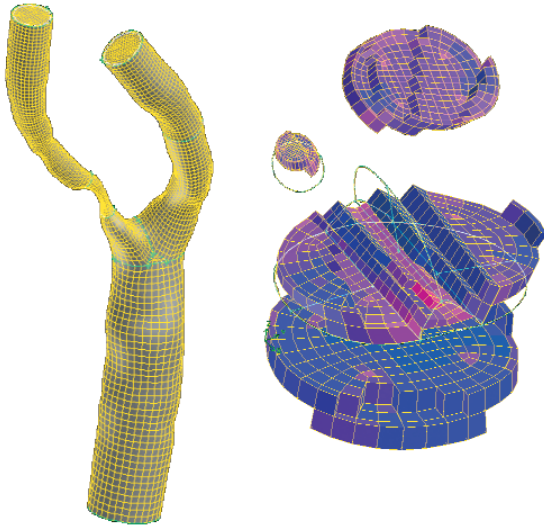


# Personalized Blood Flow Simulations

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Hexahedral mesh generation for a bifurcating blood vessel



Generation of hybrid meshes of quadratic elements with adaptive boundary layer thickness for complex vascular tracts



Time-dependent streamlines and wall shear stress distribution in a realistic model of an abdominal aorta

Cardiovascular diseases represent the main cause of death in Western countries. Among them, atherosclerosis has the greatest mortality rate. Evidence that atherosclerotic plaques form near bifurcations, or branch points, has led to the hypothesis that irregular hemodynamic conditions play a role in the initiation and progression of vascular wall lesions. Both *in vitro* and *in vivo* studies have confirmed these observations, identifying wall shear stress as a major factor influencing endothelial cell dysfunction.

In years past, several research groups have investigated blood flow in large arteries using CFD. The models were initially idealized, generated with classic CAD tools on the basis of averaged *ex vivo* measurements. More recently, the problem of modeling realistic vascular segments at a patient-specific level has been addressed, taking advantage of the latest 3D angiographic techniques, such as computerized tomography (CT) and magnetic resonance (MR), which allow non-invasive acquisition of detailed anatomic information about vascular segments. At the Mario Negri Institute, GAMBIT and FiDAP have been integrated with in-house software and VTK, a free visualization library<sup>1</sup>, to generate realistic geometric models from medical images.

The images are first acquired in DICOM format from contrast-enhanced CT or MR scans. The 3D surface of the vascular wall is then extracted from the images by finding the ridges of image gradient at the interface between the contrast medium and surrounding tissue<sup>2</sup>. The resulting surface is semi-automatically edited to add flow extensions with controlled surface curvature at inlets and outlets.

In order to generate volume meshes from the extracted 3D surfaces, two different approaches have been developed for vascular tracts of differing complexity. In the first approach<sup>3</sup>, single (e.g. carotid and iliac) bifurcations are automatically decomposed into their branches, taking care to avoid sharp corners in the bifurcation region. The split surface is then exported as a neutral file,

loaded into GAMBIT, and rejoined into separate surface entities. Continuous boundary layers are defined and vessel volumes are meshed with hexahedral elements using the Cooper scheme.

For more complex vascular segments (e.g. the abdominal aorta), a second approach<sup>3</sup> is employed, which leads to the generation of hybrid meshes of wedges and tetrahedra. Models are imported into GAMBIT for surface remeshing using well-shaped linear triangles. The mesh is then exported into the in-house geometric analysis software, where surface triangles are optimally warped normal to the medial axis, creating boundary layers of wedges whose thickness smoothly adapts to the local vessel size. The linear triangles and wedges are then converted to 6- and 18-noded quadratic elements, respectively. The remaining volume is meshed with GAMBIT using 10-noded quadratic tetrahedral elements conforming to the boundary layer wedges.

Blood flow simulations are carried out using FiDAP, with careful attention taken when setting boundary conditions in order to achieve representative clinical conclusions. Specific boundary conditions are derived from the patient's echo-Doppler examination, and imposed as fully-developed pulsatile velocity profiles<sup>4</sup>. Carreau's shear-thinning model is employed for blood viscosity, with parameters correlated to the patient's hematocrit and plasma protein concentration.

CFD is now ready for patient-specific investigations of blood flow in the clinical context, where it will provide invaluable help for physicians toward a deeper understanding of the pathophysiology of cardiovascular disorders. ■

## references:

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