Modeling and simulation of flow in cerebral aneurysms

Julia Mikhal

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MESA+ INSTITUTE FOR NANOTECHNOLOGY   UNIVERSITY OF TWENTE.   MIRA BIOMEDICAL TECHNOLOGY AND TECHNICAL MEDICINE

The research presented in this thesis was done in the group Multiscale Modeling and Simulation (Dept. of Applied Mathematics), in collaboration with the group Signals and Systems (Dept. of Electrical Engineering), Faculty EEMCS, University of Twente, The Netherlands.

Computing resources were granted by the National Computing Facilities Foundation (NCF), with financial support from the Dutch Organization for Scientific Research (NWO).

Modeling and simulation of flow in cerebral aneurysms. Ph.D. Thesis, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands.

Printed by Wöhrmann Print Service, Zutphen, The Netherlands.

ISBN : 978-90-365-3433-8   DOI : 10.3990/1.9789036534338

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Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. H. Brinksma,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op vrijdag 19 oktober 2012 om 12:45 uur

door

Iuliia Olegivna Mikhal
geboren op 6 juni 1984
te Kharkiv, Oekraïne

Dit proefschrift is goedgekeurd door de beide promotoren:

Prof. dr. ir. B.J. Geurts en Prof. dr. ir. C.H. Slump

Abstract

A volume-penalizing immersed boundary method is presented for the simulation of laminar incompressible flow inside geometrically complex blood vessels in the human brain. We concentrate on cerebral aneurysms and compute flow in curved brain vessels with and without spherical aneurysm cavities attached. We approximate blood as an incompressible Newtonian fluid and simulate the flow with the use of a skew-symmetric finite-volume discretization and explicit time-stepping. A key element of the immersed boundary method is the so-called masking function. This is a binary function with which we identify at any location in the domain whether it is 'solid' or 'fluid', allowing to represent objects immersed in a Cartesian grid. We compare three definitions of the masking function for geometries that are non-aligned with the grid. In each case a 'staircase' representation is used in which a grid cell is either 'solid' or 'fluid'. Reliable findings are obtained with our immersed boundary method, even at fairly coarse meshes with about 16 grid cells across a velocity profile. The validation of the immersed boundary method is provided on the basis of classical Poiseuille flow in a cylindrical pipe. We obtain first order convergence for the velocity and the shear stress, reflecting the fact that in our approach the solid-fluid interface is localized with an accuracy on the order of a grid cell. Simulations for curved vessels and aneurysms are done for different Reynolds number (Re). The validation is performed for laminar flow at $Re = 250$, while the flow in more complex geometries is studied at $Re = 100$ and $Re = 250$, as suggested by physiological conditions pertaining to flow of blood in the Circle of Willis.