Multi-scale modeling of blood flow in cardiovascular prosthetic devices

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This work will present work on the modeling of blood flow at three disparate scales, viz. the macro- (cm, i.e. vessel/device scale), meso- (100s of microns) and micro- (cellular dimensions) scales. Blood flow phenomena at each scale form critical components in the overall performance and safety of cardiovascular prostheses; for example thrombotic events triggered by some implants (such as mechanical heart valves, PVADs, stents etc) are manifested at the vessel scale by a cascade of events spanning spatial and temporal scales from the micro- to macro-scales. Thus, the distinct phenomena at each scale and the intimate connections across scales must be captured in modeling efforts that seek to predict the performance of conceived designs of such prostheses and to guide new designs. The present group has performed extensive work in the modeling of blood flow at each scale. Three-dimensional simulations of flows through heart valves have been performed. The computer code performs on HPC platforms (terragrid) and can resolve fine flow features as well as narrow gaps (such as leakage and hinge gaps) that play key roles in the initiating pathologies such as thrombosis. Meso-scale simulations of blood flow have been performed where the cells are modeled as ellipsoidal particles with dynamic coupling with the underlying plasma. Cell-cell interactions including aggregation phenomena have been modeled in this framework. The micro-scale cell dynamics, including deformation and collision have been captured using an immersed boundary framework. Results on each of these scales will be presented.

A key aspect of multi-scale modeling in the cardiovascular system is to bridge phenomena across scales. The work will suggest routes for inter-scale communication in two ways: 1) the micro- and meso-scale blood dynamics will be connected by means of a novel technique involving artificial neural network to "learn" closure laws based on micro-scale direct numerical simulations; 2) the meso- and macro-scales will be bridged using a continuum bridging domain approach, across pre-defined handshake regions. With these two approaches it is shown that a unified computational approach can be developed to allow for multi-scale computations of blood flow in complex, moving domains typical of cardiovascular devices. The combination of methods chosen provides a seamless way in which to model and compute blood dynamics at all three identified scales but challenges associated with efficient computation in HPC systems must be addressed so that physiological flow conditions and blood properties (such as Hematocrit) can be approached. These challenges are highlighted in the presentation.