Computationally Efficient Fluid-Particle Dynamics Simulations of Arterial Systems

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Abstract. Realistic and accurate computer simulations of the particle-hemodynamics in arterial systems can be a valuable tool for numerous biomedical applications. Examples include optimal by-pass grafting and optimal drug-delivery, as well as best medical management concerning the cardio-vascular system. However, such numerical analyses require large computer resources which may become prohibitive for extended sets of arterial bifurcations. A remedy is to develop a hybrid model where the first few generations of the bifurcating arteries of interest are simulated in full 3-D, while a 1-D model is then coupled for subsequent bifurcations. Alternatively, a 1-D computer model can be directly employed to simulate fluid-particle transport in complex bifurcating networks.

Relying on a representative axial velocity profile, a physiological 1-D model has been developed and validated, which is capable of predicting with reasonable accuracy arterial flow, pressure field and elastic wall interaction as well as particle transport. The usefulness of the novel 1-D simulation approach is demonstrated via a comparison to 3-D blood flow and microsphere transport in a hepatic artery system, featuring as outlets one major branch and four small daughter vessels. Compared to the 3-D simulation, the 1-D analysis requires only about 1% of computational time. The hybrid modeling approach would be also applicable to the human respiratory tract to evaluate the fate of inhaled aerosols.

A simple and cost-effective way to simulate particle-hemodynamics is using a 1-D model for simulating arterial pressures and flow rates as well as microsphere transport, based on assumptions involving the use of a simple algebraic pressure-area relation, an exponential elasticity model for the vessels, and considering only unidirectional flow with a representative skewed velocity profile. In summary, the novel contributions are:

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- Particle tracking in arteries via 1-D fluid modeling and selection of an averaged, skewed velocity profile based on 3-D simulation results to provide more realistic friction and inertia term values for modeling a flow system with bifurcations.

- The 1-D model can be coupled to a 3-D model so that simulations can be run for larger regions of vascular or lung-airway systems.

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Key words: 1-D modeling, skewed representative velocity profile, fluid-structure interaction, particle tracking.

1   Background and information

A novel technique for optimal targeting of drugs onto solid tumors has been proposed by Kleinstreuer et al. [1] and further numerically analyzed for liver tumors [2]. For realistic and accurate computer simulations it has to be assumed that the geometry of the vasculature is 3-D and blood flow is non-Newtonian, transient, laminar and incompressible. Also, the drug-particles in dilute suspensions are spherical and non-interacting; but, the walls of the arteries are flexible, giving rise to the need of proper fluid-structure interaction. These fluid-particle dynamics simulations require high computational time and cost, even for only a few generations. Thus, simulating arterial flow and pressure fields in any extended set of arterial bifurcations could be computationally prohibitive. A remedy is the development of a 3-D/1-D coupled model. In this, the first few generations of the arterial system would be simulated in full 3-D, while a 1-D model would be used for subsequent bifurcations (see Fig. 1). Alternatively, a 1-D computer model can be employed to simulate fluid-particle transport in complex bifurcating networks *directly*.
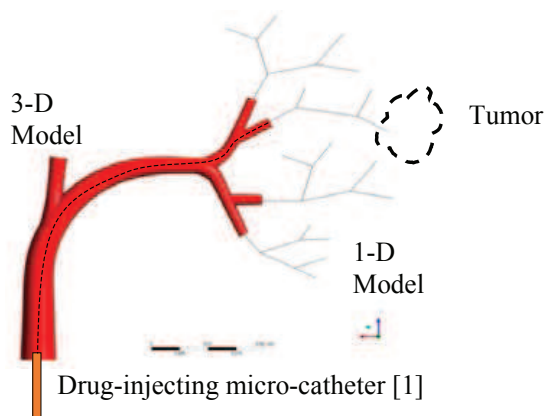

Figure 1: Sample application of a coupled 3-D/1-D model for direct tumor-targeting.