A realistic MR compatible thoracic aortic phantom to study coarctations using catheterization and cine PC-MRI sequences

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Introduction: Aortic coarctations represent 5% to 7% of congenital heart disease. Surgery is indicated when a patient has a transcatheter systolic coarctation gradient of > 20 mm Hg[1], however a debate exist for gradients lower but closest to 20 mmHg. Echocardiography is the most available method to study hemodynamics parameters[2], however, is operator dependent, and pressures are over-estimated. Catheterization is the gold standard method[2], but is invasive, non-exempt of risk and patient is exposed to x-rays. Therefore, new methods need to be developed to obtain pressure gradients no invasively, however developing these methods from patient imaging data can be difficult to achieve. In this work, we have built a realistic thoracic aortic phantom MR compatible to simulate different grade of stenosis, which can be used to validate different hemodynamic parameters obtained from PC- MRI data under controlled experiments.

Methods: The phantom is a close circuit integrated by a MR compatible unit pump with a control unit (CardioFlow 5000 MR, Shelley Medical Imaging Technologies) and a realistic thoracic aortic model built with flexible silicone (T-S-N 005, Elastrat). Four non-return valves (Spears, USA) were installed in the ascending aorta (AAo), descending aorta (DAo), coronary arteries and in supra-aortic vessels. Additionally, shut off valves were added in the DAo, supra-aortic vessels, and in the coronaries to regulate the flow distribution between the different vessels. The liquid used in the system consist of a blood mimicking fluid homemade with 60% water and 40% glycerol (Orica Chemicals), which was contained in a 20 L tank. We built small pieces made of Technyl to simulate different aortic coarctation diameters, which were place in the DAo just after the aortic arch. Additionally, we equipped the system with a catheterization unit to measure invasive pressure along the coarctation. For this purpose, two catheters (5 French, 0.35 in, AngioDynamics) were placed 2 cms before and after the coarctation, which were connected to a patient monitor (Contec Medical System).

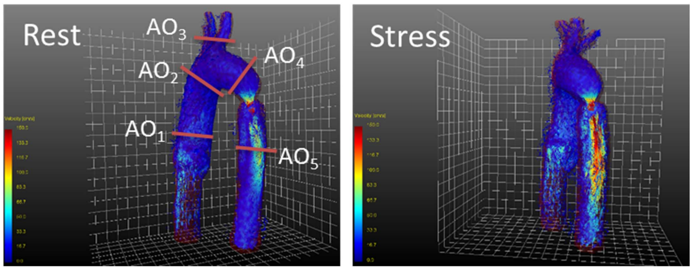

Figure 1: Pathlines are represented in the aortic phantom with the 9 mm coarctation along the cardiac cycle in both rest (left) and stress (right) conditions. Velocities (cm/s) are represented in a color scale (red are higher velocities and blue are slower

Experiments were performed on a 1.5 T MR-system (Achieva, Philips, Netherlands). Four different situations were studies: a phantom without and with a 9 mm aortic coarctation, and under rest and stress conditions. The rest and stress condition were achieved by changing the flow rate from 83 bps to 136 bps. For each situation we acquired a 2D and 3D PC-MRI of low and high resolutions (In this work parameters were analyzed with the low resolution acquisition). Parameters of the 3D PC-MRI acquisition were: spatial resolution of 0.89 x 0.89 x 0.89 mm3, temporal resolution: 40 ms and 20 ms for the rest and stress experiment. For the 2D PC-MRI the parameters were: spatial resolution of 0.6 x 0.6 x 8 mm3 and temporal resolution of 9.8 ms and 8.8 ms for the rest and stress condition. VENC was set to 250 cm/s and 550 cm/s for rest and stressed conditions. The 2D PC MRI were acquired in 5 section of the aorta (Figure 1), and the 3D PC MRI was acquired in the entire phantom. For each experiment we measured the maximum velocity, mean blood flow rate, systolic pressure gradient with the catheterization system and using the Bernoulli equation calculated using the maximum velocities obtained from 2D and 3D PC-MRI. Analyses were performed with commercial software GTFlow 2.0.10 (Gyrotools LCC). We tried to configure the shut off valves so that we always obtain a flow relation between supra-aortic vessels and descending aorta equal to 45%/55%.

Figure 2: Comparison of the net forward Flow (ml/s) between 4D and 2D at rest (left) and stress (right) conditions in the AO1(A and B) and AO5 (C and D) positions

Results: An example of pathlines using the 9 mm coarctation in normal and stress condition is depicted in Figure 1. In stress conditions, increased velocities are observed. Analysis of the flux curves showed an excellent agreement between 2D and 3D PC-MRI acquisitions (Figure 2). Analysis of the total net forward flow for the low spatial resolution images lead to mean difference values for the different sections between the 2D and 3D PC-MRI of 5.1 ± 8.3 ml/s for rest and 1.6 ± 3.0 ml/s for stress for the 9 mm coarctation case. Analysis of the pressure obtained with the catheters and using the simplified Bernoulli equation with maximum velocity obtained from 2D and 3D PC-MRI sequence is depicted in table 1. As can be seen pressure gradient are over-estimated respect to catheterization with the Bernoulli equation for the 2D and 3D PC-MRI but are closest for the latest case.

	Rest		Stress	
	AO4	AO5	AO4	AO5
Cat (mmHg)	134/12	129/7	156/59	136/38
Systolic gradient AO4-AO5	5		20	
Vmax 2D (cms/s)	0,34	2,08	0,48	3,5
Bernoulli 2D (mmHg)	12		36	
Vmax 4D (cms/s)	0,4	1,8	1,2	3,7
Bernoulli 4D (mmHg)	7,84		25	

Table 1: Pressures measured with catetherization and Bernoulli equation with 2D and 4D PC-MRI in both rest and stress conditions in the phantom with a 9 mm coarctation.

Discussion: Flux curves had an excellent agreement between 2D and 3D PC-MRI acquisitions, though, local values of net flow were slightly different, probably due to the different temporal resolution between 2D and 3D PC-MRI. Phantom had physiologic systolic pressure and positive diastolic pressure; however, the latest is still low respect to a physiologic diastolic pressure. In future experiment we will add a compliance chamber to regulate the diastolic pressure. In this work, we compared gradient pressures obtained from catheterization with values obtained by using the Bernoulli equation, which revealed an overestimated gradient pressure obtained from the 2D PC-MRI data and a closer value from 3D PC MRI. We will investigate if pressure gradient obtained by solving the Navier Stokes equation using 3D PC-MRI delivers values closer to the gold standards. The data generated with the proposed phantom is highly desirable to be used in to computational fluid dynamics, since we can perform controlled experiments and obtain images with high image quality.

Conclusion: We have shown that our thoracic aortic phantom is a realistic model with realistic physiological conditions, which can be used to validate physiological measurements obtain from 2D and 3D PC MRI in conditions like aortic coarctations under controlled experiments.

References: 1 Feltes TF, et al. Circulation, 2011. 2 Jurcut R et al. Journal of Medicine and Life 2011. Fondecyt-11100427, ACT-079 and VRI PUC.