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Numerical and experimental assessment of turbulent kinetic energy in an aortic coarctation

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ABSTRACT

The turbulent blood flow through an aortic coarctation in a 63-year old female patient was studied experimentally using magnetic resonance imaging (MRI), and numerically using computational fluid dynamics (CFD), before and after catheter intervention. Turbulent kinetic energy (TKE) was computed in the numerical model using large eddy simulation and compared with direct *in vivo* MRI measurements. Despite the two totally different methods to obtain TKE values, both quantitative and qualitative results agreed very well. The results showed that even though both blood flow rate and Reynolds number increased after intervention, total turbulent kinetic energy levels decreased in the coarctation. Therefore, the use of the Reynolds number alone as a measure of turbulence in cardiovascular flows should be used with caution. Furthermore, the change in flow field and kinetic energy were assessed, and it was found that before intervention a jet formed in the throat of the coarctation, which impacted the arterial wall just downstream the constriction. After intervention the jet was significantly weaker and broke up almost immediately, presumably resulting in less stress on the wall. As there was a good agreement between measurements and numerical results (the increase and decrease of integrated TKE matched measurements almost perfectly while peak values differed by approximately 1 mJ), the CFD results confirmed the MRI measurements while at the same time providing high-resolution details about the flow. Thus, this preliminary study indicates that MR-based TKE measurements might be useful as a diagnostic tool when evaluating intervention outcome, while the detailed numerical results might be useful for further understanding of the flow for treatment planning.

1. Introduction

Aortic coarctation is a congenital disease where the aorta is narrowed, impairing blood flow to downstream blood vessels and organs. Pathologic features include cardiac hypertrophy and degenerative changes in the proximal aorta (Nichols et al., 2011), and increased blood pressure in the upper part of the body because of the small volume receiving the full stroke volume. The severity of the coarctation before as well as after intervention is usually estimated by a catheter measurement of the blood pressure gradient across the coarctation. The narrowing of the aorta creates a flow jet with high velocity, inducing a very complex turbulent flow field. It has been suggested that morbidity among patients with aortic coarctation can be explained by altered hemodynamics and vascular biomechanics (O'Rourke and Cartmill, 1971). Recently, researchers have characterized changes of hemodynamic parameters such as pulse blood pressure, aortic capacitance, and wall shear stress due to the presence of an aortic coarctation (Frydrychowicz et al., 2008; LaDisa et al., 2011a, 2011b; Coogan et al., 2012). Hemodynamic changes caused by the coarctation can result in endothelial dysfunction, dedifferentiation of arterial smooth muscle, and medial thickening (Menon et al., 2012).

In order to assess the flow, MRI (magnetic resonance imaging) measurements can give information of the flow field and it has recently been shown that it is possible to estimate the turbulent kinetic energy (TKE) using MRI (Dyverfeldt et al., 2008). Numerical modeling with computational fluid dynamics (CFD) can provide additional insights at a significantly higher resolution compared to MRI. Besides what-if scenarios and intervention planning, high-resolution details of the flow can be investigated as the resolution in CFD, in essence, is limited only by computer power. Accurate treatment of boundary conditions and turbulent flow must be considered to obtain reliable results.

In an aortic coarctation, the blood flow can transition from a well structured laminar state to a chaotic turbulent state, which is

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challenging to model. A common approach used in engineering applications is to use a RANS model (Reynolds-Averaged Navier–Stokes), where the effect of the turbulent fluctuations on the mean flow is modeled through different turbulence models. As noted by Yoganathan et al. (2005), RANS models are not the ideal choice for disturbed cardiovascular flows, but instead, a scale-resolving turbulence model such as large eddy simulation (LES) would be more suitable, due to its ability to resolve velocity fluctuations and to handle transition to turbulence. There have been a number of studies using LES on idealized blood vessels with a constriction (Mittal et al., 2003; Paul and Mamun Molla, 2009; Gårdhagen et al., 2010), and very good agreement compared to experimental results has been found, demonstrating the potential for modeling both physiological and pathological low-Reynolds number turbulent flows with LES.

Olivieri et al. (2011) computed steady flow in native and surgically repaired aortic arches in order to correlate hemodynamic indices with the incidence of late morbidity. They found that varying patterns of wall shear stress as a result from abnormal wall remodeling may be involved in clinical vascular dysfunction. The effect on cardiac work load when virtually removing a coarctation was investigated by Kim et al. (2009). They used a deformable wall with uniform properties throughout the domain, and a lumped parameter heart model to account for the changes in velocity and pressure before and after intervention. They found a reduction in the afterload on the left ventricle after intervention, as blood pressure levels decreased. Recently, Arzani et al. (2011) simulated the flow through an aortic coarctation with rigid walls using a second-order accurate “direct numerical simulation”, with the purpose of validating numerical predictions of TKE with *in vivo* MRI measurements. Their results showed a good agreement between measurements and numerical results, with a relative difference on the order of 10%.

In this study, the flow through an aortic coarctation in a 63-year old female was studied. Balloon dilatation without stenting was performed to increase the diameter and catheter measurements showed a decrease in pressure drop after intervention, with increased blood flow through the coarctation as a result. Therefore, two cases were studied using CFD: blood flow through the coarctation before and after intervention, from hereon denoted as pre- and post-intervention. The goal of the study was to resolve the flow features, and to compare the kinetic and turbulent kinetic energy obtained in the numerical simulations to MRI measurements. A long-term goal would be to use flow features derived from measurement techniques or numerical simulations, or a combination thereof, as an aid in diagnosis, evaluation and treatment planning of aortic coarctations.

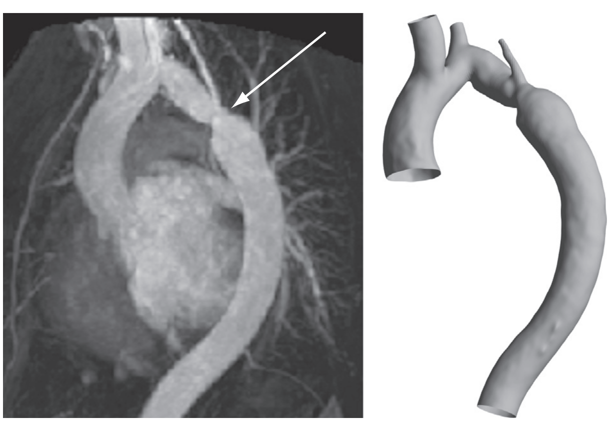

Fig. 1. *Left*: Maximum intensity projection (MIP) image of the heart and aorta. The white arrow indicate the location of the aortic coarctation. *Right*: CAD surface of the aortic geometry after intervention (notice that the vessel is still constricted).

2. Method

Here a short overview of the method is described; details on the CFD model and MRI acquisition are given in the supplementary materials. For CFD, the model included the ascending aorta, two arteries leaving the aortic arch, an artery leaving the aorta in the vicinity of the coarctation, and the descending and thoracic aorta, see Fig. 1. Geometry and inflow boundary profiles were obtained from MRI data. MRI was also used to directly measure the time-resolved velocity and TKE field in the 3D volume encompassing these vessels.

2.1. Numerical model

A scale-resolving turbulence model, LES, was employed to resolve the turbulent features in the flow. The WALE subgrid model was used to handle the turbulent scales smaller than the grid size, while the larger scales were resolved. Details on the turbulence model have been described in earlier work (Lantz and Karlsson, 2011). The simulations were carried out using ANSYS CFX 14.0. Velocity profiles measured by MRI were prescribed in the ascending aorta, providing physiologically accurate inlet boundary conditions, while measured mass flow rates were specified in the two vessels leaving the aortic arch. A pressure boundary condition was set in the descending aorta. The mesh sizes were on the order of 7 Million anisotropic hexahedral cells, with finer resolution near the walls and in the immediate post-stenotic region where most turbulent structures were found. Mesh independency tests and two-point correlations were carried out to ensure that the mesh resolution was fine enough, see supplementary materials for details. Phase averages of the velocity field were computed in the CFD simulation, and it was found that 12 cardiac cycles were needed to ensure statistically convergent results. A comparison between LES and simpler RANS turbulence models was performed, see the supplementary materials.

Using the Reynolds decomposition to decompose the velocity signal u into a mean $\overline{u}$ and a fluctuating component u', the amount of turbulent fluctuations can

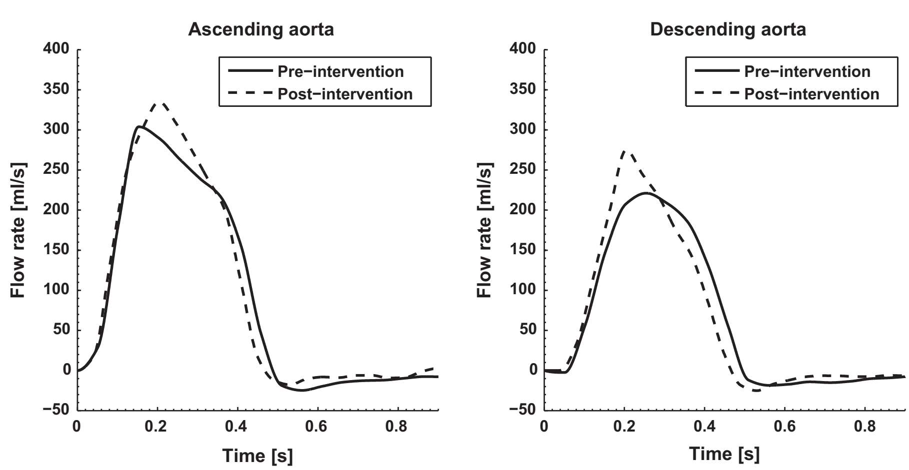

Fig. 2. Measured flow rates in the ascending and descending aorta before and after intervention. Notice how the peak flow rate increase after intervention.