Vortex formation and instability in the left ventricle

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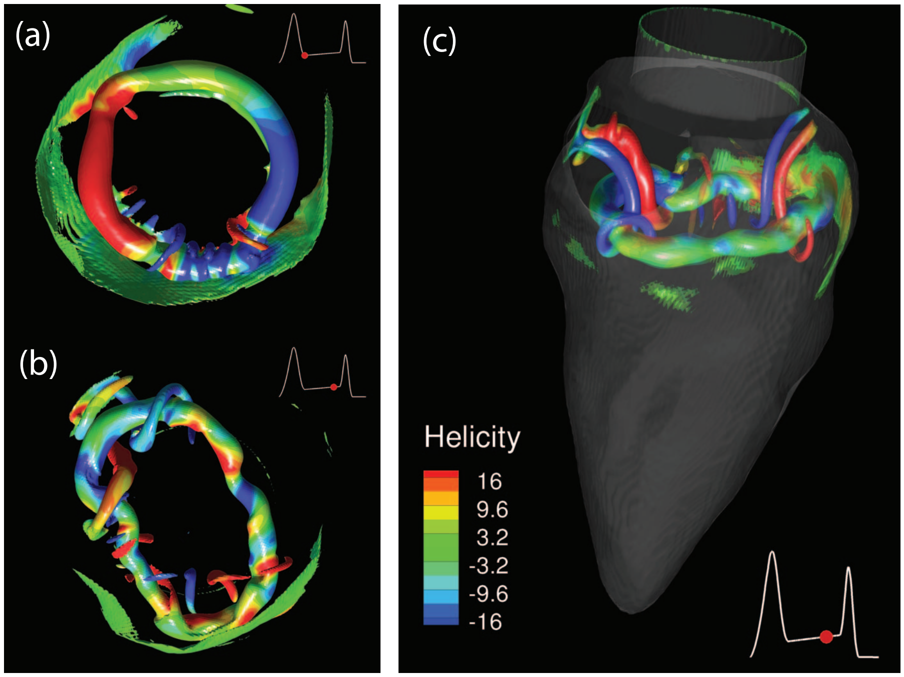

FIG. 1. The mitral vortex ring visualized by an iso-surface of vorticity magnitude colored by helicity density at two instants in time during diastolic filling. (a) and (b) show the vortical structures as viewed from the apex of the heart. (c) shows the anterior-posterior view of the vortex structure at the same instant in time as in (b). The red dot in the volume flow rate inset in each figure marks the corresponding time instant during the cardiac cycle.

Vortex formation and instability in the left ventricle

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We carry out high-resolution direct numerical simulation to investigate the vortex dynamics of the diastolic phase of blood flow in an anatomic left ventricle (LV) chamber at physiologic conditions. We reconstruct the anatomic left heart geometry from magnetic resonance imaging data of a healthy subject. The details of the LV kinematic model and the computational setup can be found in Le,[1] and Le and Sotiropoulos.[2]

In the Gallery of Fluid Motion video, we describe in detail the three-dimensional formation and subsequent instability of the mitral vortex ring, which is initially formed during early diastolic filling (E-wave). During the initial phase of the E-wave, the simulations reveal the existence of a well-defined vortex ring formed at the edge of the mitral orifice. After the E-wave, this vortex ring is fully formed and propagates toward the LV apex. The subsequent structure and fate of the ring is visualized in Fig. 1 in terms of an instantaneous iso-surface of vorticity magnitude colored with

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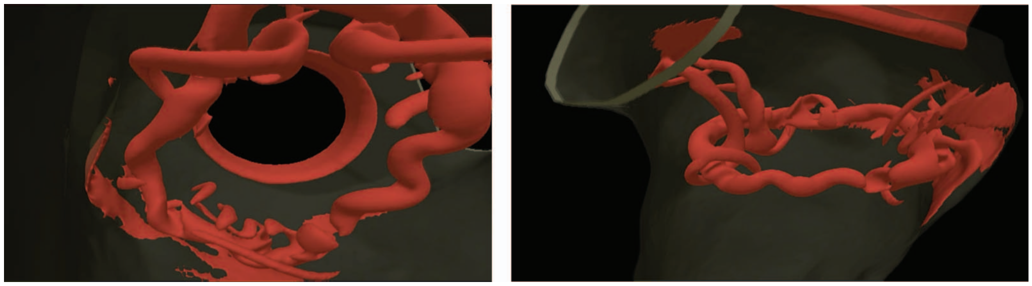

FIG. 2. Snapshots taken from a virtual reality visualization depicting the impingement of the mitral vortex ring on the left ventricular wall during late diastolic filling. The mitral vortex ring is visualized by an iso-surface of vorticity magnitude. Left: anterior/posterior view; Right: View from the apex of the heart. The video is recorded on the PowerWall of the Minnesota Supercomputing Institute (enhanced online) [URL: http://dx.doi.org/10.1063/1.4747164.1].

helicity contours. As seen in this figure, the initially circular ring becomes inclined and propagates toward the LV posterior wall. Vortex-wall interactions induce the formation of secondary vortex tubes, denoted as trailing vortex tubes, that grow from the wall and wrap around the primary ring. These trailing vortex tubes begin to interact with and destabilize the mitral vortex ring through complex twisting core instabilities, which are evident in Figs. 1(b), 1(c), and 2.

As the mitral vortex ring advances toward the apex, its initially circular shape (Fig. 1(a)) is deformed as it is strained laterally to acquire an elliptical shape as seen in Fig. 1(b). Both the twisting of the secondary vortex tubes around the ring's core as well as the growth of twisting instabilities along the ring's core intensify. At the end of diastole (see Fig. 2), the vortex ring impinges on the LV wall and begins to break down into small-scale structures. The dynamics of the mitral vortex ring uncovered by our simulations is broadly similar to the dynamics of vortex rings from inclined nozzles.[3] In both cases, the vortex evolution and subsequent breakdown is dominated by the growth of secondary vortex tubes due to wall-vortex and vortex-vortex interaction, the wrapping of these tubes around the core of the primary ring, and the growth of complex, twisting instability modes.[3]

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