In-vitro Turbulence Mapping in Prosthetic Heart Valves using Generalized Phase-Contrast MRI

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Introduction

Turbulence, characterized by velocity fluctuations, is a sign of suboptimal hemodynamics in prosthetic heart valves [1]. Turbulence causes pressure drops and exposes endothelial cells and blood constituents to abnormal stresses which can lead to blood trauma and promote the pathogenesis of atherosclerosis. Phase-contrast MRI (PC-MRI) has previously been shown to be valuable for the assessment of the mean velocity field around prosthetic heart valves [2]. In addition to mean velocity quantification by conventional velocity mapping, PC-MRI can be used to quantify turbulence intensity via intravoxel velocity standard deviation (IVSD) mapping [3]. In short, this is achieved by exploiting that the presence of multiple spin velocities within a voxel reduces the MR signal magnitude under the influence of a bipolar gradient. The aim of this in-vitro study is to apply PC-MRI turbulence measurements to common types of prosthetic heart valves.

Materials and Methods

Prosthetic valves with a diameter of 27 mm but with different effective orifice areas (EOA) were examined under steady flow conditions (12 L/min) in a Perspex phantom with an ovoid chamber downstream from the valve. A blood-mimicking fluid with a kinematic viscosity of 0.12 cm^2/s was used. Four valves were studied: Björk-Shiley Monostrut® (tilting-disc, EOA: 3.34 cm^2), St Jude Medical Standard® (bileaflet, EOA: 4.09 cm^2), Medtronic Mosaic® (stented, EOA: 2.81 cm^2), and Medtronic Freestyle® (stentless, EOA: 3.75 cm^2).

Three-directional, 3D PC-MRI measurements were made using a flow-compensated gradient-echo pulse sequence with interleaved three-directional flow-encoding on a clinical 1.5 T scanner (Philips Achieva, Philips Medical Systems, Best, the Netherlands). A flip angle of 15°, a voxel size of 2x2x2 mm^3 and three signal averages were used in all measurements. Additional imaging parameters are summarized in table 1. Velocity and IVSD data were acquired in separate scans with different settings of the velocity encoding range (VENC) parameter. For each voxel, the mean velocity vector was computed by conventional phase subtraction whereas the IVSD in three directions was obtained from the PC-MRI signal magnitude relationship [3]. The IVSD in three directions allows for the computation of the turbulent kinetic energy (TKE) [4], which is a direction-independent measure of turbulence intensity. The velocity data were corrected for concomitant gradient field effects and background phase errors.

Table 1. Imaging Parameters

Valve	VENC [m/s] (Vel/IVSD)*	TR [ms] (Vel/IVSD)*	TE [ms] (Vel/IVSD)*
Tilting-disc	140/90	5.9/6.2	3.3/3.6
Bileaflet	140/90	5.7/5.9	3.2/3.5
Stented	170/90	5.7/6.0	3.2/3.5
Stentless	140/90	5.7/6.0	3.2/3.5

Vel = mean velocity data acquisition
IVSD = turbulence data acquisition

Results

Mean velocity and turbulence data were acquired successfully in all four prosthetic valves (Figure 1). Jet-like flow emerged from the valve orifices. In general, elevated values of turbulence intensity were detected at the flow jets' periphery. The maximum values of TKE (in J/m^3) were 100, 115, 200 and 145 for the tilting-disc, bileaflet, stented, and stentless valves, respectively. The highest TKE value was associated with the valve with the smallest EOA.

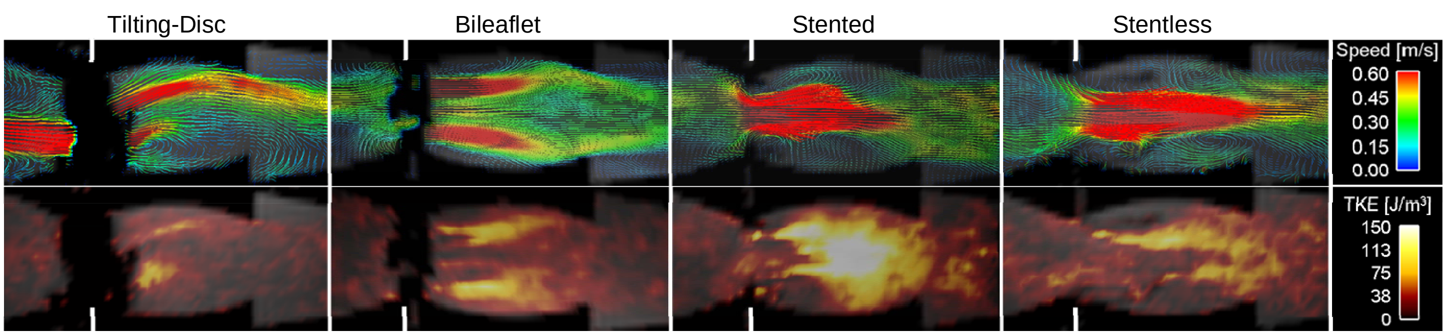

Figure 1. Flow, from left to right, across the four different prosthetic heart valves is shown. In the upper row, the mean velocity fields are visualized by streamlines, color-coded according to speed. In the lower row, turbulence maps color-coded according to turbulent kinetic energy (TKE) are shown. The white lines indicate the locations of the valves. Signal void caused by metal are seen the mechanical valves.

Discussion

We have successfully applied PC-MRI turbulence measurements to investigate in-vitro flow characteristics associated with common designs of prosthetic heart valves. Elevated values of turbulence intensity were present downstream from all valves. Distinct differences in the extent and degree of turbulence intensity, as well as in the mean velocity field, were observed between the different valve types.

This approach to the non-invasive assessment of turbulent flow has previously been shown to be feasible both in-vitro and in-vivo [3, 4]. It adds a new dimension to the hemodynamic evaluation of current and future prosthetic heart valves that may impact design, patient selection and implantation strategies.

References

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