On recent progress in combined computational- and experimental-physical transport phenomena in biomedical applications

Saša Kenjereš[1]

[1] Transport Phenomena Section, Department of Chemical Engineering, Delft University of Technology

We present some recent research highlights dealing with our current progress in combined computational and experimental physical transport phenomena, with a primary focus on the biomedical applications. The transport of mass, momentum, species, and energy - within biological systems - plays a fundamental role in the functioning of cells, tissues, and organs. It is recognized that some variations in biological transport processes can trigger a complex chain of biochemical reactions leading to various diseases (e.g., allergies, asthma, diabetes, atherosclerosis, cancer, etc.). The mathematical modeling and advanced computer simulations of the underlying mechanisms responsible for physical transport phenomena in living systems, can be powerful tools for potential predictions of the onset location and progression of various diseases. Detailed testing, validation, and verification of such mathematical models and computer simulations is crucial for potential clinical medical applications, Refs.[1-4]. Here we will address two clinically interesting cases: (i) a patient-specific saccular aneurysm detected in the brain vascular system (7T MRI scanning performed at Amsterdam UMC), (ii) a model of the left ventricle with biological valves (in collaboration with EMC Rotterdam, LUMC Leiden and Ghent University, Belgium).

The intracranial aneurysms are local enlargements of blood vessels occurring within the cerebrovascular system. Their rupture causes almost 500,000 annual deaths worldwide. A better understanding of fundamental mechanisms behind their growth and potential rupture may open new routes for timely prevention and treatment. In the literature, by performing the CFD of the patient-specific aneurysm geometries, various criteria have been proposed to identify a potential rupture location. These criteria include estimations of the time-averaged wall shear stress (TAWSS), oscillatory shear index (OSI), and vortex-saddle point structure with accompanying low-pressure region. To validate our present generation of the advanced CFD codes, we perform comparative assessment of numerical simulations with the state-of-art optical flow measurements techniques (Stereoscopic Particle Image Velocimetry (SPIV); Tomographic PIV (TomoPIV)) and clinical Magnetic Resonance Imaging (7T MRI) - under identical working conditions. The optical flow visualizations require a build-up of an optically accessible phantom with identical or scaled anatomical geometry obtained from the MRI or CT scans. We have developed a full cycle in making 3D rapid-prototyping printed transparent organic silicon phantoms from the 3D MRI and/or CT scans. In Figure 1, we compare obtained results from different experimental modalities: SPIV (2D-3C / all three velocity components measured in a plane), TomoPIV (3D-3C full volumetric measurements with complete velocity vector) and MRI (3D-3C but with limited resolution compared to optical measurements). We demonstrated that by combining MRI/CFD approach, which was tested with our optical measurements under identical clinical conditions, significant improvements in estimating the WSS distribution along the aneurysm wall can be obtained.

The second example is the analysis of the flow patterns in one of the heart chambers, the left ventricle (LV). Observation of changes in characteristic LV blood flow patterns is associated with early detection of potential heart failure. At present, two primary clinical techniques for analysis of the LV blood flow dynamics are the MRI and echocardiography. Each of the techniques suffers from some limitations, e.g., MRI measures full 3D blood flow patterns in time (so called 4D Flow MRI), but requires relatively long acquisition times (averaging over 100s of cardiac cycles) and has relatively low temporal resolution (20-30 phases per cardiac cycle). The clinically available echocardiography can acquire 15-100 frames per second, but not all vectors components can be measured. We perform a comparison of the current generation of MRI and ultrasound clinical techniques with our optical measurements on a human left ventricle model. Due to its superior spatial and temporal resolutions, results of SPIV and TomoPIV measurements can be used for further calibration and refinements of the clinical techniques, Figure 2. Additionally, we also perform the CFD simulations, which entirely mimic the experimental conditions. Here, particular challenges involve a dynamic motion of the left-ventricle surface, and the movement of the biological valves. We have developed a novel in-house simulation approach based on the radial-basis-function morphing method to include dynamic meshing (Wu and Kenjeres (2019)). The most interesting experimental results are shown in Figure 2. Finally, the CFD results are shown in Figure 3.

In conclusion, we stress the importance of combined experimental and numerical studies in providing detailed synergetic insights into physical transport phenomena in various biomedical applications.

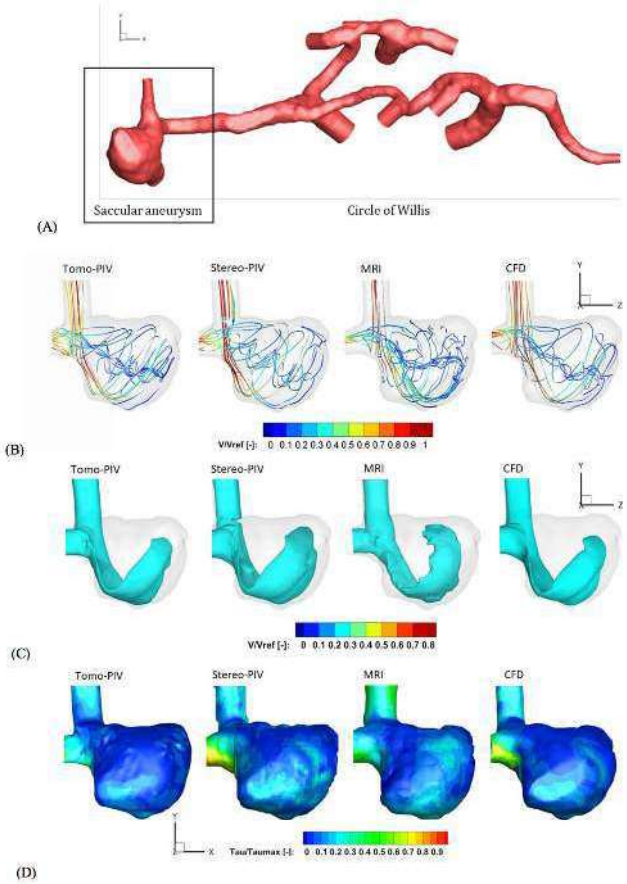

Figure 1. Comparison between different experimental modalities (SPIV (2D-3C), TomoPIV (3D-3C), MRI) and CFD for a patient-specific saccular aneurysm detected in the brain vascular system (Circle of Willis): (A) the location and geometry of the aneurysm (from MRI scans); (B) the 3D distributions of the pathlines coloured by velocity magnitude, (C) extraction of 3D isosurface of the velocity magnitude (|V| = 0.3 m/s), (D) distribution of the wall shear-stress (WSS) along the walls of the aneurysm; Courtesy of Kenjeres Lab (2019) and Amsterdam UMC.

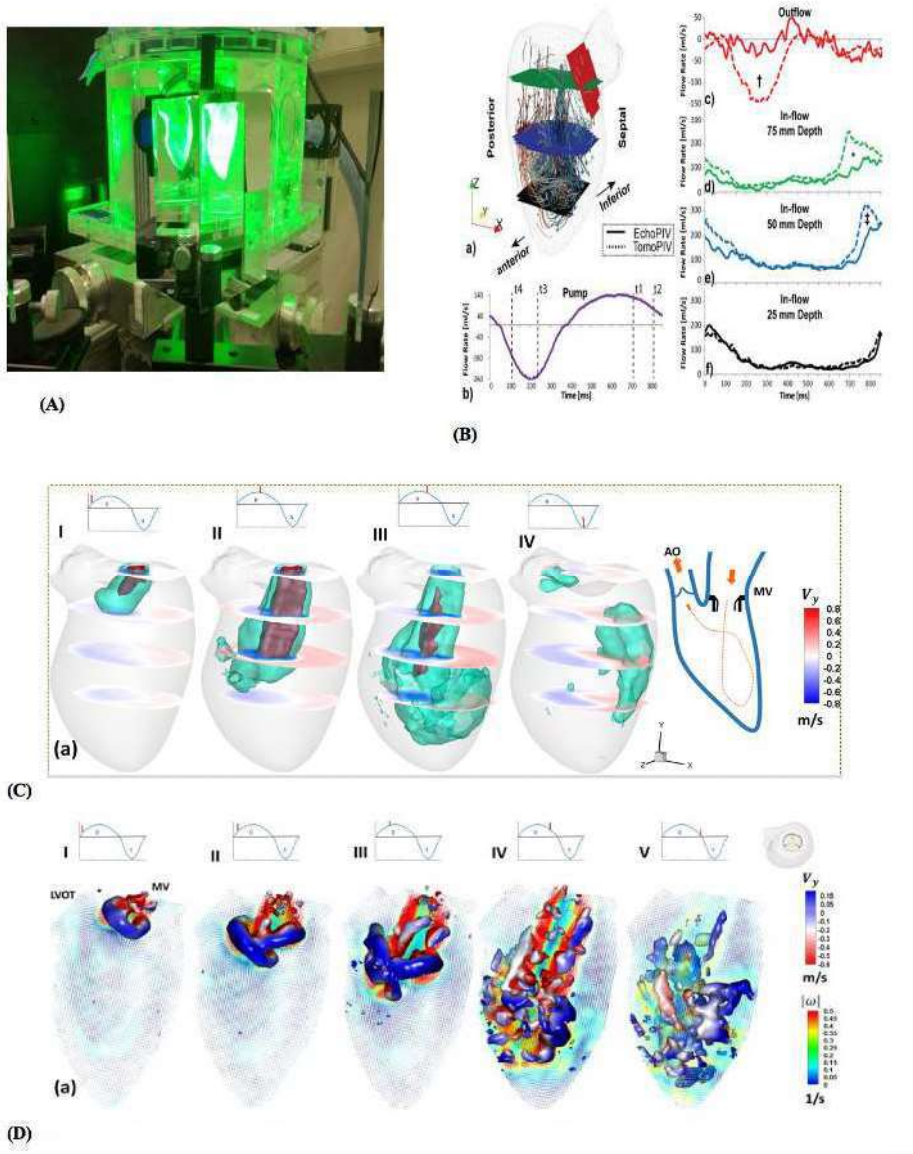

Figure 2. (A) The laser illumination of the working tomographic PIV experimental setup for the moving heart measurements; (B) Comparison between optical (TomoPIV) and ultrasound (US) measurements under identical working conditions; (C) the 4D reconstruction of the velocity field from the TomoPIV; (D) extraction of the coherent structures from the 4D TomoPIV measurements coloured by instantaneous axial velocity – superimposed with vorticity magnitude in the central vertical plane; (Refs: Saaid et al. (2019), Voorneveld et al. (2020))

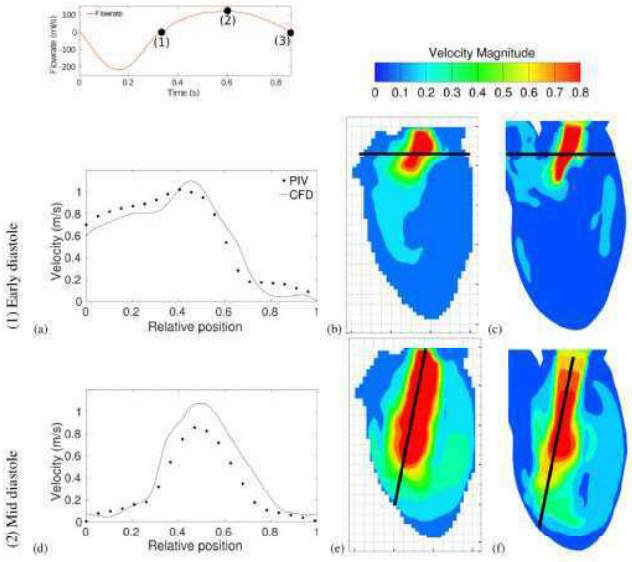

Figure 3. Comparative assessment of the newly developed CFD (based on the in-house developed radial-basis-function morphing moving mesh approach for dynamic changes of the left-ventricle surface and moving biological valves) (c-f) and tomographic PIV measurements (b-e): contours and profiles of the velocity magnitude at two characteristic time-instants of the cardiac cycle, (i) early diastole (-top) and (ii) middle diastole (-bottom) (Refs: Xu and Kenjeres (2019))

References

1. Kenjeres S. and Righolt B.W. (2012) Simulations of magnetic capturing of drug carriers in the brain vascular system. Int. J. Heat and Fluid Flow 35, 68-75.
2. Kenjeres S. and de Loor A. (2014). Modeling and simulation of low-density-lipoprotein (LDL) transport through multi-layered wall of an anatomically realistic carotid artery bifurcation. Journal of the Royal Society Interface 11, 2013094, 1- 13.
3. Nemati M., Lozen G.B., van der Wekken N., van de Belt G., Urbach H.P., Bhattacharya N., Kenjeres S. (2015). Application of full field optical studies for pulsatile flow in a carotid artery phantom. Biomedical Optics Express 6, 4037-4050.
4. Kenjeres S. (2016) On recent progress in modelling and simulations of multi-scale transfer of mass, momentum and particles in bio-medical applications. Flow, Turbulence and Combustion 96, 837-860.
5. Khalafvand S.S., Voorneveld J.D., Muralidharan A., Gijsen F.J.H., Bosch J.G., van Walsum T., Haak A., de Jong N., Kenjeres S. (2018) Assessment of human left ventricle flow using statistical shape modelling and computational fluid dynamics. Journal of Biomechanics 74, 116-125.
6. Voorneveld J., Muralidharan A., Hope T., Vos H.J., Kruizinga P., van der Steen A.F.W., Gijsen F.J.H., Kenjeres S., de Jong N. and Bosch J.G. (2018) High frame rate ultrasound particle image velocimetry for estimation of high velocity left ventricular flow patterns.IEEE Transaction on Ultrasonics, Ferroelectrics, and Frequency Control 65, 2222-2232.
7. Saaid H., Voorneveld J., Schinkel C., Bosch J.G., Westenberg J., Gijsen F., Segers P., Verdonck P., Kenjeres S., Claessens T. (2019) Tomographic PIV in a model of the left ventricle: 3D flow past biological and mechanical heart valves. Journal of Biomechanics 90, 40-49.
8. Khalafvand S.S., Xu F., Westenberg J., Gijsen F., Kenjeres S. (2019) Intraventricular blood flow with a fully dynamic mitral valve model. Computers in Biology and Medicine 104, 197-204.
9. Kenjeres S., van der Krieke J. P., Li C. (2019), "Endothelium resolving simulations of wall shear-stress dependent mass transfer of LDL in diseased coronary arteries", Computers in Biology and Medicine 114, 103454, 1-12.
10. Voorneveld J., Saaid H., Schinkel C., Radeljic N., Lippe B., Gijsen F.J.H., van der Steen A. F. W., de Jong N., Claessens T., Vos H. J., Kenjeres S., Bosch J. G. (2020), "4D Echo-Particle Image Velocimetry in a Left Ventricular Phantom", Ultrasound in Medicine and Biology 46 (3), 805-817.