Simulating the hemodynamic environment in the zebrafish embryonic heart in four dimensions

Yoke Yin Foo*, Shuhao Shen, Huiping Shermaine Tay, Nurgul Imangali, Martin L Buist, Nanguang Chen, Christoph Winkler, Choon Hwai Yap

National University of Singapore, Singapore

Recent studies suggested that proper blood flow plays a pivotal role in the early stage of heart development and in congenital heart malformations, underlying the importance of understanding the fluid mechanical environment of the embryonic heart. This study aims to perform an in-depth study of fluid mechanics in several normal 5 days post-fertilization (dpf) zebrafish embryonic ventricles via image-based computational fluid dynamics (CFD) simulation.

Several embryos from a transgenic line, Tg(phiC31.attP.2A, -0.8myl7: EGFP), which marks the myocardium with GFP, were investigated. The embryonic hearts were imaged with a custom-built line-scanning focal-modulation microscope at 5 dpf. Dynamic-mesh CFD was performed in ANSYS via a mathematical model of ventricular wall motion.

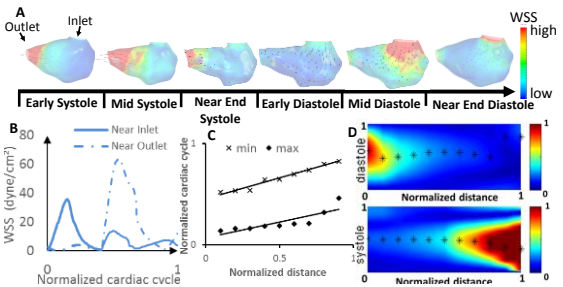

Figure 1. (A) WSS color contour over the cardiac cycle; (B) WSS and (C) Maximum and minimum cross-sectional areas plotted versus time. (D) Blood velocity averaged over the cross-section as a function of ventricular centerline distance (from inlet to outlet) and normalized cardiac phases. Asterisks mark peak velocity time points for a particular cross-section.

The zebrafish hearts exhibited a wave-like motion (Figure 1C), where systolic contraction and diastolic relaxation started near the inlet and spread like a wave to the outlet, a configuration that is shown to be flow energy efficient, but the absence of pressure and velocity waves (Figure 1D) rule out impedance pumping mechanism. Inflow velocities were higher near the inlet and smaller at the outlet, and vice-versa for outflow velocities. Consequently, wall shear stress (WSS) waveforms at the near inlet region were interestingly out of phase with those at the near outlet region. Large spatial variations of WSS was observed.

We characterized the fine details of fluid dynamics in the zebrafish embryonic heart at 5 dpf. Data serves as benchmark for disease model to be compared to. The embryonic ventricle exhibited energy efficient wave-like contractile motion and substantial spatial variability in WSS.