ACADEMIC RESEARCH

FREE PASSAGE

Simulation aids diagnosis and treatment planning for aortic coarctation.

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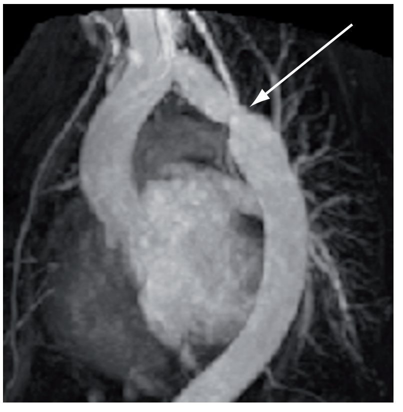
Aortic coarctation is a birth defect in which the aorta is narrowed, causing impaired blood flow to downstream blood vessels and organs. This narrowing of the aorta creates a flow jet with high velocity, inducing a very complex turbulent flow field. Since the aorta is narrowed, the left ventricle in the heart must generate a much higher pressure than normal to force enough blood through the aorta and deliver it to the lower part of the body. If the narrowing is severe, the left ventricle may not be strong enough to push blood through the coarctation, resulting in lack of blood to the lower half of the body. The severity of the coarctation before and after treatment is measured using a catheter to determine the blood pressure gradient across the coarctation.

Magnetic resonance imaging (MRI) is used to assess the flow field and estimate the turbulent kinetic energy (TKE), a direction-independent measure of turbulence intensity. But MRI can measure only the patient's existing condition, while the surgeon would like the ability to predict flow conditions that would result from potential interventions. MRI also provides only a very rough assessment of the flow field, while surgeons would prefer to have a much more detailed assessment for diagnosis and intervention planning.

USING CFD TO STUDY A COARCTATION

Researchers at Linköping University are addressing this challenge by using ANSYS CFX computational fluid dynamics (CFD) software to simulate the turbulent blood flow through an aortic coarctation both before and after surgical intervention. In a recent study, experimental data were obtained through MRI of a 63-year-old female patient with an aortic coarctation, both before and after balloon dilation, to increase the diameter of the coarctation.



MRI image of aortic coarctation

CAD model created from MRI image

The goal of the study was to resolve the flow features and to compare flow features and TKE in numerical simulations to MRI measurements.

Researchers uploaded the geometry of the aorta to a cardiac image analysis software package. This process provided a CAD representation of the inner aortic wall that, in turn, was used as the boundary for the fluid domain. The mesh size was about 7 million hexahedral cells with increased mesh density in the immediate region downstream of the coarctation, where the most turbulent structures were found. The researcher used velocity profiles measured by MRI as an inlet boundary condition in the ascending aorta, while he specified measured mass flow rates in the vessels leaving the aortic arch. A pressure boundary condition was set in the descending aorta.

TURBULENCE MODELING

In aortic coarctation, the flood flow can transition from a laminar to turbulent flow, which requires the use of turbulence models. The most common turbulence modeling approach involves the use of Reynolds-averaged Navier–Stokes (RANS) models that average the velocity field, pressure, density and temperature over time and make no attempt to model turbulent structures. This approach is limited in modeling aortic coarctation because it lacks the ability to determine the local impact of turbulence and to model the transition from laminar flow to turbulence.

Linköping University researchers used the large-eddy simulation (LES) turbulence model to predict the influence of turbulence as a function of time and resolve turbulent structures. LES models are usually several orders of magnitude more computationally expensive than the RANS approach. However, incorporating high-performance computer resources (where available) speeds up the computation and makes LES attractive.

The research team accessed the Triolith supercomputer at the National Supercomputer Centre (NSC) in Linköping, Sweden. A typical simulation used 160 compute cores on 10 compute nodes for about a week. Each node has two Intel E5-2660 (2.2 GHz Sandy Bridge) processors with eight cores each and 32 GB of RAM. The data written from the simulation exceeds 1 TB. It was found that 12 cardiac cycles were needed to ensure statistically convergent results.

CFD CORRELATES WELL WITH MEASUREMENTS

The fluctuations in turbulence measured by MRI and computed by CFD in the pre-intervention model agreed very well. The numerical model underestimated maximum TKE by 13 percent compared to MRI measurements. The maximum TKE difference between MRI and CFD was less than 8 percent during the systolic acceleration or build-up phase and less than 4 percent for the systolic deceleration or decay phase. Systolic refers to the contraction of the heart that occurs during each cardiac cycle and causes blood pressure to increase to its peak level. There was a 0.03-second time difference between measured and computed build-up slopes, while the decay slopes were almost identical.

The post-intervention model showed a decrease in TKE as a result of the increased coarctation diameter. The peak values differ between measurement and simulation by 1.5 millijoules and 0.06 seconds, and the buildup and decay slopes are not captured as well as in the pre-intervention case. The build-up slope of the CFD results was steeper than the MRI results, and the decay slope for the simulation agreed well in shape with the MRI result but was 0.03 seconds earlier. For both cases, the increase in TKE started just after peak flow rate with maximum values in the systolic deceleration phase. Turbulence levels were almost zero during systolic acceleration and peak systole, as acceleration tends to stabilize the flow. The simulation predicted a maximum value of 1,464 Pa, while the measurement was slightly lower with 1,315 Pa in the pre-intervention model. In the post-intervention model, the maximum values were 838 Pa and 723 Pa in CFD and MRI results, respectively.

Surgeons would like the ability to predict flow conditions that would result from potential interventions.

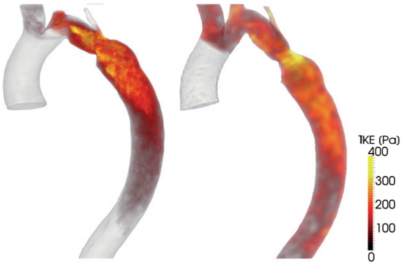
The CFD plots of TKE clearly show details that cannot be seen in the MRI measurements. Approximately 2,500 MRI volume elements or voxels were used in the MRI image, while about 3,185,000 mesh cells were used in the CFD model. The computational results show that the jet forming in the throat of the coarctation impinges on the distal arterial wall in the pre-intervention case. This could provide an explanation as to why some patients experience post-stenotic expansion or dilatation of the aorta directly past a coarctation.

The two totally independent methods used to obtain TKE values, CFD and MRI, agreed very well. This indicates that CFD predictions are reliable and reproducible. CFD has the advantage of predicting the outcome of an intervention prior to its being performed; it also provides much greater resolution than MRI measurements. So CFD might be used as a complement to traditional procedures when evaluating the outcome of an intervention. The numerical model can also provide insights and details about the flow field that are not visible in the much-coarser MRI measurements.

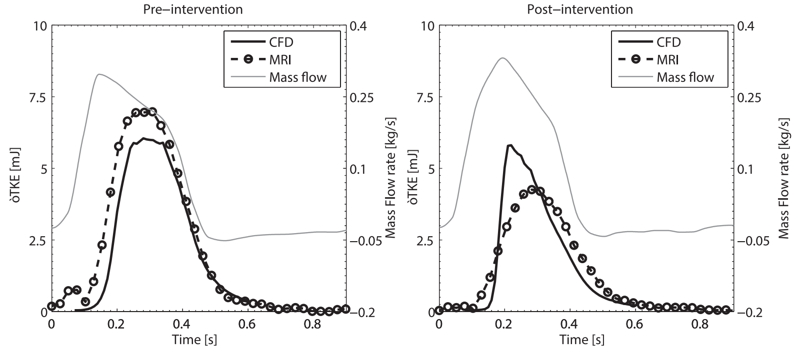
There is great interest from clinicians in this technology, especially in pressure estimations and flow quantification. However, there is still a fair amount of skepticism toward CFD as a result of the assumptions that are made, because many clinicians don't understand the theory, and because of the computing power that is required. As the technology continues to mature, there will be more and more CFD in clinical practice, and intervention planning, in particular, will become a reality.

	Cross section of coarctation (mm²)	Upstream blood pressure (mmHg)	Downstream blood pressure (mmHg)	Pressure drop (mmHg)	Cardiac output ascending aorta (L/min)	Cardiac output descending aorta (L/min)
Before intervention	106	135/44	113/37	22	4.5	3.1
After intervention	145	132/46	124/48	8	5.2	3.5

Measurements before and after treatment



Turbulent kinetic energy for both CFD simulation (left) and MRI (right). CFD results provide much more detailed information.



Pre- and post-intervention CFD results overlaid on MRI measurements

Reference

Lantz, J.; Ebbers, T.; Engvall, J.; Karlsson, M. Numerical and Experimental Assessment of Turbulent Kinetic Energy in an Aortic Coarctation. *Journal of Biomechanics*, **2013**, Vol. 46, pp. 1851–1858.