A Novel Approach to Quantitative Analysis of Intra Vascular Ultrasound Images

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Abstract

Quantitative Coronary analysis on intravascular ultrasound data (QCU) is commonly performed by semi-automated contour tracing in cross-sectional images of IVUS pullback procedures (frame-based method). For the assessment of volumes derived from the cross-sectional areas (CSA), different contours of corresponding structures need to be traced in many frames resulting in a time-consuming procedure.

In order to get a more efficient analysis procedure, a novel approach has been developed that exploits semi-automatic contour tracing in several reconstructed longitudinal cut-planes (L-Mode displays).

1. Introduction

IntraVascular UltraSound (IVUS) allows the study of artherosclerotic plaques by visualisation of both vascular lumen and vessel wall. The technique is used to evaluate effects of pharmaceutical agents (progression-regression studies) and new interventional procedures. Three-dimensional reconstruction is used for quantitative analysis.

In a pullback procedure of an IVUS study, a series of tomographic images is acquired either continuously (by means of withdrawal of the catheter at uniform speed), or gated by the ECG signal [1,2]. Values for the volumes of structures of interest are commonly derived from measurement of cross-sectional areas (CSA) in many individual frames. For a typical analysis segment length of 2 cm, as many as 1000 frames are available from a motorised pullback procedure recorded on video tape. Since analysis of such a large number of frames is infeasible, a selection of images (e.g. 1 frame/mm) is usually taken for quantitative analysis, leading to a significant decrease of longitudinal resolution and hence to a deterioration of the accuracy of measured volumes and segment length.

To increase the analysis speed while minimising data loss, a novel IVUS analysis method was developed and tested in cooperation with Curad B.V. (Curad B.V., Wijk bij Duurstede, The Netherlands). The applied approach focuses on the tracing of contours in reconstructed longitudinal cut-planes (L-Mode displays). The number of L-Mode contours to be traced is independent of the number of frames in the analysis.

2. IVUS analysis

The newly developed analysis module is DICOM (Digital Imaging and Communications in Medicine) based. IVUS pullback studies, selected from a database maintained by a DICOM image server, are loaded into the module for display and analysis. Multiple pullback studies can be displayed simultaneously to enable comparison of baseline and follow-up studies. The operator can define multiple regional analysis segments of the pullback for separate analysis of (for example) reference and target segments. Analysis results are written to the database. The data can be retrieved by means of SQL queries for subsequent (statistical) evaluation (Fig. 1).

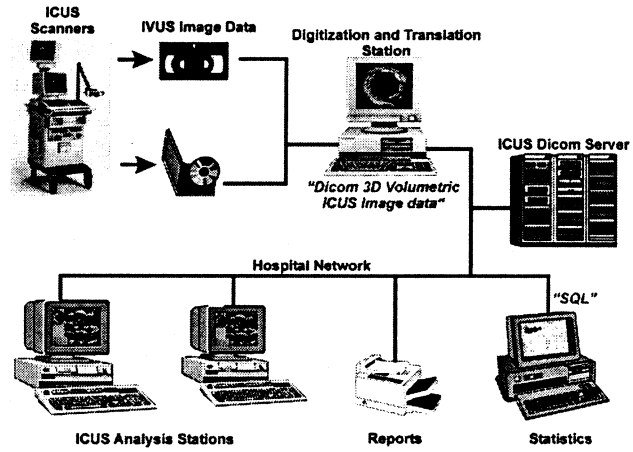

Figure 1. Overview of the IVUS analysis infrastructure.

2.1. Acquisition

The IVUS images as used in the analysis can have their origin from multiple sources:

- DICOM IVUS images.
- Images from video tape are grabbed and converted to DICOM.
- Images from other proprietary digital formats are

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converted to DICOM, such as the output of the ECG-gated TomTec acquisition station [2].

2.2. L-Mode reconstruction

Of a selected IVUS study the cross-sectional images are displayed in a video loop. In addition, two reconstructed longitudinal cut-planes for orthogonal reconstruction angles are displayed as well. As many as 72 L-Mode views at 5 degree intervals can be selected for display and subsequent contour tracing.

The L-Mode images augment the feasibility to recognise relevant tissue structures. In case of an ECG-gated acquisition, the L-Mode images have a continuous smooth appearance. The longitudinal resolution is usually fixed to .2 mm. For non-gated continuous motorised pull-back data, catheter movement due to cardiac movement and coronary pulsation lead to a discontinuous saw-teeth like L-Mode display when a selection of a few images per heartbeat is used [3]. The appearance improves drastically with temporal (and spatial) resolution by using more frames (10-15 per heartbeat) in the analysis.

2.3. L-Mode contour tracing

The improved L-Mode display enables semi-automatic contour tracing. The tracing is facilitated by an edge-detection method, using a digital Deriche filter [4-5]. This filter calculates the gradient of the image while applying a smoothing operator to the data in such a way that noise is reduced and true boundaries are enhanced. Due to the fast recursive implementation possibilities of the filter, its speed is independent of the magnitude of the smoothing parameters. The subsequent edge-thinning and edge-linking method exploits the continuity of the longitudinal contours as well as knowledge of gradient directions of the structure boundaries of interest.

Contours of Vessel, Lumen and Stent structures can be traced (Fig. 2). In stead of trying to find the structures fully automatically, the program uses starting points as defined by the user followed by an auto-tracing of the contour segment in either of the two possible directions. Pieces of the contours can be retraced in a semi-automatic procedure optimising the interaction between operator and algorithm. The former is guided by a simultaneous display of the current mouse position in the corresponding cross-sectional image. In this way, the 3 dimensional nature of the data set is fully employed.

2.4. Spline representation

The found longitudinal contour points are mapped to the cross-sectional images. Here they serve as control points for a mathematical description of closed contours encompassing the regions of interest (Vessel, Lumen and Stent). The mathematical description consists of a connected series of Bezier Curves [6]. These fourth degree polynomial functions are completely determined by two end-points (two "control-points" from the L-Mode contours) and two additional control points (not laying on the contour). These additional points determine the curvature of the Bezier segments and are calculated from a smooth continuity requirement at the transition of attached contour segments.

Although as many as 72 possible L-Mode views may lead to 72 control points, it turns out in practice that tracing 8 to 9 longitudinal contours lead to the optimal performance in terms of accuracy. The resulting cross-sectional Bezier contours can be visualized immediately superimposed on a running video loop and may be edited manually. However, it appears to be far more effective to refer to the longitudinal contour in order to make changes that affect multiple frames simultaneously. Evidently, the tracing of a total of 9 contours increases analysis speed substantially as compared to tracing many individual cross-sectional contours.

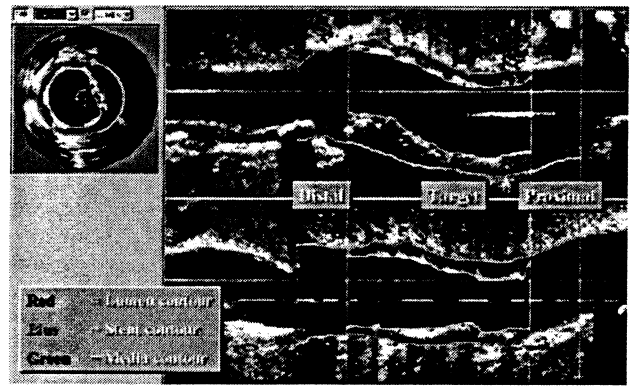

Figure 2. L-Mode display with Vessel, Lumen and Stent contours in three analysis regions.

2.5. Calculations

Quantities of interest in a cross-sectional image may be calculated from the contour information in an analytical way, based on the mathematical contour description (Fig. 3). Surface based quantities - such as the CSA - are calculated analytically by transforming the surface integral of an applicable vector field to a line integral (bounded by the Bezier curve) by means of the Stokes theorem.

As an example, a - rotationally invariant - measure of the contour symmetry can be determined by the ratio of the eigenvalues of the inertia matrix representing the surface enclosed by the contour. The second order moments (surface integrals) of the inertia matrix and hence its eigenvalues can be calculated from the contour description in a similar manner.

Volumes are determined from a summation of measured CSA's in all frames of a pullback region. Errors due to this discrete approximation are minimized due to the high longitudinal resolution implied by the method.

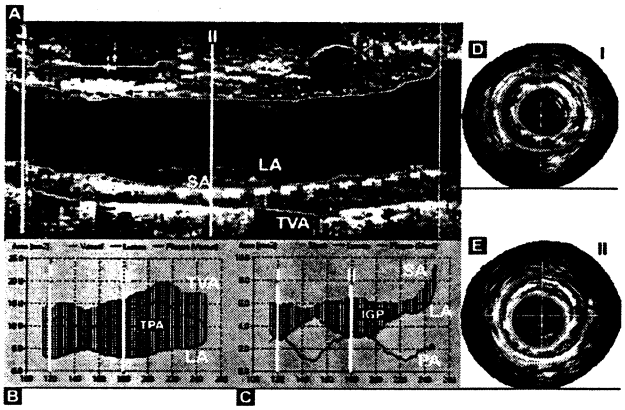

Figure 3. L-Mode View (A) and two cross-sectional images (D, E) with fitted spline contours. Plaque analysis (B) showing calculated total Vessel area (TVA), Lumen area (LA) and Total Plaque area (TPA) distributions. Similarly for the Stent analysis (C), showing the calculated Stent area (SA), Lumen area (LA) and the Ingrow plaque (IGP) distributions.

3. Validation study

A validation study was carried through on ECG-gated data sets with an average of 130 frames. In an inter-observer study, a full IVUS analysis was performed by two independent operators on 24 pullback studies. Volumes were determined and compared for lumen, stent and total vessel structures.

In addition, a Bland-Altman analysis of the new method versus a reference method [7] was performed on 25 pullback studies.

4. Results

The inter-observer correlation coefficients for lumen- (LV), stent- (SV) and total vessel (TVV) volumes resulted in r^2-values of 0.96, 0.99 and 0.99, respectively. The Bland-Altman analysis of the method versus a reference method resulted in relative differences for LV, SV and TVV of -3.8±12.34%, 9.11±7.12% and -3.95±4.06% (Fig. 4). The average analysis time was reduced from 2 hours to 12 min.

5. Conclusion

For ECG-gated IVUS pullbacks, the described novel analysis method showed dramatically reduced analysis times as compared to a reference method, without compromising accuracy. The performance for large non-gated data sets (>1000 frames) is subject of further study.

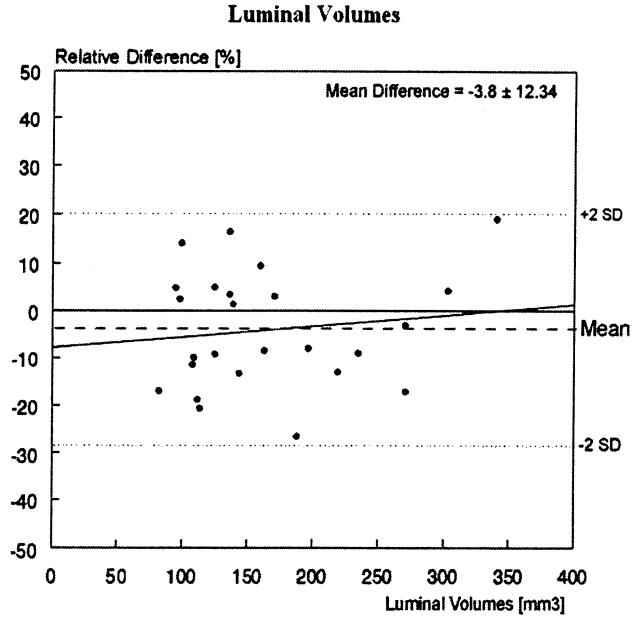

Figure 4. Bland-Altman analysis for luminal volumes of the new versus a reference analysis procedure.

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