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Post-stenotic plug-like jet with a vortex ring demonstrated by 4D flow MRI☆

Guk Bae Kim [a], Hojin Ha [b], Jihoon Kweon [a], Sang Joon Lee [c], Young-Hak Kim [d], Dong Hyun Yang [e,*,1], Namkug Kim [e,f,*,1]

[a] Biomedical Engineering Research Center, Asan Institute of Life Science, Asan Medical Center, Seoul, Republic of Korea
[b] POSTECH Biotech Center, Pohang University of Science and Technology, Pohang, Republic of Korea
[c] Department of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Republic of Korea
[d] Department of Cardiology, University of Ulsan College of Medicine, Asan Medical Center, Seoul, Republic of Korea
[e] Department of Radiology, University of Ulsan College of Medicine, Asan Medical Center, Seoul, Republic of Korea
[f] Department of Convergence Medicine, University of Ulsan College of Medicine, Asan Medical Center, Seoul, Republic of Korea

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ABSTRACT

Purpose: To investigate the details of the flow structure of a plug-like jet that had a vortex ring in pulsatile stenotic phantoms using 4D flow MRI.
Method: Pulsatile Newtonian flows in two stenotic phantoms with 50% and 75% reductions in area were scanned by 4D flow MRI. Blood analog working fluid was circulated via the stenotic phantom using a pulsatile pump at a constant pulsating frequency of 1 Hz. The velocity and vorticity fields of the plug-like jet with a vortex ring were quantitatively analyzed in the spatial and temporal domains.
Results: Pulsatile stenotic flow showed a plug-like jet at the specific stenotic degree of 50% in our pulsatile waveform design. This plug-like jet was found at the decelerating period in the post-stenotic region of 26.4 mm (1.2 D). It revealed a vortex ring structure with vorticity strength in the range of $\pm 100\ s^{-1}$.
Conclusion: We observed a plug-like jet with a vortex ring in pulsatile stenotic flow by *in vitro* visualization using 4D flow MRI. In this plug-like jet, the local fastest flow region occurred at the post-systole phase in the post-stenotic region, which was distinguishable from a typical stenotic jet flow at systole phase.

1. Introduction

Time-resolved, three-directional phase-contrast magnetic resonance imaging (PC-MRI), also known as '4D flow MRI', has been used to investigate various hemodynamic features in the heart and blood vessels [1,2]. This imaging technique has been successfully employed to visualize streamlines and pathlines based on time-resolved 3D velocity data at each voxel [3–5]. Several hemodynamic phenomena or indices quantitatively measured using 4D flow MRI have been introduced to aid diagnoses, including wall shear stress distribution on the blood vessel [1,6,7], a vortex of blood flow in the main pulmonary artery [8], and a vortex ring in the left ventricle [9]. Understanding flow-related physiology in normal and abnormal states is expected to provide additional insights into a range of cardiovascular diseases [10].

In our current study, we describe the flow structure of a 'vortex ring' that was separated from the main stream during the decelerating period of diastole phase in a post-stenotic area. Typically, a vortex ring has been observed in a jet or slug flow after ejection from a nozzle. The presence of a vortex ring structure in the ventricular flow has been detected when the left ventricle is filling as the blood 'jets' from the atrium through the mitral valve. A vortex ring in mitral inflow was initially recognized by *in vitro* visualization [11–13], and then was confirmed by analyses based on color Doppler mapping [14,15] and MRI [9,16,17].

Another generating mechanism of 'vortex ring' structure is found in stenotic flow. A pulsatile flow in stenotic vessel can make a vortex ring at the post-stenotic region during hydrodynamic deceleration at the post-systole phase [18,19]. This separation of hydrodynamic momentum from the main stream results in a locally faster velocity region, even at near diastole phase, which is briefly described by a 'plug-like jet' [18] (see 'b' in Fig. 3B). The plug-like jet has been recently introduced in studies of computational fluid dynamics, but it has not yet been investigated using clinical machines, such as MRI, and its clinical importance has not been fully established. In our present study, the hydrodynamic structure of a plug-like jet with a

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* Corresponding authors.
E-mail addresses: donghyun.yang@gmail.com (D.H. Yang), namkugkim@gmail.com (N. Kim).
[1] Equally contributed to this work.

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vortex ring was quantitatively measured by 4D flow MRI in two different stenotic phantoms, and then its clinical significance was discussed.

2. Methods

2.1. Phantom preparation

The experimental setup consisted of a container to equip a stenotic phantom, a pulsatile pump, and a reservoir (Fig. 1). We tested a pulsatile Newtonian flow in two stenotic phantoms with a 50% or 75% reduction in area, which were designed with consideration of the shape of a sinusoidal function [18]. For more accurate shaping, phantoms were manufactured using a 3D printer (ProJet 3510 SD, 3D Systems, Rock Hill, SC) with VisiJet Crystal, a rigid material (Fig. 2A). They had a circular cross-section with a 22 mm internal diameter (D) and a 440 mm length. We used a blood analog working fluid composed of a 40:60 glycerol and water mixture (by weight), which was previously described by Mann *et al.* [20]. The kinematic viscosity (v) of the working fluid was 3.85×10^{-6} m^2/s. A twin-pulsatile life support system (T-PLS®, New heartbio.BHK, Seoul, Korea) was used to circulate the working fluid via the stenotic phantom at a pulsating frequency of 1 Hz.

2.2. MR imaging

Image acquisition was performed on a 3 T scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany). The spatial resolution was $1.6 \times 1.6 \times 1.6$ mm^3, the number of phases per cycle was 46, and the velocity encoding ranges were 0–100 and 0–300 cm/s for the 50% and 75% stenoses, respectively. The details of the acquisition parameters are provided in Table 1. The phantom was located at the center of the scanner bore with a flow direction that was parallel to the magnetic field.

2.3. Vorticity, vortex ring, and flow characteristics

Based on data measured by 4D flow MRI, the vorticity of the plug-like jet could be quantitatively calculated. Vorticity ($\vec{\omega}$) was defined as the curl of the velocity vector and could be three-dimensionally expressed in Cartesian coordinates:

$$\vec{\omega} = \nabla \times \vec{v} = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) \times \left(v_x, v_y, v_z\right) = \left(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}, \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}, \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right)$$

From the velocity field of (v_x, v_z), the y-axis directional vorticity field of ω_y (Fig. 4D) can be acquired by:

$$\omega_y = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) \times \left(v_x, 0, v_z\right) = \left(\frac{\partial v_z}{\partial x} - \frac{\partial v_x}{\partial z}\right)$$

Based on the described vorticity definition, the hydrodynamic structures of vorticity fields were quantitatively analyzed using an in-house analysis tool (MATLAB, MathWorks, Natick, MA).

Regarding fluid mechanics, enlargement of a vessel in a post-stenotic region creates a larger vortex layer as a consequence of the velocity difference between the outer flow of the main stream and the fluid attached to the wall (see blue-colored arrows at systole phase in Fig. 4D). This emerging vorticity can be strained by the higher velocity of the main stream flow, so it enters into the flow as a compact vortex, even during the accelerating period. The subsequent decelerating momentum at diastole phase induces a plug-like jet, which creates a vortex ring structure as it is in harmony with the reverse flow in the vortex layer (see red-colored arrows at diastole phase in Fig. 4D). The generation of this structure depends upon the stenotic degree and pulsatile waveform.

From the pulsatile waveform of sectional average velocity (V_{avg}) measured at the pre-stenotic position of -1.5 D (Fig. 2B), the peak-to-mean flow ratio was 3.64, which could be in the range of

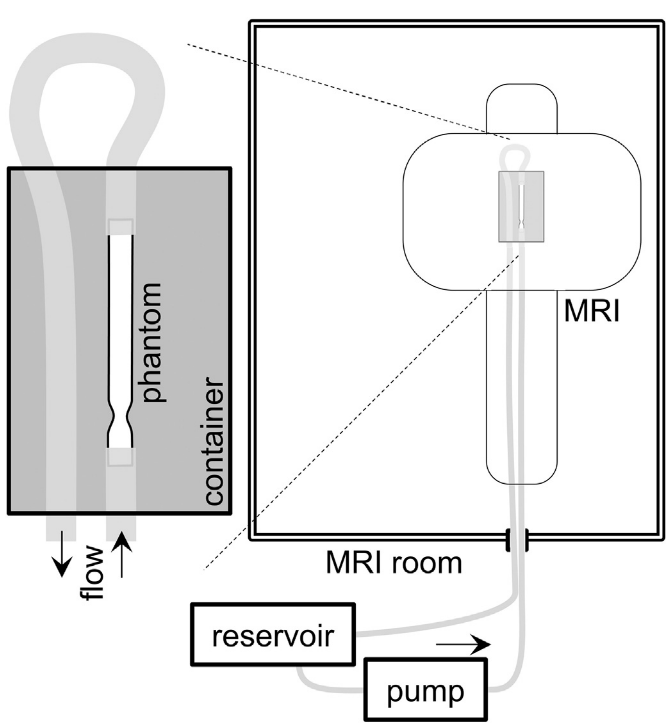

Fig. 1. Schematic representation of the experimental set up for investigating the pulsatile stenotic flow in phantom using 4D flow MRI.