On-Site 3-D Reconstruction and Visualization of Intravascular Ultrasound based upon Fusion with Biplane Angiography

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1. INTRODUCTION

Intravascular ultrasound of the coronary arteries (IVUS) is becoming a well-established complementary method to angiography for cardiovascular diagnosis and supervision of coronary interventions [1]. Using a catheter with an ultrasonic transducer in its tip, pulled back during imaging, the vessel cross-sections can be imaged, depicting the lumen as well as the vessel wall, including the composition and location of the plaque [2]. This information cannot be obtained from angiographic images. However, a major drawback of IVUS is its inability to reconstruct the vessel segment geometrically correct, i.e. considering the vessel curvature when assigning the detected plaque to specific locations. For coronary interventions, it is important to know the accurate location and dimensions of the lesion, e.g. for stenting. Since lesion assessment and intervention usually take place during the same session, a quick estimation of the vessel parameters is as important as a more detailed analysis of the treatment results after intervention. We developed a comprehensive system for spatial fusion of the coronary angiography and the intravascular ultrasound data. It allows a real-time reconstruction and visualization of the respective vessel segment, the latter by using a standardized visualization language (VRML [3]) for platform-independent presentation.

2. METHODS

The biplane angiograms are taken immediately at pullback start. They are used to extract the catheter path automatically along the expected pullback trajectory by a dynamic programming approach. From the known imaging geometry, an accurate 3-D model of the catheter path within the respective vessel segment is generated. For this purpose, a 3-D reconstruction system previously developed and validated at the German Heart Institute of Berlin is utilized [4]. For IVUS acquisition, motorized pullback is routinely used. In this way, a constant speed of the pullback can be ensured. This is important for determining the correspondence between the two

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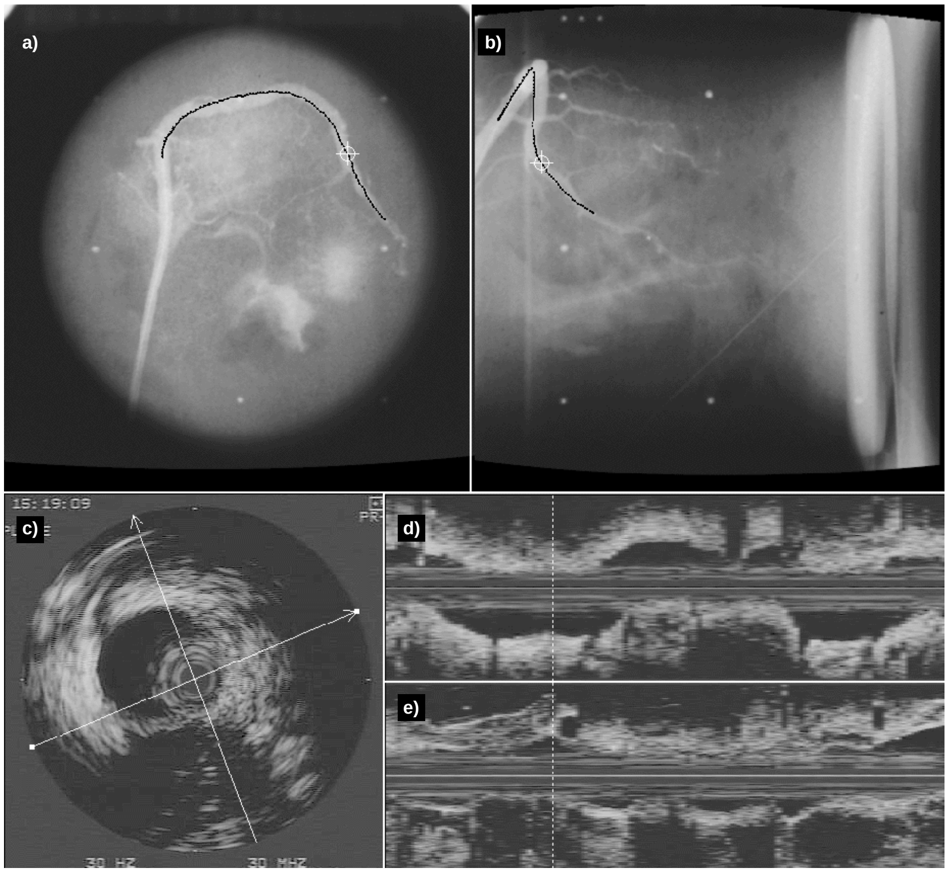

Figure 1: Graphical user interface for correspondence matching. a), b) Angiograms of the vessel, where $\oplus$ marks the transducer location for c) the current IVUS frame. The lines in c) indicate the slicing directions for d), e) longitudinal reconstructions, with current IVUS frame marked by vertical lines.

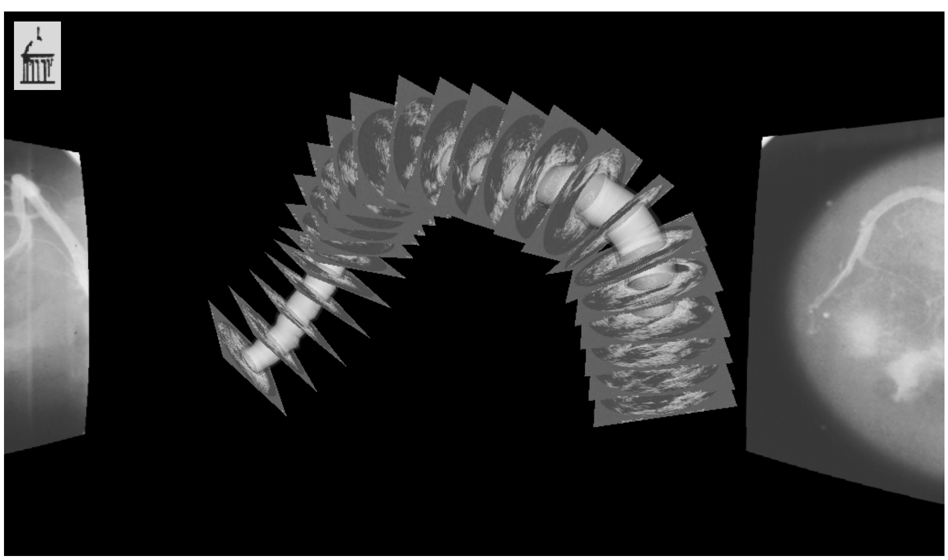

Figure 2: VRML display of the cadaveric pig heart presented in Figure 1. It includes the angiograms and some IVUS frames in their geometrically correct locations and orientations as well as the tubular vessel wall surface from IVUS segmentation.

angiograms and the set of IVUS images, which is calculated from the time function [5]. For each IVUS frame, its location can be determined and indicated as corresponding points within the angiograms, and selecting a point in one of the angiograms will deliver the corresponding IVUS frame (Fig. 1). The entire vessel segment can automatically be reconstructed as a VRML-2.0 model, containing the spatially correct locations of the angiograms, X-ray sources, and all IVUS frames, or a specific subset thereof, in their correct orientations (Fig. 2). Since most of these steps can be performed in real-time, an on-site application during the procedure is feasible, provided that the image data are available directly in a digital format.

2.1 Orientation of the IVUS Frames

For the solution of the problem concerning the orientation of the IVUS frames in 3-D space, we developed a two-stage approach. First, the relative changes between adjacent IVUS frames are calculated from the catheter path using a discrete version of the Frenet-Serret rules [6]. Second, the absolute orientation of the frame set is determined from the out-of-center position of the imaging catheter in 3-D, using a non-iterative statistical approach [7]. This however requires the segmentation of the lumen outline from both angiograms and IVUS data. These outlines are reconstructed into 3-D and then automatically aligned by our approach. Once available, the segmented lumen can be included into the visualizations as well (Figs. 2, 4).

2.2 IVUS Data Visualization using VRML and Volume Rendering

VRML scenes are directly generated from the mapped 3-D contours. For each contour, a set of representative vertices is generated for a fixed number of radial sectors to downscale the amount of data. Between adjacent contours, these representatives are automatically triangulated and converted into a VRML-2.0 Shape node with IndexedFaceSet geometry [3].

While the VRML scenes provide accurate visualization of the vessel geometry, the visual assessment of the IVUS pixel data needs further consideration. By mapping the IVUS frames into a voxel cube of configurable size, a 3-D volume model can automatically be generated and processed for visualization. Common voxel-based tools can be used for slicing, maximum intensity projection (MIP), etc. However, these tools are sometimes not sufficient when applied to IVUS data. Due to the high amount of noise, the MIP images are highly distorted by local peaks. Based upon simulation of X-ray imaging [8], we developed a new projection technique applicable to IVUS data projection. X-rays are based on an integration of the energy reductions defined by the local densities $\rho(i)$ along each ray j passing through $n_{\mathrm{vox}}(j)$ voxels, i.e.

$$\rho_{\mathrm{ray}}(j) = \frac{1}{n_{\mathrm{vox}}(j)} \sum_{i \in \mathrm{ray}(j)} \rho(i) \tag{1}$$

where the ρ values are normalized within the range from $\rho = 0$ (background) to $\rho = 1$ (saturation). For IVUS, the geometric mean is calculated over all energies remaining after passing each voxel along a specific search ray,

$$\rho_{\mathrm{ray}}(j) = 1 - \prod_{i \in \mathrm{ray}(j)} (1 - \rho(i))^{\frac{1}{n_{\mathrm{vox}}(j)}} \tag{2}$$

This energy-complement projection enhances the visibility of echo peaks, e.g. caused by calcifications, which would be suppressed in the conventional simulation (Figs. 3, 4).

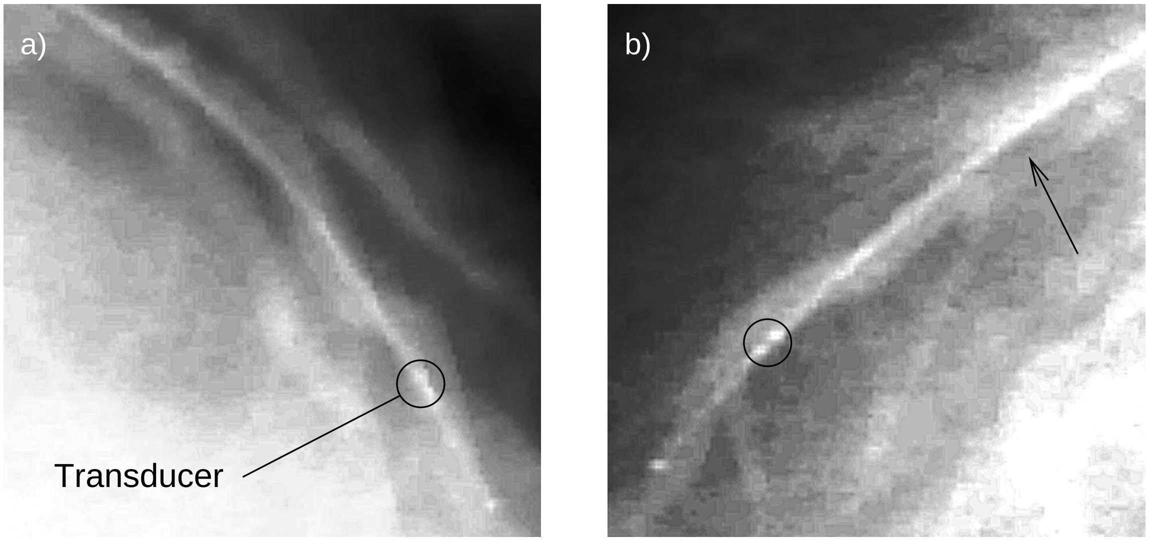

Figure 3: Angiograms in a) 30° RAO and b) 60° LAO projections of a human left anterior descending artery, with a poorly visible stenosis in the proximal part (arrow).

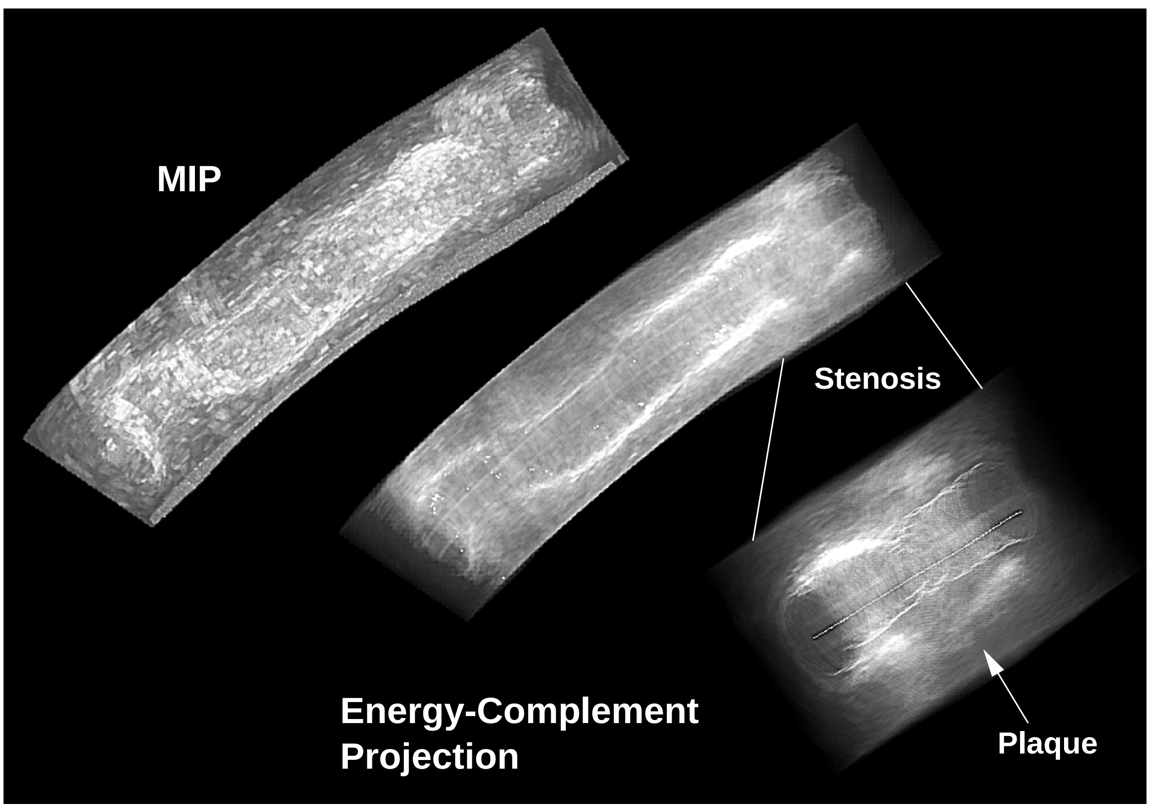

Figure 4: Comparison between volume rendering by conventional maximum intensity projection (MIP) and the proposed energy-complement projection method. With our approach, vessel structures are not obstructed by noise, catheter and vessel wall can be estimated even without inclusion of the segmentation data. The detail shows the stenotic part in higher resolution ($380\times380\times380$ voxels of $50\,\mu$m in size) along with segmented lumen and catheter path marked in 2-D image data before reconstruction. The plaque can be easily identified.

3. RESULTS

As reported earlier, we validated our algorithms in several studies, using phantoms and cadaveric pig hearts for assessment of the accuracy and reproducibility of the methods [4–7]. The in-vivo application is part of an ongoing study, with currently three patients undergoing routine coronary intervention evaluated. The developed data fusion method was applied to vascular segments of interest with 40, 64, and 77 mm length in the left anterior descending, left circumflex, and right coronary arteries. The IVUS images were obtained using sheathed 2.9 F and 3.2 F 30 MHz catheters (Boston Scientific, San Jose, CA), with a constant motorized pullback speed of 0.5 mm/s applied. The angiograms were acquired at a biplane Siemens HICOR cath-lab with DICOM output. Since no reliable independent standard exists for patients, no quantitative validation was possible in-vivo and results were assessed qualitatively. In all three analyzed in-vivo cases, the reported data fusion approach successfully determined the visually correct coronary vessel representation, as was determined from both VRML scenes and volume renderings.

4. CONCLUSIONS

Our system provides a high accuracy in 3-D reconstruction of the vessel topology, and a spatially correct assignment of plaque and wall data as delivered by the IVUS segmentation. It works on a highly automated level and allows many functions to operate in real-time. The geometrically accurate and realistic visualizations of the vessel, along with the localization of specific IVUS frames and matching with the corresponding angiographic views, clearly enhances the assessment of lesions and the evaluation of treatment results.

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