ON RECENT PROGRESS IN COMBINED COMPUTATIONAL- AND EXPERIMENTAL-PHYSICAL TRANSPORT PHENOMENA IN BIOMEDICAL APPLICATIONS

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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 sacular 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 shea-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))
REFERENCES


