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A biomechanical insight into aortic root pathophysiology: Fluid-Structure Interaction (FSI) simulations based on MRI-derived geometries

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Background: the aortic root (AR) is the anatomic and functional unit that constitutes the proximal portion of the outflow tract of the left ventricle, including the aortic valve (AV). AR pathologies have high incidence and mortality and require surgical intervention; to this purpose, surgical techniques and devices are continuously developed. Bicuspid aortic valve (BAV) is the most common congenital cardiac anomaly affecting the AR and it usually results from the fusion of two out of the three AV leaflets. BAV alters AR hemodynamics and tissue stresses and, in more advanced pathological scenarios, it can be lethal, in that it is often associated with ascending aorta (AA) dissection.

Objective: numerical modeling can provide detailed and quantitative information on AR biomechanics, improving the understanding of AR physiology and allowing the analysis of clinically relevant problems. In particular, the quantification of the biomechanical alterations induced by BAVs may contribute elucidating the processes underlying the advancement of the pathological condition and the relation between BAV and AA dissection.

Methods: Fluid-structure interaction (FSI) modeling was used to characterize AR biomechanics through the cardiac cycle. Magnetic resonance imaging (MRI) was performed on 10 healthy subjects and 8 BAV-affected patients. Multiple long-axis and short axis cut-planes were acquired for the upper ventricular chamber, the AR and the AA. Geometrical parameters were manually measured, including AV commissures mutual position, Valsalva sinuses position and extent, sino-tubular junction (STJ) dimensions, and AA dimensions and spatial orientation. Averaged measurements values were used to define the corresponding 3-D geometrical models of AR and AA. The same constitutive models and boundary conditions were assumed for both models. AV tissues stress-strain response was described as non-linear, elastic and transversely isotropic, aortic wall response was modeled as linear, elastic and isotropic, and blood was assumed as a Newtonian, inviscid and nearly incompressible fluid. Both ends of the solid model were constrained with respect to translations. Physiological time-dependent blood pressures were applied at the inlet, i.e. the aorto-ventricular junction, and at the outlet, 25 mm distally from the STJ, of the fluid domain. FSI was simulated through a combined Lagrangian-Eulerian approach within the commercial software LS-DYNA.

Results: simulations highlighted the potential of the FSI modeling approach as a suitable tool both to assess AR physiological dynamics and to study fluid-dynamic abnormalities and structural alterations associated to BAV. As concerns the BAV model, in diastole the AV was continent, but leaflets coaptation line was shifted from the valvular orifice centerline, and a minor prolapse of the fused leaflets was observed. In systole, the valvular orifice was elliptic, 50

Conclusions: the adoption of an FSI approach allowed to capture the fast transient phenomena characterizing AV function and provided, with respect to a purely structural AR model, additional quantitative information regarding blood fluid dynamics. The BAV-affected model closely reproduced the asymmetric flow pattern found in vivo by MRI and the computed hemodynamic alterations were consistent with the AA region where the typical BAV-related complications preferentially develop.