cdot (\mathrm{W}b - \mathrm{W}a)) \; / \; \mathrm{L} \tag{2}$$

$$\text{with} \quad \mathrm{L} = \|\mathrm{W}b - \mathrm{W}a\| \tag{3}$$

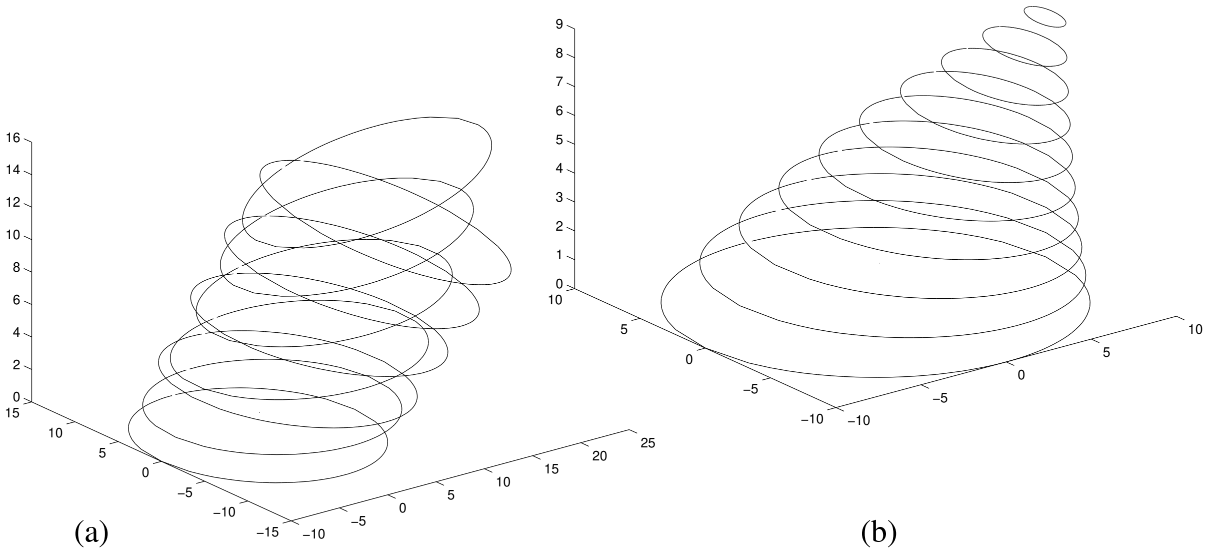
will therefore yield the areas G of the contours S after projection on a plane orthogonal to the mean direction of the vessel. In analogy to the generalized conic sections, the total volume is then calculated from the mean area of the two (now orthogonal) cross-sections over length L:

$$\mathrm{V} = \left(\frac{\mathrm{N}a + \mathrm{N}b}{2} \right) \cdot (\mathrm{W}b - \mathrm{W}a) \tag{4}$$

The total volume over a specific vessel segment is calculated as the sum over all local volumes between all adjacent contours involved in this segment.

4. RESULTS

The quantification method was validated in-vitro on 20 computer-generated 3-D objects using different sampling rates. Test volumes included a mixture of cylindrical, conical, and elliptical shapes, similar to those usually found in undiseased or moderately diseased vessels. Error rates were computed by comparing known volumes of mathematical phantoms to corresponding volumes calculated using the described method from cross-sectional data. All results were obtained using 4–10 frames per volume. For a cylindrical volume with x- and y-dimensional tilting rotations between $5°$ and $25°$, errors ranged from 0.8% to 6.75%, respectively (the worst case is shown in Fig. 5a). For a simulated 90% stenosis located in an arc (Fig. 5b), the error was 4.5% for 10 frames with inclination angles of $1.6°$ between adjacent contours. Validation in phantoms has not yet been performed, since appropriate phantoms modeling irregular shapes others than straight cylindrical or elliptical were not available. Those phantoms require to be opaque for both X-ray angiography as well as IVUS, to obtain feasible data. Validation for the reconstruction accuracy from angiograms as well as for the fusion approach itself can be found



(a) (b)

Figure 5: Two examples used for simulation; (a) a bended cylindrical object where adjacent contours have alternating orientation and substantial overlap; (b) a bended asymmetric conic section, simulating a 90%-diameter stenosis.

in [9] and [5], respectively. The in-vivo application is currently ongoing, at the cardiology of the University of Iowa Hospital and Clinics, as well as incorporating routine patient data acquired at the University Hospital Essen, Germany [6, 7]; the Brigham and Women's Hospital at Harvard Medical School, Boston MA, U.S.A.; and the University Hospital Berne, Switzerland. Figures 1 and 2 are based on this in-vivo data.

5. DISCUSSION

The proposed combination of the fusion approach between angiography and IVUS with an accurate volumetric quantification has a high potential to provide important information for diagnosis and coronary interventions. Conventional methods either neglect the vessel geometry completely, and/or are using simplified shape models like circles or ellipses. The proposed method is a straight-forward extension of the generalized conic sections frequently used in volumetric measurements. If the adjacent contours have approximately equal size and shape, and if the inclination angle between the frames is low, excellent results were observed in the simulations. Only if strong changes in one or moderate changes in at least two of these components occur between adjacent frames, volume errors $>3\%$ could be measured. Considering the small intervals of the acquired IVUS frames (usually 0.5–1.0 mm), these effects may be relevant in severe stenoses only. Both IVUS and angiographic segmentation algorithms have a high reliability, the 3-D reconstruction and fusion methods were successfully applied in all cases. Exact determination of the heart phase using the ECG signal is essential for a correct mapping of the angiographic and IVUS data to the respective phase. This is currently done manually, automated procedures are under development.

6. CONCLUSION

The presented fusion approach along with the volumetric measurement method provide an accurate assessment of coronary vessels in terms of quantification of vessel lumen and plaque volumes. It can be applied on routinely acquired data from IVUS and their corresponding angiographic images. The fusion system has a high level of automatization, thus introducing an important aid for diagnosis and coronary interventions.

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