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

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INTRODUCTION: Current clinical assessment of borderline aortic coarctation may involve cardiovascular magnetic resonance (*CMR*) but if inconclusive, invasive catheterization pressure measurements are required to evaluate the pressure gradient at rest and during pharmacological stress (isoprenaline)[1].

PURPOSE: To predict the aortic pressure distribution in patients with aortic coarctation at rest and pharmacological stress using a transient rigid-walled computation fluid dynamics model (*RW-CFD*).

METHODS: The study cohort comprises 7 patients(age 19±3 years, *mean±standard deviation*) with native or recurrent aortic coarctation and 3 control patients(age 3±2 years) with healthy aortic arches, who underwent both CMR (1.5-Intera,Philips) and catheterization at rest and pharmacological stress. The model workflow (*Figure 1*) requires, as input parameters, the aortic geometry, extracted from a CMR 3D gadolinium contrast-enhanced sequence (TR=4.4ms,TE=1.8ms,1.5-1.8mm^3), and definition of the boundary conditions. The blood flow (modelled as a Newtonian incompressible fluid) in the aortic domain is conditioned by the clinical data at three locations as follows: **(*1) Ascending aortic root*:** The inlet flow is extracted from the phase-contrast CMR flow (TR=4.7ms,TE=3ms,2.5x2.5x7mm, temporal resolution 80 phases). **(2) *Supra-aortic vessels***: The flow rate is calculated as a proportion of the inlet flow based on the assumption of a constant wall shear stress[2] **(3) *Diaphragmatic aorta***: The pressure waveform is extracted from the invasive catheter data

The clinical, invasive, aortic pressure gradients were compared with the predicted pressure distribution along the centreline in the RW-CFD model at the time of peak flow (*Table 1*).

RESULTS: **For patients with aortic coarctation**, during pharmacological stress, there was an increase in both heart rate (68±22bpm) and invasive pressure gradient drop across the coarctation (38±18mmHg, *Table*). The RW-CFD model predicted accurately the pressure drop at rest -1±7 mmHg, *Figure 2*), and gave a moderate agreement at stress 16±46 mmHg. *Table, Figure 3*). **For healthy controls**, the RW-CFD model correctly predicted the absence of a significant gradient at both rest and stress (3±3mmHg).

CONCLUSION: For patients with aortic coarctation, the RW-CFD simulations accurately predict the pressure gradient at rest and give indication of the gradient severity during stress. Furthermore, no gradient was predicted in control patients with normal aortae. These preliminary results, whilst using a simple CFD approach and a small cohort of patients, are promising. This study represents the first step towards an image-based fluid-solid-interaction CFD analysis. This more sophisticated approach is likely to overcome the current limitations and might grant additional information.

In the future, it is envisaged that CFD models could be based on a patient-specific, non-invasive and non-ionising radiation assessment such as CMR in order to predict the hemodynamic conditions in the aorta and avoid invasive cardiac catheterization.

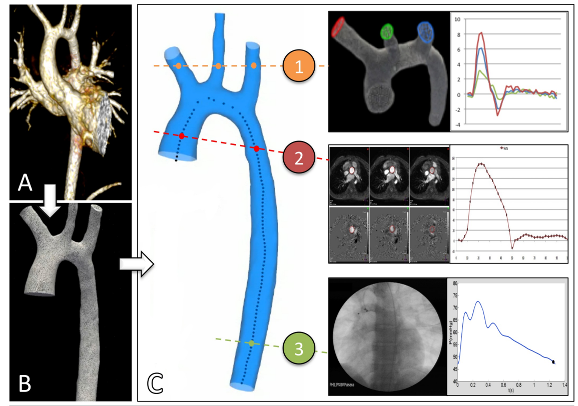

Figure 1. **Workflow to run the CFD simulation**. **A**. Contrast enhanced cardiovascular magnetic resonance (CMR) acquired to image the aortic arch. **B**. Extracted aortic geometry from the CMR dataset. **C**. Boundary condition setup in the three openings of the aortic geometry: 1) The applied flow rate is constructed as a proportion of the inlet flow in order to have a constant wall shear stress [l/min] 2) Phase-contrast CMR flow obtained in the ascending aorta [l/min]. 3) Catheter pressure measurements at the level of the diaphragmatic aorta [mmHg].

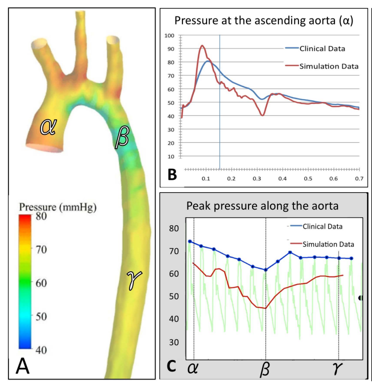

Figure 2. **CFD model results (AoCo-6). A.** CFD model pressure distribution at the instant of peak flow (vertical line) along the aorta: ascending aorta (α), aortic coarctation (β) and diaphragmatic aorta (γ). **B.** Pressure curve comparison over one cardiac cycle at the level of the ascending aorta (α), assessed by clinical catheterization invasive measurements (blue line) and simulated by the CFD model (red line). **C.** Peak pressure distribution comparison across the aortic centerline from the ascending (α) to the diaphragmatic aorta (γ), assessed by invasive catheter pullback (blue line) and simulated by the CFD model (red line). Note the pressure drop at the level of the coarctation (β) and posterior recovery. ***[Pressure expressed in mmHg]***

REFERENCES: [1]*Rosenthal E, Coarctation of the aorta from fetus to adult. Heart 2005;91:1495-1502.* [2]*Kundu, P.K. et al. Fluid mechanics. 4th ed. 2008.*

Study number	Heart rate [bpm]	ΔP Clinical [mmHg]	ΔP CFD [mmHg]	Difference in ΔP (CFD – Invasive) [mmHg]
REST CONDITION				
AoCo-1	48	23±3	22	**-1±3**
AoCo-2	86	18±3	5	**-13±3**
AoCo-3	69	12±4	9	**-2±4**
AoCo-4	81	10±2	8	**-2±2**
AoCo-5	60	20±2	31	**11±2**
AoCo-6	47	9±2	6	**-3±2**
AoCo-7	51	7±3	8	**1±3**
STRESS CONDITION				
AoCo-1	150	39±6	54	**18±6**
AoCo-2	136	40±10	23	**-17±10**
AoCo-3	130	64±6	42	**-22±6**
AoCo-4	140	66±4	44	**-22±4**
AoCo-5	102	52±7	78	**26±7**
AoCo-6	141	37±7	58	**21±7**
AoCo-7	119	69±7	179	**110**

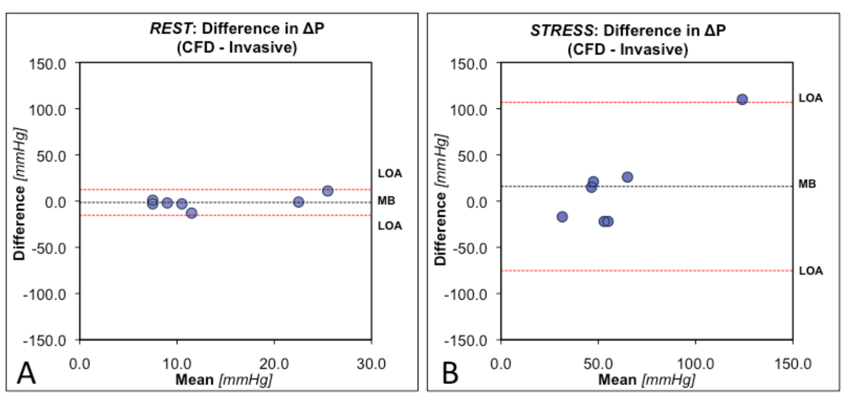

Figure 3. Bland-Altman plots: Comparison of the *clinically invasive* and the predicted *CFD* pressure gradient (mmHg) across the aortic coarctation at **rest** (**A**) and isoprenaline **pharmacological stress** (**B**). The dot-dashed grey horizontal lines represent the mean difference between CFD and invasive data (MB, mean bias), and the paired dotted red horizontal lines represent ±2 standard deviations from this mean difference (LOA, 95% limits of agreement). The CFD model predicts accurately the pressure drop at rest (excellent agreement, panel A) and gives indication of the severity during stress (fair agreement, panel B).