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A new approach for the evaluation of the severity of coarctation of the aorta using Doppler velocity index and effective orifice area: *In vitro* validation and clinical implications

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ABSTRACT

Early detection and accurate estimation of COA severity are the most important predictors of successful long-term outcome. However, current clinical parameters used for the evaluation of the severity of COA have several limitations and are flow dependent. The objectives of this study are to evaluate the limitations of current existing parameters for the evaluation of the severity of coarctation of the aorta (COA) and suggest two new parameters: COA Doppler velocity index and COA effective orifice area. Three different severities of COAs were tested in a mock flow circulation model under various flow conditions and in the presence of normal and stenotic aortic valves. Catheter trans-COA pressure gradients and Doppler echocardiographic trans-COA pressure gradients were evaluated. COA Doppler velocity index was defined as the ratio of pre-COA to post-COA peak velocities measured by Doppler echocardiography. COA Doppler effective orifice area was determined using continuity equation. The results show that peak-to-peak trans-COA pressure gradient significantly increased with flow rate (from 83% to 85%). Peak Doppler pressure gradient also significantly increased with flow rate (80–85%). A stenotic or bicuspid aortic valve increased peak Doppler pressure gradient by 20–50% for a COA severity of 75%. Both COA Doppler velocity index and COA effective orifice area did not demonstrate significant flow dependence or dependence upon aortic valve condition. As a conclusion, COA Doppler velocity index and COA effective orifice area are flow independent and do not depend on aortic valve conditions. They can, then, more accurately predict the severity of COA.

1. Introduction

Coarctation of the aorta is a congenital heart disease characterized by narrowing of the isthmus zone, the section of the descending aorta distal to the left subclavian artery. COA is encountered in 0.1% of newborns (De Mey et al., 2001) and is the third most prevailing defect in infants and children (5–8% of all congenital heart disorders) (Rao, 1995). COA often coexists with aortic stenosis (AS) (between 30% and 50%) (Brickner et al., 2000; Braverman et al., 2005). Untreated COA, in adults, can result in serious complications such as left ventricular hypertrophy, rupture of the aorta and premature coronary artery disease.

The most important predictor of successful long-term outcome in patients with COA is age at time of initial repair (Cohen et al., 1989). Early detection and accurate estimation of COA severity are then of primary importance. However, arm-to-leg blood pressure difference may not accurately represent COA severity and may significantly change with flow rate (Araoz et al., 2003; Swan et al., 2003). Doppler echocardiography and MRI trans-coarctation pressure gradients (TCPGs) are also highly dependent on flow rate and on collateral blood supply (Steffens et al., 1994; Caravalho et al., 1990). Doppler echocardiography diastolic runoff, the magnitude of the antegrade diastolic flow, has also been suggested to evaluate the severity of COA. However, it is highly dependent on aortic compliance (DeGroff et al., 2003; Tacy et al., 1999). Invasively, catheter TPCGs are highly influenced by the flow rate and pressure recovery phenomena, and peak-to-peak pressure gradient also depends on compliant properties of the aorta (Kadem et al., 2006). Furthermore, using invasive cardiac catheterization might be problematic if multiple follow-up examinations after surgical repair are required knowing that recoarctation is a common occurrence (up to 40%)

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after COA repair (Araoz et al., 2003; Boxer et al., 1986; Parks et al., 1995).

In summary, the existing parameters to evaluate the severity of COA have significant limitations. It is, then, difficult to accurately compare different patients with different COA severities or a same patient between different follow ups. Therefore, there is a crucial need to introduce new parameters capable of accurately predicting the severity of COA and clinical outcomes. Our hypothesis is that a parameter like COA velocity index defined as the ratio between pre-COA velocity and COA jet velocity and defining a COA effective orifice area using continuity equation measured by Doppler echocardiography can accurately predict the severity of COA. In order to validate our hypothesis, an original in-vitro study was performed using a mock flow circulation model with different COA severities, and different aortic valve conditions under different total flow rates.

2. Methods

We designed and constructed a mock flow circulation model which consisted of a fluid reservoir, a gear pump, realistic elastic three-dimensional models of the aorta with out-of-plane curvature (including: ascending aorta, aortic branches and descending aorta), an adjustable systemic arterial resistance and compliance (Fig. 1). We fabricated elastic models of an aorta by using a multi-silicone layer method from an anatomically shaped mold reconstructed based on a data set obtained in an adult patient by magnetic resonance imaging. With the use of this technique, successive layers of silicone were applied on the mold until both radial dilatation of the proximal aorta and total arterial compliance (determined by the ratio of pulse arterial pressure over stroke volume) match physiological values. The elastic model of the aorta used in this study has a radial dilation of the proximal aorta of 8% (physiological value around 10% (O′Rourke et al., 2008; Herment et al., 2011)) and a total arterial compliance of 1.75 ml/mmHg (physiological value 1.84 ± 0.76 ml/mmHg (Chemla et al., 1998)). The aorta does not have tapering and its diameter is 29 ± 2 mm. In this study, COA was simulated in vitro using thin rigid circular orifices (with length of 4 ± 1 mm) correctly representing a discrete COA which is one of the most common configurations of COA (Stern et al., 1991). The fluid (a mixture of 60% water and 40% glycerol, dynamic viscosity of 4 cP) is pumped from an open tank (reservoir), crosses the model of the aortic valve (bioprosthetic valve or silicone models of bicuspid and tricuspid stenoses (Blais et al., 2006)) and directed towards the arterial module. Under normal conditions (no COA) a small portion of the total flow rate (15%) is directed towards aortic arch branches. However, when a COA is present, depending on its severity, a larger portion of the total flow rate bypasses the COA (forwarded towards the aortic branches and potential collaterals) (Markl et al., 2009; Hope et al., 2010). Including aortic arch branches is essential for the investigation of COA hemodynamics and represents a significant advantage compared to previous in vitro setups dedicated to COA (Seifert et al., 1999; De Mey et al., 2001). In this study, the proportion of the total flow directed towards aortic arch arteries was adjusted following a mathematical modeling of the flow through COA (Table 1) (Keshavarz-Motamed et al., 2011). Then, the flow in aortic arch arteries is redirected towards the main reservoir, while the flow in the descending aorta is directed towards the model of the arterial system. The compliance and the resistance of the systemic arterial system can be adjusted to ensure physiological aortic pressure waveforms. Instantaneous flow rates were measured by two electromagnetic flowmeters (Carolina Medical Electronics, East Bend, NC, USA, 600 series, accuracy of 1% full scale) at the level of the ascending aorta and aortic arch arteries.

The pressures in the left ventricle, aorta, upstream from the COA and downstream of COA were measured using Millar catheters (Millar Instruments, Houston, TX, USA, SPC 360S, accuracy 0.5% full scale) located 20 mm upstream of the valve, 20 mm downstream of the valve, 20 mm upstream of the COA and 20 mm downstream of COA, respectively. Pressure measurements were used to determine: peak-to-peak, mean and maximal catheter TCPGs.

Doppler echocardiographic measurements were performed using a HP Sonos 5500 ultrasound machine (Philips healthcare, Best, The Netherlands) with a probe of 2.5 MHz. The probe was positioned on the elastic aorta and the ultrasound beam was oriented towards the COA. Both pre-COA and post-COA instantaneous velocities were measured. The measurements were performed three times and averaged. Doppler echocardiographic measurements included mean ($TCPG_{mean}$) and maximal ($TCPG_{max}$) trans-COA pressure gradients using simplified energy equation (the unsteady flow component and the energy losses by turbulence and friction are neglected), with considering pre-COA velocity ($TCPG = 0.5\rho[V^2 - V_P^2] \equiv 4[V^2 - V_P^2]$) and without considering pre-COA velocity ($TCPG = 0.5\rho V^2 \equiv 4V^2$) (De Mey et al., 2001). Where V is the velocity at COA vena contracta, V_P is the velocity proximal to COA, ρ is the blood density and the number 4 (mmHg s^2/m^2) is obtained by replacement of the blood density and unit conversion from Pa to mmHg. COA Doppler velocity index was defined as $DVI|_{COA} = V_{max}|_{pre-COA} / V_{max}|_{post-COA}$; i.e., the ratio between upstream COA peak velocity (measured with pulsed-wave Doppler) and downstream COA peak

Table 1
Distribution of the flow rate directed toward aortic arch arteries and through COA for different severities of COA used in this study.

	Flow through COA (L/min)	Flow through aortic arch arteries (L/min)
COA 50%	70% of total flow rate	30% of total flow rate
COA 75%	60% of total flow rate	40% of total flow rate
COA 90%	45% of total flow rate	55% of total flow rate

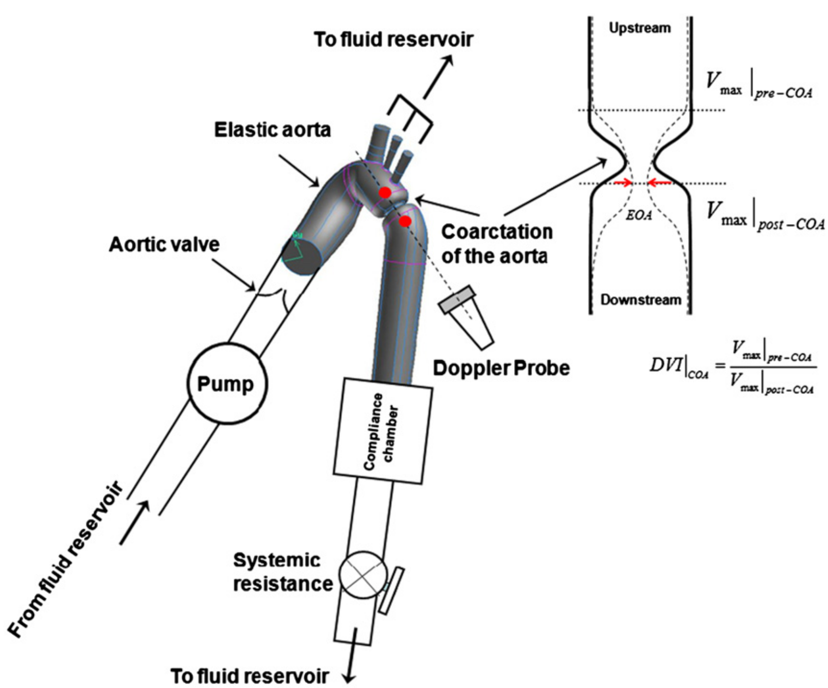

Fig. 1. Schematic diagram of the *in vitro* flow model.