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Temporal analysis of 3-D coronary plaque morphology and hemodynamic shear stress distribution *in vivo*

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Abstract

This paper reports an approach to combine multimodality fusion with computational fluid dynamics to obtain morphological data as well as local shear stress distribution from biplane angiography and intravascular ultrasound (IVUS). From each IVUS pullback, a 4-D data set is reconstructed covering multiple heart phases. The data flow within our highly-automated system is well-defined and based on standards such as DICOM, XML, and VRML. In an ongoing study involving routinely catheterized patients, our analysis is focusing on the correlation between local shear stress distribution and plaque morphology.

Keywords: Cardiovascular Disease, Data Fusion, Computational Hemodynamics

1. Introduction

The study of the progression of cardiovascular diseases as a function of hemodynamics and plaque morphology in human vasculature has gained recent interest. Previous studies of computational hemodynamics have implicated regions of flow reversal and separation, as well as relatively low wall shear stresses and oscillating shear stresses, as causes for initiation and growth of atherosclerotic plaques. Time-dependent vessel movement, changes of vessel curvature, torsion, rotation, lumen diameter, and length influence coronary hemodynamics [1]. Consequently, determination of endothelial shear stresses in the coronary vessels is highly complex. To perform computational hemodynamics and to determine plaque morphology over the heart cycle, an accurate spatio-temporal model of the vessel under consideration is required.

X-ray angiography and intravascular ultrasound (IVUS) represent the most commonly used diagnostic tools to assess coronary diseases. While conventional reconstructions from IVUS stack the frames as acquired during the catheter pullback to form a straight (pseudo-) 3-D volume, our comprehensive system considers the three-dimensional vessel curvature and reliably separates images originating from different heart phases. The fusion of the

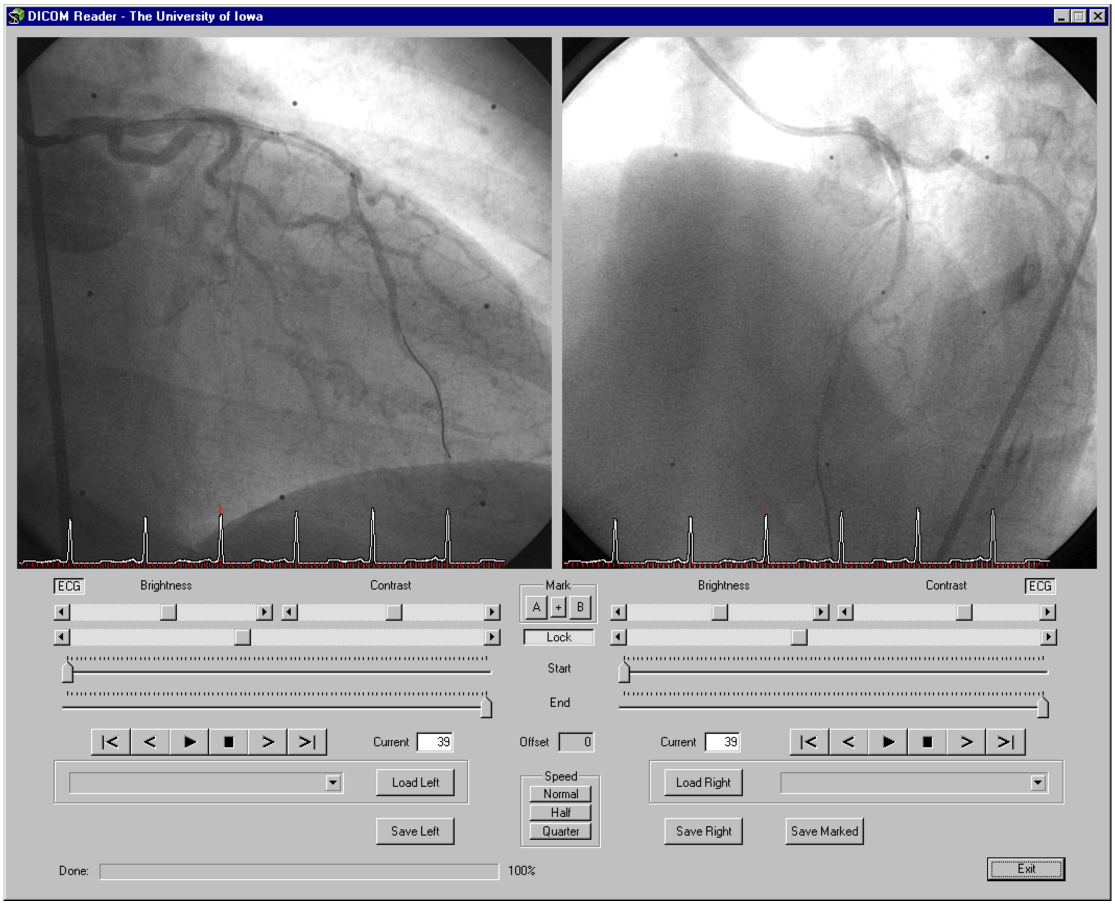

Fig. 1. Snapshot of our synchronous biplane DICOM reader applied to angiographic data with the ECG curves inserted as stored in the data set; selected frames are exported along with an XML file for patient information and acquisition parameters.

IVUS data with the pullback path as determined from x-ray angiography yields a geometrically accurate 4-D (3-D plus time) model of the coronary vasculature [2, 3]. This model is separated in a sequence of heart-phase-specific 3-D models that are used for calculating computational fluid dynamics (CFD). By determination of the inner and outer plaque boundaries, the plaque is subdivided into volume elements and mapped with the annotated finite element mesh generated during the CFD analysis. This allows a direct correlation of the local shear-stress data with plaque thickness in any given region of a vessel segment.

2. Methods

2.1 Reconstruction and fusion

Selective coronary angiography provides projectional x-ray images of contrast-filled coronary vessels and has been clinically used for decades. While angiography delivers an outline of the vessel lumen, it offers no information about the extent and the composition of

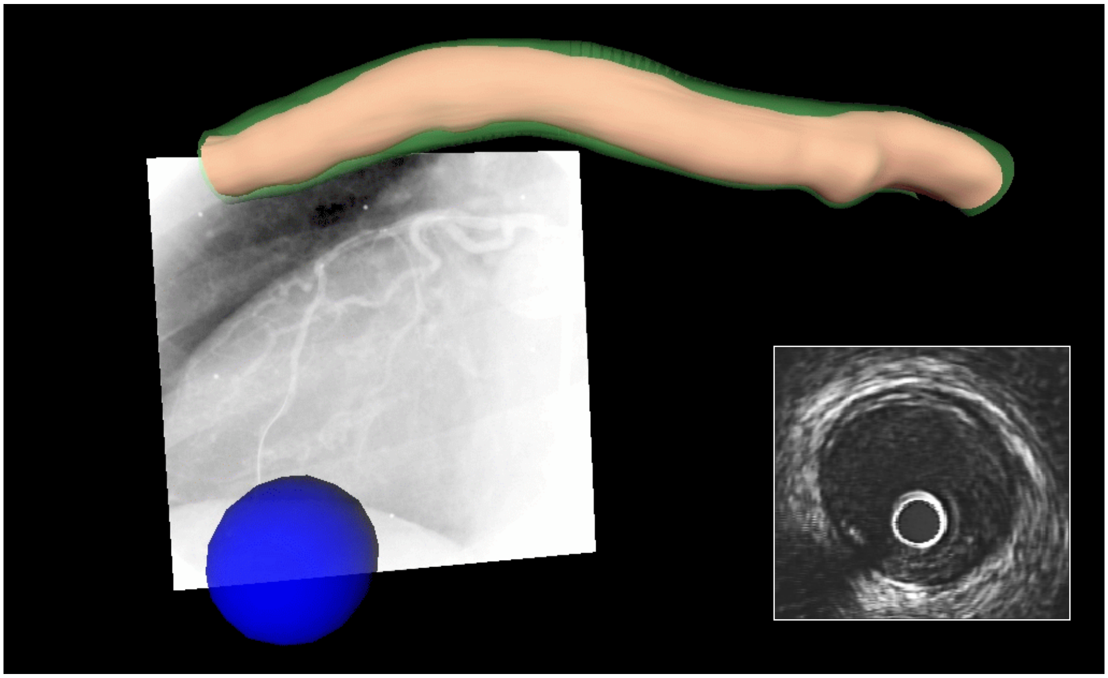

Fig. 2. Reconstructed three-dimensional scene showing the lumen contour as well as the semi-transparent adventitia contour, the world origin (sphere), and an angiogram in their correct 3-D position; inset is an example for an IVUS frame from which the contours are extracted. *[this figure available in color on-line at http://www.engineering.uiowa.edu/~ awahle]*

the plaque covering the inner coronary wall. IVUS provides detailed information about the cross-sectional layers of the vessel, but does not provide any information about the vessel curvature or the orientation of the imaging catheter to assign the detected plaque to specific locations. The fusion of corresponding data from both sources yields the desired spatio-temporal model in high accuracy [2, 3].

Conventional biplane angiographic imaging is performed together with IVUS automated pullback image acquisition. While the angiographic data is usually available on DICOM-formatted CD-R, the IVUS data is digitized from S-VHS tapes. We have developed a viewer based on the DICOM standard that can read and display biplane data sets simultaneously and can furthermore be used to sort the IVUS data by the heart phase (Fig. 1). First, a single heart cycle is selected from the biplane angiograms that depicts the vessel of interest with the IVUS catheter inserted in its most distal position (i.e., before the pullback begins). Starting at the end-diastolic pair of corresponding frames in both projections, a number of trailing frames are selected representing different heart phases following the end diastole. Since the IVUS data were acquired over multiple heart phases, the IVUS sorting process is more complex. The end-diastolic frames are marked using the R-peak of the ECG signal. The frame set is automatically sorted by location (marked end-diastolic frames) and phase (by offsetting the end-diastolic markers by a specific time interval) [2]. The sorted data are kept in an abstract directory structure, in which the Extensible Markup Language (XML) standard is used for the administration of patient/pullback-related and acquisition data.

After both angiographic and IVUS data are sorted by phase, the vessel wall and plaque is segmented by computerized detection of lumen/plaque and media/adventitia borders. Currently, the fusion process is performed separately for each phase. The catheter path is reconstructed into 3-D from the angiographic data. Based on the known speed of the automated IVUS pullback, the location of each frame can be determined from its assigned heart phase and its time stamp. The orientation of the IVUS frame in 3-D space is determined in two steps: The first step determines the relative changes in orientation from frame to frame based on differential geometry; the second step matches the 3-D orientation of the entire frame set with the vessel lumen outline as reconstructed from the angiographic projections [3]. In this way, the absolute orientation of a frame can be determined even if its individual amount of spatial information is limited. While in general the absolute orientation could be determined separately for each phase, this part of the fusion process is linked across all heart phases to obtain a more stable statistical base for the calculation. The resulting 4-D data set consists of the IVUS lumen/plaque and media/adventitia borders mapped into 3-D for each heart phase. The resolution of this data is limited by the resolution of the underlying acquisition equipment as well as the distance the catheter is pulled back within the vessel during a single heart beat. For the following evaluation steps and visualization, it can be downsampled to any desired complexity.

2.2 Determination of wall shear stress

The fusion process delivers a set of surfaces rather than volumes; however, volume descriptions are required for the CFD analysis. This process is performed using commercial meshing software. An unstructured tetrahedral mesh is employed, where the grid density has been optimized based on a compromise between the grid size and the structural integrity of the mesh. Importantly, all tetrahedral elements have approximately the same volume. After meshing, a comprehensive CFD code, U^2RANS, developed at the IIHR – Hydroscience and Engineering at the University of Iowa, is used for the simulation [4]. This code has been specifically designed for moving-grid simulations encountered in bio-fluid flows. Blood is considered an incompressible, homogeneous, and Newtonian fluid in this study. Therefore, Reynolds-averaged Navier-Stokes equations are used. Currently, we are restricting CFD analysis to a 3-D model under steady-flow conditions without moving boundaries. Pulsatile flow and the calculation of the grid velocity and deformation over the heart cycle are part of ongoing research. For the flow conditions at the inlet (i.e., vessel ostium), data were made available by either direct measurement of the coronary flow using a Doppler catheter or by indirect assessment following the contrast bolus in the 3-D reconstructed angiographic data. The results from the CFD analysis are mapped back into the original surface model produced by the fusion step and kept there as annotation to the vertex points. To determine plaque morphology, volume elements are generated between the lumen/plaque and the media/adventitia borders. Similar to the shear-stress data mapping described above, the morphology data for each volume element are mapped to the original vertex points involved.

2.3 Presentation and evaluation

For visualization of the 3-D and 4-D data, the ISO-standardized Virtual Reality Modeling Language (VRML) is used. The vertices are connected to form triangular or quadrilateral

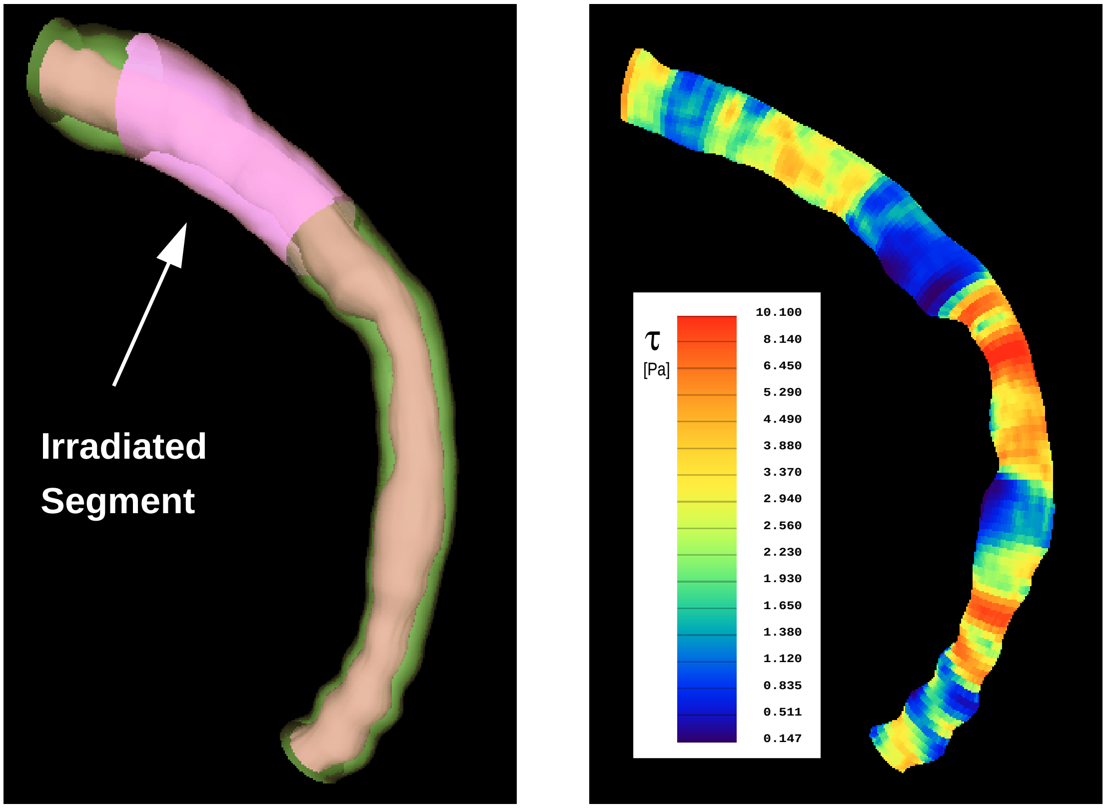

Fig. 3. Three-dimensional reconstruction of an artery subjected to brachytherapy (purple area in left panel) and the results of the CFD analysis on the non-linearly color-coded lumen surface (right). *[this figure available in color on-line at http://www.engineering.uiowa.edu/~ awahle]*

facets and converted into one indexed face set per heart phase (Fig. 2). Annotation from quantitative data (i.e., shear stress, plaque thickness, or the correlation between both) are added as color encoding (Fig. 3). While shear-stress data are available for visualization immediately after the CFD analysis is completed, morphologic parameters and correlations are part of a post-processing step that is the main focus of our current research. Animation is realized by determining the trajectory for each surface vertex point over all heart phases based on a linear interpolation scheme. Furthermore, a fly-through trajectory can be calculated and utilized for a virtual angioscopy simulation in real time [5].

3. Results

Thus far, data from 21 patients were acquired, with a subset of 15 patients undergoing catheterization at the University of Iowa Hospitals and Clinics (4 female, 11 male, age 60.7±13.3 years). The length of an evaluated vessel segment ranged from 45 to 150 mm. Patients were undergoing routine angiography, intervention, and stent placement if indicated. In 6 of the 15 patients, brachytherapy with intravascular seeds was performed. Two cases involved atherectomy, another patient had a transplanted heart. The acquired data were split into 6–8 phases, depending on heart rate. In one case, severe arrhythmia prevented the 4-D analysis, thus only the end-diastolic phase was considered and premature beats were excluded. In all cases, the observed shear stress agreed with the expected distributions. Shear stresses increased substantially in areas of high plaque thickness which corresponded to stenotic regions. Shear stress was also somewhat increased in distal segments due to narrowing of the vessel lumen. The latter observation may be artifactual since presence of branches is not yet considered in the CFD analysis. Areas of expected flow separation and reverse flow were identified reliably.

4. Discussion and conclusion

In this ongoing study, the ability to reconstruct the 3-D morphologically realistic geometry of the coronary arteries from the fusion of IVUS and angiographic imaging modalities was demonstrated in clinical image data. The coronary vessel geometry can be reconstructed as a function of time in order to delineate the motion of the artery during a cardiac cycle in a 4-D model. The system has a high level of automation and a well-defined data flow involving several platform-independent standards. The changes in the clinical acquisition protocol were minimized to reduce the burden on patients and interventional cardiologists as much as possible without jeopardizing accuracy. Future improvements will be done in 3-D/4-D IVUS segmentation, interactions between phases during the fusion process, consideration of pulsatile flow and vessel movement in the CFD analysis, and the derivation of indices to correlate plaque morphology and wall shear-stress distribution. This will contribute to our ongoing efforts to predict sites of further plaque accumulation.

Acknowledgments

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