Impact of the Cannula Insertion Depth on the Aortic Wall

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Introduction

To maintain the circulation of blood and oxygen during cardiopulmonary bypass (CPB) surgery a CPB pump, also referred as heart-lung-machine, which replace the function of the heart and the lungs, is used. By a system of tubes the blood is removed from the right side of the heart to be oxygenated outside the body. Then a cannula returns the oxygenated blood into the patient's vascularity system. The cannulation-site is the position where the cannula enters the aorta and the preferred site since 1957 for the arterial return is the ascending aorta.[1].

In this project the impact on the aortic wall due to two cannula insertion depth is investigated. The area of interest for the wall shear stress and pressure distribution is the part of the aortic wall, where the cannular jet hits it. As well the flow distribution from the cannula inflow through the aorta and into the aortic arch is analyzed. The results are compared to a physiological aorta.

Methods

The ascending aorta is segmented from Computational Tomography data and smoothed to obtain a reasonable model for a fluid simulation, using Mimics software.

The cannula with a diameter of 6 mm and the smoothed aorta are merged in 3-matics. For the evaluation three geometries are created, two geometries with different cannula insertion depths and one physiological geometry for comparison purpose, as shown in Fig. 1.

A hexdominant mesh with a base-level size of 0.7 mm is performed with Harpoon. To resolve the fluid velocities close to the aortic wall 6 boundary layers (first element size 0.06 and expansion 1.7) are included on the luminal surface in the mesh.

The nodesets are set in Icem CFD. All three geometries have a discretization size less than 300 000 elements.

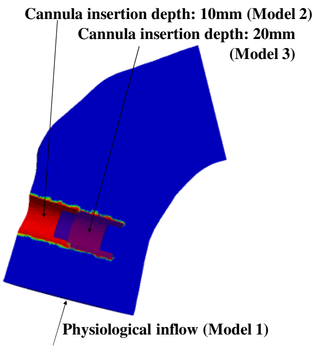

Fig. 1: Different cannula insertion depths

To simulate the appropriate flow, the Boundary Conditions (BC) are defined as follow:

The cannula inflow is a parabolic flow, which is ramped from 0.0 l/min to 3.0 l/min during the first three seconds and afterwards hold constant.

The BC for the physiological aorta inflow is set to a pulsatile inflow. [2]

To stabilize the inflow at the outlet, a Neumann Inflow Condition is applied.

A zero velocity Dirichlet BC is defined on the luminal surface, due to a no-slip condition of the walls.

To enable the calculation of wall shear stresses, a fluid stress calculation condition is defined on the luminal surface.

The fluid material has the dynamic viscosity 4.0 Ns/mm² and density 0.001 g/mm³ [2].

The input file for the Finite Element Solver Baci contains the definition of the mesh, boundary conditions and solver settings. Velocity, pressure and wall shear stresses is calculated in all 1200 time steps for the simulation of 5s, the physiological aorta is calculated for 3s.

The following results are post processed using Paraview.

Results

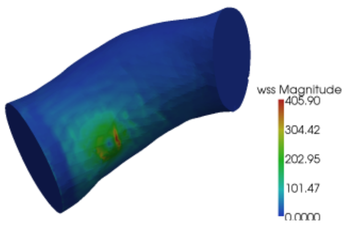

Fig. 2: WSS distribution

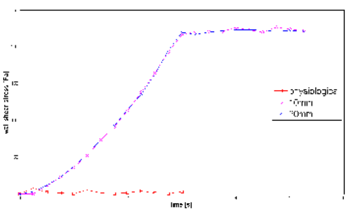

Fig. 3: 99% Maximum of WSS

Fig. 2 illustrates the distribution of the wall shear stresses (WSS) of the aortic wall that occur during an operation with a cannula. The 99% maximum of the wall shear stresses of the three different models, which occur on the aortic wall, at every 0.25 second is plotted against the time, is given in Fig. 3.

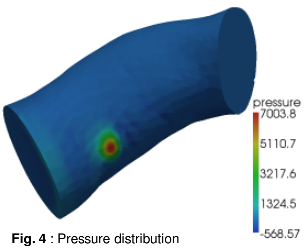

Fig. 4 : Pressure distribution

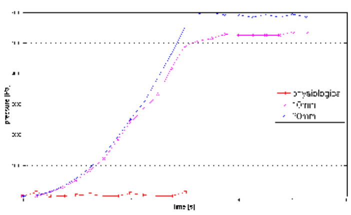

Fig. 5: 99% Maximum of pressure

In Fig. 4 the distribution of the pressure on the aortic wall during an operation with a cannula, is shown. The 99% maximum of the pressure on the aortic wall of the aorta of the three different models, calculated at every 0.25 second, is presented in Fig. 5.

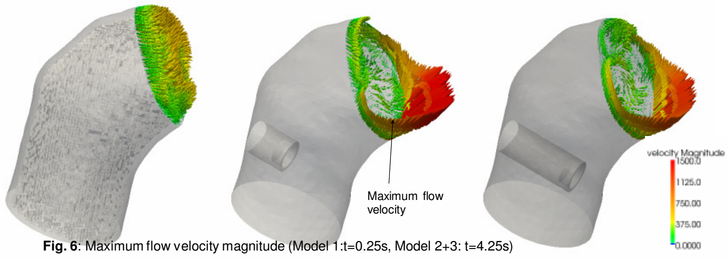

Fig. 6: Maximum flow velocity magnitude (Model 1:t=0.25s, Model 2+3: t=4.25s)

Geometry	Maximum Flow Velocity
Model 1	600 mm/s
Model 2	1500 mm/s
Model 3	1300 mm/s

Tab. 1:Maximum flow velocity magnitude

The maximum flow velocity magnitude for model 1 is almost uniform and lower, in comparison to model 2 and 3, where it occurs at the bottom of the aortic outflow with an higher maximum, as presented in Fig. 6 and Tab. 1.

All figures are made at the absolute maximum of the velocity during the simulation. In Model 2 and 3 the velocity magnitude is nearly constant, after the inflow reaches 3.0 l/min.

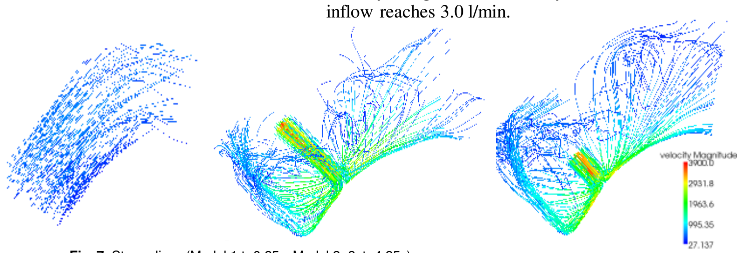

Fig. 7: Streamlines (Model 1:t=0.25s, Model 2+3: t=4.25s)

In Fig. 7 the streamlines for the three models at the time where the flow velocity magnitudes reach maximum is shown.

Discussion

The pressure and the wall shear stresses, which occur on the aortic wall in model 2 and 3, are much larger in comparison to the pressure and stresses in model 1. The 99% maximum of the wall shear stress in an aortic wall with the cannula is up to 100 times larger, than in the physiological aorta. The 99% maximum of the pressure is even 1000 times larger. As well the calculation shows that the pressure and the wall shear stress are highest in the area, where the cannula jet hits the wall. In the physiological aorta the area, where the pressure and the wall shear stresses are maximum, changes during the pulsatile flow.

The calculation also illustrates, that the cannula insertion depth has no influence on the maximum of the wall shear stresses. A deeper cannula insertion depth indeed results to a higher pressure distribution, as the energy loss of the blood jet is less. But this difference in the maximum of the pressure is negligible, in comparison to the maximum of the pressure of the physiological aorta.

The flow vectors in Fig.6 show not only the magnitude of the velocity, they also illustrate the flow velocity profile entering the aortic arch. For the geometries with the cannula the velocity is much higher at the bottom of the aortic outflow compared to the velocity at the top of the aortic outflow. The difference in the velocity profile can affect the flow distribution in the artery system. For example if the velocity is much higher at the bottom of the aortic arch than at the top, it may result in less blood flow to the arteries that lead to the neck and the brain. The risk of tissue erosion, may also be bigger the higher the velocity that is entering the aortic arch [3].

There is also a velocity magnitude difference between the two geometries with the cannula. In model 2 the maximum velocity magnitude that enters the aortic arch is higher than in model 3. As the energy of the blood jet, where the cannula is closer to the aortic wall, is higher than the energy of the blood jet of model 2, more fluid particles are able to reflect back and therefore they spread more. In comparison fluid particles of model 2, stay closer to the wall and the maximum velocity magnitude is higher.

The streamlines visualize how the fluid particles from the cannula inflow reach the aortic arch. As one can see in Fig. 7 the flow in the physiological geometry is evenly distributed compared to the geometries with the cannula. The unevenly flow distribution is due to the fact that the flow jet hits the aortic wall. The no-slip BC of the aortic inflow also influences the flow of the models with cannula.

Conclusion

In this project it can be concluded, that the wall shear stress and pressure is highest in the area, where the cannula jet hits the wall and the maximum of both are much higher compared to the maximum in the physiological aorta.

In this research just the flow profile entering the aortic arch is simulated and it is concluded that the velocity entering the aortic arch is highest at the bottom of the outflow. For a more precise description of the flow distribution in the artery system the descending aorta should be simulated as well.

For an less injuring CPB surgery the cannula insertion depth need to be optimized, as an deeper insertion depth leads to an higher pressure maximum, but also to an lower velocity maximum at the bottom of the aortic outflow.

REFERENCES:

[1] Cardiopulmonary Bypass Complicated by Inadvertent Carotid Cannulation, Ross, William T. JR. M.D.; Lake, Carol L. M.D.; Wellons, Harry A. M.D, Anesthesiology: January 1981 - Volume 54 - Issue 1 - ppg 85-86, http://journals.lww.com/anesthesiology/Citation/1981/01000/Cardiopulmonary_Bypass_Complicated_by_Inadvertent.19.aspx

[2] H.J. Kim, C.A. Figueroa, T.J.R. Hughes, K.E. Jansen, C.A. Taylor (2009)

[3] Effect of cannula length on aortic arch flow: protection of the atheromatous aortic arch, Grossi EA, Kanchuger MS, Schwartz DS, McLoughlin DE, LeBoutillier M 3rd, Ribakove GH, Marschall KE, Galloway AC, Colvin SB, http://www.ncbi.nlm.nih.gov/pubmed/7887717

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