Multiscale Mathematical Modeling of Cerebral Microcirculation and Tissue Oxygenation

Abstract

Blood microcirculation plays a crucial role in brain function by supplying neurons with oxygen and nutrients while contributing to the clearance of neurotoxic waste through a dense capillary network connected to larger tree-like vessels. Alterations in these processes can lead to neuronal dysfunction and contribute to the development of neurological and neurodegenerative disorders, including stroke, vascular cognitive impairment, and Alzheimer's disease. Understanding the complex interactions between blood flow dynamics, oxygen transport, and cellular activity is therefore essential for investigating both normal brain function and the mechanisms processes underlying neurological pathologies. In this context, we develop a multiscale mathematical model that couples blood flow dynamics within microvascular networks, oxygen transport in the circulatory system, and oxygen diffusion into the cerebral tissue. The proposed model incorporates the geometric and topological characteristics of the vascular network, together with the rheological properties of blood, to investigate how variations in capillary diameter, vascular conductance, flow heterogeneity, and tissue properties influence cerebral oxygenation. By integrating vascular architecture, hemodynamics, and oxygen transport processes, this framework provides a quantitative tool for exploring the impact of microcirculatory alterations on oxygen delivery and tissue oxygenation. Overall, this approach contributes to a better understanding of the role of microvascular dysfunction in the onset and progression of neurological disorders and provides a foundation for the identification of potential biomarkers, as well as for the development of innovative diagnostic and therapeutic strategies.

Keywords: Dynamical system, graph theory, multiscale modeling, blood microcirculation, microvascular networks, neurological pathologies.