Analysis of Wall Shear Stress for Patients with Pulmonary Arterial Hypertension by Phase-Contrast Magnetic Resonance Imaging

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Introduction: Pulmonary arterial hypertension (PAH) is a deadly disease with a high mortality rate of 20-40% within three years after identification of diagnosis. For PAH patients, both of vasoconstriction and vascular remodeling lead to a progressive increase in pulmonary vascular resistance (PVR) and in pulmonary arterial pressure (PAP) (1). Right heart catheterization (RHC) is usually used as a gold standard for hemodynamic assessments of PAH. However, invasive RHC method may not be feasible for long-term follow-up. In previous study, noninvasive phase-contrast magnetic resonance imaging (PC-MRI) has been used to derive several reliable hemodynamic parameters (2). In our previous study, a number of hemodynamic parameters have been proved to be able to differentiate patients with PAH from normal group (3). Statistically significant differences can be found in acceleration time (T_{acce}), maximal change in flow rate during ejection (max. dQ/dt), the ratio of max. dQ/dt to acceleration volume (V_{acce}), distensibility, and regurgitation fraction. Recent studies have also proposed that the condition of low shear stress (SS) can activate endothelial cells (ECs) to produce vasoconstrictor substances and to inhibit vasodilator substances and therefore may cause vasoconstriction (3, 4). As for PAH, chronically raised pulmonary blood flow causes abnormal endothelial shear stress and results in a progressive pulmonary vasculopathy with smooth muscle hypertrophy (6). However, up to our best knowledge, a study to systemically investigate wall shear stress (WSS) on PAH patients is still deficient. Accordingly, the purpose of this study is to investigate WSS in pulmonary arteries of PAH group by noninvasive PC-MRI. In addition, the index of oscillatory shear index (OSI), representing the temporal oscillation of WSS during the cardiac cycle (7) will be evaluated as well.

Methods: The study population consisted of 13 PAH patients (age: 42 ± 17 y/o; male: 6; female: 7) and 12 normal subjects without history of pulmonary disease (age: 39 ± 9 y/o; male: 5; female: 7). The PC-MRI was performed on a 1.5T clinical imager (Siemens Sonata, Erlangen, Germany) using the torso coil with prospective ECG triggering. A 2D FLASH sequence (TR/TE=22/4.8ms, flip angle=15°) with 150 cm/sec velocity-encoding gradient was acquired, sampling 90% of the cardiac cycle. Magnitude images and phase images were obtained at main pulmonary artery (MPA), right pulmonary artery (RPA) and left pulmonary artery (LPA). The regions of interest (ROIs) of cross-sections of pulmonary arteries were selected manually on magnitude images and were applied to phase images for calculation of flow velocity.

The general form of the WSS ($\vec{\tau}$) is: $\vec{\tau} = \eta \frac{\partial v}{\partial h}$, with η :viscosity, v: the velocity, and h:the height of the boundary. The definition of OSI is: $OSI = \frac{1}{2}(1 - \frac{\left| \int_0^T \vec{\tau} \cdot dt \right|}{\int_0^T |\vec{\tau}| \cdot dt})$, where T is the duration of the cardiac cycle, and $\vec{\tau}$ is the instantaneous WSS vector (7). In this study, WSS and OSI were calculated by home-developed analyzing program with usage of MATLAB (7).

Results: Figure 1 showed the time courses of mean WSS for two groups at each pulmonary arterial location. PAH patients exhibited significantly reduced WSS at MPA, RPA and LPA. The mean values of WSS and OSI during the entire time courses were shown in Fig. 2. The mean WSS at MPA of PAH group was 0.23 ± 0.07 (N/m^2), distinctly smaller than that obtained from normal subjects (0.28±0.04 N/m^2, $p<0.05$). The tendency could be observed in RPA and LPA as well ($p<0.05$ and $p<0.01$, respectively). Moreover, PAH patients revealed substantial higher OSI than that of normal subjects in locations of RPA (10.16±3.98 % and 16.47±8.57 %, $p<0.05$) and LPA (15.26±4.28 % and 21.42±8.81 %, $p<0.05$). Table1 summarized the mean values with standard deviations of WSS and OSI at locations of MPA, RPA, and LPA for normal subjects and PAH patients. To realize the circumferential variations of WSS of 12 segments for each vessel plane, the maximal and minimal WSS at each cardiac phase were measured. Figure 3 showed that the normal subject exhibited higher variations than that of PAH at MPA.

Discussion & Conclusion: In this study, WSS and OSI were evaluated to demonstrate hemodynamic changes for PAH patients. According to previous studies, lower SS may lead to vasoconstriction (3, 4). The manifest reduced values of WSS, derived from noninvasive PC-MRI images, reflected the characterizing vasoconstriction in PAH group which is consistent with previous studies. Besides, PAH group showed lower maximal WSS during the cardiac cycle, indicating the diminished velocity gradient resulted from serious turbulent flows. PAH exhibited lower circumferential variations of WSS at MPA (Fig. 3). This phenomenon revealed disordered flow profiles and thus less asymmetry were shown. Moreover, PAH patients displayed increased OSI at RPA and LPA, implying remarkable oscillation of WSS at these vascular locations. In conclusion, WSS and OSI provided satisfied information to help differentiate PAH patients from normal subjects.

References:

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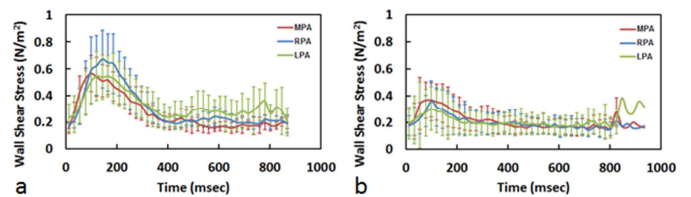
Fig. 1. The time courses of mean WSS in MPA, RPA, and LPA for 12 normal subjects (a) and 13 PAH (b).Significant decreases of WSS were shown in PAH group.
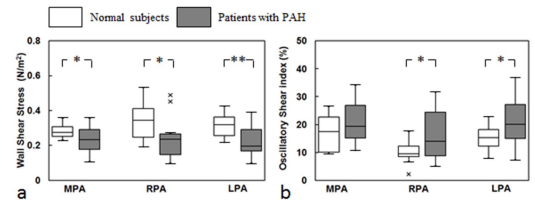

Fig. 2. The parameters of WSS (a) and OSI (b) showed statistically significant differences between normal subjects (white box) and PAH patients (gray box). *$p<0.05$, **$p<0.01$.

Table1. Hemodynamic parameters

Parameter	Location	Normal subjects (N=12)	Patients with PAH (N=13)	p-value
WSS (N/m^2)	MPA	0.28±0.04	0.23±0.07	0.015*
	RPA	0.33±0.11	0.23±0.11	0.011*
	LPA	0.32±0.06	0.22±0.08	0.002**
OSI (%)	MPA	16.62±6.43	21.12±7.14	0.055
	RPA	10.16±3.98	16.47±8.57	0.014*
	LPA	15.26±4.28	21.42±8.81	0.019*

Values are mean±SD. WSS: wall shear stress; OSI: oscillatory shear index; MPA: main pulmonary artery; RPA: right pulmonary artery; LPA: left pulmonary artery; PAH: pulmonary arterial hypertension; Statistic significance: *$p<0.05$, **$p<0.01$.
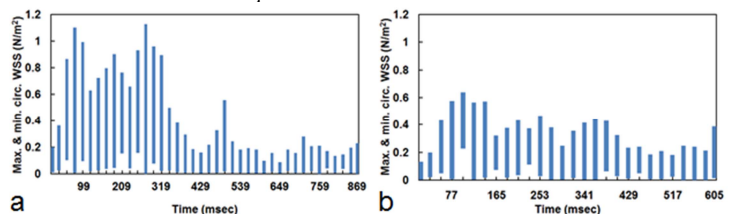

Fig. 3. The maximal (top of bar) and minimal (bottom of bar) WSS showed the circumferential variations of WSS of 12 segments at MPA. (a) A 32 y/o female normal subject. (b) A 32 y/o female patients with PAH.