

Transition to turbulence past bioprosthetic aortic valvesKaroline-Marie Bornemann¹ and Dominik Obrist²*ARTORG Center for Biomedical Engineering Research, University of Bern, Freiburgstrasse 3,
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The aortic valve is located between the left ventricle and the aorta. A healthy valve opens fully and closes tightly ensuring the pumping function of the heart. However, when the aortic valve is compromised, it may not open fully anymore. This pathological condition is called aortic stenosis and requires the replacement of the native valve with a valve prosthesis [1]. One possible surgical solution is bioprosthetic heart valves (BHV) which feature three flexible leaflets made of biological material. During the ejection phase of the heart, bioprosthetic aortic valves create turbulent flow which is suspected to negatively affect the valve's durability and performance [2–4]. Depending on their design, the valve leaflets may exhibit periodic oscillations—so-called leaflet fluttering—making this a complex fluid-structure interaction problem [5–8]. According to previous studies, leaflet fluttering could possibly accelerate structural valve deterioration as it imposes cyclic stresses on the biological leaflet material [9–11]. While it is known that leaflet fluttering enhances turbulence levels in the ascending aorta [12], the effect of leaflet fluttering on mechanisms of laminar-turbulent transition downstream of BHV is still poorly understood. Our contribution to the Gallery of Fluid Motion shows visualizations of the vortex development and breakdown past a fluttering and nonfluttering valve design and demonstrates the effect of leaflet fluttering on laminar-turbulent transition.

Both valve designs resemble surgical BHVs implanted in adult patients. The fluttering valve design follows the Intuity Elite (*Edwards Lifesciences*) BHV of size 21 mm. Its inherent oscillatory motion was investigated in previous studies [3,4]. As the Carpentier-Edwards PERIMOUNT Magna Ease (*Edwards Lifesciences*) BHV of size 21 mm showed nonfluttering behavior during systole in experimental studies of Ferrari and Obrist [13], we extracted its geometry via computed tomography (CT) scans. Both leaflet designs are modeled with a fiber-reinforced hyperelastic Holzapfel-Gasser-Ogden model and are inserted in a generic aortic root modeled according to Haj-Ali *et al.* [14] and Reul *et al.* [15].

A high-fidelity fluid-structure-interaction solver is used to simulate the interaction between blood flow and flexible leaflets. The fluid motion is modeled with a direct numerical simulation (DNS) approach [16] and coupled to the structural motion with a modified immersed boundary method (IBM) based on variational transfer [17].

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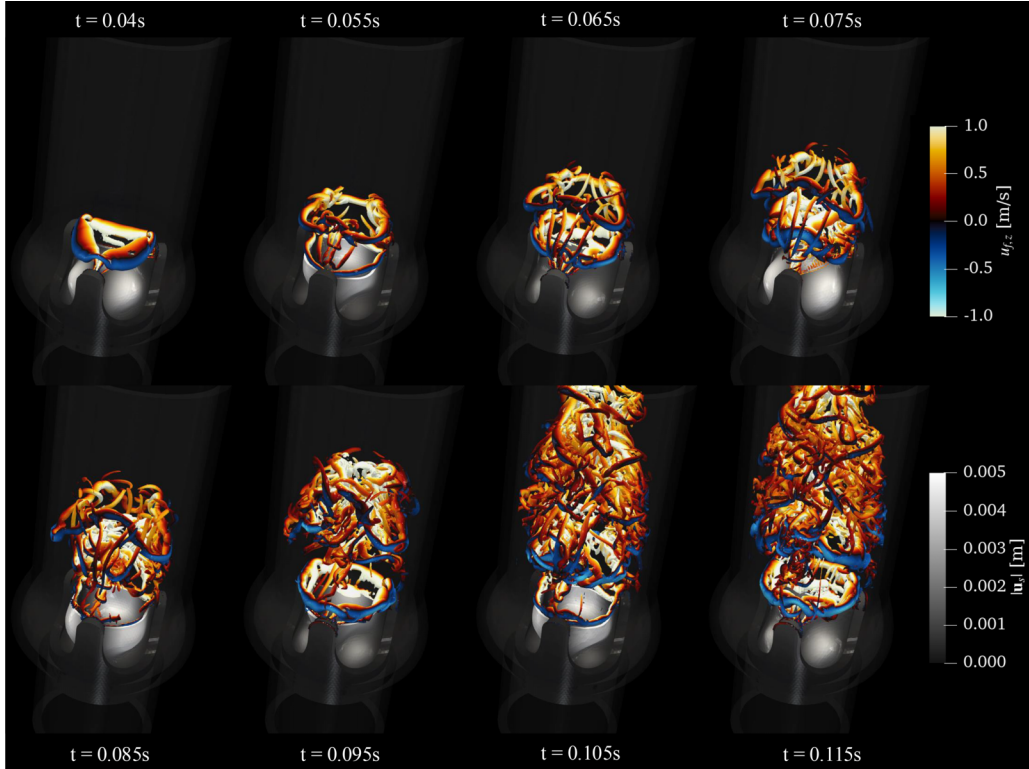


FIG. 1. Fluttering valve design: Vortex development and breakdown over time visualized by isosurfaces of the λ_2 criterion [18] colored in streamwise velocity component.

At the beginning of each cardiac cycle, the three valve leaflets start to open due to a pressure difference between the contracting left ventricle and the aorta. During this opening motion, a triangular starting vortex is formed. While the flow rate increases, the starting vortex is advected downstream and counter-rotating streamwise vortex pairs form above each valve post. When the starting vortex enters the ascending aorta, its axes deform downwards into a U shape. During this process, a second vortex is shed from the valve leaflets due to their oscillating motion. The second vortex travels faster than the starting vortex and passes through the streamwise vortices eventually causing the collapse of the latter. Meanwhile, the fluttering motion of the valve leaflets causes periodical vortex shedding at a frequency of 40 Hz. The complex interaction of starting vortex, periodically shed vortices, and counter-rotating streamwise vortices leads to the transition to turbulence of the flow downstream of the valve at approximately 0.1s after initial valve opening.

Figures 1 and 2 show the vortex development and breakdown past a fluttering valve design visualized by isosurfaces of the λ_2 criterion [18] colored in the streamwise velocity component. Caused by the oscillating leaflet motion displayed in Fig. 3, periodical vortex shedding plays an instrumental role in vortex breakdown.

But what happens to the transition to turbulence if the valve does not flutter? In Fig. 4, we see the leaflet motion of a nonfluttering valve design. After the initial valve opening, the leaflets remain in a stable open configuration. Figures 5 and 6 show the corresponding vortex development and breakdown visualized by isosurfaces of the λ_2 criterion [18] colored in the streamwise velocity component.

In contrast to the triangular starting vortex past a fluttering valve, the altered opening motion of the leaflets of the nonfluttering valve design creates a hexagonal starting vortex. Counter-rotating

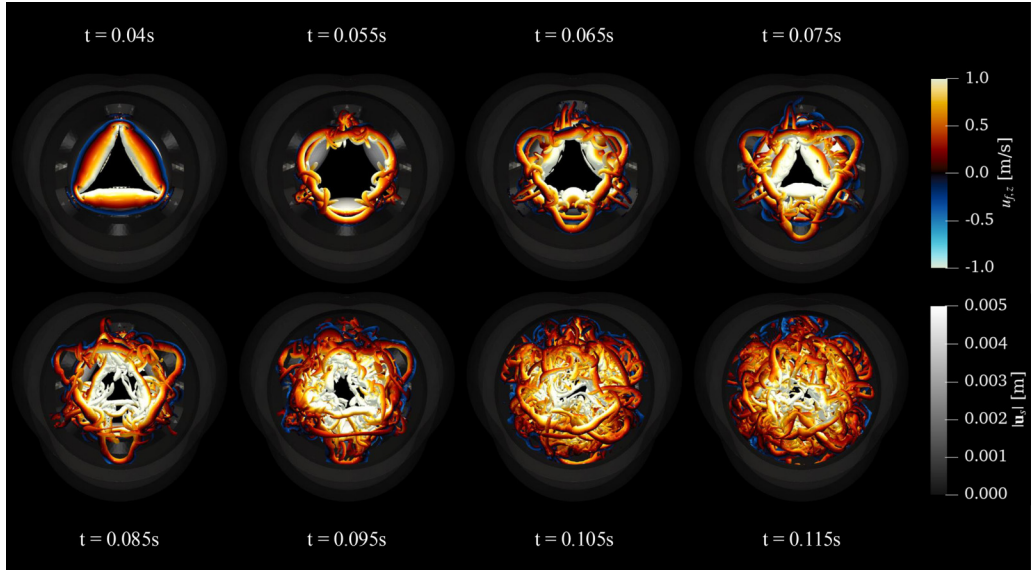


FIG. 2. Fluttering valve design: Vortex development and breakdown over time visualized by isosurfaces of the λ_2 criterion [18] colored in streamwise velocity component (top view).

streamwise vortex pairs are less pronounced. A second vortex is also shed for this design, however, due to flow separation at the nonfluttering leaflets. Also this second vortex travels faster than the starting vortex and passes through it. Afterwards, small-scale vortical structures due to flow separation enter the ascending aorta. Eventually, the flow field transitions to turbulence.

When we compare the vortex development and breakdown past a fluttering and nonfluttering valve design, we see that valve fluttering fundamentally changes mechanisms of laminar-turbulent transition. Valve fluttering leads to periodical vortex shedding coherent with the fluttering frequency of the flexible leaflets. In the absence of fluttering, small-scale vortical structures form due to flow separation at the trailing edge of the leaflets.

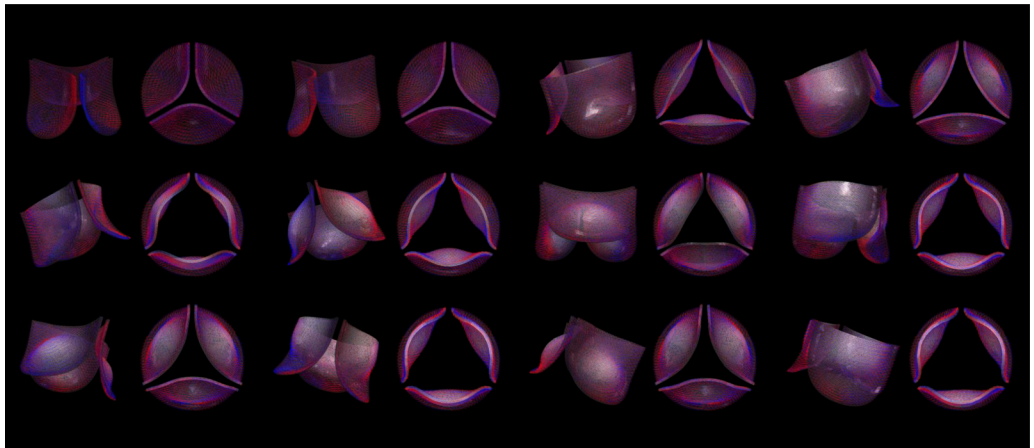


FIG. 3. Fluttering valve design: Side and top view on valve leaflet motion over time (top to bottom, left to right). The reinforcing fiber sets with a respective initial angle of 120° are colored in red and blue.

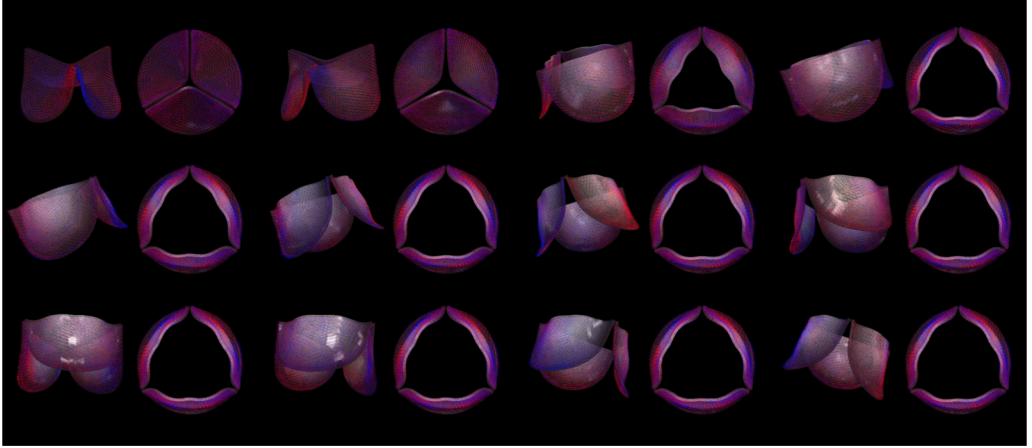


FIG. 4. Nonfluttering valve design: Side and top view on valve leaflet motion over time (top to bottom, left to right). The reinforcing fiber sets with a respective initial angle of 120° are colored in red and blue.

A comprehensive understanding of laminar-turbulent transition mechanisms related to leaflet kinematics contributes to the development of valves with improved design capable of mitigating adverse effects of turbulence.

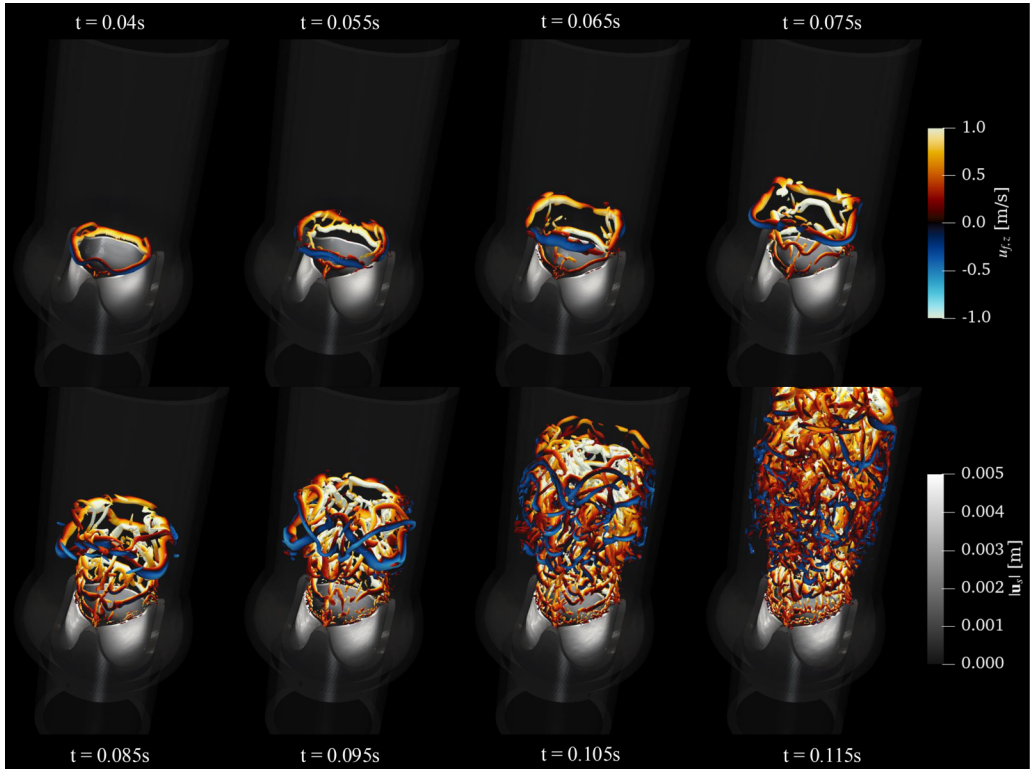


FIG. 5. Nonfluttering valve design: Vortex development and breakdown over time visualized by isosurfaces of the λ_2 criterion [18] colored in streamwise velocity component.

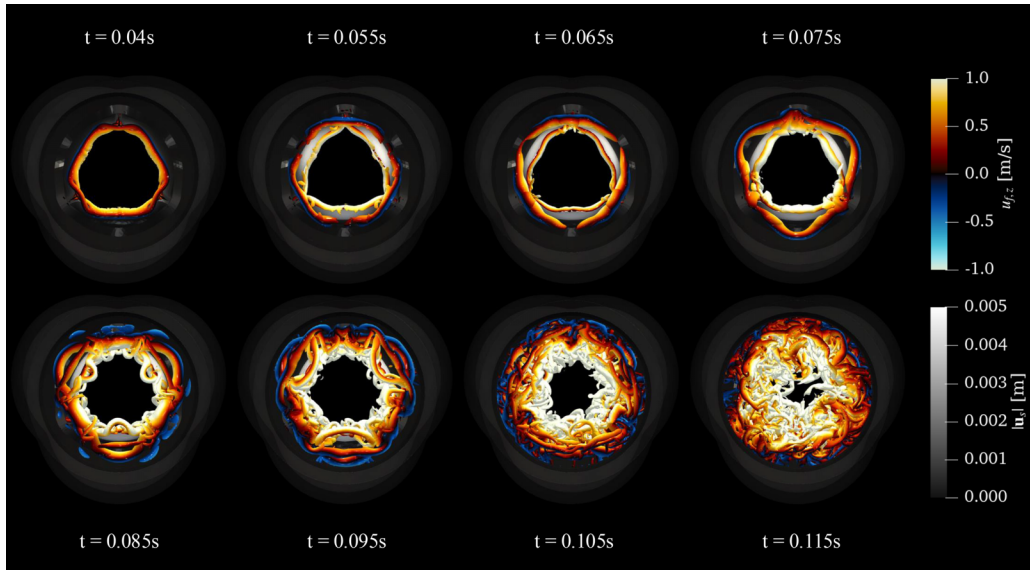


FIG. 6. Nonfluttering valve design: Vortex development and breakdown over time visualized by isosurfaces of the λ_2 criterion [18] colored in streamwise velocity component (top view).

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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