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SOFTWARE TOOLS FOR MANIPULATING FE MESH, VIRTUAL SURGERY AND POST-PROCESSING*

This paper describes a set of software tools which we developed for the calculation of fluid flow through cardiovascular organs. Our tools work with medical data from a CT scanner, but could be used with any other 3D input data. For meshing we used a Tetgen tetrahedral mesh generator, as well as a mesh re-generator that we have developed for conversion of tetrahedral elements into bricks. After adequate meshing we used our PAKF solver for calculation of fluid flow. For human-friendly presentation of results we developed a set of postprocessing software tools. With modification of 2D mesh (boundary of cardiovascular organ) it is possible to do virtual surgery, so in a case of an aorta with aneurism, which we had received from University Clinical center in Heidelberg from a multi-slice 64-CT scanner, we removed the aneurism and ran calculations on both geometrical models afterwards. The main idea of this methodology is creating a system that could be used in clinics.

Cardiovascular diseases are common and correct diagnostic is very important. Using the data from modern medical devices, it is possible, after adequate preparation, to simulate blood flow. Simulation can be useful because we can measure, modify boundary conditions and results (shear stress, particle tracking, velocities, etc.) as we want without real interventions on the specific patient. This is used in predictive medicine too, because progress of disease can be simulated.

The input data in this study is the aorta. STL that we received from University Clinical center in Heidelberg from a multi-slice 64-CT scanner. The patient who was scanned had an aorta aneurism, so we created two different 3D meshed models, the "real" model with the aneurism and the other without the aneurism. The number of finite elements in one case and the other differs because of different volumes of models, but the parameters we set for meshing (quality of 3D mesh) were the same. Calculation was done on both models with the same boundary conditions. For representation of the results, we developed a set of post-processing tools.

GEOMETRICAL MODELING

In this study, the first step was to prepare the input data for 3D meshing. Due to the threshold of the medical device there were many sufficient objects. The first step was the removal of independent objects, and the second step was the removal of objects that were attached to the main object. For this purpose of preparing the boundary in C++, we developed a set of software tools (STL Tools) that work with COG (Center Of Gravity) algorithm [1]. For cutting and presentation of the mesh we used Gmsh [2], and for patching we used our software tools.

As it is obvious from the Fig. 1, after this "3D cleaning" we get a nice and smooth boundary of the main object. That boundary is 3D meshed afterwards.

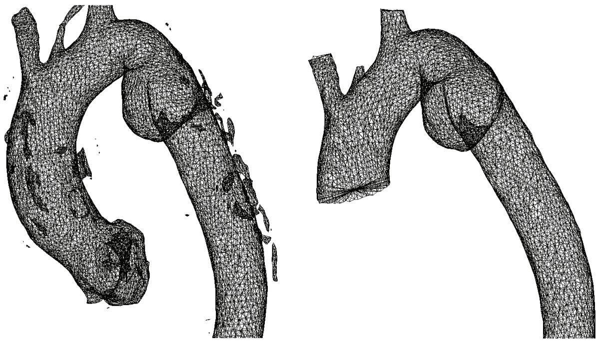

Figure 1. Preparing the boundary.

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After we obtained the first results for this aorta model, we came across the idea to virtually remove the aneurism. This removal was semi-automatic, because we manually set the connection nodes (Fig. 2).

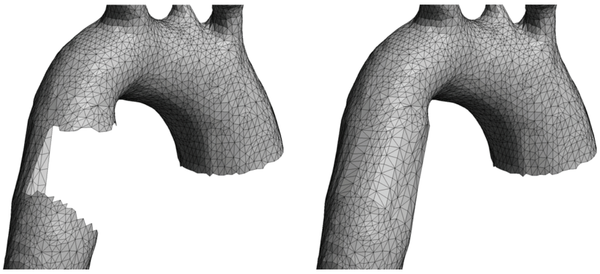

Figure 2. Aneurism removal.

MESH

When the boundary is finished, a 3D meshing is employed. Due to the stability and accuracy our finite element solver PAKF uses a 3D 8-node finite element for CFD analysis so our goal is to achieve an 8 nodal "brick" mesh. This procedure we did in two steps. First, we used a well-known Tetgen [3] to mesh the space defined by the surface triangle mesh into tetrahedrons, and afterwards we used our re-mesh program to get the 8 nodal 3D elements. In this re-meshing procedure we also used the COG algorithm, thus every tetrahedron was split into four bricks [1].

After 3D meshing, the input boundary conditions were prescribed (*e.g.*, input and output fluid velocity profiles) and afterwards the calculation was performed. For both aorta models the mesh independence was reached at 350000 to 680000 finite elements.

POST-PROCESSING

The calculation was done on GRID, on 20 computational nodes. The obtained results were satisfactory thus we created a set of post-processing software tools for book-friendly representation of the results. The calculation was done for both aorta models (in several different mesh qualities).

Our PAKF solver [4] prints UNV file format, and we use our software for 3D drawing of results. In one calculation 50 GB of data is written in many UNV files (usually one UNV per time step). The problem with UNV is that all physical quantities are written in one file. Therefore, for large models we found that the POS format is more useful, so we created converters from UNV to POS. POS is also standard post-processing format, one characteristic of POS is that one file is printed for one physical quantity.

For different representations, we created specific tools as it will be shown in the figures below. The main idea is to get adequate subset of the set for given physical quantity (in scalar or vector representation). Some of the results are shown in Figs. 3–7.

Figure 3. Particle trajectories.

Data-mining

For additional information about the wall, we developed a data-mining application which collects information of adequate physical quantity for a prescribed set of nodes. Values that are collected are used afterwards for calculation of mean wall shear stress distribution (Fig. 8), and oscillatory shear index (Fig. 9). Below are the equations (where t_s is the surface traction vector).

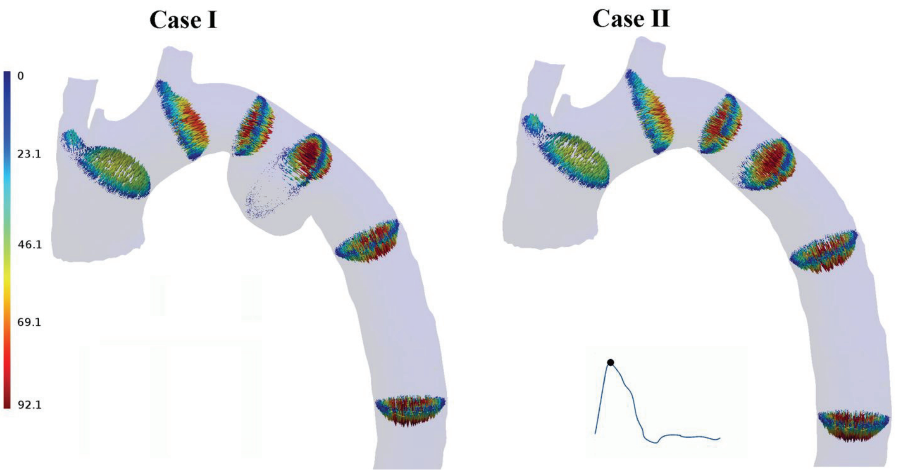

Figure 4. Velocity profile for a peak systole phase for Case I (aorta with aneurism) and Case II (aorta without aneurism).

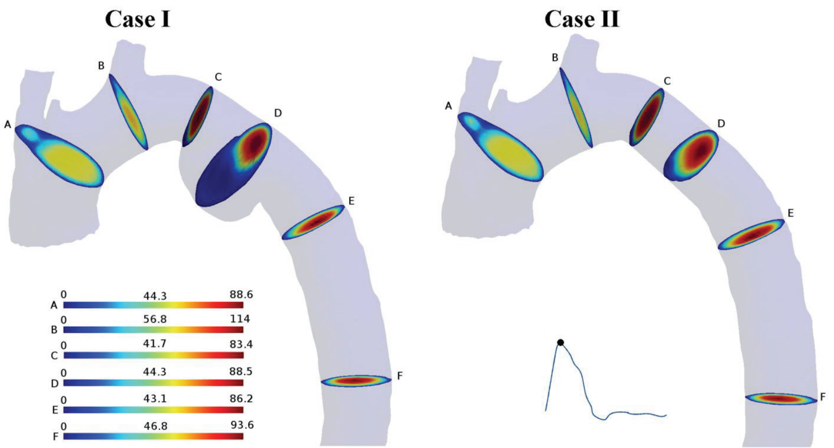

Figure 5. Effective velocity at different cross-sections for a peak systole phase for Case I (aorta with aneurism) and Case II (aorta without aneurism).

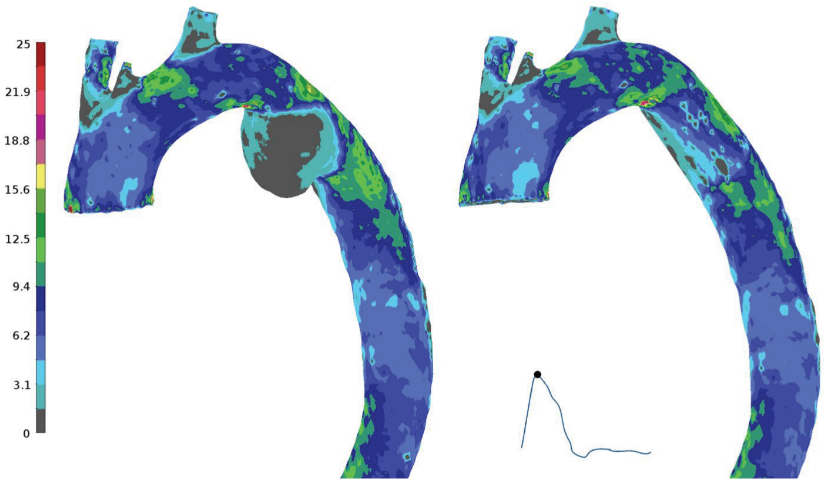

Figure 6. Magnitude wall shear stress distribution along the aorta with branches, at the peak systolic flow for Case I (aorta with aneurism) and Case II (aorta without aneurism).

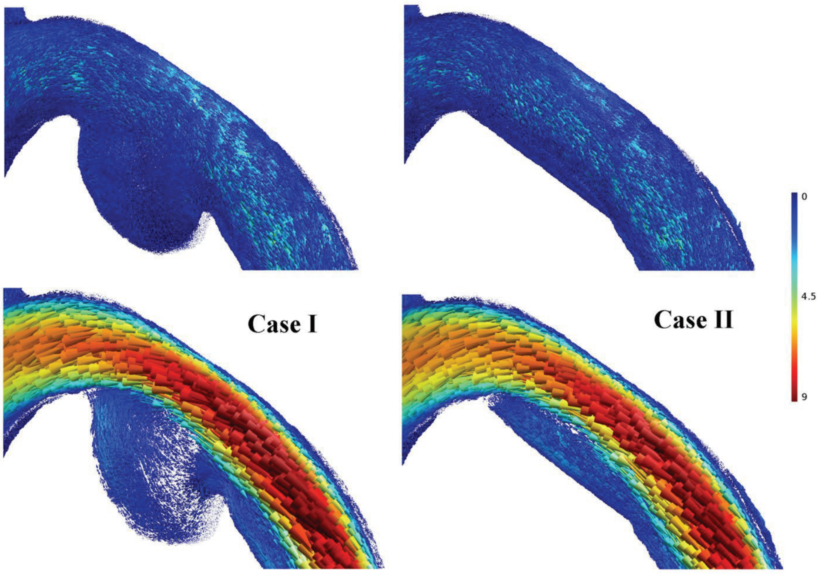

Figure 7. Velocity vector field for the vertical cutting plane for the systolic end; t = 0.34 s for both cases.

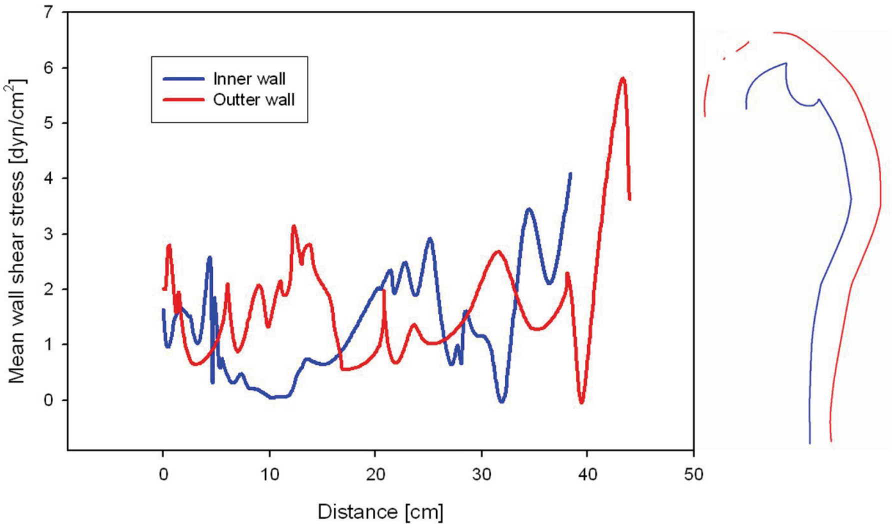

Figure 8. Mean wall shear stress distribution along the inner and the outer side wall in the frontal plane of the aorta cross-section.

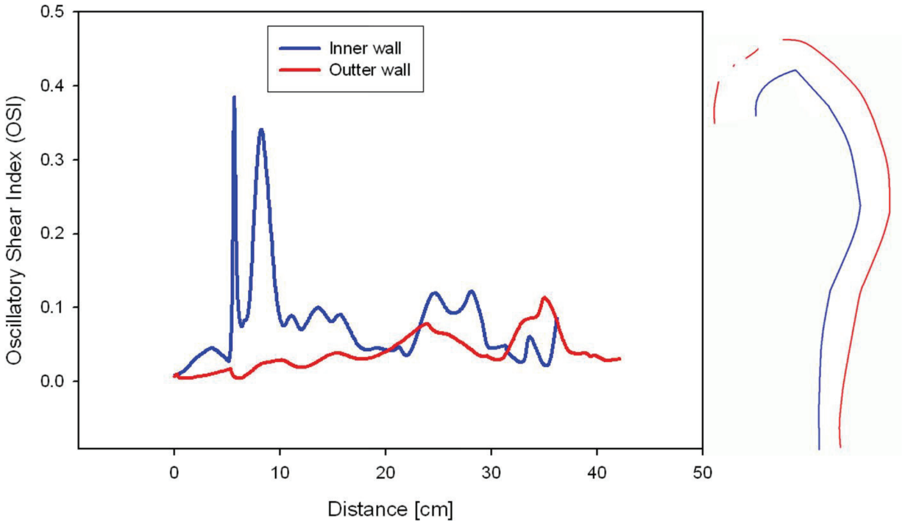

Figure 9. Oscillatory Shear Index (OSI) along the inner and the outer side wall in the frontal plane of the aorta cross-section.

$$\tau_{mean} = \left| \frac{1}{T} \int_0^T t_s dt \right|$$

$$\tau_{mag} = \frac{1}{T} \int_0^T \left| t_s \right| dt$$

$$OSI = \frac{1}{2} \left(1 - \frac{\tau_{mean}}{\tau_{mag}} \right)$$

CONCLUSION

Our main goal is to create a user-friendly system, which could be used by medicine staff in clinics. We do have cooperation with many medicine doctors that have helped us in this project, so our future development will be guided by their needs.

We do hope that this methodology will be in clinical practice soon.

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IZVOD

SOFTVERSKI ALATI ZA MANIPULISANJE MREŽOM KONAČNIH ELEMENATA, VIRTUELNA HIRURGIJA, I POST PROCESIRANJE

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(Naučni rad)

U ovom radu opisan je skup softverskih alata koje smo razvili sa ciljem proračunavanja strujanja fluida kroz kardiovaskularne organe. Naši softverski alati rade sa podacima koji se dobijaju sa CT skenera, ali bi mogli da se koriste i bilo koji drugi 3D ulazni podaci. Za diskretizaciju u konačne elemente koristili smo Tetgen generator tetraedarne mreže, kao i softver koji smo mi razvili sa ciljem konverzije tetraedralnih elemenata u osmočvorne (brick) konačne elemente. Kada smo formirali adekvatne 3D modele koristili smo naš PAKF solver za proračunavanje strujanja fluida. Sa human-friendly prikazivanja rezultata razvili smo i niz alata za post-procesiranje. Modifikovanjem 2D mreže (zida kardiovaskularnog organa) moguće je uraditi virtuelnu hirurgiju, te smo u slučaju jedne aorte sa aneurizmom, koju smo dobili iz Univerzitetskog kliničkog centra u Hajdelbergu sa višeslojnog CT skenera, uklonili aneurizmu i vršili proračunavanje strujanja fluida za oba slučaja nakon toga. Osnovna ideja za nas je kreiranje sistema koji bi mogao da se koristi u klinikama.

Ključne reči: Generisanje mreže konačnih elemenata • CFD simulacija • Post-procesiranje
Key words: Mesh generation • Brick mesh • CFD simulation • Post-processing