Automatization of 3D Reconstruction of Coronary Arteries from Angiography Projections using AI-enhanced Segmentation Techniques

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Abstract. Fractional flow reserve (FFR) is one of the clinical diagnostics measurements that are performed to assess the physiological significance of stenosis potentially present in coronary arteries. Virtual fractional flow reserve (vFFR) is an alternative non-invasive approach that consists of performing the 3D reconstruction of the patient-specific coronary artery and afterwards applying techniques of computational fluid dynamics (CFD) to obtain the vFFR value. Within this paper, a new approach is presented, that combines the AI-enhanced segmentation of DICOM images obtained during X-ray angiography (XRA) examination and 3D reconstruction and finite element (FE) mesh generation. This enables an automated reconstruction and numerical simulations of blood flow through patient-specific coronary arteries. The developed software is accurate, executes in a timely manner and is intuitive to use, which makes it a useful tool for the clinicians to perform hemodynamic analyses of the state of coronary arteries. It can thus provide assistance in the treatment planning that is adapted to the particular patient.

Keywords: X-ray angiography, image segmentation, 3D reconstruction, CFD, FFR calculation.

1 Introduction

Fractional flow reserve (FFR) is one of the clinical diagnostics measurements that are performed to assess the physiological significance of stenosis potentially present in coronary arteries. Virtual fractional flow reserve (vFFR) is an alternative non-invasive approach that consists of performing the 3D reconstruction of the patient-specific coronary artery and afterwards applying techniques of computational fluid dynamics (CFD) to obtain the vFFR value. Several studies in literature proposed approaches to perform this task [1-3]. However, most of the previously proposed techniques include manual intervention from the clinician. In this study an approach is presented, that combines the AI-enhanced segmentation of DICOM images obtained during X-ray angiography (XRA) examination and 3D reconstruction and finite element (FE) mesh generation. In order to calculate the FFR equivalent, the approach proposed in literature [4] is used. The so-called virtual functional assessment index (vFAI) is calculated. In literature it was shown that this approach can accurately predict the clinically measured values of FFR [4,5]. The whole combined approach is implemented in a software that is fully automated and enables the user to analyze the results of the simulation of blood flow.

The paper is organized as follows. Section 2 presents the combined approach, the developed software is presented in Section 3, and Section 4 concludes the paper.

2 Materials and Methods

The segmentation of patient-specific DICOM images obtained during XRA examination is first performed by using image filtering techniques for region of interest extraction. Image filtering was conducted in seven consecutive phases using different filters and image transformations. Namely, loaded XRA images were passed through a contrast limited adaptive histogram equalization (CLAHE) filter, followed by color inversion and top-hat transformation for creating a new base image in which coronary arteries were more distinguished from the surrounding heart tissue. A ridge detection hessian matrix filter was applied to determine the standout vessel bodies, followed by a Gaussian blur filter whose purpose was to reduce discontinuations along main vessels and eliminate small disturbances in the background of the image. After image blurring, a system of 32 Gabor filters with different combinations of orientations and wavelength amplitudes was applied for edge detection. The final step in image filtering was determining the largest extracted continuous bodies of foreground pixels and merger of all other foreground pixels, that do not belong to this body with the background of the image since they do not belong to the main coronary artery tree, or are too small to have an impact on overall FFR calculation. This image filtering pipeline coupled with binary image skeletonization resulted in coronary artery centerline information necessary for reconstruction in 3D space. Additionally, branch length equalization based on multipoint matching and duplicate removal was conducted in order to avoid manual point annotation in multiple X-Ray views. Epipolar geometry based on XRA C-ARM position and matching point pair positions in different views was used to create the centerline and surface point cloud reconstructions in 3D space.

This extracted data was then used in the 3D reconstruction process. The centerline points that were obtained during segmentation were used to define the parameterized centerline, as a non-uniform B-spline [6]. The surface point cloud was used to create the cross-sections (patches) along the parameterized centerline, that were further used to define the parametric NURBS surface (Non-Uniform Rational Basis Splines) [6]. The 3D FE mesh of the coronary artery was then created using the NURBS surface [7,8].

FFR value is clinically measured during coronary angiography examination, under the induction of hyperemia, by measuring two pressure values. When the measured pressure distal to the arterial stenosis (P_d) is divided by the aortic pressure (P_a), the value of FFR is obtained. The vFAI index used in this study is calculated by performing two numerical simulations. These simulations were performed using the FE method [9], more specifically using the in-house developed software PakF [10]. The validation of this software was performed in many papers published in literature [9-11] and during many EU financed projects. In order to simulate the 3D blood flow, the Navier-Stokes equations and continuity equation were solved within the mentioned software. The blood is considered as viscous incompressible fluid. The zero velocity is prescribed on all nodes on the wall of the artery. The two mentioned simulations that had to be performed in order to calculate the vFAI value differ only in the prescribed boundary conditions. In both cases the pressure of 100 mmHg is prescribed at the inlet, while the flow rate is prescribed at the outlet. For the first simulation, the flow rate is equal to 1 ml/s, and for the second the value of prescribed flow rate is 3 ml/s. These precise values are prescribed because they correspond to the average blood flow during rest and under stress, respectively. The pressure gradient is obtained for both considered cases, and then the relationship between pressure gradient ΔP and flow rate Q is defined as follows:

$$\Delta P = 0 + f_v Q + f_s Q^2 \tag{1}$$

where f_v and f_s are the coefficients of pressure loss due to viscous friction and flow separation, respectively [12]. The values of pressure gradient calculated for two considered cases are used to calculate these coefficients, and then the following relation can be defined:

$$\frac{P_d}{P_a} = 1 - f_v \frac{Q}{P_a} - f_s \frac{Q^2}{P_a} \tag{2}$$

Using this relation, a graph of dependence of the value P_d/ P_a from blood flow can be drawn and the vFAI can be calculated as the area under this curve, compared to the reference area. More details about this procedure can be found in cited literature [4,5], where this approach to calculate the FFR alternative was also extensively validated and it was demonstrated that it agrees well with clinically measured values of FFR for large clinical datasets.

3 Results

The proposed approach is implemented within in-house developed software. The AI-enhanced segmentation is implemented in programming language Python using primarily image processing libraries SkImage and OpenCV, as well as the numerical operation simplification library NumPy, while the 3D reconstruction is implemented in programming language C++, with the interface and visualization that were implemented with the use of OpenGL and GLUT libraries.

Fig. 1 shows the results of the segmentation, i.e. extracted centerlines and patches placed along the centerlines. On the left, the original the patient-specific DICOM XRA images are shown.

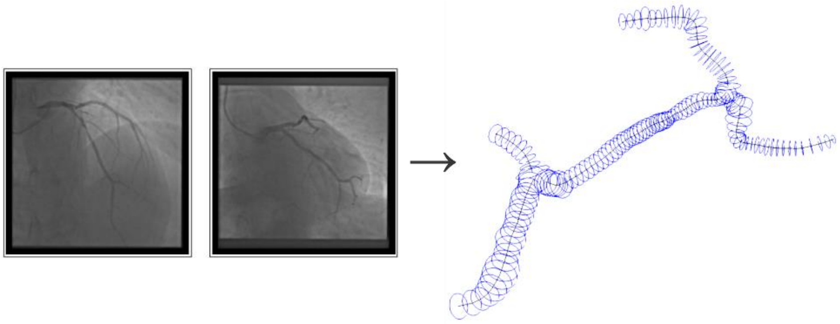

Fig. 1. Results of the automated AI-enhanced segmentation. The original patient-specific DICOM images (on the left) and the extracted centerline data together with obtained patches.

Fig. 2 shows a screenshot of the developed software, after the performed numerical simulation. Within the numerical simulation, not only the value of FFR equivalent is calculated, but the full blood flow simulation is performed which enables the visualization of the hemodynamic quantities. In Fig. 2 the distribution of wall shear stress (WSS) is shown.

4 Conclusion

Within this study an approach for automated segmentation and 3D reconstruction of patient-specific coronary angiography images is presented, where the final goal is to calculate the equivalent of invasively measured FFR, called vFAI. An important benefit of the vFAI calculations applied in the presented approach is that the results can be obtained within a few minutes, which makes it very applicable for automated software that executes almost in real time, like it is the one presented in this study. Another benefit of the numerical simulations applied in this study is that besides the vFAI value, other hemodynamic quantities, including velocity and WSS are also calculated and visualized within the developed software, which enables the user (clinician) a more thorough analysis of the state of the patient-specific coronary artery. The developed software is accurate, executes in a timely manner and is intuitive to use, which makes it a useful tool for the clinicians and it can therefore provide assistance in the treatment planning that is adapted to the particular patient.

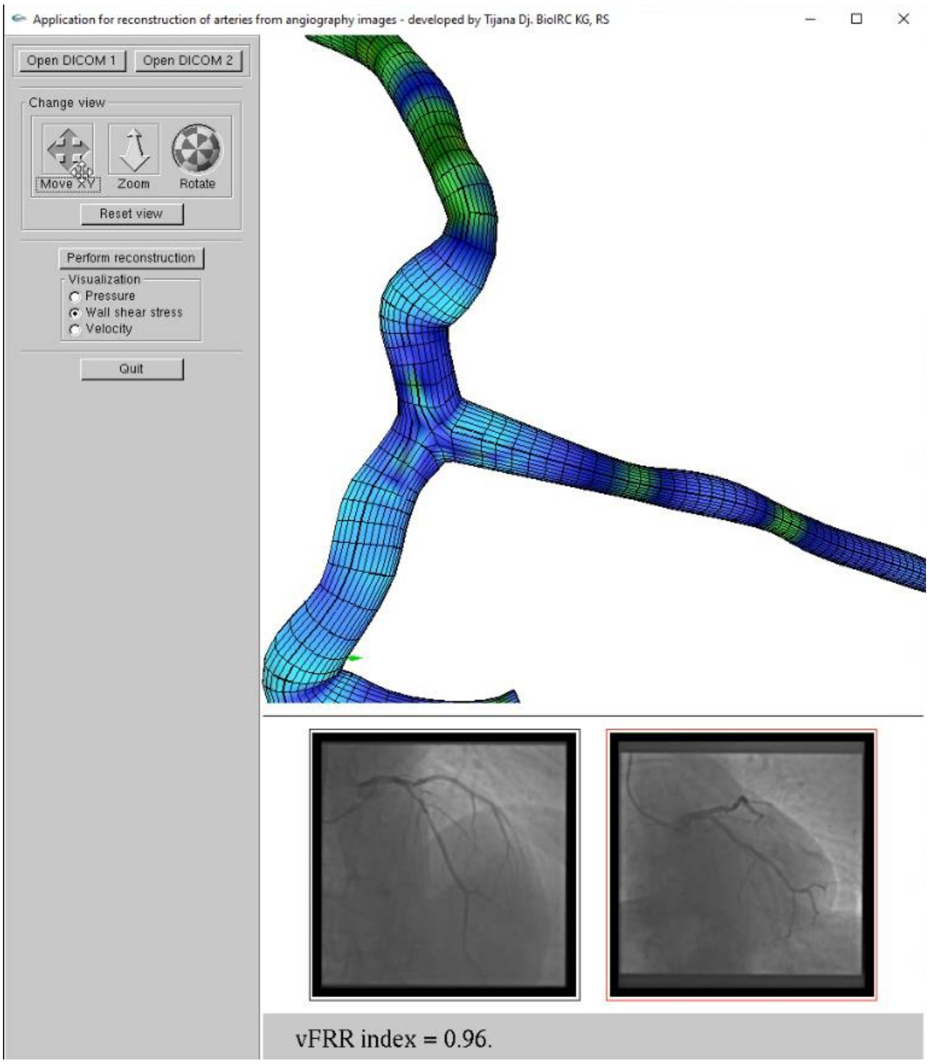

Fig. 2. Screenshot of the developed software, with calculated FFR equivalent value and shown distribution of WSS.

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