3D large scale simulation of a stented aortic heart valve

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The pressure on top & bottom sides of leaflets forms thin boundary layer along the fixed edges (Fig. 4), while on the belly region it takes moderate values.

Numerical approximation
New numerical techniques are developed to alleviate reported difficulties [1] associated with the accuracy and the stability of calculations at high Reynolds number in three dimensions:

- open inflow/outflow boundary conditions
- second order time integration scheme with automatic adaptation of the time step
- discontinuous Lagrange multipliers for matching the meshes of leaflets and blood & regions with different discretizations (typically $10^6$ number of unknowns).

Introduction to the physical problem
The aortic heart valve (AHV) ensures unidirectional blood flow from the left ventricle to the aorta during the cardiac cycle (Fig. 1), while its proper function is essentially controlled by the surrounding hemodynamic environment (HE). Computational fluid dynamics (CFD) permit the Resolution of HE at the microscale, overcoming some of the inherent limitations of experimental techniques.

Objective of current work
To develop a new, efficient and robust finite element algorithm for the simulation of AHV, which can be used as:
- design tool for tissue engineering heart valves
- diagnostic tool for clinical applications

Physical model
Blood flows through a 3D stented AHV (Fig. 2) of mean diameter $w=24$ mm and total length $H=4w$, due to a time-varying pressure gradient. It also exhibits non-Newtonian behavior that is described with the Carreau-Yasuda model [2]. All leaflets are assumed to behave as incompressible neo-Hookean solids with constant density.

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Results
A global assessment of the blood-leaflets interaction is given in Fig. 3. The aortic leaflets move in response to blood flow. The opening procedure takes place in a symmetric manner, though the model is fully 3D.

Fig 1. A human heart and its semilunar valves

Fig 2. Schematic drawings of the model of the aortic valve

Fig 3. Snapshots from the deformation of the mesh due to the motion of the leaflets during the systolic phase

Fig 4. Distribution of the pressure on the aortic side of the leaflets during the systolic phase

Fig 5. Distribution of the streamwise ($v_x$), radial ($v_r$), azimuthal ($v_\theta$) velocity components and the pressure of the blood across the outlet of the aortic root (Fig. 2)

Conclusions
- A new fully 3D algorithm has been developed for the simulation of the motion of the leaflets of the aortic valve at nearly physiological conditions ($Re_{peak}=2,000$).
- For first time, the true rheological behavior of the blood is taken into consideration.

References