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Quantification of coronary hemodynamics and plaque morphology using x-ray angiography and intravascular ultrasound

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Abstract

While the mechanisms of plaque development in coronary arteries are not yet completely understood, vessel geometry and its influence on hemodynamics are of major importance. This manuscript presents an overview on our method for spatio-temporal modeling of the coronary arteries by fusion of data from x-ray angiography and intravascular ultrasound (IVUS) and elaborates on the aspects of 4-D computational hemodynamics as well as an approach to directly correlate vessel geometry with plaque morphology.

Key words: Cardiovascular plaque, computational hemodynamics, data fusion, biplane angiography, intravascular ultrasound

1. Introduction

Understanding the mechanisms of plaque development in coronary arteries and the roles of hemodynamics and vessel geometry is of utmost importance for predicting areas of future plaque development and for increasing diagnostic and interventional options. The distribution of plaque correlates with the vessel geometry [1]. It is commonly hypothesized that plaque accumulation is associated with locations

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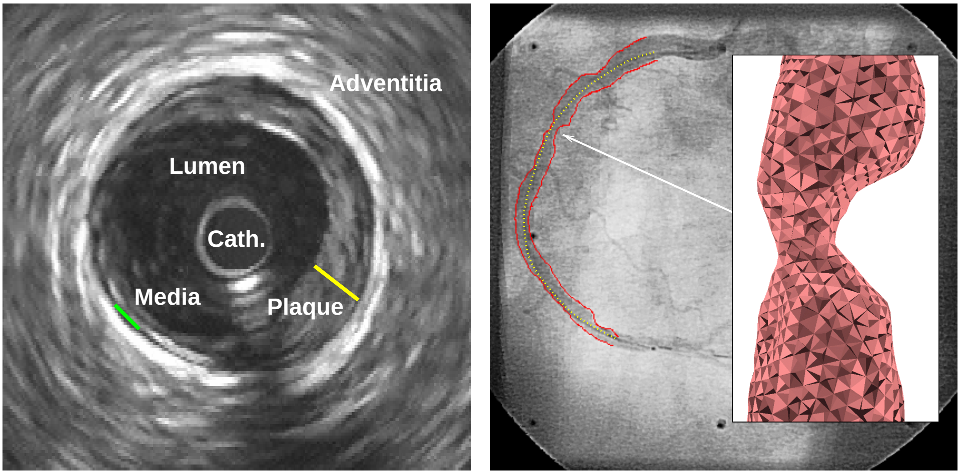

(a) (b)

Fig. 1. (a) example of an intravascular-ultrasound image; the layers are clearly visible, along with some eccentric plaque; (b) extraction of the IVUS catheter path (dotted line) and the lumen from one of the angiograms, the inset shows the tetrahedral mesh of the lumen after 3-D fusion.

of low wall shear stress along the boundaries of the vessel lumen. Recent studies have demonstrated that the compensatory enlargement (remodeling) of the artery indeed coincides with low shear stress, as long as no vessel narrowing occurs [2]. The relationship between plaque development and shear-stress distribution was also shown in longitudinal studies by repeated imaging of the same patients [3]. Since the shear-stress distribution depends directly on the geometry of the vessel, it is mandatory to derive a spatial (3-D) or spatio-temporal (4-D) model of the patient's vascular anatomy as accurately as possible to perform these analyses.

2. Methods

2.1. *Spatio-temporal modeling by data fusion*

X-ray coronary angiography remains the method of choice in imaging of the coronary arteries [4]. It delivers accurate information on the vessel geometry and allows a 3-D reconstruction from the projectional images if at least two viewing angles are used. Since the analysis is based on contrast images depicting the vessel lumen only, any information on the extent of plaque has to be obtained indirectly from the lumen model [5]. IVUS, on the other hand, delivers accurate cross-sectional data, including the vessel wall, and allows to some extent a classification of the plaque tissue [6]. Figure 1(a) shows an example of the vessel appearance in IVUS. To cover a vessel segment, the IVUS catheter is pulled back with a constant speed during continuous acquisition. While the stacking of the IVUS frames to form a 3-D volume may be sufficient for a general assessment of the vessel and local stenoses [7,8], it simplifies the vessel geometry too much for the determination of complex hemodynamic and geometric indices. *Fusion* of the geometric data obtained from angiography with the cross-sectional data from IVUS combines the advantages of both modalities while mostly eliminating their disadvantages.

Our fusion system has been described in detail in [9,10]. Biplane angiographic imaging (or a pair of single-plane angiograms) of the vessel filled with diluted contrast dye and the IVUS catheter inserted to its distal endpoint is performed prior to the IVUS pullback, as illustrated in Fig. 1(b). From the angiograms and the known imaging geometry, the 3-D pullback path is reconstructed, along with an approximation of the lumen shape. The IVUS images are segmented for the lumen/plaque and media/adventitia borders [11]. The fusion process automatically locates the IVUS frames along the 3-D pullback path and finds the optimum match of the segmented lumen surface in the IVUS frames with the 3-D lumen surface reconstructed from the angiograms [9]. When the 3-D models of all heart phases are combined [12], the 4-D model describes two tubular surfaces moving in 3-D space. To perform the hemodynamic analyses, the lumen is modeled as a finite-element tetrahedral mesh, as shown in Figure 1(b). The vessel wall (i.e., plaque and media) is modeled as a structured radial mesh to determine plaque thickness.

2.2. *Wall shear-stress calculation*

Several computational fluid dynamics (CFD) systems exist to determine the shear-stress distribution along the vessel wall [2,3,12]. For our studies, tetrahedral meshing is performed using a commercial meshing system (Gambit, Fluent Inc., U.S.A.) after extending the vessel on both ends to ensure fully-developed flow. The U^{2}RANS system developed at the Iowa Institute of Hydraulic Research [13] is utilized to perform the CFD simulation. This system is also well-suited for moving-grid 4-D analyses. Since only a limited number of phases can be reconstructed during the fusion process, the set of 3-D models (each representing a single phase) is connected using cubic splines to obtain intermediate phases prior to mesh generation. After the CFD simulation converged to a solution, the shear-stress values at the lumen/plaque surface are extracted and mapped back into the original 3-D or 4-D data set. For visualization in VRML or Tecplot, color coding is used. For further quantitative analyses, the data can be exported in XML and Tecplot formats [10].

2.3. *Plaque morphology and vessel geometry*

The CFD analyses describe in Section 2.2 are computationally expensive, yet able to accurately consider the most complex vessel geometries. In a related study, we attempted to directly correlate circumferential plaque distribution with the geometry of the vessel [14]. As can be seen in Fig. 2(a/b), it is a common observation that plaque tends to accumulate on the *inner* bend of a curved vessel (inner curvature) rather than on the *outer* bend (outer curvature). Thus, our aim was to identify

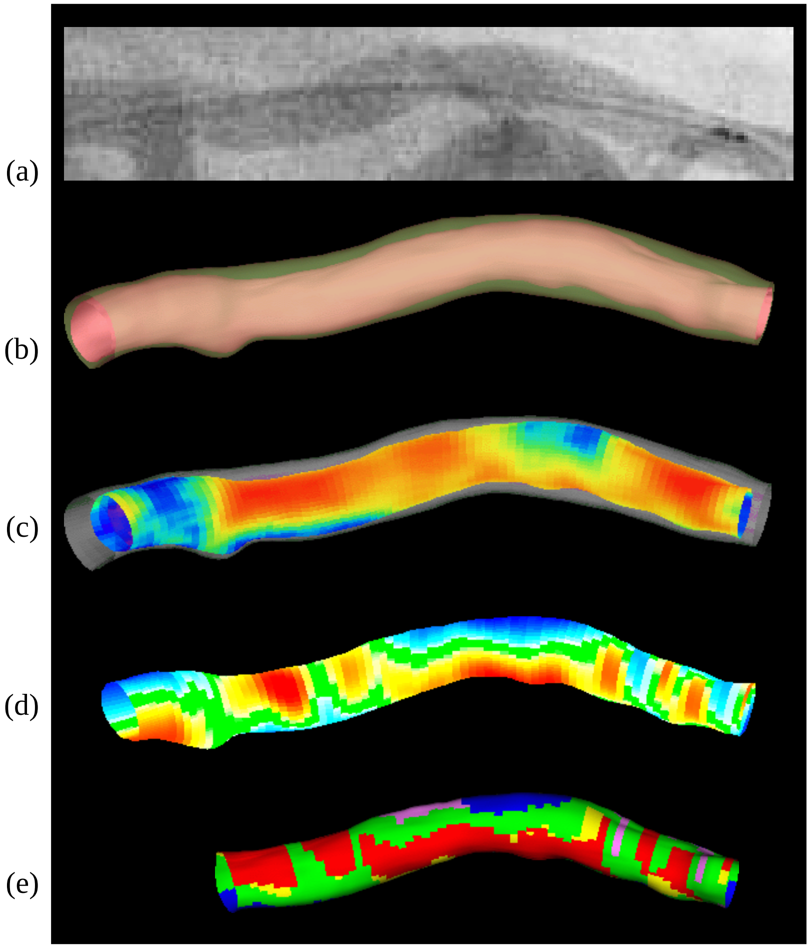

Fig. 2. Morphology/geometry analysis: (a) part of the original angiogram; (b) 3-D model in the same view, note that the left circumflex branch has not been modeled; (c) plaque distribution; (d) local curvature; (e) classification results of the left anterior descending branch distal of the bifurcation — *please refer to the on-line copy for a color version of this figure.*

the frequency of vessel regions for which high plaque accumulation coincides with locations at the inner curvature of the vessel and vice versa. The plaque thickness is determined with respect to the vessel centerline as the distance between the two contours, see Fig. 2(c). We defined a *curvature index* that combines the magnitude of the local curvature with the circumferential position of a specific contour point [14]. Red color in Fig. 2(d) represents *inner*, blue color *outer* curvature, and green indicates areas of low local curvature. The combination of these parameters yields five regions as shown in Fig. 2(e): Red color combines *inner* curvature with *above-average* circumferential plaque distribution, and blue color combines *outer* curvature with *below-average* plaque accumulation, thus in accordance with the observation. Yellow and magenta are the respective contrary regions, and green again marks areas excluded due to low local curvature.

3. Results and discussion

The fusion and CFD systems were validated in computer simulations and in-vitro experiments [9,12]. To date, shear-stress and morphological analyses were performed in 37 vessel segments, with more patient data being included in this ongoing study. Using our fusion approach, CFD measurements applied on 3-D end-diastolic in-vivo data from 10 patients showed a high reproducibility [15]. In a limited set of patients, an interdependence between plaque progression and shear stress could be shown using longitudinal studies [3]. In the morphological study, plaque distribution was concentrated on the inner curvature in 29 out of the 37 vessel segments analyzed [14]. While our results indicated a direct relationship between vessel geometry and circumferential plaque distribution in main vessels of low overall tortuosity, the blood-flow and plaque-distribution patterns are too complex in secondary branches or vessels with non-trivial geometry. Therefore, shear-stress calculations in computer-based systems remain necessary to fully understand the mechanisms of plaque development.

In summary, data fusion from biplane angiography and intravascular ultrasound yields new perspectives in 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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References

[1] M. H. Friedman, P. B. Baker, Z. Ding, B. D. Kuban, Relationship between the geometry and quantitative morphology of the left anterior descending coronary artery, Atherosclerosis 125 (1996) 183–192.

[2] J. J. Wentzel, E. Janssen, J. Vos, J. C. H. Schuurbiers, R. Krams, et al., Extension of increased atherosclerotic wall thickness into high shear stress regions is associated with loss of compensatory remodeling, Circulation 108 (2003) 17–23.

[3] P. H. Stone, A. U. Coskun, S. Kinlay, M. E. Clark, M. Sonka, et al., Effect of endothelial shear stress on the progression of coronary artery disease, vascular remodeling, and in-stent restenosis in man; in-vivo 6-month followup study, Circulation 108 (2003) 438–444.

[4] J. H. C. Reiber, G. Koning, J. Dijkstra, A. Wahle, B. Goedhart, F. H. Sheehan, M. Sonka, Angiography and intravascular ultrasound, in: M. Sonka, J. M. Fitzpatrick (Eds.), Handbook of Medical Imaging — Volume 2: Medical Image Processing and Analysis, SPIE Press, Bellingham WA, 2000, pp. 711–808.

[5] E. Wellnhofer, A. Wahle, E. Fleck, Progression of coronary atherosclerosis quantified by analysis of 3-D reconstruction of left coronary arteries, Atherosclerosis 160 (2002) 483–493.

[6] X. Zhang, C. R. McKay, M. Sonka, Tissue characterization in intravascular ultrasound images, IEEE Transactions on Medical Imaging 17 (1998) 889–899.

[7] C. von Birgelen, E. A. de Vrey, G. S. Mintz, A. Nicosia, N. Bruining, et al., ECG-gated three-dimensional intravascular ultrasound: Feasibility and reproducibility of the automated analysis of coronary lumen and atherosclerotic plaque dimensions in humans, Circulation 96 (1997) 2944–2952.

[8] J. D. Klingensmith, P. Schoenhagen, A. Tajaddini, S. S. Halliburton, E. M. Tuzcu, S. E. Nissen, D. G. Vince, Automated three-dimensional assessment of coronary artery anatomy with intravascular ultrasound scanning, American Heart Journal 145 (2003) 795–805.

[9] A. Wahle, G. P. M. Prause, S. C. DeJong, M. Sonka, Geometrically correct 3-D reconstruction of intravascular ultrasound images by fusion with biplane angiography — Methods and validation, IEEE Transactions on Medical Imaging 18 (1999) 686–699.

[10] M. E. Olszewski, A. Wahle, R. Medina, S. C. Mitchell, M. Sonka, Integrated system for quantitative analysis of coronary plaque via data fusion of biplane angiography and intravascular ultrasound, in: H. U. Lemke, et al. (Eds.), Computer Assisted Radiology and Surgery (CARS 2003), Elsevier, Amsterdam, 2003, pp. 1117–1122.

[11] M. E. Olszewski, A. Wahle, S. C. Mitchell, M. Sonka, Segmentation of intravascular ultrasound images: A machine learning approach mimicking human vision, in: H. U. Lemke, et al. (Eds.), Computer Assisted Radiology and Surgery (CARS 2004), Elsevier, Amsterdam, 2004. *(this volume)*

[12] A. Wahle, S. C. Mitchell, S. D. Ramaswamy, K. B. Chandran, M. Sonka, Four-dimensional coronary morphology and computational hemodynamics, in: M. Sonka, K. M. Hanson (Eds.), Medical Imaging 2001: Image Processing, Vol. 4322, SPIE Proceedings, Bellingham WA, 2001, pp. 743–754.

[13] Y. G. Lai, A. J. Przekwas, A finite-volume method for fluid flow simulations with moving boundaries, Computational Fluid Dynamics 2 (1994) 19–40.

[14] A. Wahle, M. E. Olszewski, S. C. Vigmostad, R. Medina, A. U. Coskun, et al., Quantitative analysis of circumferential plaque distribution in human coronary arteries in relation to local vessel curvature, in: Proc. 2004 IEEE International Symposium on Biomedical Imaging, IEEE Press, Piscataway NJ, 2004.

[15] A. U. Coskun, Y. Yeghiazarians, S. Kinlay, M. E. Clark, O. J. Ilegbusi, et al., Reproducibility of coronary lumen, plaque, and vessel wall reconstruction and of endothelial shear stress measurements in-vivo in humans, Catheterization and Cardiovascular Interventions 60 (2003) 67–78.