SimVascular: An Open-Source Integrated Environment for Anatomic Modeling and Blood Flow Simulation

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Introduction: Clinical and research interest in imaged-based, patient-specific blood flow simulation has dramatically increased in the last two decades. Three key factors have driven the field: decreasing cost of computer hardware, improvements in the accuracy and resolution of volumetric diagnostic medical imaging, and advances in modeling and simulation from a dedicated and growing field of engineers, scientists, and medical researchers. Now that blood flow simulation has reached the clinic there is more commercial and research interest than ever in the field. While a growing list of commercial packages have added capabilities targeted primarily at device designers and industry, there is a clear need for open-source platforms to enable large-scale research studies to advance academic research. SimVascular, originally released in 2007, was the first integrated open-source environment for realistic image-based blood flow simulation. The NSF funded revitalizing SimVascular beginning in 2013 to eliminate the dependence on three external commercial libraries, modernize the user interface, and provide state-of-the-art modeling tools for the community. To enable large-scale and optimization studies, a generalized vascular model is being developed based on previous work developed in part for the Vascular Model Repository (VMR, www.vascularmodel.org).

Materials and Methods: The SimVascular (www.simvascular.org) pipeline consists of two primary applications: a front-end for anatomic modeling and an integrated flow solver. The front-end application has recently been overhauled with Qt widgets in part by utilizing code from another open-source effort (MITK, www.mitk.org). The front-end enables users to interact with 3-D imaging data, create anatomic models, perform geometric modeling operations (e.g. virtual surgeries), create meshes, and assign boundary conditions for simulation. An augmented vascular model is then generated using XML with attached data saved using popular standardized and open file formats (VTK, www.vtk.org). A fully integrated open-source blood-flow solver (svSolver, www.svsolver.org) is included within SimVascular. The finite-element based solver includes a custom, scalable linear solver with performance comparable to the previously utilized closed-source commercial library in SimVascular. Linearized wall deformation can be modeled using the Coupled-Momentum Method with spatially varying wall thickness and elastic modulus. Simulation results are typically viewed using the versatile open-source scientific-visualization package ParaView (www.paraview.org).

Results and Discussion: SimVascular and its sister project svSolver are the only fully integrated open-source code packages currently available for image-based patient-specific blood flow simulation. The versatility and broad application of the SimVascular package has been demonstrated with the creation of a public repository, VMR, consisting of over 120 anatomic models and 100 simulations results. Recent improvements in SimVascular include a complete overhaul of the GUI and the elimination of its former dependence on commercial, closed-source libraries. Compilation has been simplified by eliminating Fortran code in the front-end as well as including CMakbuild support. The full source code is hosted on Github with documentation and samples provided via the websites. New techniques for anatomic modeling in SimVascular include robust techniques for integrating 2-D and 3-D image segmentation enabled by custom robust surface intersection code for triangulated surfaces. Ongoing research efforts include directly creating NURBS patches from discrete triangulated surfaces, improved image segmentation using machine learning techniques, and adding a Python scripting interface to support optimization efforts.

Translational Impact: Since 2013, SimVascular has had over 1,600 unique downloads and has been utilized in over 120 abstracts and journal publications.

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