In Vivo Blood Flow Characteristics in the Proximal Pulmonary Arteries of Healthy Children and Adults at Seated Rest and During Cycling Exercise

C. P. Cheng[1], R. J. Herfkens[2], C. A. Taylor[1,3], J. A. Feinstein[4]

[1]Mechanical Engineering, Stanford University, Stanford, CA, United States, [2]Radiology, Stanford University, Stanford, CA, United States, [3]Surgery, Stanford University, Stanford, CA, United States, [4]Pediatrics, Stanford University, Stanford, CA, United States

Introduction

Diseases that involve pulmonary artery blood flow, such as congenital heart anomalies or acquired pulmonary vascular disease, can negatively influence the right ventricular workload, ventilation-perfusion matching, and cause significant morbidity and mortality. Furthermore, states of physiologic stress, such as physical exercise, may amplify abnormalities that exist at rest. For example, abnormalities of the right ventricular outflow tract and pulmonary valve (e.g. tetralogy of Fallot) likely alter how pulmonary blood flow and pulmonary regurgitation change with the stress of exercise [1]. In order to better detect abnormalities in pulmonary artery blood flow in patients, we must first understand the pulmonary flow characteristics in healthy subjects at rest and during dynamic exercise.

Methods

Seven healthy subjects aged 20-30 years and ten healthy subjects aged 10-13 years with no history of cardiopulmonary or systemic disease were recruited and imaged in a General Electric 0.5T interventional magnet (GE Signa SP). Each subject's chest was securely strapped to the back of an upright seat in the center of the open magnet to minimize torso motion during the scans. The subject's legs were free to pedal a custom MR-compatible exercise cycle as depicted in Figure 1 (top) and described in previous work [2]. Cine phase-contrast MRI (cine PC-MRI) was used to obtain time-resolved anatomic and through-plane velocity maps [3] in the right (RPA), left (LPA), and main (MPA) pulmonary arteries. Double-oblique image planes were prescribed as shown in Figure 1 (bottom). Cardiac gating was timed to pulse plethysmography from the subject's finger and respiratory compensation was performed with respiratory bellows wrapped around the diaphragm [4]. The cine data was retrospectively reconstructed to 24 frames for the cardiac cycle. Scan parameters included: 25 msec TR, 10 msec TE, 30º flip angle, 7 mm slice thickness, 28 by 28 cm square field of view, 256 by 192 k-space image matrix, and a 150 cm/sec through-plane velocity encoding gradient. The cine PC-MRI scans were performed at rest and during steady-state cycling exercise (150% of resting heart rate). Pedaling resistance and speed were adjusted for each subject to minimize torso motion.

Instantaneous blood flow rates were computed from the time-resolved series of magnitude and velocity images for each cine acquisition. Lumen segmentations were obtained by image segmentation on the MR magnitude data and instantaneous flow rates (*Q*) were computed by integrating 2nd order baseline-corrected velocity values over the lumen cross-sections [5]. Reversal of blood flow was quantified by the reverse flow index (RFI) defined as the amount of retrograde flow compared to total flow and given by the equation: $\mathrm{RFI} = \frac{1}{2}\left(1-\int_0^T Q\,dt \Big/ \int_0^T |Q|\,dt\right)$ where *T* is the period of the cardiac cycle.

Results

The adults (2 males/5 females, 26.4+/-3.2 years, 64.0+/-11.8 kg) increased their heart rate from 66.3+/-13.2 to 100.9+/-19.4 beats per minute (bpm) ($p<0.05$) while the children (6 males/4 females, 11.9+/-1.1 years, 47.9+/-10.2 kg) increased their heart rate from 81.2+/-11.5 to 121.2+/-17.2 bpm ($p<0.05$) from rest to exercise. The adults and children achieved average exercise workloads of 38.7+/-11.3 and 33.9+/-9.8 watts, respectively.

Mean blood flow data are shown in Figure 2 (top). For both age groups, mean blood flow increased in the RPA (Adults = 2.3+/-0.5 to 4.1+/-0.5 L/min, $p<0.05$; Children = 2.0+/-0.5 to 3.7+/-0.7 L/min, $p<0.05$), LPA (Adults = 2.1+/-0.5 to 4.2+/-1.3 L/min, $p<0.05$; Children = 1.6+/-0.4 to 2.9+/-0.8 L/min, $p<0.05$), and MPA (Adults = 4.0+/-1.2 to 8.4+/-1.6 L/min, $p<0.05$; Children = 4.1+/-0.6 to 7.2+/-0.8 L/min, $p<0.05$). Greater LPA blood flow was observed in the adults as compared to children at rest ($p<0.05$) and during exercise ($p<0.05$). RFI data are shown in Figure 2 (bottom). For the adults, RFI decreased non-significantly in the RPA (0.002+/-0.003 to 0.000+/-0.000), LPA (0.043+/-0.045 to 0.024+/-0.020), and MPA (0.039+/-0.031 to 0.008+/-0.008), while in the children, RFI decreased significantly in the RPA (0.005+/-0.004 to 0.000+/-0.000, $p<0.05$) and LPA (0.041+/-0.019 to 0.014+/-0.016, $p<0.05$), and non-significantly in the MPA (0.014+/-0.012 to 0.006+/-0.006). The adults experienced significantly greater reverse flow in the MPA as compared to the children at rest ($p<0.05$).

Discussion

Blood flow increased similarly in the proximal pulmonary arteries as a result of lower extremity exercise in the adults and children. However, the adult group exhibited a more even distribution to the right and left lungs (Rest = ~52/48, Exercise = ~50/50) as compared the pediatric group (Rest = ~56/44, Exercise = ~56/44) for both rest and exercise. This difference may indicate the development of more balanced pulmonary flow distribution with adulthood. Flow reversal characteristics were also similar between the two age groups in that the RFIs of the LPA and MPA were both greater than of the RPA at both rest and during exercise. This indicates that the flow regurgitation in the MPA of normal subjects may originate predominantly from the LPA while the RPA is in relative isolation. This phenomenon may occur because the geometry of the pulmonary bifurcation is such that the LPA branches more directly off of the MPA while the RPA branches off at a sharp angle. The greater MPA flow reversal of the adults as compared to the children at rest suggests that the adults may have greater right ventricular afterload and that the presence of disease-related pulmonary regurgitation may be less well-tolerated with increasing age. In addition, decreased pulmonary flow reversal from rest to exercise for both age groups could increase the differential between healthy subjects and patients with abnormal pulmonary flow, aiding disease assessment.

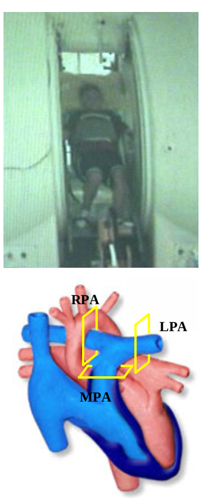

Figure 1. (Top) A subject pedaling the MR-compatible exercise cycle in the 0.5T open magnet and (bottom) an illustration of the scan planes for MR flow measurements.

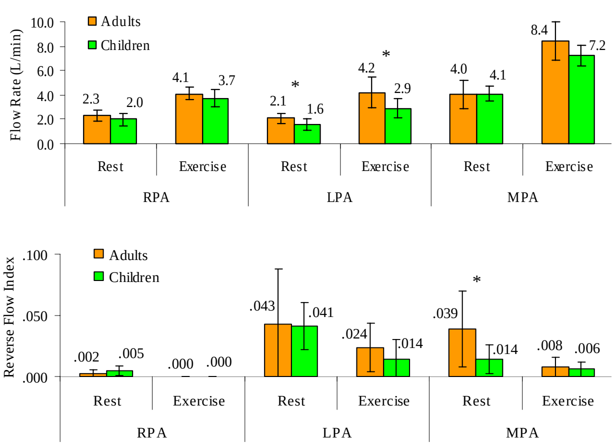

Figure 2. Population averages for adults and children of (top) mean blood flow and (bottom) reverse flow index (RFI) in the right (RPA), left (LPA), and main (MPA) pulmonary arteries at rest and during exercise. * Denotes a statistically significant difference between adults and children (p<0.05).

Acknowledgements

Dr. Norbert Pelc, Amy Lightner, Jason Pelc, Stanford Radiology Department, volunteer subjects, NSF No. 0205741, NIH P41RR09784.

References

[1] Roest AAW, Helbing WA, Kunz P, van den Aardweg JG, Lamb HJ, Vliegen HW, van der Wall EE, and de Roos A, Radiology 2002; 223: 204-211.
[2] Cheng CP, Herfkens RJ, and Taylor CA, Magnetic Resonance in Medicine 2002; 49(3): 581-585.
[3] Pelc NJ, Herfkens RJ, Shimakawa A, and Enzmann DR, Magnetic Resonance Quarterly 1991; 7(4): 229-254.
[4] Fredrickson JO, Wegmuller H, Herfkens RJ, and Pelc NJ, Radiology 1995; 195: 169-175.
[5] Bernstein MA, Zhou XJ, Polzin JA, King KF, Ganin A, Pelc NJ, and Glover GH, Magnetic Resonance Medicine 1998; 39: 300-308.