Computers in Biology and Medicine 44 (2014) 97–109

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

A simple framework to generate 3D patient-specific model of coronary artery bifurcation from single-plane angiographic images

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A R T I C L E I N F O

Article history:
Received 24 April 2013
Accepted 28 October 2013

Keywords:
X-ray coronary angiography
Image processing
Bifurcation coronary arteries
3D reconstruction
Mesh
Finite element analysis

A B S T R A C T

Although computer-based simulations, such as structural finite element analysis, have proven their usefulness to support procedural planning of coronary stenting, the link between the clinical practice and these engineering techniques is still limited to research test-cases. A key point to further promote such an interaction is to generate in a fast and effective manner the computational grids from the medical images. Hence, the present study proposes a simple framework to generate 3D meshes of coronary bifurcations from a pair of planar angiographic images obtained by X-ray angiography, which is the gold standard technique for the diagnosis of coronary artery stenosis.

1. Introduction

Coronary artery disease, which is the main cause of death worldwide [1], is due to atherosclerotic lesions narrowing the arterial lumen, i.e., stenosis, and decreasing the blood supply to the heart muscle. Coronary stenosis can occur in different parts of coronary tree but, among the others, lesions involving coronary bifurcations are more frequent and challenging to treat by current percutaneous coronary interventions [2].

Nowadays, X-ray quantitative coronary angiography is the *gold standard* technique for coronary stenosis detection. This technique, widely available among interventional cardiologies, overcomes subjective visual estimation of lesion severity caused by high degree of the intra-observe variability present in the traditional X-ray angiography technique, providing objective quantification of the coronary artery disease [3].

Nevertheless, this procedure has still bi-dimensional limitations due to the vessel overlap and foreshortening [9], which are of particular interest in the bifurcated coronary artery evaluation owing to their complex geometric configuration. Recently, advanced technologies evolving in 3D coronary artery modelling have been introduced from the X-ray angiography technique, in particular in the case of complex lesions concern the bifurcated coronary arteries, i.e., CardioOp (Paieon, Rosh Ha'Ayin, Israel) and CAAS QCA 3D (Pie Medical, Maastricht, The Netherlands) [9–12]. On one hand, such innovative commercial softwares quantify accurately the coronary lumen disease overcoming these bi-dimensional limitations into clinical practice, on the other hand, the resulting 3D coronary patient-specific models provide nowadays the information useful to generate mesh-grid models to use in finite element analysis (FEA). Indeed, recent studies have highlighted the potential role of realistic computer-based simulations based on coronary models derived directly from medical images, as a valuable support to the pre-procedural planning [4–6].

In particular, Mortier et al. [7] generated the coronary bifurcation model from three-dimensional (3D) geometrical information on the lumen of a left coronary tree, obtained by the rotational angiography using the dedicated Allura 3D-CA software.[1] In a similar manner, Morlacchi et al. [8] performed structural FEA of coronary stenting exploiting image-based reconstructions of the coronary bifurcation, which are created combining the information from conventional coronary angiography and computed tomographic angiography. Further, in the work proposed by Goubergrits et al. [13], the image-based coronary reconstruction, using the CAAS QCA 3D commercial software,[2] stands out the usefulness of bifurcated artery models generated from the X-ray

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http://dx.doi.org/10.1016/j.compbiomed.2013.10.027

angiographic images to study the wall shear stress profiling in the coronary arteries.

Although these studies highlight the potentiality of realistic numerical simulations from image-based models, the link between the clinical practice and these engineering techniques is unfortunately still limited to research test-cases. In fact, even if several medical-imaging commercial workstations achieve the 3D coronary reconstruction, they are not able to build immediately FEA-suitable meshes, requiring thus *ad hoc* implementation of outer hardware and software, as discussed by Goubergrits et al. [13] and De Santis et al. [14], especially for 3D bifurcated coronary mesh models.

Given these considerations, it is clear that a key point to further promote the integration between clinical practice and the engineering tools is to generate in a fast and effective manner the computational grids directly from angiographic images used in the clinical practice [15], by-passing the coronary artery generation through these workstations.

Although, other angiographic imaging techniques, i.e., computed tomographic angiography (CTA), magnetic resonance angiography (RMA), intra-vascular ultrasound (IVUS), are investigated as alternative or in combination to the X-ray angiography [40,43], they are restricted to a limited number of patients and not many available in the clinical practice. Whereas, X-ray angiography, which has been validated with respect to the CTA and RMA for coronary surface reconstruction and flow estimation [13], remains the current technique used in coronary artery diagnosis and treatment among the cardiologies.

Hence, the present study proposes a simple framework to generate 3D FEA-suitable meshes of coronary bifurcations from a given pair of X-ray planar images to increase the integration and interaction between clinical practice and complex patient-specific computer based analyses.

In this context, we offer a novel user-friendly tool, available also for the interventional cardiology, in order to evaluate the bifurcated coronary morphologies and morphometries directly available to numerical analyses from medical images.

2. Materials and methods

In this study we define a methodological framework, resembling the work-flow depicted in Fig. 1. After images acquisition, two projected views are selected and then elaborated, first in an image processing and, then, in a specific 3D modelling procedures, which are implemented in Matlab (The MathWorks Inc., Natick, MA, USA). The image processing consists in the image enhancement to improve the image quality and in the segmentation procedure for the coronary lumen contouring. The 3D coronary artery modelling (skeletoning) is generated from the 3D centerline reconstruction and the mean radii values computed thanks to the segmentation procedure. Finally, the algorithm generates automatically the vessel mesh model, computing also the main features of the bifurcated coronary artery, i.e., diameters, lumen area, bifurcation angles, stenosis degree. In the following we discuss each step of the work-flow. All the analyses presented in this study are performed off-line after the completion of angiographic study, through the use of an Intel Core 2 Duo CPU/3.23 of RAM, with a computational time of 4–5 min.

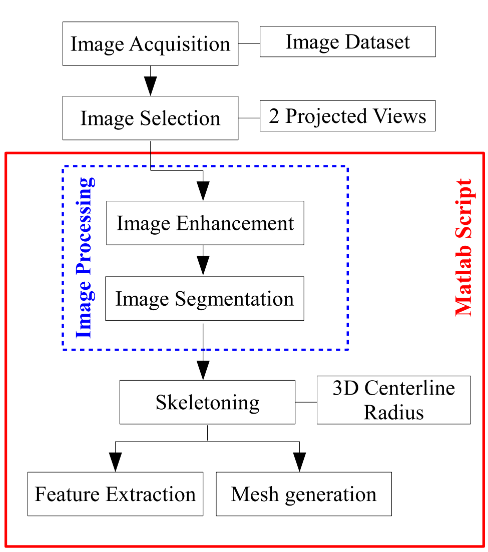

Fig. 1. Schematic work-flow of the 3D reconstruction procedure.

2.1. Image acquisition

The input of the framework is a set of medical images, in DICOM format, acquired by X-ray coronary angiography (General Electric, Schenectady, NY, USA). This technique consists in the radiologic visualisation of the coronary tree, thanks to contrast-dye injections performed through minimally invasive catheterization. Usually, cine-angiographic sequences at 15 frames per second are acquired with the flat detector angles selected by the interventional cardiologist. Each frame of this sequence represents a projection of the coronary artery into a single-plane system. Moreover, the images are also correlated to the cardiac cycle by electrocardiographic gating [16]; this approach allows to reduce the artefacts due to the cardiac motion and facilitates the choice of different views at the same cardiac phase. Usually, the end-diastolic phase is preferred [17] because, in this specific time frame, the lumen is fully filled by the contrast-dye and thus it is easy to visualise [18].

During the image acquisition the table movement is minimised by an iso-centering procedure [19,20]. Each image contains not only the patient's data but also the image acquisition settings, which include, among the others, focal-spot to image intensifier distance (SID), field of view (FOV), flat panel orientation, imager pixel spacing (IPS), and estimated radiographic magnification factor (ERMF). Other image metadata can be derived; for instance, the pixel spacing (PS) is computed as the ratio between IPS and ERMF for both views.

Each angiographic view is defined by the flat detector orientation in terms of the left or the right anterior oblique (LAO or RAO) angle and the caudal or cranial (CAUD or CRAN) angle with respect to the iso-center point. Moreover, the flat detector motion is characterised by constant SID and iso-center value in order to establish a pointwise correspondence between the two views [21,17,22].

2.2. Image selection

For the 3D coronary artery reconstruction, two projection views at the same cardiac phase are selected from the angiographic sequence with a constant CAUD/CRAN angle and varying LAO/RAO angle value; for instance, Fig. 2 shows an example of two angiographic images having a pixel resolution of 512×512 and an IPS of 0.2875 mm.

2.3. Image processing

Once the two views are selected, for each of them, it is necessary to enhance the image quality and to detect the edge contours of the lumen as described in the following subsections.