PRESSURE GRADIENT PREDICTION IN AORTIC COARCTATION USING A COMPUTATIONAL-FLUID-DYNAMICS MODEL: Validation against invasive pressure catheterization at rest and pharmacological stress

Julio Sotelo[1,2], Israel Valverde[3,4], Philipp Beerbaum[5], Heynric B. Grotenhuis[6], Gerald Greil[7], Tobias Schaeffter[7], Reza Razavi[7], Daniel E. Hurtado[2], Sergio Uribe[1,8], and C. Alberto Figueroa[7,9]

[1]Biomedical Imaging Center, Electrical Engineering Department, Pontificia Universidad Catolica de Chile, Santiago, RM, Chile, [2]Structural and Geotechnical Engineering Departement, Pontificia Universidad Catolica de Chile, Santiago, RM, Chile, [3]Pediatric Cardiology Unit, Hospital Virgen del Rocio, Seville, Spain, [4]Cardiovascular Pathology Unit, Institute of Biomedicine of Seville (IBIS), Seville, Spain, [5]Hannover Medical University, Hannover, Niedersachsen, Germany, [6]Child Cardiology Department, Leiden University, Leiden, Netherlands, [7]Division of Imaging Sciences and Biomedical Engineering, King's College London, London, United Kingdom, [8]Radiology Department, School of Medicine, Pontificia Universidad Catolica de Chile, Santiago, Chile, [9]Department of Surgery and Biomedical Engineering, University of Michigan, Michigan, United States

Target audience: Cardiologist, Radiologist, Medical Physics, Biomedical Engineers.

Purpose: Aortic Coarctation (AoCo) accounts for 5-8% of the children with CHD[1]. Even after successful early repair, life expectancy is still markedly due to long term complications (hypertension)[2-4]. If the imaging diagnosis and ambulatory pressure are inconclusive, invasive diagnostic catheter investigations may be required to evaluate the pressure gradient across the aorta at rest[5], or unmask such a gradient by the use of isoprenaline to mimic physical exercise. The application of image-based computational fluid dynamics (CFD) in patients with AoCo appears promising as a non-invasive alternative diagnostic tool. The objective of this research is to know if a simple MRI based CFD model protocol can accurately predict the pressure gradient in patients with AoCo.

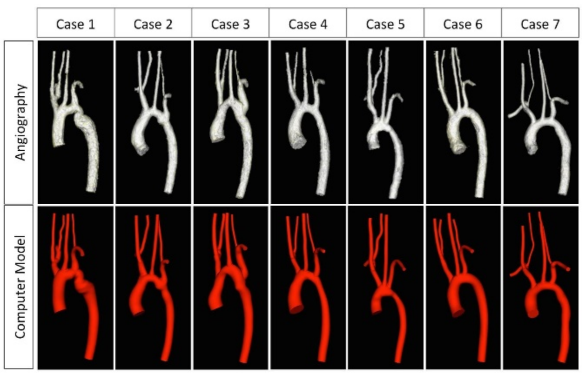

Fig. 1. Magnetic resonance angiography (first row) and solid models used for the CFD simulation (second row).

Methods: The study population included 7 cases with aortic coarctation (mean ± standard deviation; age 19.4±4.6 years, weight 71.9±17.1 kg), who had a previous combined MRI (CE-MRA and 2D CINE-PC) and cardiac catheterization study. The data were acquired in a 1.5T Intera MRI scanner and BT Pulsera cardiac radiography unit, Philips, Best, Netherlands.2D Cine-PC cardiac catheterization study was performed in rest and stress conditions. The 3D CE-MRA data was used to create geometric solid models of the aorta using the custom software SimVascular (simtk.org). The solid models were then discretized using a tetrahedral mesh generation program (MeshSim, Simmetrix, Clifton Park, NY). The 2D PC-MRI data at the level of ascending and diaphragmatic aorta were used to determine flow waveforms and distribution and to estimate the stiffness of the Aorta in these locations. The numerical method of SimVascular solves the Navier-Stokes equations for the flow of an incompressible Newtonian fluid within a deformable domain using a stabilized finite element formulation. Simulations were performed for rest and stress conditions. An average of 4-6 cardiac cycles were run for each case and the computational time oscillated between 24-48 hours for each simulation. We compared the mean (PG mean-mean) and peak to peak (PG peak-peak) value of the pressure gradient obtained between Catheter and CFD using Bland-Altman and Wilconxon Test.

Results: We have an average of PG mean-mean between all cases of 2.85±2.47mmHg for the catheterization and 2.76±1.64mmHg for the simulation. For the PG peak-peak, we have an average between all cases of 10.36±6.54mmHg for the catheterization and 9.77±6.39mmHg for the simulation. In stress conditions we obtained an average of PG mean-mean between all cases of 12.59±8.61mmHg for the catheterization and 11.25±7.60mmHg for the simulation. For the PG peak-peak, we have that the average between all cases of 52.71±22.11mmHg for the catheterization and 37.38±21.64mmHg for the simulation. The Wilcoxon test showed no significant difference between the catheterization and CFD for the PG mean-mean in rest and stress and PG peak-peak at rest, however we found a statistically significant difference when comparing the PG peak-peak at stress (p value of 0.018).

Discussion: The pressure gradients obtained at rest conditions were in good agreement with the ones obtained from catheterization. Additional simulations found that the systematic underestimation for the PG peak-peak pressure obtained from CFD at stress was due to an incorrect estimation of the stiffness distribution of our models.

Conclusion: In conclusion we can use a systematic method to predict non-invasively pressure gradients using CFD simulation based on cardiovascular MRI.

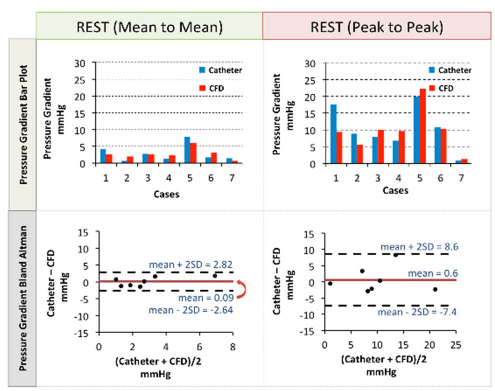

Fig. 2. Pressure gradients comparison between simulation CFD and Catheterization, for all cases in rest condition.

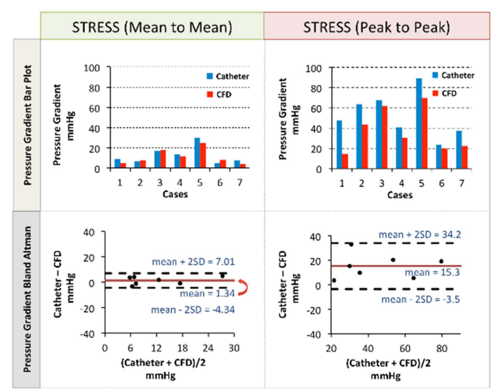

Fig. 3. Pressure gradients comparison between simulation CFD and Catheterization, for all cases in stress condition.

References: 1. Vriend JW and Mulder BJ. Int J Cardiol. 2005. 2. Toro-Salazar OH, et al. AM J Cardiol. 2002. 3. Giordano U, et al. Cardiol Young. 2009. 4. Gillett C, et al. Pediatr Cardiol, 2011. 5. Beekman RH. Coarctation of the aorta. In: Allen HD, et al. Philadelphia, Lippincott Williams & Wilkins, 2001.

Funding: The authors gratefully acknowledge support from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 307532. VRI # 44/2011 (Pontificia Universidad Católica de Chile), Anillo ACT 079 and FONDECYT #11100427 and #11121224. JS thanks CONICYT and Ministry of Education of Chile, with his higher education program, for scholarship for doctoral studies. Lastly, the authors acknowledge Simmetrix, Inc. (http://www.simmetrix.com/) for their MeshSim mesh generation library.