The Vascular Model Repository: A Public Resource of Medical Imaging Data and Blood Flow Simulation Results

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Patient-specific blood flow simulations may provide insight into disease progression, treatment options, and medical device design that would be difficult or impossible to obtain experimentally. However, publicly available image data and computer models for researchers and device designers are extremely limited. The National Heart, Lung, and Blood Institute sponsored Open Source Medical Software Corporation (contract nos. HHSN268200800008C and HHSN268201100035C) and its university collaborators to build a repository (www.vascularmodel.org) including realistic, image-based anatomic models and related hemodynamic simulation results to address this unmet need. [DOI: 10.1115/1.4025983]

Methods

The repository includes patient-specific models and blood flow simulations for six areas of clinical hemodynamic interest: the aorta, cerebral, coronary, aortofemoral and pulmonary arteries, and anatomies for single ventricle congenital heart disease surgical procedures. A collection of animal models is also included. Critical considerations are discussed below.

Clinical Data. Clinical collaborators carefully selected, deidentified, and provided imaging data (e.g., volumetric image computed tomography angiography (CTA)/magnetic resonance angiography (MRA) scans) and relevant available physiologic data (e.g., sphygmomanometer blood pressures, catheterization pressures, flow measures, phase contrast magnetic resonance imaging (PCMRI) data, etc.) for inclusion in the repository. Common anatomic variations and varying disease states were included.

Anatomic Models. For each volumetric image data set, a patient-specific anatomic model was generated using a custom version of SIMVASCULAR.[1]

Modeling Assumptions. Patient-specific inflow waveforms were prescribed at the inlet(s) of each model when available. In other cases, representative waveforms were based on scaling average waveforms based on body surface area (BSA) or literature values. An idealized Womersley velocity profile was typically assigned. In most simulations, the vessel walls were assumed to be rigid. Flow distributions to each outlet were determined based on clinical data when available. Otherwise, flow distributions were based on literature data. Boundary conditions assigned at the outlets were usually a relationship of pressure and flow (e.g., resistance) or a three-element Windkessel model.

Table 1 Select repository statistics

Abnormal anatomy	76%	Studies with pressure measurements	69
MRA scans	68	Average mesh size (elements)	2.1 M
CTA scans	52	Total image files	7 GB
PCMRI studies	47	Total simulation result files	71 GB
Male studies	58%	Female studies	42%

Blood Flow Simulations. The models were discretized, boundary conditions were assigned, and a custom hemodynamic solver was used to simulate blood flow under varying physiologic conditions (e.g., rest, mild exercise, etc.). Outlet boundary conditions were iteratively tuned to match clinically measured pressures and target flow splits. Final meshes (~2–3 M elements) were adapted from initial meshes based on a posteriori error estimates to verify mesh independence for target values.

Dissemination. The deidentified medical-imaging data, anatomic models, finite element meshes, and representative simulation results were posted to a publicly accessible website[2] in popular file formats (i.e., digital imaging and communications in medicine (DICOM)- and Visualization ToolKit–formatted files).

Results

The repository currently contains 120 unique image data sets (Table 1), including 52 computed tomography scans and 68 MRA scans, with over 40 of the magnetic resonance scans including 2D PCMRI data. The deidentified DICOM data is included in the repository as zip-compressed files and consists of over 7.2 GB of data. One hundred twenty-six distinct anatomical models have been included in the repository modeling over 3600 vessels. In addition to models of normal anatomy (24% total), a variety of diseased anatomic states, such as abdominal aortic aneurysms (15 models), aortic coarctation (eight models), coronary aneurysms for patients with Kawasaki disease (six models), post–coronary artery bypass grafting surgery (three models), cerebral aneurysms (seven models), pulmonary arterial hypertension (six models), and Glenn and Fontan procedures in patients with single-ventricle heart disease (13 models) are included. Typically, adaptive meshing strategies and convergence analyses have been utilized to increase confidence in the quality of the simulation results. The average mesh size for the final simulations was $2.1 \times 10^6 \pm 5 \times 10^5$ elements. In excess of 71 GB of compressed simulation result files are included in the repository. Simulations for 100 unique anatomically models at rest as well as 29 simulated exercise states for 17 separate models are included.

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[1]http://www.simvascular.org

[2]http://www.vascularmodel.org

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