Modelling and simulation of fluid-structure interaction in arterial vessels via a multiscale constitutive framework

Elisabetta Monaldo

Master Thesis in Medical Engineering
Department of Civil Engineering and Computer Science, University of Rome "Tor Vergata", Italy
Email: elisabettamonaldo@libero.it
Supervisor: Giuseppe Vairo (vairo@ing.uniroma2.it)

Extract from the Supervisor's reference letter

… Within the context of the Master Thesis project, Elisabetta Monaldo has developed a computational tool for simulating fluid-structure interaction processes in arterial segments. The project aimed to furnish a contribution towards the understanding of dominant mechanisms related to the aetiology, the onset and the evolution of some vascular diseases (e.g., aneurysm), developing some computational methodologies and techniques useful for supporting clinicians in choosing the optimal patient-specific therapeutic strategy.

Fluid-structure interaction in arterial vessels has been described by combining the double multiscale nature of vascular physiopathology in terms of both tissue properties and blood flow. Addressing the mechanical response of arterial tissues, it is modelled via a nonlinear anisotropic multiscale constitutive rationale, based on parameters having a clear histological and biochemical meaning only, without any phenomenological description. In detail, by adopting the novel constitutive approach recently conceived by my research group in cooperation with the Leibnitz University in Hannover, the hierarchical arrangement of collagenous constituents is described via a homogenized multiscale technique, able to account for both geometrical and material nonlinearities at different scales, by modelling: entropic and enthalpic mechanisms at molecular level; straightening, interaction and stretching mechanisms of collagen fibrils and fibers; interaction and coupling mechanisms occurring among layers constituting the lamellar structure of the vascular tissue. Moreover, pulsatile blood flow is described by coupling a three-dimensional fluid domain (undergoing physiological inflow conditions) with a zero-dimensional Windkessel-type model, which allows reproducing the influence of the downstream vasculature, furnishing a realistic description of the outflow proximal pressure.

The proposed formulation has been implemented in a nonlinear finite-element scheme, able to simulate the fluid-structure interaction via an Arbitrary-Lagrangian-Eulerian (ALE) approach. As a result, the proposed computational tool allows assessing the risk of thrombus deposition induced by alterations with respect to homeostatic conditions in wall shear stresses (WSS). To this aim, the WSS evaluation has been performed via a dedicated post-processing phase based on the Three-Band-Decomposition method, recently proposed by a research group of the University Campus Bio-Medico of Rome.

The computational tool developed by Elisabetta Monaldo has been firstly applied to perform a parametric investigation on different ideal geometries of aneurysmatic segments, highlighting model capability to detect vessel configurations characterized by high clinical risks related to altered WSS and to possible localization mechanisms, thereby resulting in the identification of geometries much more prone to onset and evolution of pathological processes. Afterwards, a case study associated to a patient-specific aortic abdominal aneurysmatic geometry has been numerically investigated, highlighting advantages gained from the proposed multiscale strategy, as well as showing the effectiveness in integrating the proposed computational tool with both imaging techniques and clinic-oriented post processing procedures.

In conclusion, the Master Thesis of Elisabetta Monaldo has provided, in my opinion, a significant insight in the field of cardiovascular biomechanics, moving towards a refined in silico assessment of vessel mechanics, in terms of reliable quantities to be employed in therapeutic decisions and clinical/surgical planning.

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Proceedings VII Meeting Italian Chapter of the European Society of Biomechanics (ESB-ITA 2017)
28-29 September 2017, Rome - Italy
ISBN: 978-88-6296-000-7