

Image-based mesh generation in the field of cardiology

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We are developing a high-performance computer system to simulate coronary hemodynamics in the clinical domain of coronary artery disease. This system will be suitable for both the diagnosis and therapy of coronary artery disease. The diagnosis of cardiovascular disease and the planning of therapy should be based on a fair knowledge of the patient's hemodynamic state. This is particularly true of coronary artery disease in cases where severe stenoses in the epicardial arteries increase the resistance to flow. Moreover, the highly disturbed flow around stenoses accelerates the progression of the atherosclerotic changes and may cause the formation of and development of thrombi.

We will focus on three-dimensional computer simulation studies of the flow of blood within the epicardial arteries, especially around stenoses (narrowing), since in such sections the knowledge of the flow pattern is highly important to the assessment of the severity of coronary artery disease. We use the commercial CFD software package FIDAP which is based on the finite element method. For our three-dimensional CFD simulation studies [4, 5], we need a fair knowledge of the geometry of the epicardial arteries. Moreover, we must generate a mesh. Both the acquisition of the geometry and the mesh generation activities are challenging tasks. In the next section, we will deal with the acquisition of the geometry based on angiograms. This description will be followed by a section focusing on a semi-automatic mesh generation method which allows us to generate a high-quality mesh that comes close to an optimal mesh. In this section, we will also present simulation results.

Acquisition of the geometry of the epicardial arteries

In the clinical domain of coronary artery disease, cardiologists frequently take biplane angiograms to acquire the geometry of the epicardial arteries and especially to assess stenosis severity by exploiting the morphologic information about these lesions that the images provide. In many cases, the morphologic characteristics of a stenosis are identified simply by performing a visual inspection of both angiograms. However, it seems clear that this method of assessing coronary lesion severity is rather limited. It is apparent

that for reliable diagnoses and predictions, cardiologists need more accurate and better reproducible methods of the acquisition of the patient-specific morphologic (morphometric) characteristics of the flow domain within the epicardial arteries. In current clinical practice, the information contained in the biplane angiograms is not fully exploited for diagnoses and clinical decisions, since cardiologists do not have a representation of the genuine three-dimensional geometry of the epicardial arteries at their disposal, and therefore frequently overlook diffuse narrowing [1]. However, we aim at a three-dimensional representation of the tree-like structure of the epicardial arteries.

A prerequisite for carrying out this reconstruction task in clinical settings is the largely automatic segmentation of the coronary arteries in the biplane X-ray angiograms. This is a rather difficult task, since we have to reckon with noise, artefacts and other flaws which deteriorate the image quality. We developed an advanced segmentation technique using our *a priori* knowledge that the epicardial arteries have a tree-like tubular structure with sections of different size. We exploit this *a priori* knowledge to detect the representation of the coronary artery tree among noise, artefacts and other weak spots of the angiogram. Our approach utilises differential geometric criteria [2]. We developed a Hessian-based artery enhancement filter which is based on a multi-scale filtering approach. This filter is well suited to detect tubular structures, which in our case are the tubular structures of the epicardial arteries. We use a skeleton-based technique to segment and later three-dimensionally reconstruct the arteries. At first we compute the skeleton of these vessels. This skeleton forms an appropriate basis for the final steps of the segmentation process which comprises the determination of the boundaries of the coronary arteries in the original image and the precise determination of the final centrelines. One of the two projections of a biplane angiogram before image processing is shown in Figure 1(a); the skeletonised angiogram can be seen in Figure 1(b). In Figure 2, the segmented arterial tree and the final centrelines are depicted. After these aforementioned final steps of our segmentation approach, the biplane angiograms permit the aspired three-dimensional reconstruction. Although a few methods for the three-dimensional reconstruction of the coronary arteries (flow domain) have already been developed [3], they could not be introduced into clinical practice due to their insufficient accuracy. We use an improved reconstruction method which we have developed earlier and is described in [5]. As a result, we obtain a wireframe model of the geometry of the epicardial arteries.

Mesh generation approach

The patient-specific flow domain within an epicardial artery must be discretised by generating a mesh. Starting with the aforementioned geometric model of the flow domain within the epicardial arteries, we generate a high-quality mesh based on *a priori* criteria as has been described in [5]. This is an important and challenging task because the quality of the mesh affects the accuracy of the solution, the CPU time, and the memory requirements. Generating a high-quality mesh is difficult since numerical methods such as the finite element method require well-shaped elements which cannot be easily constructed in our complicated flow domains. The size of the elements has a strong impact on the accuracy and expense in terms of memory demands and CPU time. Specifically, we generate a structured mesh with anisotropic features to avoid distorted elements and employ a multi-block mesh generation approach. We use the commercial mesh generator GAMBIT and a new meshing approach to attain a high-quality mesh (for details we

refer to [5]). Figure 3 shows the wire frame model of a section of an epicardial artery and illustrates some basic characteristics of our mesh; the mesh of a stenosed section of an epicardial can be seen in Figure 4. The result of a three-dimensional simulation study of the flow of blood in a stenosed section of a coronary artery is also presented in Figure 4 (variation of the absolute value of the velocity on longitudinal cutting plane).

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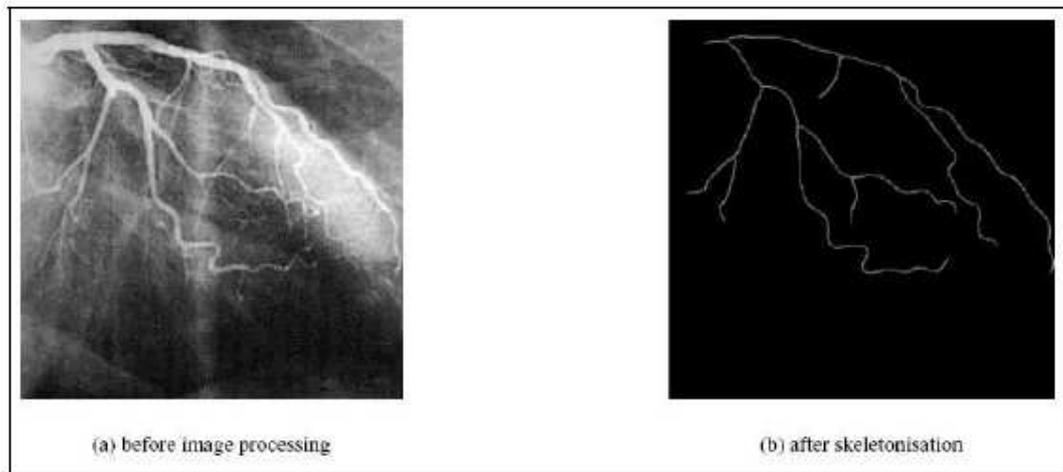


Figure 0.1: Coronary angiogram: (a) before image processing, (b) after skeletonisation

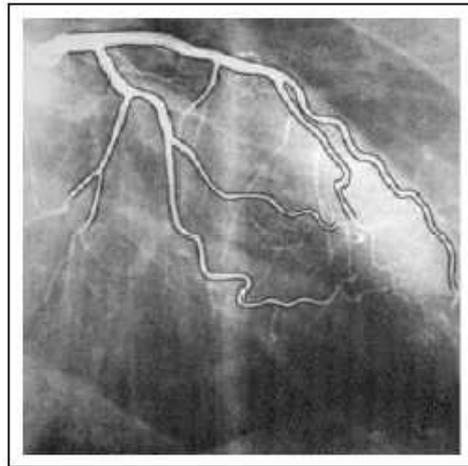


Figure 0.2: Final result of the entire segmentation process

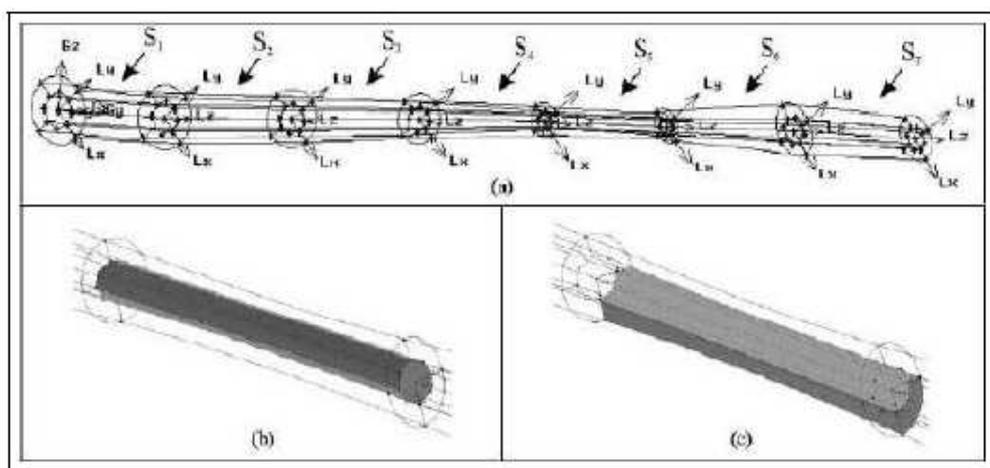


Figure 0.3: Geometric modelling and multi-block meshing approach: (a) wire frame model of a section of an epicardial artery; (b) core block with generated mesh; (c) peripheral block with generated mesh

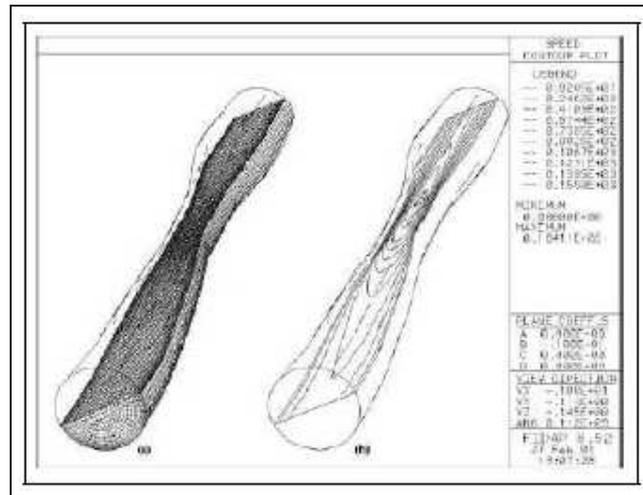


Figure 0.4: (a) Representation of an generated mesh. (b) Contour plot of the variation of the absolute value of the velocity(on longitudinal cutting plane)