Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 569 (2006) 310–313
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Integration of multi-modality imaging for accurate 3D reconstruction of human coronary arteries in vivo

George D. Giannoglou[a,*], Yiannis S. Chatzizisis[a], George Sianos[a], Dimitrios Tsikaderis[b], Antonis Matakos[c], Vassilios Koutkias[d], Panagiotis Diamantopoulos[e], Nicos Maglaveras[d], George E. Parcharidis[a], George E. Louridas[a]

[a]*Cardiovascular Engineering and Atherosclerosis Laboratory, 1st Cardiology Department, AHEPA University Hospital, Aristotle University Medical School, 1 St. Kyriakidi Street, 54636, Thessaloniki, Greece*

[b]*Saint Luke's Hospital, Thessaloniki Heart Institute, Thessaloniki, Greece*

[c]*Electrical & Computer Engineering Department, Aristotle University School of Engineering, Thessaloniki, Greece*

[d]*Laboratory of Medical Informatics, Aristotle University Medical School, Thessaloniki, Greece*

[e]*Biomedical Modelling Unit, Department of Engineering and Design, School of Science & Technology, University of Sussex, Brighton, UK*

Available online 11 September 2006

Abstract

In conventional intravascular ultrasound (IVUS)-based three-dimensional (3D) reconstruction of human coronary arteries, IVUS images are arranged linearly generating a straight vessel volume. However, with this approach real vessel curvature is neglected. To overcome this limitation an imaging method was developed based on integration of IVUS and biplane coronary angiography (BCA). In 17 coronary arteries from nine patients, IVUS and BCA were performed. From each angiographic projection, a single end-diastolic frame was selected and in each frame the IVUS catheter was interactively detected for the extraction of 3D catheter path. Ultrasound data was obtained with a sheath-based catheter and recorded on S-VHS videotape. S-VHS data was digitized and lumen and media-adventitia contours were semi-automatically detected in end-diastolic IVUS images. Each pair of contours was aligned perpendicularly to the catheter path and rotated in space by implementing an algorithm based on Frenet–Serret rules. Lumen and media-adventitia contours were interpolated through generation of intermediate contours creating a real 3D lumen and vessel volume, respectively. The absolute orientation of the reconstructed lumen was determined by back-projecting it onto both angiographic planes and comparing the projected lumen with the actual angiographic lumen. In conclusion, our method is capable of performing rapid and accurate 3D reconstruction of human coronary arteries in vivo. This technique can be utilized for reliable plaque morphometric, geometrical and hemodynamic analyses.

PACS: 87.59.Dj; 07.05.Pj; 43.35.−c; 43.35.+d

Keywords: Coronary artery; Imaging; Angiography; Ultrasonics; Three-dimensional

1. Introduction

In the recent years, intravascular ultrasound (IVUS) has become increasingly important in the imaging of coronary atherosclerosis. IVUS is a catheter-based technique, which provides two-dimensional (2D) high-resolution tomographic images of coronary arteries and, therefore, accurate information about luminal area, wall thickness and composition [1]. The added value of IVUS is that it enables three-dimensional (3D) reconstruction of coronary arteries, therefore permitting reliable calculation of plaque burden. Routinely, 3D reconstruction is performed by stacking of adjacent 2D images and summating their plaque areas [2]. However, this approach completely ignores the vessel curvature and the axial movements of the catheter during the pullback [3].

To overcome these limitations, a new imaging method was developed, combining 3D geometrical information obtained by biplane angiography with volumetric data

*Corresponding author. Tel./fax: +30 2310 994837.
E-mail address: yan@med.auth.gr (G.D. Giannoglou).

0168-9002/$ - see front matter
doi:10.1016/j.nima.2006.08.057

derived from IVUS, ultimately resulting in geometrically correct 3D reconstruction of coronary arteries [3–9]. In other words, the angiographic data provide the spatial trajectory of the IVUS catheter, serving as stem, on which the IVUS tomographic images are positioned and orientated in space. In this work we describe the reconstruction method in details, reporting at the same time its clinical perspective.

2. Methods

2.1. Biplane angiograms and IVUS catheter path reconstruction

The principal steps of the entire method are schematically presented in Fig. 1. Initially, IVUS catheter was inserted through a 6F guiding catheter into the investigated coronary artery. With the catheter at its most distal location, a biplane coronary angiogram was recorded while the contrast agent was injected for 3–5 s at adequate concentration to depict both IVUS catheter and luminal edges. In order to secure better imaging resolution, the utilized angiographic projections were set to be orthogonal; preferably at RAO 30° and LAO 60° with zero cranial or caudal orientation. All biplane angiograms, along with ECG for synchronization, were recorded in DICOM format at a rate of 12.5 fps and image size of 512×512 pixels with 8-bits grey scale.

From each angiographic projection a single end-diastolic frame was selected corresponding to the peak of R-wave on ECG. Using a well-validated quantitative angiography software package based on minimum cost algorithm (CAAS II, Pie Medical Imaging, Maastricht, The Netherlands) the luminal outlines were semi-automatically detected in each frame. For conversion of pixel size to its actual size in mm, the scaling factor was determined in each projection, using 6F guiding catheter as reference. Upon unsatisfactory lumen detection, possibly due to geometrical distortions or vessel overlapping, the luminal outlines were manually corrected.

Both end-diastolic frames were transferred in a commercially available computer aided design (CAD) software (Rhinoceros 3.0, Robert McNeel & Associates, Seattle, WA, USA), in order to delineate the IVUS catheter from the tip of the transducer up to the outlet of the guiding catheter. To improve the detection accuracy, both frames were rectified with an appropriate noise-reduction filter. The resulted 2D b-spline curves were extracted vertically to the corresponding angiographic planes and intersected with each other, creating a 3D curve; this curve corresponded to the geometrically correct IVUS catheter path [7].

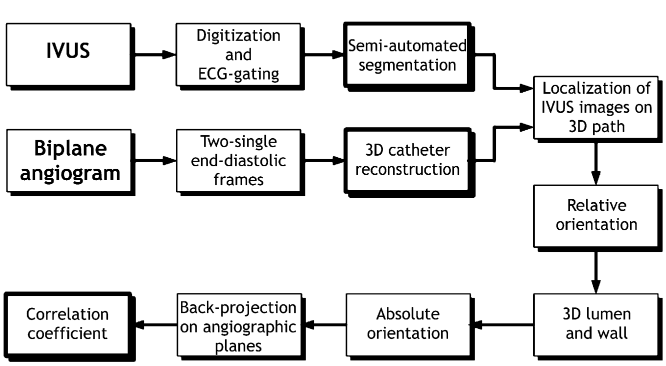

Fig. 1. Basic steps of the 3D reconstruction algorithm.

2.2. Intravascular ultrasound acquisition

IVUS was performed with a mechanical imaging system (ClearView, Boston Scientific, Natick, MA, USA) and a 2.6F sheath-based catheter, incorporating a 40 MHz single-element transducer rotating at 1800 rpm, and yielding 30 fps (Atlantis SR Pro). A motorized pullback device was used to withdraw the catheter from its most distal point up to the outlet of the guiding catheter at a constant speed of 0.5 mm/s. All ultrasound data, along with the ECG, were recorded in 0.5-in. S-VHS videotape. S-VHS data was digitized in a rate of 7.5 fps by an integrated to the IVUS console frame-grabber and the end-diastolic images (512×512 pixels with 8-bit grey scale) were selected. From each image a 340×340 pixels sub-image was extracted, including the region of interest and the transducer of the catheter at the centre of the sub-image. In the resulting frame sequence, an unsharpen-mask filter was applied to augment the luminal and media-adventitia leading edges, thus compensating for noise.

2.3. Contour detection algorithm

Lumen and media-adventitia borders [1] were semi-automatically detected in the selected sequence of IVUS images by a custom-developed computer algorithm based on active contour models (snakes) [10] (Fig. 2). The first step of the segmentation algorithm included the consecutive initialization of two snakes in the first image by manually providing two initial closed contours, roughly near the luminal and media-adventitia boundaries, respectively. Afterwards, the detection algorithm was launched

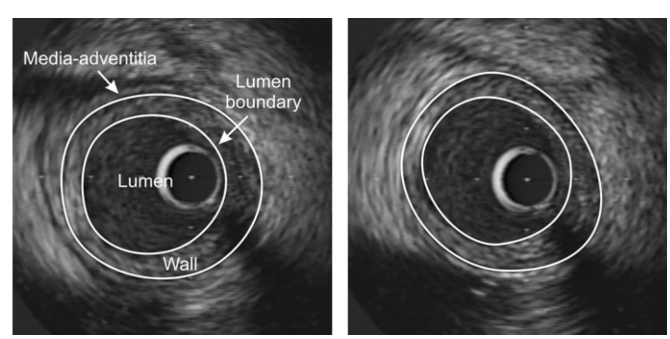

Fig. 2. Two consecutive end-diastolic IVUS images with lumen and media-adventitia boundaries semi-automatically detected. The region inside the luminal boundary constitutes the vessel lumen while the region between media-adventitia and luminal border determines the wall (left image).

and both snakes were automatically deformed by minimizing their energy function to capture the corresponding boundaries. In case the result was not satisfactory, the user could either re-initialize the snakes and launch the detection mechanism again, or interactively calibrate the algorithm by adjusting its parameters appropriately. Upon satisfactory segmentation in the first image, the algorithm was applied automatically in the second image, utilizing the detected contours of the first image as the initialization scheme. The same process was repeated for the rest images of the sequence. The user could review the final output and, if it was not the optimal one in part of the image sequence, the above process was iterated, starting from the frame where the detected boundary diverged from the actual one.

Once the contour detection was completed, an image processing software MIMICS (Materialise N.V., Belgium) was utilized for the conversion of contours to computer aided design (CAD) entities, i.e. IGES files.

2.4. Relative orientation of each pair of contours

The 1-mm distance markers in original IVUS images were used for pixel size calibration. All pairs of contours (luminal and media-adventitia) were assigned equidistantly onto the 3D catheter path so that the transducer tip of each pair was on the path. Since the angular rotation of IVUS catheter during pullback could distort the real geometry of the reconstructed artery, the correct rotational orientation of luminal contours was determined by applying a Frenet-Serret theorem-based algorithm [3,7].

2.5. Absolute orientation of the reconstructed dataset

The correctly orientated luminal and media-adventitia contours were interpolated with additional intermediate contours, generating a 3D lumen and vessel volume, respectively. To determine the spatially correct orientation of the reconstructed vessel, the interpolated lumen was iteratively rotated with 1-degree increment searching for the best possible match with the corresponding angiographic luminal edges [7]. This was accomplished quantitatively by back-projecting the reconstructed lumen onto each angiographic plane and comparing the projected with the angiographic luminal outlines, through a custom-developed automated algorithm implemented in Matlab (The MathWorks Inc., Natick, MA, USA). The correlation coefficients between these outlines were calculated for each angle of rotation and the angle with the maximum correlation coefficient determined the absolute orientation of the reconstructed artery.

3. In vivo reconstructed arteries

The reconstruction method was successfully implemented in vivo in 17 human coronary arterial segments (right coronary artery, RCA, $n = 7$; left anterior descending, LAD, $n = 3$; left circumflex artery, LCx $n = 6$; first diagonal branch, D_1, $n = 1$) derived from nine patients. All patients were randomly selected during routine diagnostic and therapeutic coronary interventional procedures. The Institutional Medical Ethics Committee approved this study, and all patients gave written informed consent.

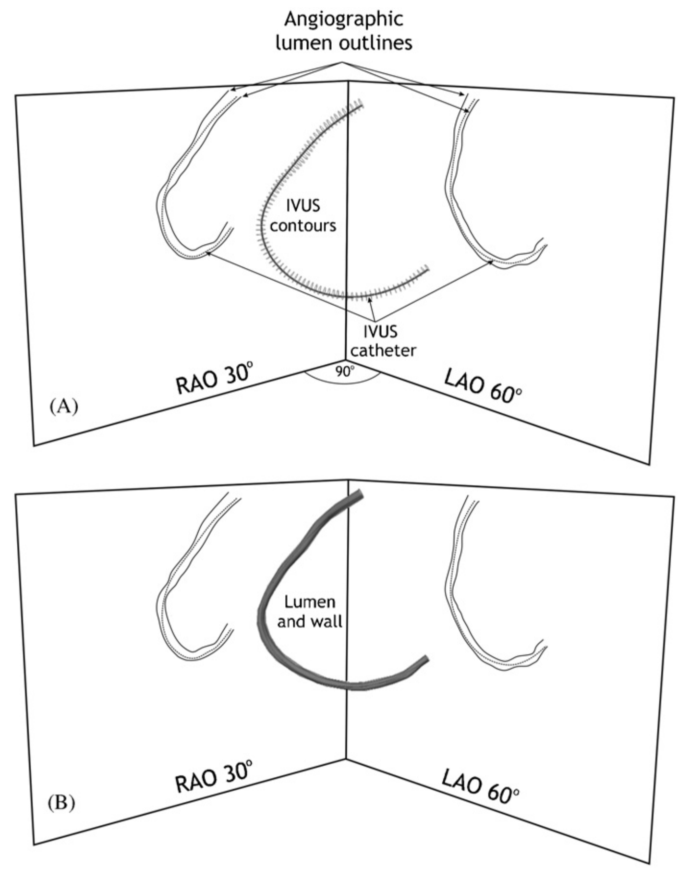

Fig. 3. A 3D reconstructed right coronary artery. The orthogonal biplane imaging system along with the luminal edges and the IVUS catheter trajectory is also illustrated. Initially, the IVUS contours were located onto the catheter trajectory and orientated in space (3A). Afterwards, the contours were interpolated by generation of intermediate contours, creating a 3D vessel volume (3B). The IVUS catheter within the reconstructed lumen is also depicted.

Fig. 3 illustrates a 3D reconstructed RCA (length, 108.7 mm). In Fig. 4, a sub-segment of the same artery is presented in higher magnification. On average, the whole reconstruction process from the image processing up to the final volume rendering lasted approximately 3 hours.

4. Conclusions and clinical perspectives

Spatially correct 3D reconstruction of human coronary arteries constitutes an imaging method based on integration of two existing imaging modalities, namely biplane angiography and IVUS. Its applicability, accuracy and reproducibility were found extremely high [3–9]. The added value of our technique is the integration of an active

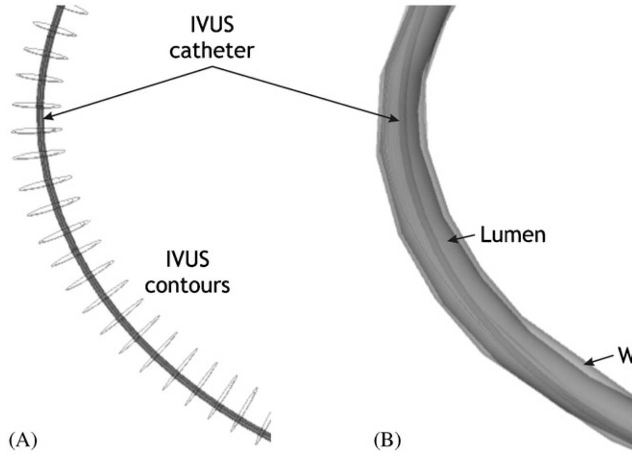

Fig. 4. A sub-segment of a 3D reconstructed right coronary artery. 4A presents lumen and media-adventitia contours of the reconstructed artery, while 4B shows the resulting lumen and wall after contour interpolation. The IVUS catheter within the reconstructed lumen is also depicted in both images.

contour-based model for reliable and time-saving segmentation of IVUS images.

The reconstruction method could potentially constitute a valuable diagnostic and research tool. As far as the diagnostic contribution is concerned, the method enables in vivo accurate morphometric analyses of coronary plaques helping the cardiologist in decision-making [11]. Furthermore, the method could be used for customized planning of intracoronary brachytherapy [12].

With regards to its investigational utility, the reconstruction technique facilitates the investigation of particular geometrical characteristics associated with atherosclerosis [13]. In addition, it facilitates calculation of coronary flow through application of Computational Fluid Dynamics rules thereby enabling the study of the effect of local hemodynamic environment (e.g. shear stress, tensile stress) on atherogenesis, plaque progression and vascular remodeling [14].

Acknowledgements

This work was granted by the Greek State Scholarships Foundation, the Aristotle University Research Committee and the Hellenic Harvard Foundation.

References

[1] G.S. Mintz, S.E. Nissen, W.D. Anderson, S.R. Bailey, R. Erbel, P.J. Fitzgerald, F.J. Pinto, K. Rosenfield, R.J. Siegel, E.M. Tuzcu, P.G. Yock, J. Am. Coll. Cardiol. 37 (2001) 1478.

[2] C. von Birgelen, E.A. de Vrey, G.S. Mintz, A. Nicosia, N. Bruining, W. Li, C.J. Slager, J.R. Roelandt, P.W. Serruys, P.J. de Feyter, Circulation 96 (1997) 2944.

[3] A. Wahle, G.P.M. Prause, S.C. DeJong, M. Sonka, IEEE Trans. Med. Imaging 18 (1999) 686.

[4] C.J. Slager, J.J. Wentzel, J.C.H. Schuurbiers, J.A. Oomen, J. Kloet, R. Krams, C. von Birgelen, W.J. van der Giessen, P.W. Serruys, P.J. de Feyter, Circulation 102 (2000) 511.

[5] R. Cothren, R. Shekhar, M. Tuzcu, S.E. Nissen, J.F. Cornhill, D.G. Vince, Int. J. Card. Imaging 16 (2000) 69.

[6] A.U. Coskun, Y. Yedhiazarians, S. Kinlay, M.E. Clark, O.J. Ilegbusi, A. Wahle, M. Sonka, J.J. Popma, R.E. Kuntz, C.L. Feldman, P.H. Stone, Catheter. Cardiovasc. Interv. 60 (2003) 67.

[7] G.D. Giannoglou, Y.S. Chatzizisis, G. Sianos, D. Tsikaderis, A. Matakos, V. Koutkias, P. Diamantopoulos, N. Maglaveras, G.E. Parcharidis, G.E. Louridas, Coron. Artery Dis. 17 (2006) 533.

[8] Y.S. Chatzizisis, G.D. Giannoglou, A. Matakos, C. Basdekidou, G. Sianos, A. Panagiotou, C. Dimakis, G.E. Parcharidis, G.E. Louridas, Coron. Artery Dis 17 (2006) 545.

[9] Y.S. Chatzizisis, M.Sc. Dissertation, 2004, Aristotle University of Thessaloniki, Thessaloniki, Greece.

[10] G. Kovalski, R. Beyar, R. Shofti, H. Azhari, Ultrasound Med. Biol. 26 (2000) 527.

[11] J.D. Klingensmith, P. Schoenhagen, A. Tajaddini, S.S. Halliburton, E.M. Tuzcu, S.E. Nissen, D.G. Vince, Am. Heart J. 145 (2003) 795.

[12] F. Weichert, H. Muller, U. Quast, A. Kraushaar, P. Spilles, M. Heintz, C. Wilke, C. von Birgelen, R. Erbel, D. Wegener, Med. Phys. 30 (2003) 2530.

[13] R. Krams, J.J. Wentzel, J.A.F. Oomen, R. Vinke, J.C. Schuurbiers, P.J. de Feyter, P.W. Serruys, C.J. Slager, Arterioscler. Thromb. Vasc. Biol. 17 (1997) 2061.

[14] P.H. Stone, A.U. Coskun, S. Kinlay, M.E. Clark, M. Sonka, A. Wahle, O.J. Ilegbusi, Y. Yeghiazarians, J.J. Popma, J. Orav, R.E. Kuntz, C.L. Feldman, Circulation 108 (2003) 438.