A Matrix Differential Equation Approach for Strongly Coupled Arterial Blood Flow and Cerebral Tissue Perfusion Simulations

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Abstract:
Computational modelling of blood flow in vascular networks and brain tissue is crucial in understanding organ-scale cerebrovascular conditions like ischaemic stroke. Coupled models predict the impact of arterial blockages on tissue perfusion, but verification, sensitivity analysis, and uncertainty quantification remain challenging due to strongly coupled differential and algebraic equations.
This study presents analytical solutions for a simplified linear problem describing blood flow in a strongly coupled model of large arteries and capillaries within the brain tissue. Both models have been the subject of previous investigations regarding cerebral blood flow in health and disease, e.g., [doi.org/10.1016/j.compbiomed.2023.107543, doi.org/10.1016/j.compbiomed.2021.104802]. The primary variable in the porous continuum model is perfusion pressure coupled with a steady-state arterial network model based on arterial blood pressure. The solution applies boundary and interface conditions to accurately represent blood flow between arterial and tissue domains.
The framework is tested using a single bifurcation including three arteries connected to a tissue column. Analytical results are compared with numerical solutions from finite element (continuum) and direct linear system solvers (network model). The findings provide a rigorous framework for model verification, sensitivity analysis, and uncertainty quantification. The results also highlight the need for sufficiently low tolerance in relation to interface conditions in numerical simulations.
The model is applied to analyse the impact of large artery occlusion on tissue perfusion, supporting future 2D and 3D studies. This analytical framework enhances in silico stroke research which aims to assist in clinical decision-making and digital twin-based healthcare solutions. Potential applications within the GEMINI project (https://eur03.safelinks.protection.outlook.com/?url=https%3A%2F%2Fdth-gemini.eu%2F&data=05%7C02%7CGillian.Brown%40glasgow.ac.uk%7Cb733c26694c74b6d26d908dd4c45aa2c%7C6e725c29763a4f5081f22e254f0133c8%7C1%7C0%7C638750586742537964%7CUnknown%7CTWFpbGZsb3d8eyJFbXB0eU1hcGkiOnRydWUsIlYiOiIwLjAuMDAwMCIsIlAiOiJXaW4zMiIsIkFOIjoiTWFpbCIsIldUIjoyfQ%3D%3D%7C60000%7C%7C%7C&sdata=6aL3HPb%2F09JAdNRalx0MH%2BE%2ByvVtLph6dS296znKtqQ%3D&reserved=0) are discussed to pave the way for advancing stroke treatments through computational modelling. The proposed framework contributes to multi-scale and multi-physics tissue models for medical device and drug development.