Application of Code Saturne for the Numerical Analysis of Blood Flow through Human Arteries

G. Shanthakumar, T. Le, S. Jimenez, C. Hengefeld, M. Behbahani

Objective

- **computational simulation** of the **flow field** in the carotid bifurcation arteries, aortic arch and an abdominal aortic aneurysm (AAA)
- numerical description and validation of **steady** as well as **pulsatile flow conditions**
- detection of critical areas with **recirculation** and **pathological shear stress**
- this study shall serve as a basis for the investigation of **aneurysms** and **stenosed arteries**

Methods

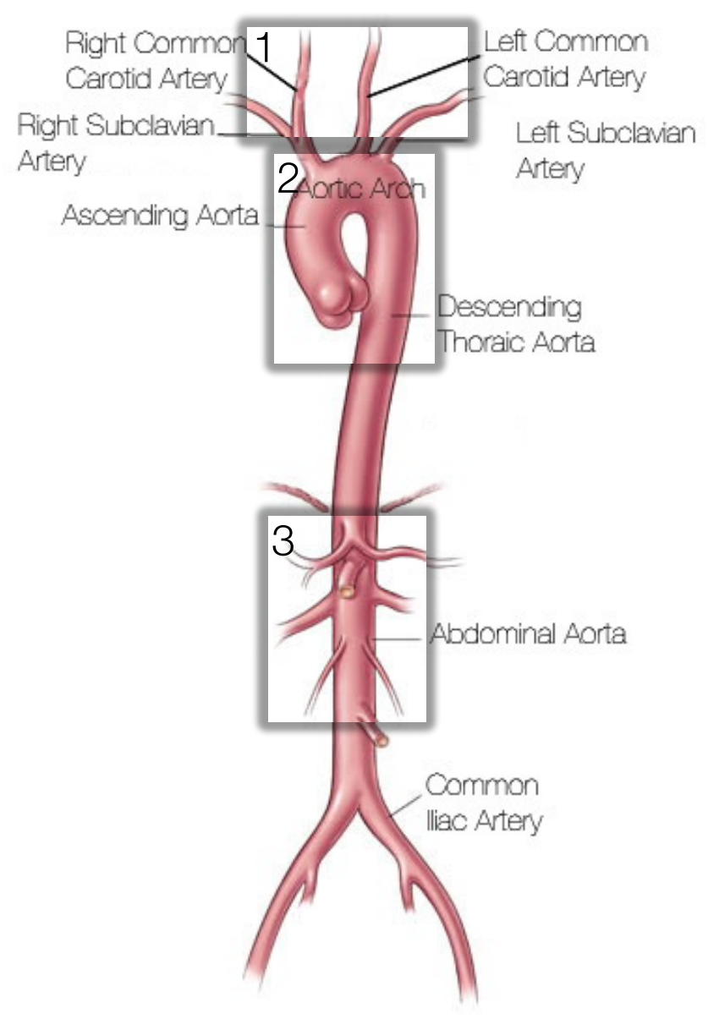
- three-dimensional flow governed by incompressible Navier-Stokes equations
- blood modeled as Newtonian fluid
- use of unstructured (tetrahedral) meshes
- open-source solver Saturne and post-processors Salome and Paraview are applied
- time-dependent boundary conditions reflecting measurements of flow rates in concerned arteries
- comparison with available PIV (particle imaging velocimetry) measurements

Medical Conditions of the Vascular System

1. Carotid Arteries
critical region for carotid artery stenosis, increasing the risk for a stroke

2. Aortic Arch
critical area for atherosclerosis which may lead to organ damage, heart attack and stroke as well as increasing the risk for aneurysms

3. Abdominal Aorta
critical region for abdominal aortic aneurysms which may ultimately lead to aortic rupture



Computational Results

1. Blood Flow in the Carotid Bifurcation Arteries

- the carotid artery geometry is based on a model by Kien T. Nguyen [1] used to create a mesh with 0.45 million elements
- parabolic inflow at a constant flow rate of 0.742 L/min
- common carotid artery (CCA) inflow diameter of 8 mm
- blood density of 1030 kg/m^3
- dynamic viscosity of 0.004 Pas
- steady laminar flow conditions at Re = 498

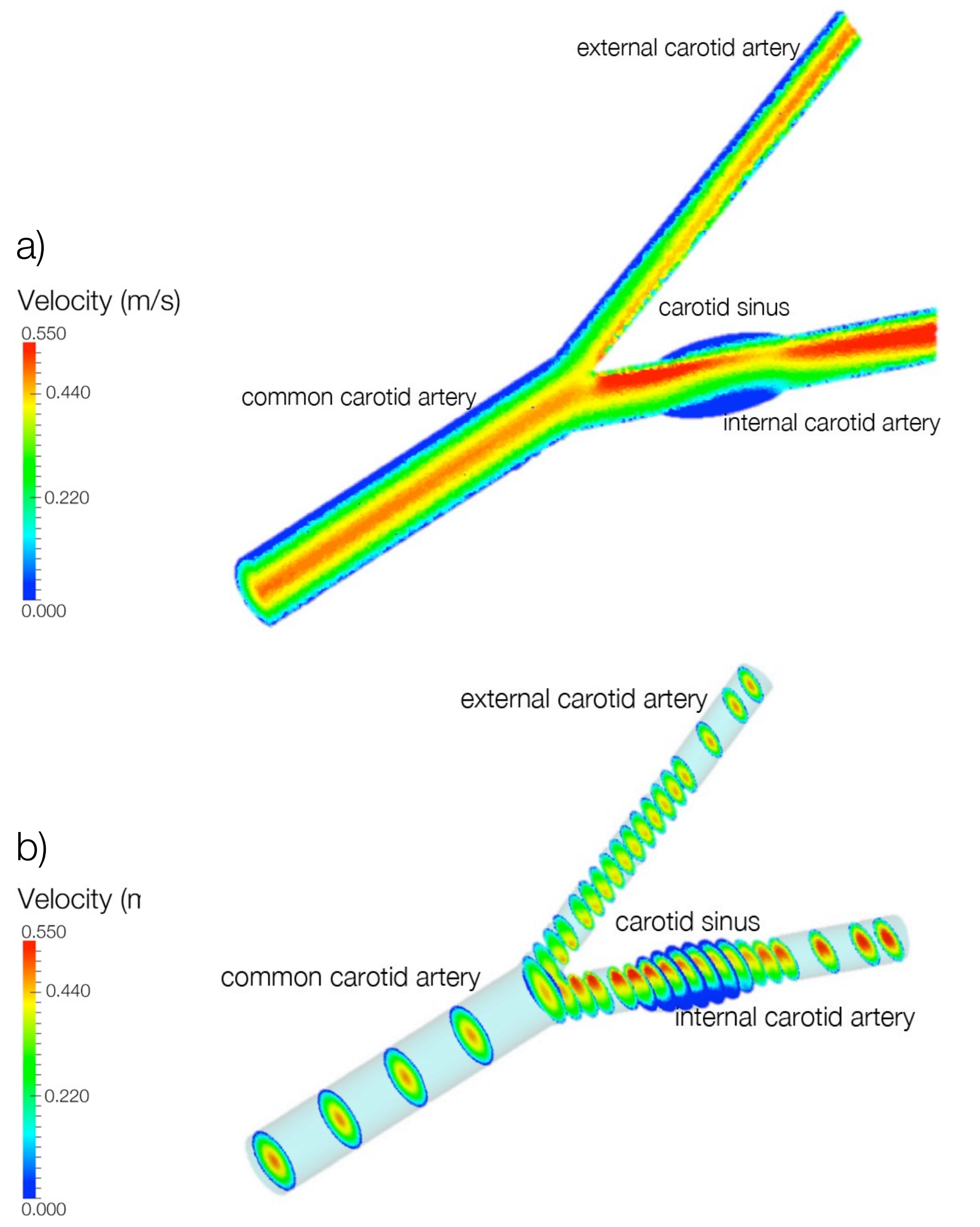


Figure 1: a) Longitudinal section of the flow profile in healthy carotid arteries
b) Cross sections of the velocity flow profile in healthy carotid arteries

- figure 1 shows that laminar blood flow is disrupted near the carotid bifurcation where separation of blood flow occurs
- the medial wall of the carotid sinus experiences higher shear stress
- the lateral wall, where low velocities prevail, experiences recirculation vortices that vary with the cardiac cycle, resulting in flow reversal and thus oscillatory and low mean shear stress
- endothelial cells exposed to shear stress undergo reorientation with their longitudinal axis aligned parallel to the direction of blood flow [2]

2. Blood Flow in the Aortic Arch

- the aortic arch geometry was created using MRI scans of a patient geometry creating a mesh of 2.47 million elements
- parabolic inflow at a constant flow rate of 3.371 L/min
- inflow diameter of 2.8 cm
- blood density of 1085 kg/m^3
- dynamic viscosity of 0.0036 Pas
- steady laminar flow conditions at Re = 770

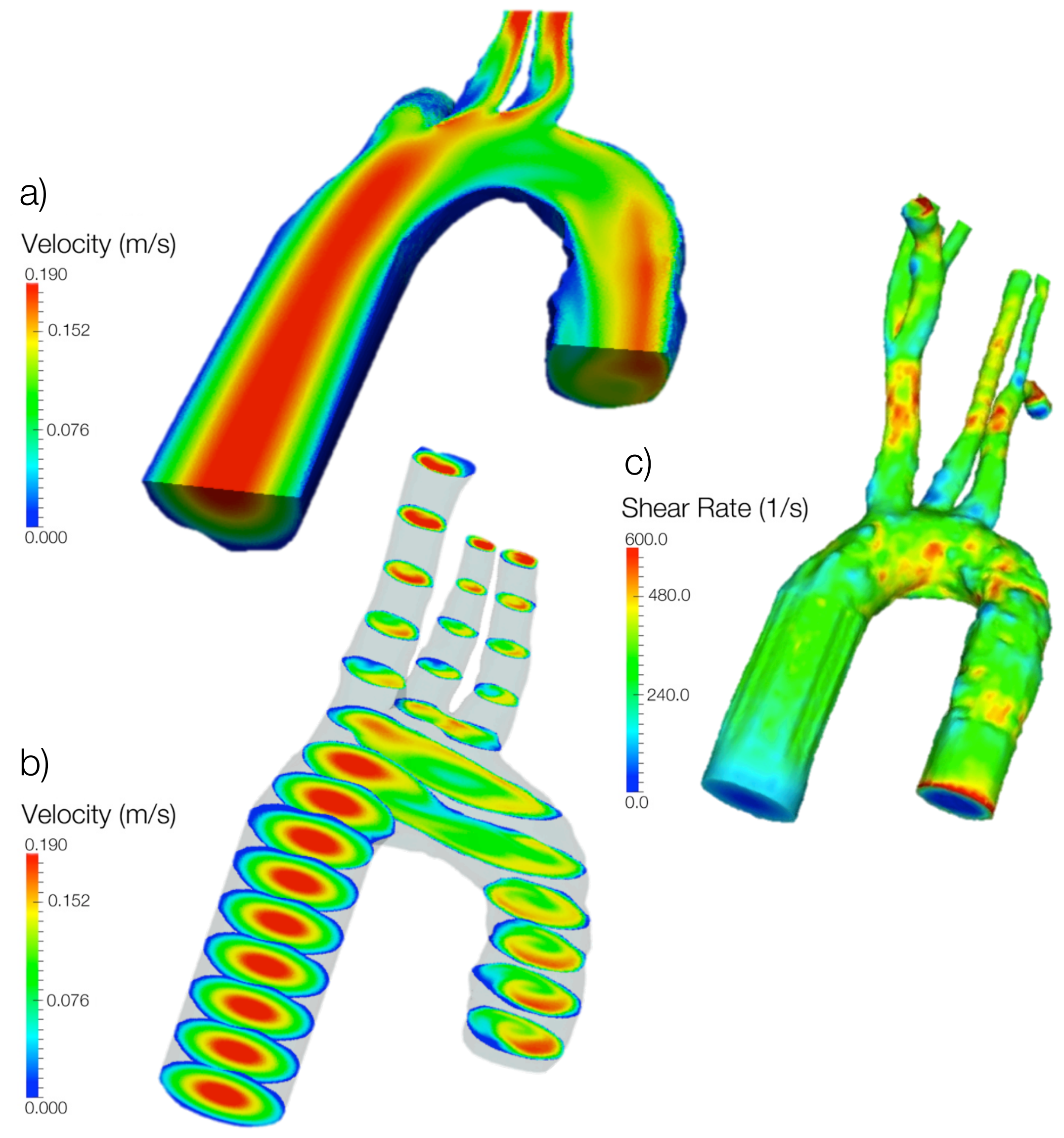
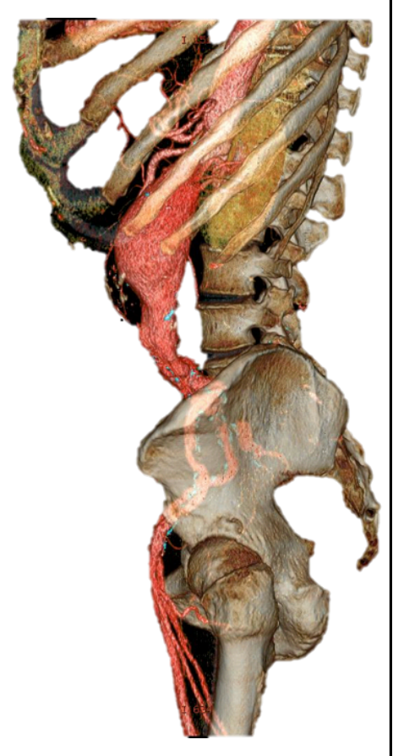


Figure 2: a) Longitudinal section of the velocity flow profile in the aortic arch
b) Cross sections of the velocity flow profile in the aortic arch
c) Wall shear rate values along the vessel walls of the aortic arch

- figures 2 a) and b) show the development of excentric maximal velocities in the descending aorta in accordance with studies of velocity profiles in similar geometries, such as bent pipes
- figure 2 c) shows the wall shear rates at the vessel walls of the aortic arch
- a comparison with experimental PIV data was performed (data not shown) and showed good qualitative and quantitative agreement

3. Blood Flow in an Abdominal Aortic Aneurysm (AAA)



- the geometry for the abdominal aortic aneurysm is based on a model by Scotti [3] similar to the CT scan of a patient geometry shown to the right, creating a mesh of 1.58 million elements
- inflow diameter of 2 cm
- diameter of the sacular aneurysm is 3 cm
- blood density of 1050 kg/m3
- dynamic viscosity of 0.0035 Pas
- laminar, pulsatile flow conditions at Re = 702 modelled using a Fourier expansion [4]:

$$\dot{V} = C_1 + C_2\cos(\tfrac{2\pi t}{T}) + C_3\cos(\tfrac{4\pi t}{T}) + C_4\sin(\tfrac{2\pi t}{T}) + C_5\sin(\tfrac{4\pi t}{T})$$

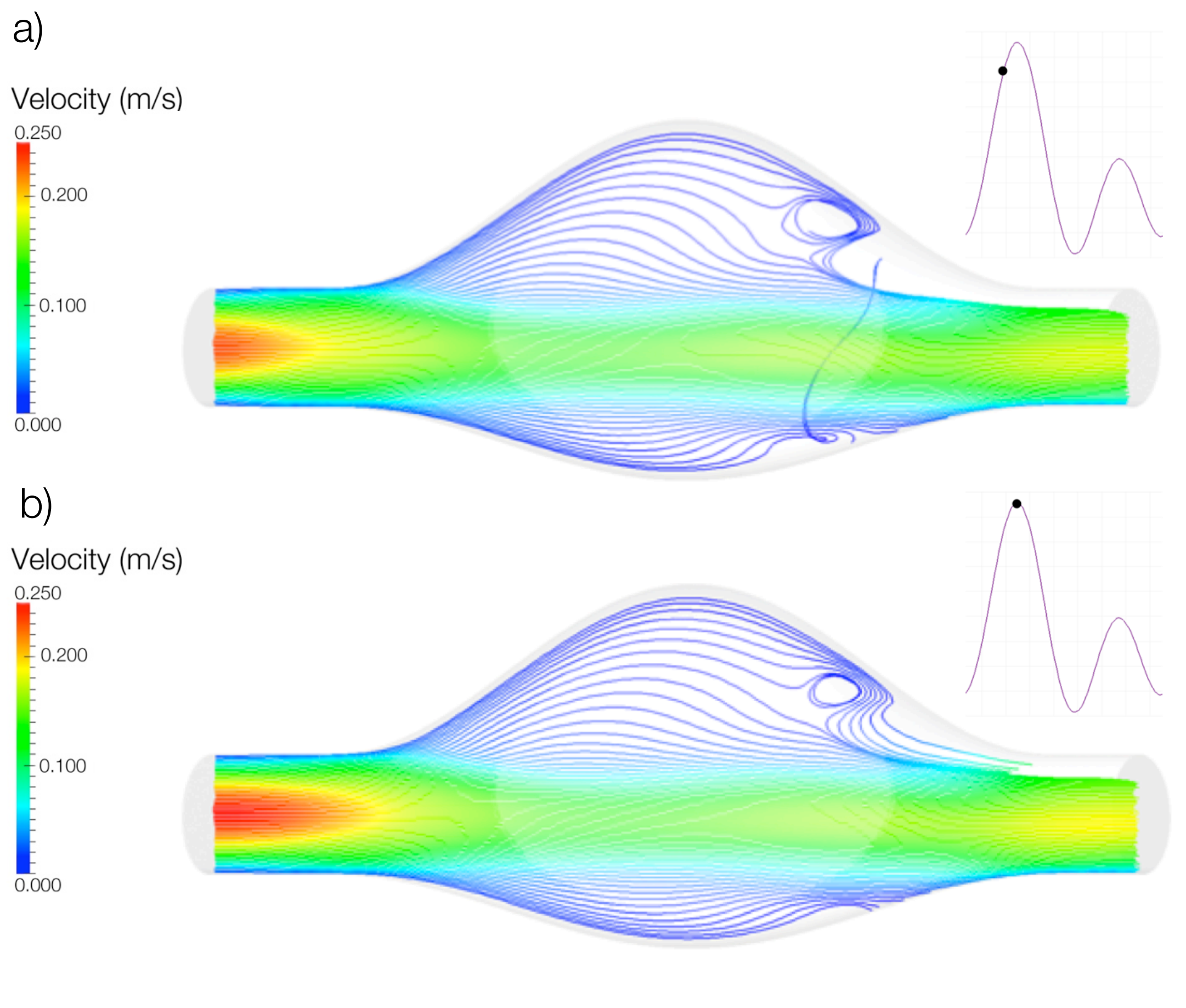


Figure 3: a) Longitudinal section of the flow profile of the AAA geometry at time t=2.65s showing the velocity profile and streamlines
b) Longitudinal section of the flow profile of the AAA geometry at time t=2.71s showing the velocity profile and streamlines

- figure 3 shows the flow field in the AAA at two different points in time of the pulsatile velocity profile
- recirculation zones prevail near the walls of the aneurysm, especially towards the thinning end of the vessel and are changing with time
- recirculation zones are characterised by low shear stress known to increase the risk of aneurysm growth
- the wall shear stresses (WSS) have been calculated (data not shown) and are very low in the aneurysmal sac

Outlook

- investigation of pulsatile flow
- a stenosed internal carotid artery (ICA) will be analysed using a modification of patient geometries based on MRI scans
- a thrombosis model will be applied to investigate how altered blood flow in stenosed vessels influences platelet reactions

- simulations including pulsatility as well as the opening and closing of the aortic valve
- elastic behaviour of the aorta (Windkessel-effect) remains to be elucidated to account for the complexity of the human vascular flow situation
- inclusion of coronary arteries branching from the aorta into the simulation and study of stenosis and thrombotic complications in those arteries

- 80% of AAAs have shown to develop intraluminal thrombus growth
- WSS has been shown to strongly influence aneurysm growth and shall be further studied
- a coupling of the flow model, a thrombosis model and a wall growth model have already been established and will serve as a basis for thorough analysis of aneurysm growth

Conclusion

- critical regions of flow separation, high and low shear stress as well as recirculation zones could be identified
- the numerical study shows good agreement with experimental flow measurements also for complex geomentries and steady flow conditions
- CFD (computational fluid dynamics) is a useful tool for **flow feature prediction** in blood vessels
- pulsatile flow results show changes of flow conditions and recirculation areas over time

References

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Contact

Prof. Dr.-Ing. Mehdi Behbahani
email: behbahani@fh-aachen.de
Faculty for Medical Engineering and Techno-Mathematics
FH Aachen, Campus Jülich
Institute of Bioengineering
Biomaterials Laboratory
Heinrich-Mußmann-Str. 1
52428 Jülich

http://www.fh-aachen.de