Transition to Turbulent Flow in Heart Valve Prostheses

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Introduction

Turbulent aortic flow has long been recognised as a symptom of aortic valve stenosis [1]. It is believed that turbulence is physiologically unfavourable in the aorta, as it correlates with elevated drag and shear stress levels. It can lead to endothelial dysfunction and blood trauma. Quantitative turbulent flow analysis, as the core concept of *in-vivo*, *in-vitro* and *in-silico* studies, can be directly used for valvular disease diagnosis and testing of existing prostheses. Understanding the transition process to turbulence in the aorta can further act as a cornerstone for the optimal design of aortic valve prostheses, in particular, for mechanical prostheses, for which, blood damage and coagulation are major limitations. Recent post-operative survey studies [2] report lower mortality rates and re-operation need for the recipients of mechanical prostheses, as compared to biologic ones. However, mechanical valves are connected with higher risks of post-operative trauma, such as bleeding and stroke. Preventing the turbulence in and past a mechanical prosthesis can reduce such adverse events, and offer a design with reliable performance and longevity.

Methods

Herein, we report our ongoing work on understanding the mechanisms of transition to turbulence in such prostheses. We resort to high-order direct numerical simulations (DNS) of systolic blood flow in the proximity of a bileaflet mechanical valve. In order to capture the unstable modes of blood motion and their interaction in the complex wall-bounded geometry of valve and sinuses, scale-resolving simulations (25 micrometer grid spacing) are performed on massive number of CPUs/GPUs of a Cray XC50 supercomputer (CSCS's Piz Daint).

Results and Discussion

DNS results have unveiled critical vortex shedding on the valve leaflets. It becomes evident only by ultra-high resolutions that there exists a stagnation point on the leaflet's thin leading attachment surface. (Figure 1). The significant transverse flow near the leading edge forms a vortex which elongates over the leaflet's inner side by gaining systolic momentum and eventually separates at a second stagnation point on the leaflet. Vortices are then shed and grow spatially as they move downstream. Such boundary layer modes then appear to interact with Burger vortices developing at the trailing edge of the leaflets. This interaction seems to trigger transition to turbulence. In contrast, the outer sides of the valve leaflets, feature stable Falkner-Skan type boundary layers. In order to study the critical inter-leaflet instabilities, linear stability theory is locally applied. Efforts are then made towards suppressing such unstable modes, predicted by hydrodynamic stability theory.

References

[1] Roberts, W.C., et al., 1971, *The American journal of cardiology*, *27*(5), pp.497-506.
[2] Goldstone, A.B., et al., 2017, *New England Journal of Medicine*, *377*(19), pp.1847-1857.