Medical Decision-Making: Incompressible Blood Flow Simulation for the Coronary Artery and Bifurcation Stenosis with CFD Module

Houneida Sakly, Mourad Said, and Moncef Tagina

1 Background

Recently, cardiovascular disease is considered dramatically increased. The common type of death that is mainly due to heart disease or stroke, which is caused by the accumulation of plaques on the endothelial walls of the coronary arteries [1]. The coronary artery disease (CAD) induces to a reduction in the oxygen level at the myocardium and this has been related to the antecedents of cardiovascular disease such as myocardial infarction, stroke and unstable angina [2]. Despite the diversification of risk factors, in particular high cholesterol, diabetes and hypertension, being of a systemic nature, the plaques are located at specific sites of the coronary artery where an endothelial shear disorder occurs [3–5]. In recent years, the additional explanation that has been shown for plaque formation is blood pressure/shear stress [6, 7].

The appearance of atherosclerosis that is based on observation plays a role in the identification of blood behavior. According to the distribution of vascular inflammation and plaques near the lateral branches or arterial stenosis, the blood trajectory n It is not uniform and at the slightest curvature of curvatures where blood flow is relatively low [8, 9]. The inflow of blood flow on the vessel wall is caused by shear stress is reflected via the behavior of endothelial cells. The shear stress leads to shear deformation of the cells and subsequently the inflammatory component and the progression of the plaque [10].

H. Sakly (✉) · M. Tagina
COSMOS Laboratory -National Institute of Computer Sciences – Campus University of Mannouba, Mannouba, Tunisia
e-mail: houneida.sakly@esiee.fr

M. Said
Radiology and Medical Imaging Unit, International Center Carthage Medical, Monastir, Tunisia

© Springer Nature Switzerland AG 2020

L. Chaari (ed.), *Digital Health in Focus of Predictive, Preventive and Personalised Medicine*, Advances in Predictive, Preventive and Personalised Medicine 12,
https://doi.org/10.1007/978-3-030-49815-3_6

The main objective in our study is to analyze the impact of CFD modules on a 3D artery model for a blood flow of normal physical characteristic and detect if there are anomalies via velocity value study and pressure.

2 Related Works

The detection of coronary stenosis is crucial for decision making in coronary revascularization. With the advancement of digital fluid dynamics (CFD), flow accuracy is limited due to the adopted modeling approach. To overcome this problem, a new non-invasive method based on CFD is proposed [11]. The study in [12] focuses on examining the effects of hyperemic flow, such as velocity, shear wall in 3D coronary artery models with and without stenosis on the hydrodynamic parameters. 3D coronary artery models suffer from a > 50% shrinkage of the light surface to simulate the hyperemic flow condition. In contrast, the decrease in pressure was found downstream of the stenosis relative to the coronary artery without stenosis. The analysis provides a view of the distribution of shear stress and pressure drop across the walls to understand the effect of hyperemic flow under both conditions. The research developed in [13] shows the effectiveness of 3D modeling of the artery on the Coronary CT Angiography-derived Fractional Flow Reserve via the Machine Learning Algorithm versus Computational Fluid Dynamics technique. The severity of the stenosis is assessed relative to invasive angiography and angiographic stenosis and does not necessarily apply with hemodynamic accuracy when the fractional flow reserve is used as a reference. In this context, Machine Learning algorithms improve the performance of CTA by correctly reclassifying hemodynamically no significant stenosis and CFD-based CT [14]. The study of the correlation between left coronary bifurcation angle and coronary stenosis as assessed by coronary angiography coronary angiography (CCTA) analysis generated by digital fluid dynamics (CFD) [15]. MV *et al* [16] proposes a reconstruction of the right coronary artery from the angiogram of a patient. The flow analyzes were performed using the Digital Fluid Dynamics (CFD) method focusing on the geometry of the stenosis characterized by areas of stasis, multidirectional velocity, and high wall shear stress. A clinical review was proposed by JM *et al* [1] for the prognostic indications for quantifying the severity of coronary artery disease and invasive and non-invasive imaging technologies to quantify the anatomical parameters of coronary stenosis. The application of image-based CFD simulation techniques [17, 18] to elucidate the effects of hemodynamics in vascular physiopathology on the initialization and progression of coronary artery disease. At this stage Blood flow presents the key for localization and progression of coronary heart disease [19]. CFD simulation based on 3D luminal reconstructions is used to analyze local flow fields and flow profile due to changes in vascular geometry. It helps to identify the risk factors for the development of coronary heart disease [20].

2.1 *Methods and Materials*

A 3D model of the artery has been reconstructed with a geometry that contains 4 nodes, 6 edges, 4 faces. The Hex-dominant algorithm for only CFD module has been adopted with internal meshing mode and moderate finesses. The Blood-type fluid parameterization was set with a Newtonian model viscosity, (ν) Kinematic viscosity = 0.00004 m^2/s, (ρ) Density = 1056 kg/m^3. A second 3D for this bifurcation model is composed of two nodes, 6 edges, 6 faces, 1 volumes. The mesh was generated with Max global cells = 100,000,000, Resolve feature angle = 30, Solver iterations = 150, Relax iterations = eight. Therefore, the boundary conditions is defined as follows: Pressure inlet = 1184 (Pa), the turbulence kinetic energy = 0.00375 (m^2/s^2) and the specific dissipation rate = 3.375 (1/s) for the blood fluid.

3 CFD Studies on Coronary Artery Disease

In order to predict the flow field, particle transport and related phenomena in the region of interest, the numerical methods are used by computational fluid dynamics to solve the set of main equations (continuity and Navier-Stokes equations) for blood flow). The CFD procedure includes the pre-processing phase, which essentially contains the construction of the geometry (artery) to represent the domain of interest, discretization of the domain with meshes as well as the description of the physical model and the boundary conditions. The post-processing part is dedicated for the presentation of the results and the numerical resolution of the equations. The coronary arteries are very curved and are mobile and deformable; this is why the flow study is considered a hard task which leads to in-depth studies on CFD to analyze coronary artery disease in recent decades. To minimize the numerical diffusion and to reduce the number of elements, the generation of the coronary artery model consists of defining the fluid and structural domains that are meshed with hexahedral cells.

4 Results and Discussion

4.1 *Dedicated for Coronary Artery Analysis*

A model of coronary stenosis acquired with CT with a maximum diameter 3.27 mm, minimum diameter 1.08 mm, length 29.66 mm, and a main tortuosity 0.11 mm presented in Fig. 1a was selected. The reconstruction of the 3D model was generated in Fig. 1b.

In order to minimize the numerical diffusion and to reduce the number of elements we adopted the geometry of the artery in Fig. 2. For the generation of

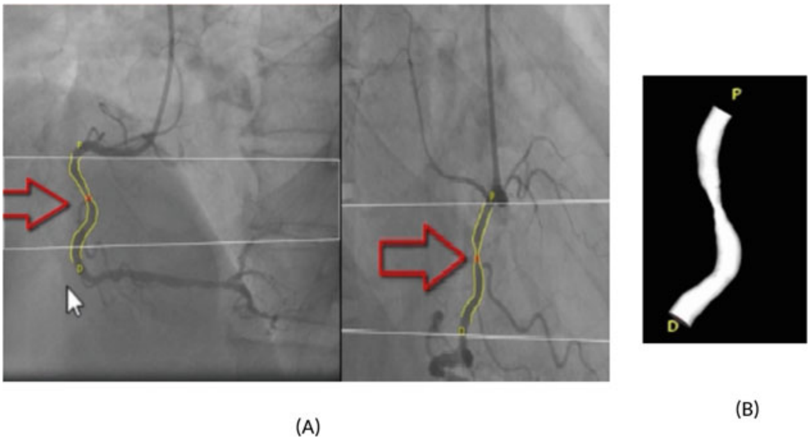
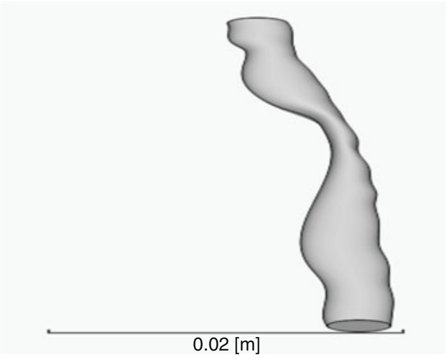


Fig. 1 Reconstruction of the 3D coronary artery model

Fig. 2 Model of the artery in 3D



the model of coronary artery, the fluid and structural domains are in mesh with the hexahedral cells.

The next step is to define the meshing mode. We have used an internal meshing, which is typically used for pipe flow and valves. It will place the mesh inside the body and attempt to generate multiregional and will surround the materiel point and extend until the boundaries of the artery as shown in Fig. 3.

The mesh quality are depicted in Table. 1 as follows after finishing parallel processing:

Due to the variation of the blood flow with the cardiac cycle, the flow in the coronary artery is unstable. The inflow and outflow conditions allow the observation of the hemodynamic changes of the arterial system, including the coronary artery. Therefore, the boundary conditions is defined as follows: velocity inlet and outlet = 0.2 m/s and arterial pressure = 76 mmHg in the diastole phase [21]. The fluid solver completed the parallel computation for execution time = 318.52 s and ClockTime = 340 s and the residual simulation is presented as follows in Fig. 4.

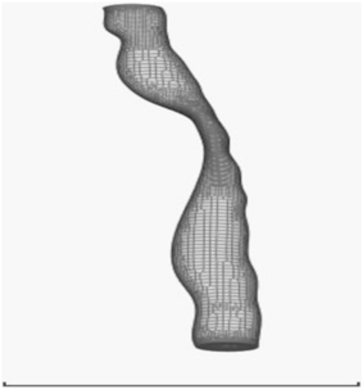


Fig. 3 Mech of the artery

Table 1 Mesh quality metrics

Mesh quality metrics	
Median	1.043005289846296
Min	1.0000000202514494
Max	59.82625634572443
Average	2.7749034006189257
Standard deviation	3.3558916335140054

0-th percentile: 1.0000000202514494
20-th percentile: 1.006279489227181
40-th percentile: 1.0199218383015278
60-th percentile: 1.1554712432086376
80-th percentile: 6.693254767354305
100-th percentile: 59.82625634572443

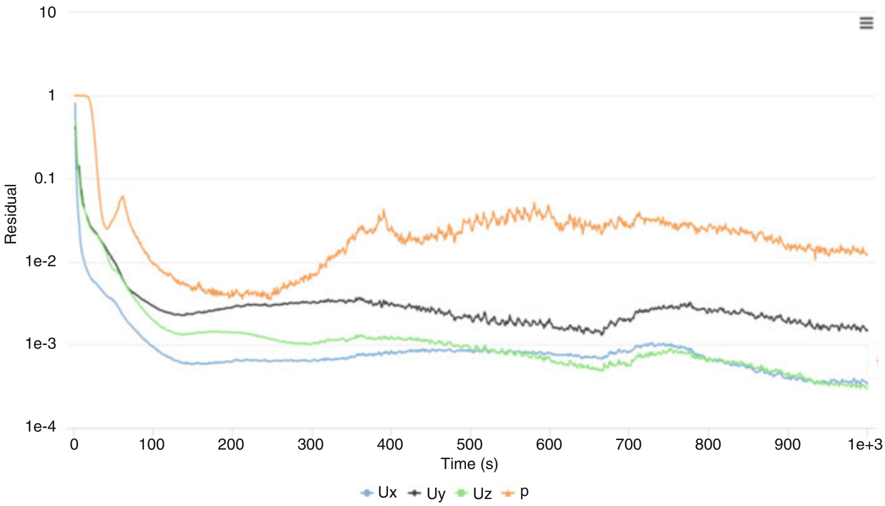


Fig. 4 The residual simulation

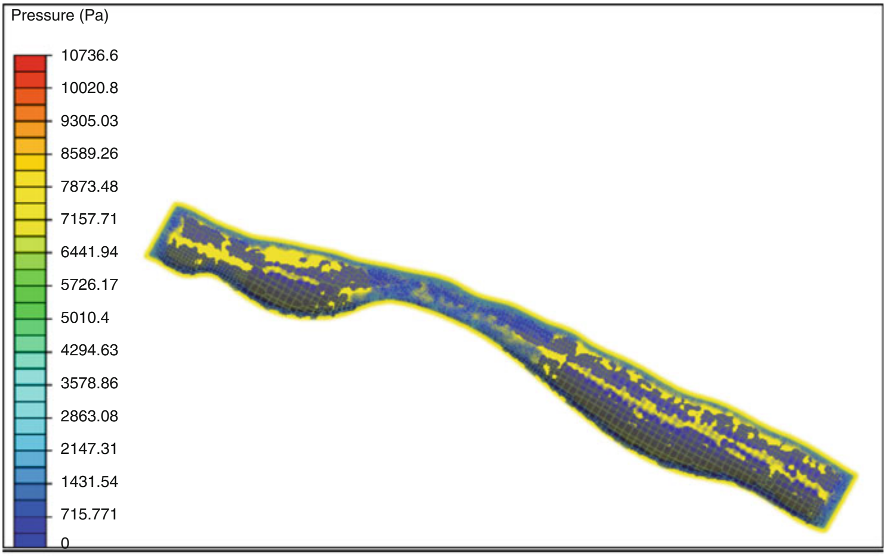


Fig. 5 Simulation of the pressure

The inlet and outlet boundary conditions are based on a physiological flow rate and pressure of the aorta. The average blood flow in the left coronary artery is estimated to be about 57 ml / min, reaching a maximum of 105 ml/min during the diastolic phase according to average human coronary blood flow data that are available in the literature [22–24]. A flow simulation is conducted over a time-span of several cardiac cycles, which are represented by time steps. The time steps can be divided into a number of coupling iterations, with each time step converged to a residual target of less than 1×10^{-4} by approximately 100 iterations. A total of 600 time steps are required to achieve satisfactory convergence for fluid simulation when all velocity component changes from iteration to iteration are less than 10^{-6} [25, 26]. The solution field simulation shows a decrease in pressure as well as the velocity value in the stenotic segment as shown in Figs. 5 and 6.

4.2 Dedicated Bifurcation Analysis

In a research setting, coronary arterial analysis (QCA) is used after coronary angiography or intervention to evaluate the effectiveness of treatments such as ballooning, stenting, or drug therapy. For coronary device studies, QCA is performed on images acquired before treatment, immediately after treatment and follow-up. The main dedicated laboratories usually perform the analysis for independent analysis. The most important search parameters, calculated using QCA, are: the acute luminal gain; MLD which gives insights on the acute efficacy of the device and is defined as

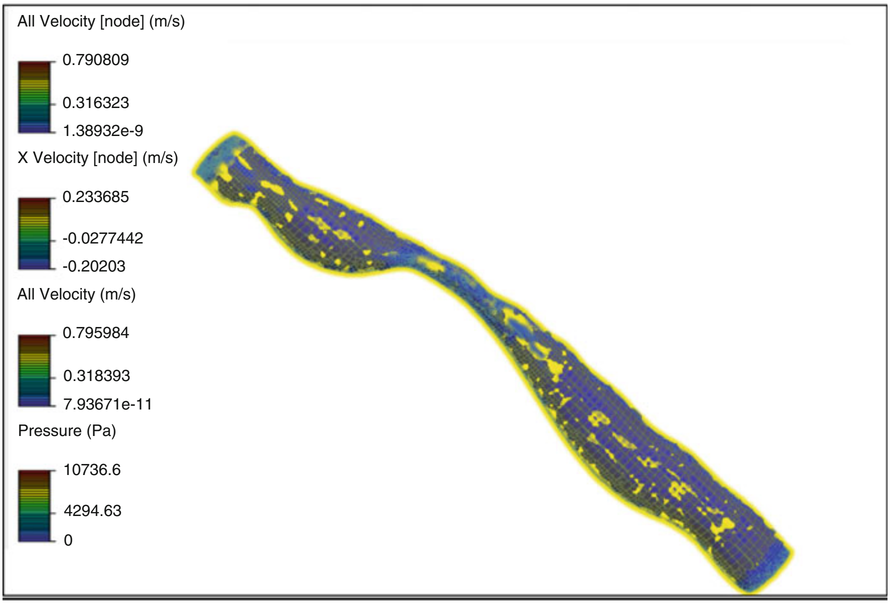


Fig. 6 Simulation of the velocity

post-procedural, the luminal loss which is the estimator for restenosis and defined as post-procedural MLD and the binary angiographic restenosis which is the incidence of percent diameter stenosis>50% [27].

By adopting the same methodology for the conception of coronary artery QCA offers a dedicated bifurcation analysis option to overcome the major challenges in quantifying bifurcation lesions as seen in Fig. 7:

The processed model is a pathological case with occlusion 60%. A second 3D for this bifurcation model is composed of two nodes, 6 edges, 6 faces, 1 volumes. The mesh was generated with Max global cells = 100,000,000, Resolve feature angle = 30, Solver iterations = 150, Relax iterations = eight. Therefore, the boundary conditions is defined as follows: Pressure inlet = 1184 (Pa), the turbulence kinetic energy = 0.00375 (m^2/s^2) and the specific dissipation rate = 3.375 (1/s) for the blood fluid. The final processing of the Solver finished with the initial residual = 8.49079723516e-07, Final Residuel = 8.49079723516e-07, average solving K: 7.12500637921e-05, Execution Time = 1923.11 s and Clock Time = 2075 s as showed in Fig. 8.

The results of analysis of the arterial bifurcation with the CFD modules represent a considerable advantage, because now, for these cases also, the previous and subsequent data can be compared and these patients can be included. Due to blood reflux in the stenotic segment, velocity as well as pressure take up significantly negative values, which may give indications for detecting the position of the stenosis as indicated in Fig. 9.

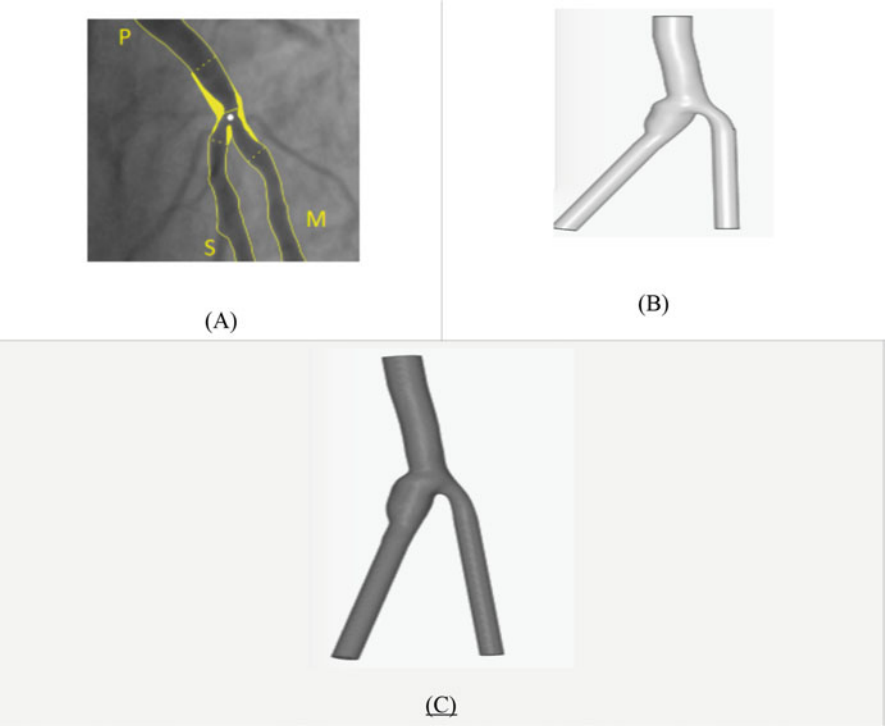


Fig. 7 (**a**) Reconstruction of the 3D bifurcation model;(**b**) Model of the bifurcation in 3D; (**c**) Mech of the bifurcation

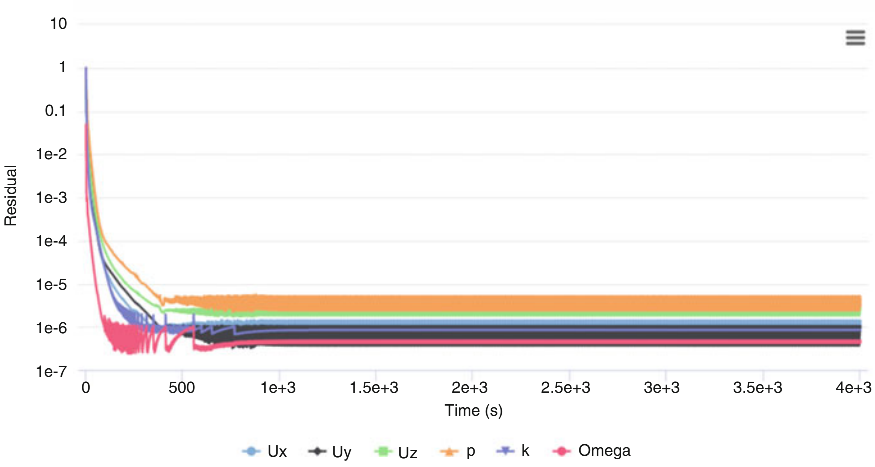


Fig. 8 Convergence plot of the solution

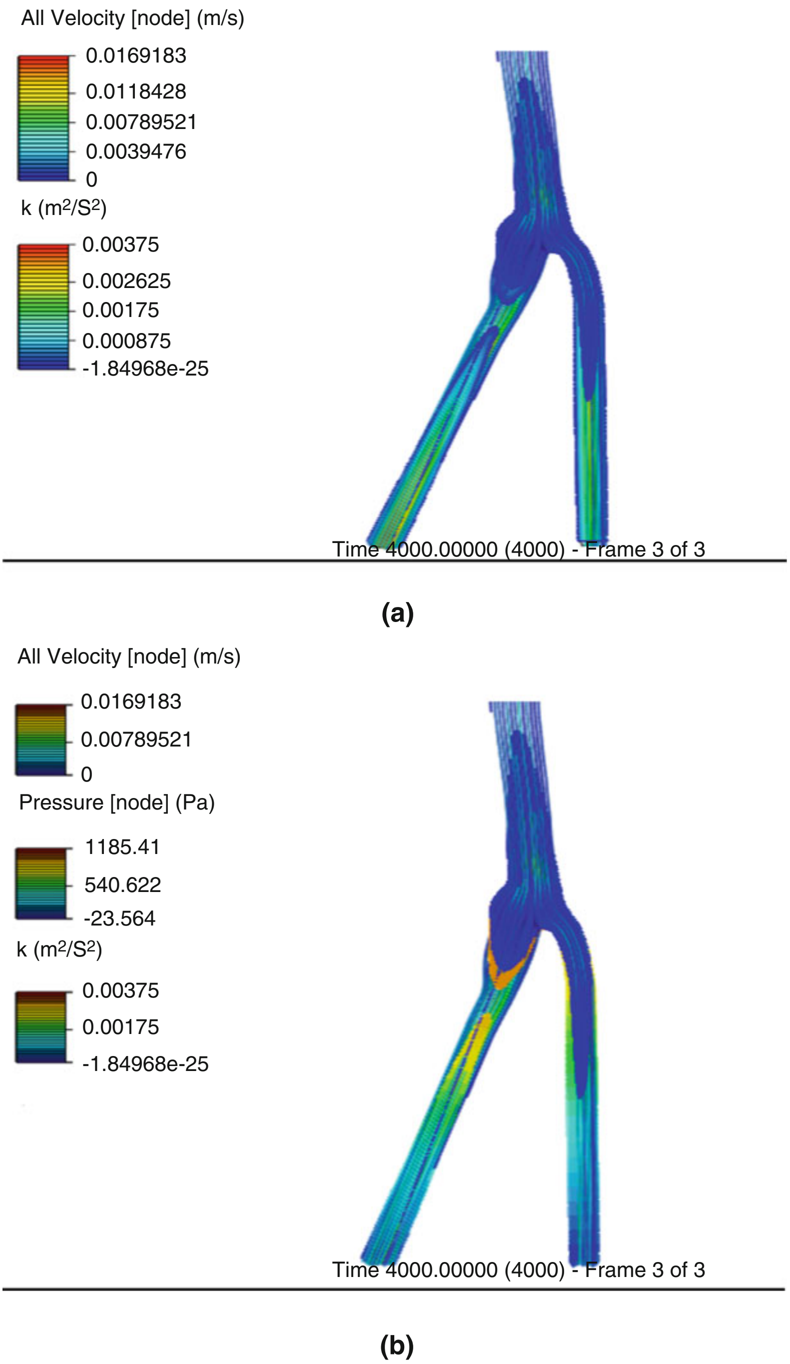


Fig. 9 (**a**) simulation of the velocity (**b**) simulation of the pressure

5 Conclusion

In summary, promising results have been depicted with the use of CFD for the diagnosis of coronary artery disease. With the advancement of CFD methods and image processing techniques, the detection of additional indications for coronary heart disease will be elucidated using specific CFD applications [28–31].

References

1. Zhang, J.-M., et al.: Perspective on CFD studies of coronary artery disease lesions and hemodynamics: a review. Int. J. Numer. Methods Biomed. Eng. **30**(6), 659–680 (2014)
2. Heitzer, T., Schlinzig, T., Krohn, K., Meinertz, T., Münzel, T.: Endothelial dysfunction, oxidative stress, and risk of cardiovascular events in patients with coronary artery disease. Circulation. **104**(22), 2673–2678 (2001)
3. Caro, C.G., Fitz-Gerald, J.M., Schroter, R.C.: Arterial wall shear and distribution of early atheroma in man. Nature. **223**(5211), 1159–1160 (1969)
4. Friedman, M.H., Hutchins, G.M., Bargeron, C.B., Deters, O.J., Mark, F.F.: Correlation between intimal thickness and fluid shear in human arteries. Atherosclerosis. **39**(3), 425–436 (1981)
5. Lutz, R.J., Cannon, J.N., Bischoff, K.B., Dedrick, R.L., Stiles, R.K., Fry, D.L.: Wall shear stress distribution in a model canine artery during steady flow. Circ. Res. **41**(3), 391–399 (1977)
6. Shaaban, A.M., Duerinckx, A.J.: Wall shear stress and early atherosclerosis: a review. AJR Am. J. Roentgenol. **174**(6), 1657–1665 (2000)
7. Wang, Y., et al.: High shear stress induces atherosclerotic vulnerable plaque formation through angiogenesis. Regen. Biomater. **3**(4), 257–267 (2016)
8. Davies, P.F., Polacek, D.C., Shi, C., Helmke, B.P.: The convergence of haemodynamics, genomics, and endothelial structure in studies of the focal origin of atherosclerosis. Biorheology. **39**(3–4), 299–306 (2002)
9. Chaichana, T., Sun, Z., Jewkes, J.: Computation of hemodynamics in the left coronary artery with variable angulations. J. Biomech. **44**(10), 1869–1878 (2011)
10. Helderman, F., et al.: Effect of shear stress on vascular inflammation and plaque development. Curr. Opin. Lipidol. **18**(5), 527–533 (2007)
11. Xie, X., Zheng, M., Wen, D., Li, Y., Xie, S.: A new CFD based non-invasive method for functional diagnosis of coronary stenosis. Biomed. Eng. Online. **17**(1), 36 (2018)
12. Kamangar, S., et al.: Influence of stenosis on hemodynamic parameters in the realistic left coronary artery under hyperemic conditions. Comput. Methods Biomech. Biomed. Engin. **20**(4), 365–372 (2017)
13. Tesche, C., et al.: Coronary CT angiography-derived fractional flow reserve: Machine learning algorithm versus computational fluid dynamics modeling. Radiology. **288**(1), 64–72 (2018)
14. Coenen, A., et al.: Diagnostic accuracy of a Machine-learning approach to coronary computed tomographic angiography-based fractional flow reserve: result from the MACHINE consortium. Circ. Cardiovasc. Imaging. **11**(6), e007217 (2018)
15. Sun, Z., Chaichana, T.: An investigation of correlation between left coronary bifurcation angle and hemodynamic changes in coronary stenosis by coronary computed tomography angiography-derived computational fluid dynamics. Quant. Imaging Med. Surg. **7**(5), 537–548 (2017)
16. Caruso, M.V., De Rosa, S., Indolfi, C., Fragomeni, G.: Computational analysis of stenosis geometry effects on right coronary hemodynamics. Conf. Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. IEEE Eng. Med. Biol. Soc. Annu. Conf. **2015**, 981–984 (2015)

17. Zhang, J.-M., et al.: Numerical simulation and clinical implications of stenosis in coronary blood flow. Biomed. Res. Int. **2014**, 514729 (2014)
18. Papafaklis, M.I., et al.: Functional assessment of lesion severity without using the pressure wire: coronary imaging and blood flow simulation. Expert. Rev. Cardiovasc. Ther. **15**(11), 863–877 (2017)
19. Javadzadegan, A., Moshfegh, A., Qian, Y., Ng, M.K.C., Kritharides, L., Yong, A.S.C.: The relationship between coronary lesion characteristics and pathologic shear in human coronary arteries. Clin. Biomech. Bristol. Avon. **60**, 177–184 (2018)
20. Sun, Z.: Coronary CT angiography: beyond morphological stenosis analysis. World J. Cardiol. **5**(12), 444–452 (2013)
21. Vignaux, O.: Imagerie cardiaque: scanner et IRM, 2nd ed. Elsevier Masson (2011)
22. Vlachopoulos, C., O'Rourke, M., Nichols, W.W.: McDonald's blood flow in arteries: theoretical, experimental and clinical principles, 6th edn. CRC Press, London (2011)
23. Berne, R. M., Levy, M. N.: Cardiovascular physiology. The C.V. Mosby Company, (1967)
24. Boutsianis, E., et al.: Computational simulation of intracoronary flow based on real coronary geometry. Eur. J. Cardio-Thorac. Surg. Off. J. Eur. Assoc. Cardio-Thorac. Surg. **26**(2), 248–256 (Aug. 2004)
25. Siauw, W.L., Ng, E.Y., Mazumdar, J.: Unsteady stenosis flow prediction: a comparative study of non-Newtonian models with operator splitting scheme. Med. Eng. Phys. **22**(4), 265–277 (2000)
26. Elhadj, S., Akers, R.M., Forsten-Williams, K.: Chronic pulsatile shear stress alters insulin-like growth factor-I (IGF-I) binding protein release in vitro. Ann. Biomed. Eng. **31**(2), 163–170 (2003)
27. Ramcharitar, S., et al.: A novel dedicated quantitative coronary analysis methodology for bifurcation lesions. Euro Intervent. J. Eur. Collab. Work. Group Interv. Cardiol. Eur. Soc. Cardiol. **3**(5), 553–557 (2008)
28. Frauenfelder, T., et al.: Flow and wall shear stress in end-to-side and side-to-side anastomosis of venous coronary artery bypass grafts. Biomed. Eng. Online. **6**, 35 (2007)
29. Knight, J., et al.: Choosing the optimal wall shear parameter for the prediction of plaque location-a patient-specific computational study in human right coronary arteries. Atherosclerosis. **211**(2), 445–450 (2010)
30. Wellnhofer, E., Osman, J., Kertzscher, U., Affeld, K., Fleck, E., Goubergrits, L.: Flow simulation studies in coronary arteries–impact of side-branches. Atherosclerosis. **213**(2), 475–481 (2010)
31. Chaichana, T., Sun, Z., Jewkes, J.: Impact of plaques in the left coronary artery on wall shear stress and pressure gradient in coronary side branches. Comput. Methods Biomech. Biomed. Engin. **17**(2), 108–118 (2014)