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Coronary Angiography and Intravascular Ultrasound — Spatio-Temporal Modeling and Quantification by Data Fusion

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Abstract

The accurate representation of vessel geometry and plaque morphology is an important factor in the assessment of coronary atherosclerosis. The two most frequently used imaging modalities in interventional cardiology are x-ray angiography and intravascular ultrasound (IVUS). Considered separately, each of these modalities has certain advantages and disadvantages. Combined, substantially more information is delivered since they complement each other. We have developed a comprehensive system for fusion of coronary image data from biplane angiography and IVUS, resulting in a 3-D or 4-D (3-D plus time) model of the vessel under consideration. This article gives a brief overview on the underlying methods and the clinical applications.

1 Introduction

In the analysis of coronary atherosclerosis, the knowledge about the vessel geometry and plaque morphology is of utmost importance. Selective coronary angiography has been the method of choice for decades [1]. There are inherent limitations of x-ray angiography however, which can only deliver information about the vessel lumen and is subject to distortions such as foreshortening. Analysis on the plaque distribution, e.g., for the purpose of quantifying the extent of diffuse atherosclerosis in a coronary artery [2,3], can only be done indirectly from the vessel lumen. Further, determination of the lumen shape may be ambiguous in small vessels such as coronaries if only the projected lumen profiles are available, even though comparable methods were shown effective in larger vessels and ventricles [4, 5]. Intravascular ultrasound (IVUS) has evolved as a complementary imaging modality to obtain cross-sectional images of vessel wall and plaque [1,6–8]. The main drawback of the conventional way of creating 3-D IVUS datasets by a straight stacking of 2-D frames acquired during a slow pullback is an inaccurate representation of the vessel geometry. Combining the information on the vessel course delivered by biplane angiography with the cross-sectional data obtained from IVUS results in an optimum use of the available data towards an accurate 3-D model of the vessel [1, 9–11]. This data fusion approach also can be performed by acquiring the image data over the entire heart cycle and afterwards sorting them into several heart phases, thus generating a 4-D (3-D plus time) dataset [12, 13]. The flow chart in Fig. 1 shows the order of the different steps of preprocessing, fusion, and evaluation.

2 Methodology

The image acquisition process consists of two steps to obtain the input data required for the fusion process: (1) biplane angiographic imaging of the vessel filled with diluted contrast dye and the

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IVUS catheter inserted to its distal endpoint; (2) continuous IVUS image acquisition of an up to 12 cm long vessel segment with 0.5 mm/s motorized pullback. The resulting dataset is split into phases based upon the ECG signal, thus forming multiple 3-D datasets of corresponding heart phases [13]. A detailed description of our fusion approach can be found in [9, 10]. Importantly, the angiograms depict the vessel outline and the prospective path of the IVUS transducer during pullback (Fig. 2a/b). These are used to map the IVUS frames into 3-D space. Pullback path and lumen outline can be reconstructed based upon some known parameters of the imaging geometry and known reference points within the images for refinement [2,14]. The IVUS frames, an example of which is shown in Fig. 2c, are segmented for lumen/plaque and media/adventitia borders, their 3-D locations along the pullback path identified by their timestamps, and their 3-D orientations determined by a statistical approach finding the best fit of the IVUS frame set with respect to the 3-D angiographic lumen outline. All phases combined, the 4-D model describes two moving tubular surfaces, which can be used to define finite-element meshes for the vessel wall, including accumulated plaque, and the lumen. As best suitable for the following evaluation steps, the lumen is represented as an unstructured tetrahedral mesh (Fig. 2d) to model arbitrarily shaped volumina by homogeneously sized elements, and the vessel wall is represented by a structured mesh with radial sectors and multiple layers (Fig. 3c). The use of ISO/IEC and industry standards, specifically DICOM® for input image data, XML to organize data flow, VRML for visualization, and Tecplot® for contour and mesh data, allows efficient data handling and exchange with evaluation and display tools.

3 Applications

There are many applications for which the model resulting from angio/IVUS fusion can be used. In addition to static or interactive 3-D and 4-D visualization techniques [13, 15], including virtual angioscopy (Fig. 2e), the quantification of new morphological and hemodynamic indices on a truly spatial model is of paramount interest. Local volumina of plaque and vessel lumen can be calculated in a geometrically correct model [16], thus obtaining a substantially higher accuracy as compared to conventional 2-D methods. The models can be used as input for algorithms of computational fluid dynamics (CFD), e.g., to estimate the local wall shear stress [13,17,18] and to verify common assumptions on the correlation between wall shear stress, plaque thickness, and curvature [19]. Further, the fusion method can be used to evaluate the results of interventional procedures, e.g., brachytherapy. Intravascular brachytherapy is a method to reduce the probability of recurrent in-stent restenosis, where the underlying dosing model assumes optimum conditions. However, as shown in Fig. 3, conventional assumptions of a centered delivery catheter cannot be assured in practice. By locating the beta-radiation sources and approximating the accumulated doses in a grid of points in the irradiated vessel segments, inaccuracies in the dose prescription and problems in the design of the brachytherapy catheters can be identified [20].

4 Results and Conclusions

In this ongoing study, we have thus far acquired data from 36 routine patients, 11 of which underwent intravascular brachytherapy, and 2 were heart-transplant patients. The results to date are showing (1) that the fusion approach can be used to create models suitable for computational hemodynamic studies [13], (2) that there is a dependency between vessel curvature and circumferential plaque distribution [19], and (3) that geometrically correct brachytherapy models show a higher variance in dose as compared to conventional models [20]. In summary, data fusion from biplane

angiography and intravascular ultrasound opens new perspectives on studying the development of plaque in the process of coronary atherosclerosis, and allows a better assessment of the results from interventional procedures than either modality alone can deliver.

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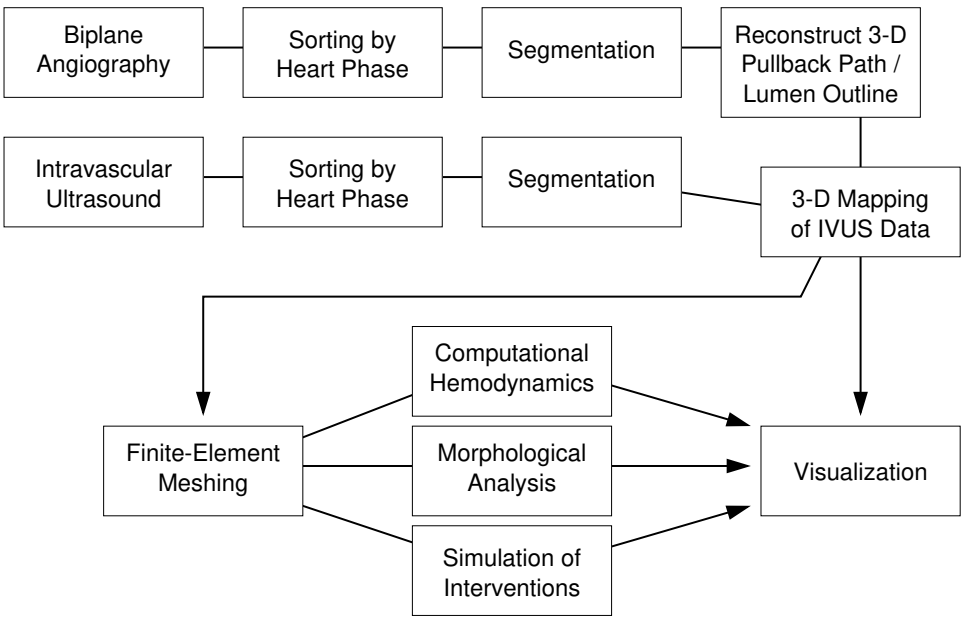

Figure 1: Flowchart of the fusion process: Acquisition of angiographic and IVUS data (top, left to right), followed by evaluation of the resulting model and visualization (bottom).

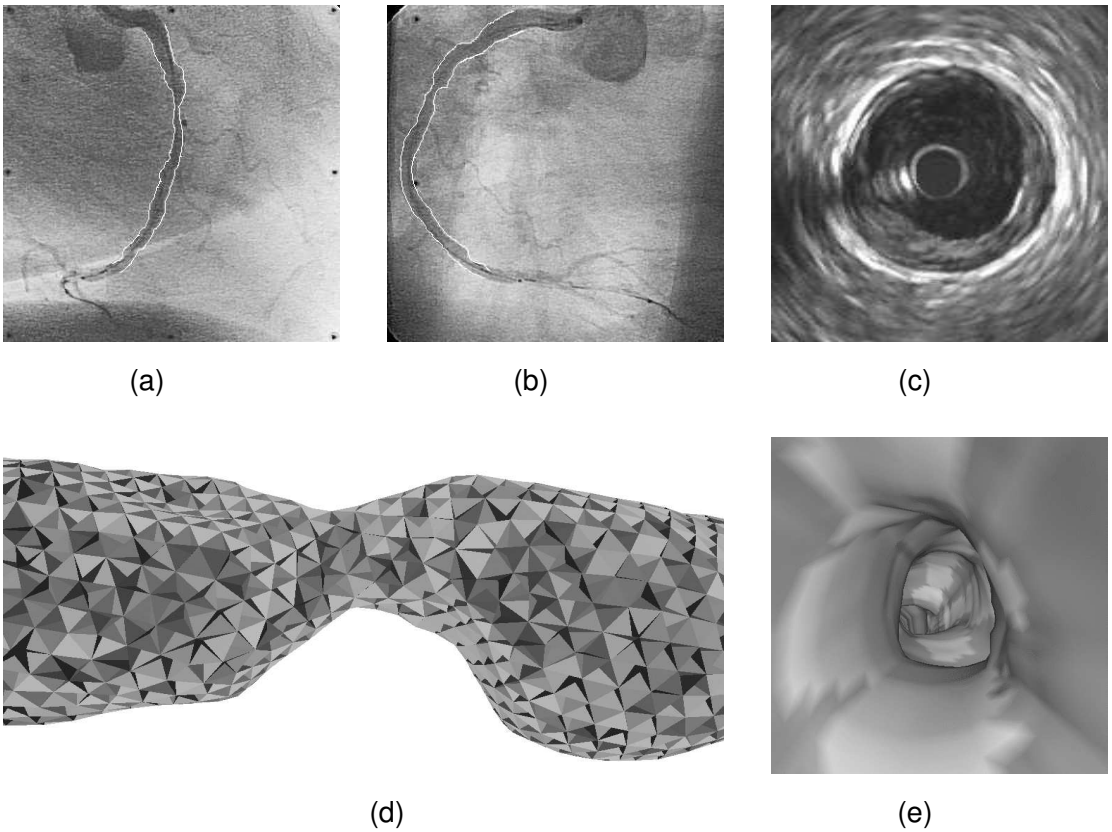

Figure 2: Fusion process and grid generation on in-vivo patient data: (a) right and (b) left anterior oblique projections of a stenosed right coronary artery before treatment, with the IVUS catheter depicted as a black line within the white lumen borders; (c) IVUS image approx. 1 cm distal from the most stenotic location showing the catheter itself in the center, the lumen, plaque, a narrow black ring representing the media, and the adventitia; (d) after segmentation and 3-D fusion, the volume enclosed by the lumen surface is filled with a tetrahedral unstructured mesh for CFD analysis; (e) endoscopic view within the vessel lumen from the postition of (c) towards the stenosis.

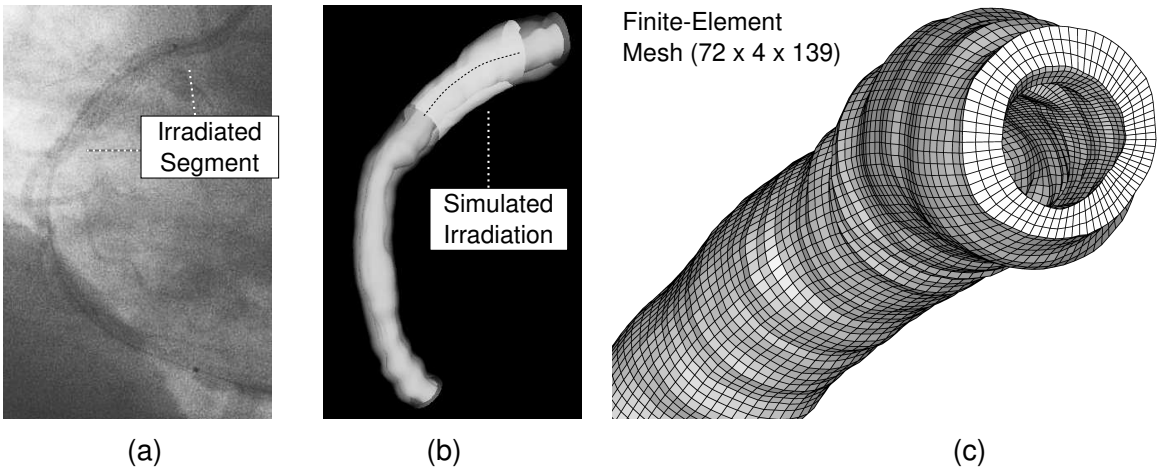

Figure 3: Simulation of the intravascular brachytherapy treatment: (a) right coronary artery with in-stent restenosis after treatment; (b) 3-D model of the lumen/plaque and media/adventitia interfaces, with the irradiated segment and the simulated source train included; (c) finite-element mesh used to estimate the dose delivered in each intersection point.