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Original Article

Three-dimensional reconstruction of coronary arteries based on the integration of intravascular ultrasound and conventional angiography

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ABSTRACT

Background: Coronary three-dimensional reconstruction with the combination of intravascular ultrasound and angiography offers advantages over computed tomography angiography of coronary arteries. The authors aimed to present the pilot phase of the validation of a new model of three-dimensional reconstruction of coronary arteries.
Methods: This study used angiography and intravascular ultrasound examinations already performed by clinical indication in individuals with known or suspected stable coronary artery disease. Image processing, segmentation, and three-dimensional reconstruction were conducted following specific methodology. For geometrical characterization purposes, tridimensional center lines were obtained.
Results: Three vessels were reconstructed: two left anterior descending arteries and one left circumflex artery. The vessel lumen volume and the overall plaque burden could be easily viewed with three-dimensional reconstruction. The geometric characterization revealed increased absolute values of length, tortuosity, curvature, and torsion, featuring a greater complexity of the center line of the diseased lumen relative to the center line of the external elastic membrane.
Conclusions: This new methodology, which integrates conventional angiography and intravascular ultrasound, has increased the practicality of the reconstructions, with a gain in volumetric accuracy of the vessel and overall visualization of key aspects of atherosclerotic disease, such as plaque remodeling and distribution.

Reconstrução tridimensional de artérias coronárias a partir da integração do ultrassom intracoronário e da angiografia convencional

Palavras-chave:
Ultrassonografia de intervenção
Angiografia
Imagem tridimensional
Aterosclerose

RESUMO

Introdução: A reconstrução tridimensional coronária com a combinação do ultrassom intracoronário e da angiografia apresenta vantagens em relação à angiotomografia de coronárias. Objetivamos apresentar a fase piloto de validação de um novo modelo de reconstrução tridimensional de artérias coronárias.
Métodos: Foram utilizados exames de angiografia e ultrassom intracoronário já realizados por indicação clínica em indivíduos com suspeita ou diagnóstico de doença arterial coronária estável. O processamento das imagens, a segmentação e a reconstrução tridimensional foram realizados seguindo metodologia específica. Para fins de caracterização geométrica, foram obtidas as linhas de centro tridimensionais.
Resultados: Foram reconstruídos três vasos, sendo duas artérias descendentes anteriores e uma artéria circunflexa. O volume da luz do vaso e a carga de placa global puderam ser visualizados com facilidade com a reconstrução tridimensional. A caracterização geométrica revelou aumento dos valores absolutos do comprimento, tortuosidade, curvatura e torsão, caracterizando uma maior complexidade da linha de centro da luz doente, em relação à linha de centro da membrana elástica externa.

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Conclusões: Essa nova metodologia, que integrou angiografia convencional e ultrassom intracoronário, aumentou a praticidade das reconstruções, com ganho em acurácia volumétrica do vaso e visualização global de aspectos-chave da doença aterosclerótica, como remodelamento e distribuição da placa.

Introduction

Some studies use biplane angiography (AX) for three-dimensional reconstruction of the coronary artery lumen.[1,2] However, AX is limited to defining the vessel lumen. Intravascular ultrasound (IVUS) is an accurate intravascular imaging technique for plaque quantification and location, since it allows for an accurate assessment from the adventitia to the intima. The combined use of IVUS and AX offers an interesting alternative for coronary three-dimensional reconstruction, outperforming coronary angiotomography (CT) in terms of accuracy. The ability to reconstruct the entire three-dimensional arterial wall allows for exploitation of the spatial characteristics of plaque. It can also be used for extracting geometrical features for studying the development and progression of atherosclerotic plaques, and for computational fluid dynamics models assessing the hemodynamics repercussions of the plaque.[3]

This study aimed to present the pilot phase of validation of a new three-dimensional reconstruction model.

Methods

Acquisition of images

For the development of this method, AX and IVUS, performed by clinical indication in patients with known or suspected stable coronary artery disease, from two institutions, the Hospital Sírio-Libanês and the Instituto do Coração, Hospital das Clínicas, University of São Paulo Medical School (FMUSP), both located in the city of São Paulo, SP, Brazil. After compilation, the anonymized data were analyzed by the research team in association with the Laboratório Nacional de Computação Científica (LNCC), where they were processed and integrated. The research project that incorporates this manuscript was approved by the Research Ethics Committee of Hospital Sírio-Libanês and of Hospital das Clínicas (FMUSP).

Reconstructions resulting from IVUS-AX were reprocessed, and geometric shapes of the lumen and the external elastic membrane (EEM) were extracted. Subsequently, the center lines and corresponding volumes of the lumen and the plaque were estimated. Finally, a set of geometric descriptors, calculated from the center line, were used to characterize the geometric shapes of the lumen and the EEM, and the difference between center lines was attributed to the presence of atherosclerotic plaque.

For the acquisition of IVUS images, the iLabTM system was used (Boston Scientific Corporation, Natick, USA), which allowed for the acquisition grayscale-scanned ultrasound images. The intracoronary ultrasound catheter Atlantis™ SR Pro was used (Boston Scientific Corporation, Natick, USA), consisting of a mechanical ultrasound catheter with a frequency of 40 MHz. Automatic IVUS catheter pullbacks were performed in the catheter sheath at the rate of 0.5 mm/s, beginning in the mid-distal third towards the artery ostium, with sectional tomographic image acquisition at a rate of 30 frames/sec.

The movement of the IVUS catheter and vessel curvature hampered the volumetric estimation of plaque burden. The movement of the catheter was corrected using only frames acquired in the diastolic phase of the cardiac cycle.[4] However, the incorporation of vessel curvature required a location within the catheter space in order to estimate the correct position of the frames in cross-sectional images. Therefore, before the pullback, orthogonal AX was performed in the left anterior oblique and right anterior oblique projections, with cranial and caudal angulation, to estimate the catheter and the sheath spatial location.

Preprocessing and segmentation

To correct the catheter movement due to heartbeat, the frames associated with end-diastolic phase of the cardiac cycle were selected. The mathematical details were provided in a previous publication of this group.[5] The choice of the end-diastolic phase was due to the minor displacement of the catheter, ensuring a more accurate spatial location during catheter pullback.

The study with IVUS provides a low signal-to-noise ratio (SNR), making vessel lumen and EEM recognition and, in turn, that of plaque burden, difficult. To reduce noise and preserve the structures of interest, an anisotropic diffusion method was employed.[6]

The vessel geometry extraction (segmentation) was performed using an adapted method of active contours.[7] The energy functions used specifically in the process of minimization of active contours to extract the contour of the vessel lumen and EEM were, respectively,

$$\mathscr{E}_{\mathrm{lumen}} = \frac{1}{2}\int_0^1 \left(\alpha\frac{d\mathbf{v}^\ell}{ds} + \beta\frac{d^2\mathbf{v}^\ell}{ds^2} + \kappa\mathbf{F}_{\mathrm{GVF}}\mathbf{v}^\ell + \kappa_p\mathbf{n}\mathbf{v}^\ell + \eta\gamma e^{-\frac{\|\mathbf{v}^\ell-\mathbf{v}^e\|^2}{\gamma}} \right) \mathrm{ds}$$

$$\mathscr{E}_{\mathrm{EEM}} = \frac{1}{2}\int_0^1 \left(\alpha\frac{d\mathbf{v}^e}{ds} + \beta\frac{d^2\mathbf{v}^e}{ds^2} + \kappa\mathbf{F}_{\mathrm{GVF}}\mathbf{v}^e + \kappa_p\mathbf{n}\mathbf{v}^e \right) \mathrm{ds}$$

the variables of these equations are described in articles by Maso Talou,[7] Kass et al.,[8] and Xu and Prince.[9]

To begin the process of segmentation, manual initialization of the contours was made in the first frame of the sequence of end-diastolic phases of IVUS. Subsequent frames took into account the contours of the previous frame to initialize the method. In case of a failed frame contour or if not sufficiently accurate, the operator redefined the required contours in that frame and continued the segmentation process.

Three-dimensional reconstruction

The orthogonal AX allowed optimal viewing of the catheter and of bifurcations. Observing the cardiac cycle, two frames of AX in diastolic phase were drawn: one with and the other without contrast. The lack of contrast allowed for a full visualization of the IVUS catheter. In addition to these conditions, the IVUS catheter sheath was segmented from the aortic sinus until the end of the transducer, with a biplane snake strategy.[10] During snake initialization, the operator indicated only two points in AX: the location of the transducer and the aortic sinus, generating a straight line between these points. Then, the functional power of snake was optimized to get the segmentation of the catheter as a parametric curve c (s), $s \in [0.1]$.