Faculty and Postdoc, Medical, Biomedical and Health Sciences

Computational and experimental investigation of cardiovascular flows: AAA investigation as an example

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BACKGROUND

- Abdominal aortic aneurysm (AAA) is the dilatation of the aorta beyond 50% of its normal diameter.
- It is reported that 4–8% of men and 0.5–1% of women above 50 years of age bear an AAA.
- If left untreated, AAA might gradually expand until rupture; the most catastrophic complication of the aneurysmal disease that is accompanied by a striking overall mortality of 80%.
- The precise mechanism leading to AAA rupture remains unclear.

OBJECTIVE

To characterize the disturbed hemodynamics within AAAs which will help to understand the mechanobiological development of the condition which will contribute to novel therapies

METHODOLOGY

- Computational modeling:

The problem is first defined mathematically, and the solution is approximated with numerical techniques to get the characteristics of flow by following the steps:

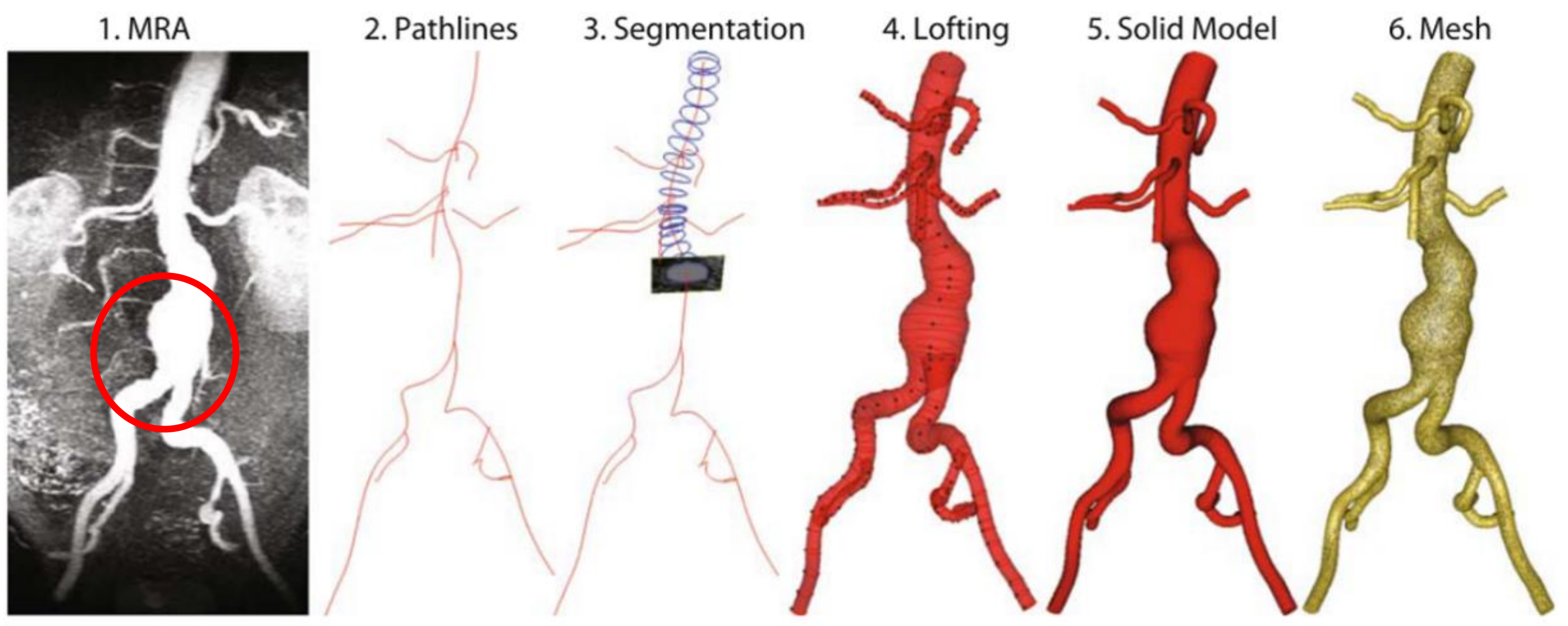
- Segmentation of medical images to construct 3D model
- Discretization of the problem domain into finite elements (Meshing)
- Applying related inlet and outlet boundary conditions considering the pulsatile flow
- Performing finite element analysis (FEA)
- Post-processing the results

The governing equations in fluid domain:

$$\rho_f \frac{\partial \mathbf{v}}{\partial t} + \rho_f (\mathbf{v} - \mathbf{w}) \cdot \nabla \mathbf{v} - \nabla \cdot \boldsymbol{\tau}_f = \mathbf{f}_f^{\mathrm{B}}$$

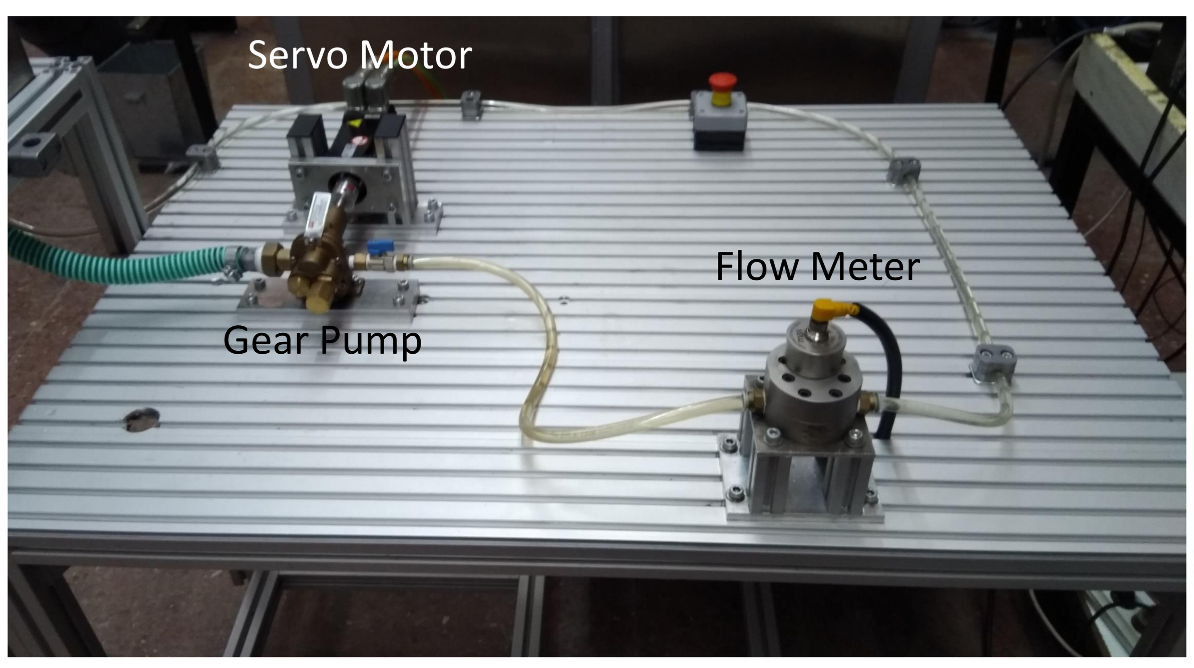
$$\nabla \cdot \mathbf{v} = 0$$

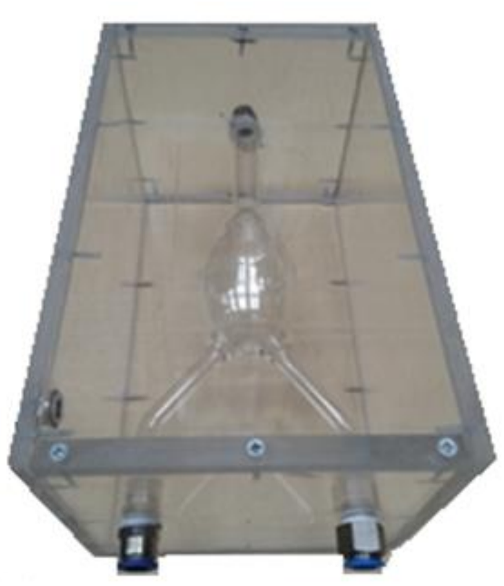
where ρ_f: mass density of fluid, $\mathbf{v}$: fluid velocity vector, t: time, $\mathbf{w}$: velocity of the fluid domain (i.e. moving coordinate velocity), $\boldsymbol{\tau}_f$: fluid stress tensor, $\mathbf{f}_f^{\mathrm{B}}$: body forces.



- Experimental setup:

We formed a research group with the collaboration of Middle East Technical University. Currently, we completed an experimental flow measurement setup providing physiological flow pattern in a phantom geometry. We use the particle image velocimetry (PIV) system, which enables the characterization of the flow using transparent AAA phantoms.





AAA phantom

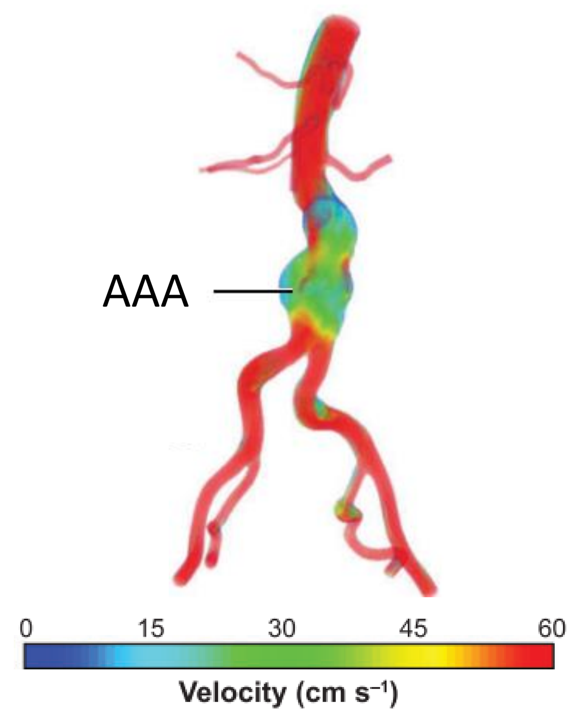
In experimental setup, the main component is the gear pump and servo motor combination, supplying physiological fluid flow into downstream, in which there is a flow meter that can instantaneously measure flow rate through system. After a necessary distance making sure that fully developed flow conditions are obtained, AAA phantom, which is placed inside a transparent box filled with stagnant working fluid to prevent refraction problems, is located and PIV experiments can be performed with proper alignment of laser and camera.

CURRENT KNOWLEDGE

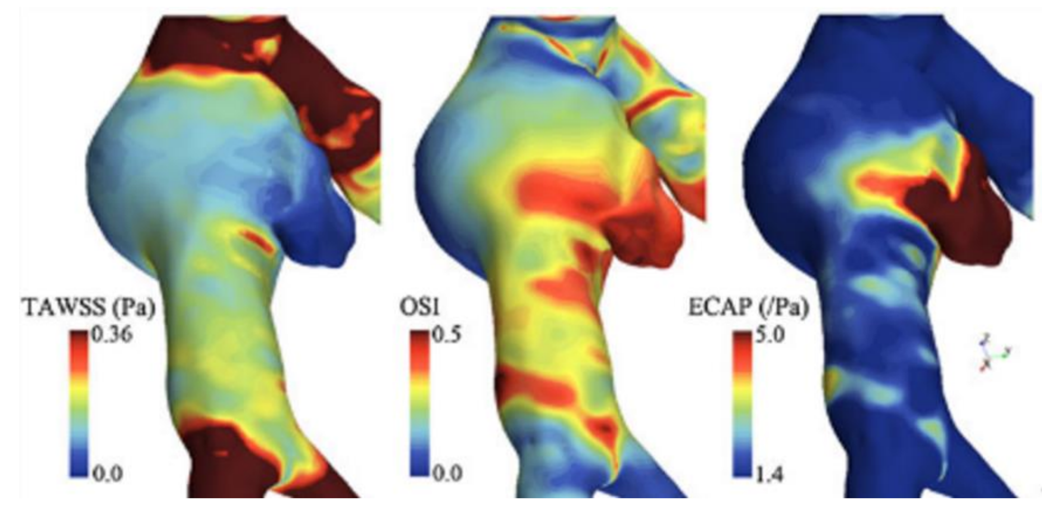
Important hemodynamic parameters are time averaged wall shear stress (TAWSS), oscillatory shear index (OSI), endothelial cell activation potential (ECAP) and the flow velocity profile in fluid domain. OSI is a measure defining the unidirectionality of shear stress which is sensitive to turbulence. ECAP is the ratio of OSI to TAWSS.

While the blood flow in normal aorta is mainly anterograde with high WSS, during AAA, circulatory flows emerge within the vessel. Hence, flow becomes disturbed with oscillatory characteristics leading to low WSS [1].

The increase in maximum aneurysm diameter leads to additional turbulence-induced stresses, and increased stresses result in increased diameter, which is a self-perpetuating mechanism for further dilatation.



Velocity profile in AAA [1]



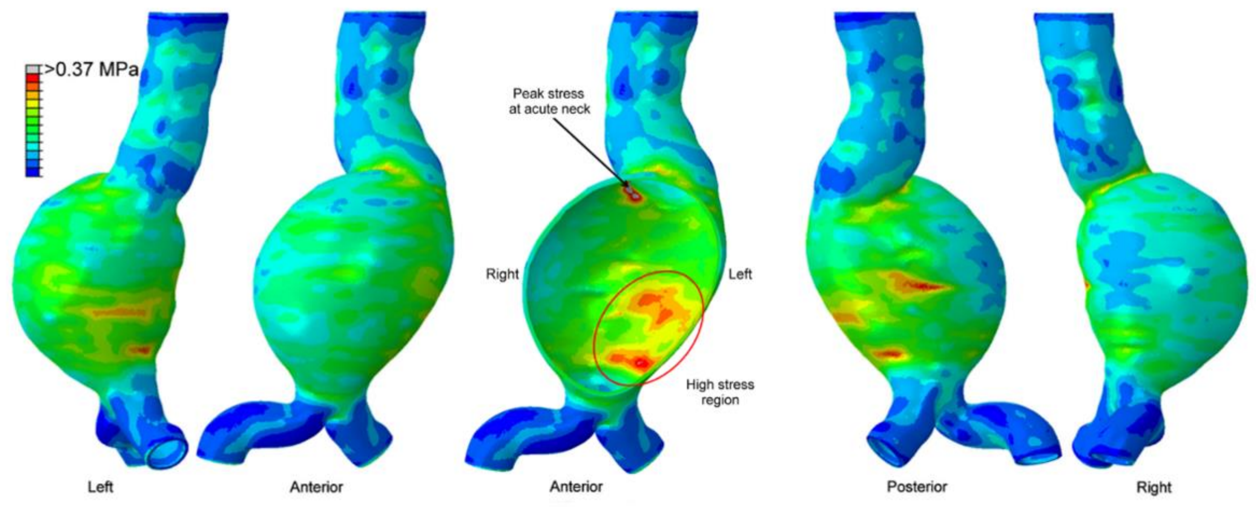
Disturbed hemodynamic parameters in AAA flow: TAWSS, OSI, ECAP [2]

The locations with low WSS, high OSI and high ECAP are prone to thrombus formation and have a higher risk of rupture [2].

The rupture sites are found to be near the fluid stagnation regions which have nearly zero WSS with high WSS gradients (WSSG).

In the aneurysm sac, rupture sites have WSS lower than 0.1 Pa, and no rupture occurs at the location with peak pressure or large pressure gradient.

To simulate deformation of AAA tissue under the effect of blood hemodynamics accurately, fluid-structure interaction (FSI) approach needs to be adapted. This is because of the strong interactions between flowing blood and vessel walls. Blood flow generates unsteady forces on vessel walls that causes deformation of the walls. These deformations in turn influence blood flow patterns.



Wall stress distribution on AAA performing FSI [3]

The peak wall stress on the posterior AAA wall is within the range of 290 to 450 kPa, while non-aneurysmal aorta has a peak stress around 120 kPa. The maximum wall stress is generally observed at the transition of sac to neck of AAA wall [3].

POTENTIAL DEVELOPMENT

For the current practice, when maximum AAA diameter exceeds 5-6 cm or diameter growth rate is higher than 1 cm per year, open surgery or endovascular treatment methods are performed considering the life expectancy of the patient. However, using the maximum AAA diameter alone as an indicator may not be accurate.

We aim to develop a predictive tool for the biomechanical assessment of AAA to identify the cases with high rupture risk. Wall stresses, OSI and WSS will be used as potential indicators in addition to the maximum AAA diameter through computational studies and experimental verification.

In the models, we will consider the intraluminal thrombus, plaque formation, varying arterial thickness, patient-specific boundary conditions and heterogeneous wall material properties to improve the accuracy of the biomechanical AAA assessment.

CONCLUSION

Disturbed flows or abnormal stresses are correlated with expected rupture locations, which helps to understand progression of the condition. Such an approach can also be used for generating predictive computational tools.

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[3] Doyle, B.J., McGloughlin, T.M., Miller, K., Powell, J.T., and Norman, P.E. (2014). Regions of High Wall Stress Can Predict the Future Location of Rupture of Abdominal Aortic Aneurysm. *Cardiovasc Inter Rad* 37(3), 815-818.