ABOUT THE EFFICIENCY OF THE INTRACARDIAC FLOWS: A COMPUTATIONAL STUDY OF THE MITRAL VALVE EFFECT

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Introduction

During each cardiac cycle, the left heart receives around 60 ml of fresh blood from the lungs and expels the same amount into the systemic circulation via the aorta. It is expected that the efficiency of this process is somehow linked to the normal/pathological evolution of the heart. Disturbances in the electrophysiological processes leading to muscle contraction can very likely induce energy loss, as can the way in which blood flows through the heart. For example, the well-organized vortex that develops in the left ventricle at end-diastole is believed to ease energy conservation and blood ejection during systole [1], whereas turbulence is a source of extra dissipation. The aim of this work is to quantify the extent to which the structure of the intraventricular flow impacts the amount of energy dissipated during each cardiac cycle.

Methods

The study relies heavily on the numerical strategy developed by Chnafa et al. [2], where a time-evolving 3D mesh consistent with the actual motion of the left heart is generated from medical images (CT Scan or MRI) using segmentation and registration algorithms. The mitral valve is modeled as proposed in [3] and its effect on flow is reproduced using an Immersed Boundary Method (IBM) [4]; a similar IBM is used to model the aortic valve as a simple planar object introduced during the diastolic phase to prevent blood backflow from the aorta. The resulting computational domain includes the four pulmonary veins, the left atrium and ventricle, the ascending aorta, in addition to the two valves mentioned above. The Navier-Stokes equations are then solved using an arbitrary Lagrangian-Eulerian framework as implemented in the widely validated YALES2BIO in-house solver [5], with an appropriate description of turbulence by Large Eddy Simulation [6].

For the patient-specific geometry of [2], four mitral valve (MV) geometries were considered to produce different types of intraventricular flow - see Table 1.

REF	Case A	Case B	Case C
Normal MV	Anterior jet deflection	Wider opening	Smaller opening

Table 1: Characteristics of the 4 MV considered.

Results

Phase-averaged velocity fields for the four cases considered are shown in Figure 1 to illustrate that flow structure is indeed strongly affected by mitral valve geometry. Compared with REF, Cases A to C clearly show the deflection, widening and restriction of the E-wave jet that fills the ventricle in mid-diastole.

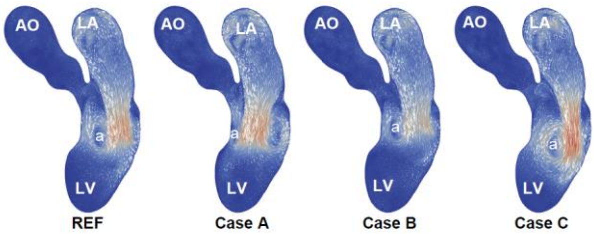

Fig. 1: Phase-averaged velocity at mid-diastole. Long-axis cut. LV: left ventricle; AO: Aorta; LA: Left atrium.

The phased-averaged viscous dissipation integrated over the ventricle is displayed in Figure 2; Case C is the least energy-efficient geometry, while jet deflection (case A) has virtually no effect, and jet widening (case B) significantly reduces energy losses.

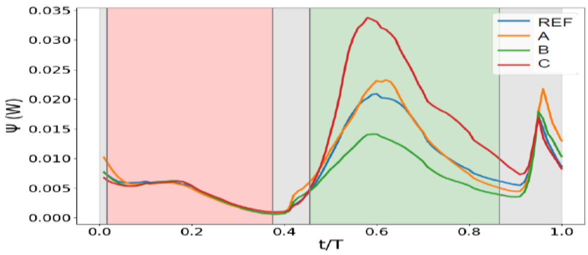

Fig. 2: Ventricle integrated viscous dissipation.

Discussion

According to the above results, intra-ventricular turbulent activity (closely related to viscous dissipation - not shown - and measurable by MRI [7]), is a good biomarker of mitral valve function. Still, integrating the curves in Fig. 2 over the cardiac cycle shows that the amount of energy dissipated (6.5 mJ for Case B; 11.5 mJ for Case C) is always a small fraction (< 2%) of the total energy expended by the ventricle. These results suggest that, in absence of regurgitation, cardiac efficiency is unaffected by mitral valve function.

References

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