

Progress towards simulation-based medical planning of intracranial aneurysm treatment, based on lattice Boltzmann DNS

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The continuing rapid advances in computer tomography (CT) have permitted the non-invasive, detailed reconstruction of the internal structure in parts of individual human bodies. This has spurred the development of a variety of new diagnostic and therapeutic methodologies, especially in neurosurgery and cardiology. In particular, the prediction of blood flow details and their interaction with malformations of major blood vessels, such as stenoses (narrowings of cross-section) in coronary and brain arteries or aneurysms (large, often balloon-shaped widenings) in aortic and intracranial vessels. Such malformations can lead either to occlusion or to rupture of arteries in very sensitive regions of the body, causing heavy damages (morbidity) and often death. The understanding of the causes for such malformations and of the effects of available treatment strategies can be improved qualitatively by numerical simulations of the blood flow (haemokinetics and, more importantly, haemodynamics in relation with natural vessel wall remodeling) using computational fluid dynamics (CFD). The idea is not new, even if only applications to intracranial aneurysms (ICA) are considered [1]. Semi-automated procedures for incorporating individual angiographic information (typically CT data of vessel geometry) for the simulation of ICA have been intensively studied in recent years [4, 5]. The final goal is the development of clinically applicable (efficient, precise, and simple to use) methodologies for supporting individually, by performing simulations for each new patient, the diagnosis and the planning of medical treatment of vessel malformations. The methodology used so far in CFD studies of various kinds of aneurysms is precisely the one that had already been developed for simulation-aided medical planning in the case of aortic stenoses [2, 3]: 1. extraction of an isolated geometric feature (stenosis with possible bypass or stent along the aorta, resp. aneurysm with possible coil, stent, etc.) from tomography data, 2. covering the extracted vessel wall geometry with an unstructured mesh, 3. meshing the vessel interior based on the result of step 2 and stringent mesh quality criteria, 4. CFD simulation, by finite-element (FEM) or finite-volume (FVM) methods, of transient flow dynamics over 3–5 pulse cycles, 5. evaluation of velocities and shear stresses from the last simulated 1–2 cycles. Steps 2–4 of this procedure are too complex (requiring specialized CFD knowledge) and too expensive for it to be useful as diagnostic tool in the general clinical practice. Therefore, dramatically simplified algorithms based on far-reaching assumptions have been proposed [2], but they are only applicable to specific types of vessels and, more importantly, result in serious modeling errors [3] which can be critical in the clinical practice.

It is possible to effectively skip the mesh generation steps 2-3 of the above methodology and to improve the flow simulation (step 4) concerning both the efficiency of calculations (including its parallel scaling on the inevitably parallel computing platform they must be executed on) and the reliability of results obtained with the much more complicated geometries occurring in practice as compared with the test cases considered in the literature. This can be done [6] by using directly the CT data raster as numerical simulation grid, and by employing a lattice Boltzmann solver instead of FEM/FVM. The efficiency on parallel computers and in complex geometries, including real brain artery trees, of such solvers developed at the authors' institute has been shown [7].

The viability of this modified approach is now demonstrated on the basis of real angiography data. Reports in the literature, that modifications in vessel geometry upstream of malformations cause flow pattern changes and, through wall remodeling, the malformations themselves, are confirmed. The necessity for individualized treatment is emphasized on the basis of the simulation results. It is argued that pressure and swirl are not less important than the shear stress that has remained so far the focus of surgeons' interest. It is shown that a larger surrounding of a malformation than simulated in previous studies must and, with the used new approach, can be taken to assure realistical flow simulation at the malformation itself. The new approach shows a clear promise of clinical applicability, as a result of dramatic improvements in simplicity and efficiency. The remaining issues to be cleared are, beside detailed validation with a large number of different patients' data, the treatment of inflow and outflow boundary conditions and the incorporation of wall elasticity. These issues remain a subject of research independent of the chosen discretization for numerical simulation. Lattice Boltzmann specifics in that respect will be considered.

References

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