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MICROSCALE FLOW STRUCTURES MEASURED DOWNSTREAM OF A MECHANICAL HEART VALVE

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INTRODUCTION

A major goal in design of prosthetic mechanical heart valves (MHVs) and other implants is to reduce the risk of mechanically induced thrombosis and haemolysis [1,2]. Since blood damage is initiated at the cellular level, it is necessary to understand the structure of the flow field at very small scales. A large-scale model MHV has been developed to allow increased spatial and temporal resolution of in-vitro measurements with particle image velocimetry (PIV) [3]. This approach, along with appropriate data processing techniques, is used to determine the flow structures downstream of the valve at finer scales than was previously possible.

MATERIALS AND METHODS

The model is based on a St. Jude Medical bileaflet valve, scaled up by a factor of 5.8 to 140 mm diameter. The model valve is mounted in a transparent model of the aortic root, connected to a computer-controlled piston pump, programmed to reproduce realistic unsteady flow conditions.

Fluid dynamic similarity is assured by preserving the Reynolds number $Re = UD/\nu$ and Womersley number $\alpha = D/2(2\pi f/\nu)^{1/2}$, where ν is the kinematic viscosity of the fluid, U is the velocity, D is the diameter and f is the heartbeat frequency. In order to preserve these two parameters, with water as the working fluid, the time scale of the experiment is increased by a factor of 118. Space- and time-resolved velocity measurements were performed using PIV with a 1-megapixel CCD camera at a measurement rate of 15 Hz. The fluid is seeded with $10\text{ }\mu\text{m}$ particles and illuminated by 532 nm laser light sheet with a thickness of approximately $100\text{ }\mu\text{m}$.

The velocity field was measured in unsteady flow at peak a Reynolds number of 6200, keeping the leaflets in the fully open position. 650 velocity maps were collected for each cycle over several regions downstream of the valve. The scaling approach results in spatial resolution of $50\text{ }\mu\text{m}$ and temporal resolution of $570\text{ }\mu\text{s}$ in equivalent physiological scale. This resolution is unprecedented; recent state-of-the-art PIV measurements are at resolution of $135\text{ }\mu\text{m} / 67000\text{ }\mu\text{s}$ [1], $1200\text{ }\mu\text{m} / 333\text{ }\mu\text{s}$ [2] and $120\text{ }\mu\text{m} / 570\text{ }\mu\text{s}$ [3].

RESULTS AND DISCUSSION

The investigation focuses on the identification of flow patterns featuring intense and/or prolonged viscous stress. Shear stress was evaluated along

instantaneous streamlines and by Lagrangian tracking through the unsteady flow field. Fig. 1 shows an example of the viscous stress along a streamline in the wake of the leaflet tip at peak systole. All the quantities are reported in equivalent physiological scale. These measurements show that blood cells can experience exposure longer than 10 ms to shear stress above the threshold for platelet activation (5 Pa according to Kroll *et al.* [4]).

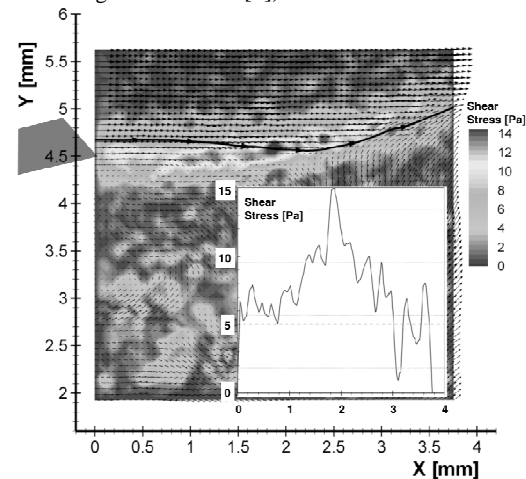


Fig. 1: Instantaneous shear stress along a streamline at systole peak. The gray shape on the left indicates the leaflet tip.

Eddy structures are identified using a wavelet analysis. Eddies start to develop across a range of scales (down to about $200\text{ }\mu\text{m}$) shortly before peak systole. The data indicate that the most intense shear stresses are associated to the structures located in the wake of the leaflet at the velocity peak.

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