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NON-INVASIVE CALCULATION OF ENERGY LOSS IN PULMONARY ARTERIES USING 4D PHASE CONTRAST MRI MEASUREMENT

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ABSTRACT

The recent development of energy based endpoints, to quantify the pathophysiology of congenital heart disease such as tetralogy of Fallot (TOF), requires accurate measurement of cardiac blood flow and pressure data. Consequently, invasive cardiac catheterization is required for those measurements. In this research we used 4D phase contrast magnetic resonance imaging (PC MRI) data to determine the pressure drop non-invasively. This enables us to obtain pressure-flow variation, which, in turn, allowed us to calculate energy loss along the branch pulmonary arteries (PA). Based on our result, we believe that the hemodynamic status of the PA of a subject can be non-invasively evaluated by both pressure drop and energy loss values along the PA.

INTRODUCTION

Patients who have undergone tetralogy of Fallot repair surgery (rTOF) are often left with progressive right ventricular (RV) dilatation due to pulmonary insufficiency (PI) and occasionally pressure overload due to residual pulmonary stenosis. Those sequelae can result in progressive RV myocardial dysfunction increasing the risk of sudden death [1]. Surgical or catheter-based pulmonary valve replacement may be required to rectify RV myocardial dysfunction. However, the timing of pulmonary valve intervention still remains subjective due to the lack of quantifiable clinical criteria [2].

Recently, energy based endpoints, such as body surface area indexed RV stroke work (RV SW_I) and energy transfer ratio (e_{MPA}) between the RV and the main PA (MPA) were proposed by our research group to evaluate the hemodynamic status of the RV and PA [2, 3]. These energy based endpoints differentiated the hemodynamics of RV and PA of rTOF patients from those of normal subjects with statistical significance (p <0.05). However, energy based endpoints require invasive pressure measurement, i.e. cardiac catheterization; limiting the applicability of energy based endpoints in practice to those patients who are undergoing catheterization.

With non-invasively measured 4D PC MRI data, i.e. 3 directional velocity data over the cardiac cycle, the relative pressure can be estimated between any regions of interest in the heart [4, 5]. Therefore, in this research we computed the pressure drop along the PA using 4D PC MRI measured data. The energy loss between the MPA and the branch PAs, such as right and left PA, was calculated using measured 4D MRI velocity data and the computed pressure drop, to quantify the status of the PA hemodynamics of a subject.

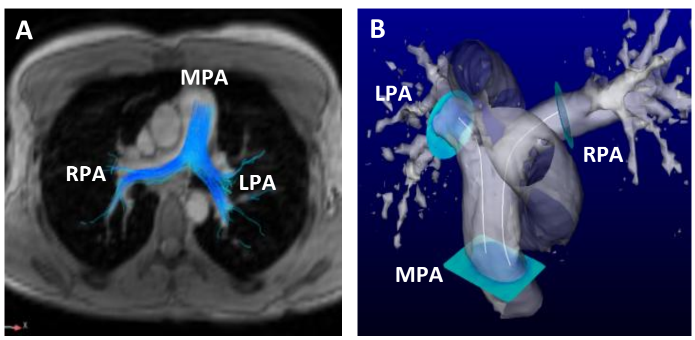

Figure 1. (A) The anatomy of pulmonary arteries (PA) with the pathlines of the blood flow from the main PA (MPA). (B) 3D phase contrast (PC) magnetic resonance angiogram (MRA) showing three planes for flow measurement

METHOD

Data Acquisition. 4D PC MRI was performed with a healthy volunteer (male, age: 29 years, heart rate: 70 beats/min) using 3.0 Tesla MRI scanner (Acheiva; Philips Medical Systems, Netherlands). Three directional velocity encoded data were acquired over the cardiac cycle. Twenty-four phases per cardiac cycle were recorded with 36 slices per each phase. The spatial resolution was 2.5 mm × 2.5 mm × 2.5 mm. The maximum encoded velocity (VENC) was 200 cm/s. The repetition time (TR) was 2.87 ms, the echo time (TE) was 1.81 ms and flip angle was 5°.

Data Analysis. The measured 4D PC MRI data were analyzed using semi-automated flow analysis software Ensight (version 9.2, CEI, Apex, NC). The anatomy of pulmonary arteries (PA), i.e. main, right and left PAs, was confirmed by magnitude images of PA with the pathlines of blood flow, in the direction from the MPA to the branch PAs (Fig. 1A) during the systolic phase.

Figure 1B shows a 3D PC magnetic resonance angiogram (MRA) of the PA with three measurement planes at MPA, RPA and LPA, respectively. These measurement planes, perpendicular to the PA, were used to compute the spatially averaged blood velocity and flow over the cardiac cycle. The pathlines of the blood flow, from the MPA towards the branch PAs, RPA and LPA, were shown in Fig. 1B. These lines were used to calculate the time varying pressure drop between the MPA and the branch PAs over the cardiac cycle.

The time varying pressure drop ($= p_{MPA} - p_{brach\ PA}$, Fig. 2) was calculated by integrating the pressure gradient along the pathlines over the cardiac cycle. The pressure gradient (*dp/dx*,*dp/dy*,*dp/dz*) field obtained from the Navier-Stokes equation (Eq. 1), assuming the fluid to be Newtonian, incompressible, and laminar [4].

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \mu \nabla^2 u_i + F_i, \quad \text{where, } i \text{ and } j = x, y, z \qquad (1)$$

where, u is the time varying blood velocity, ρ the blood density (=1,035kg/m^3), μ the blood viscosity (=0.00345 Pa/s) and F is the body force such as gravity which has an insignificant effect on the blood flow. The rate of total energy ($\dot{E}$) transferred at the PA was calculated using Eq. (2):

$$\dot{E} = p \cdot Q + \frac{1}{2}\rho u^2 \cdot Q \qquad (2)$$

where, p is the time varying pressure at the PA and Q the time varying blood flow rate at the PA. The rate of the total energy loss between the MPA and the branch PA (Fig. 3) is defined by the difference between the rate of the total energy transferred at the MPA and the rate of the total energy transferred at the branch PAs as in Eq. (3):

$$\dot{E}_{total\ Loss} = \dot{E}_{MPA} - \dot{E}_{RPA} - \dot{E}_{LPA} \qquad (3)$$

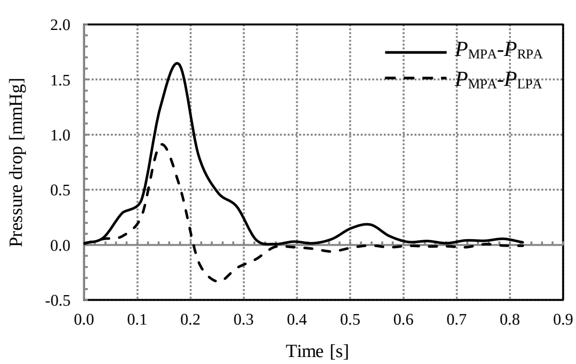

Figure 2. The pressure drop between main PA (MPA) and the branch PA, RPA and LPA over the cardiac cycle.

RESULT AND DISCUSSION

The pressure drop along the MPA to RPA was higher than that along the MPA to LPA in Fig. 2. It is because the area change between the MPA and the RPA was more pronounced compared to that between the MPA and the LPA (the diameters of PAs were 16.1 mm, 11.0 mm and 12.6 mm for the MPA, RPA and LPA, respectively). The negative pressure drop, i.e. the back flow, was observed between the MPA and the LPA at the late systole phase. We believe that the negative pressure drop was due to the anatomical abnormalities such as some narrowing of the daughter branches of the LPA.

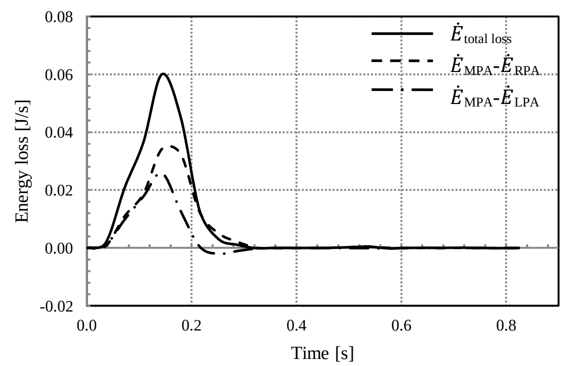

Figure 3. Energy loss between the MPA and the branch PAs over the cardiac cycle.

The net total energy loss, $E_{total\ loss}$, over the cardiac cycle was 0.0065 J. The net energy loss between the MPA and the RPA (0.0042 J) was higher than that between the MPA and the LPA (0.0023 J) since the pressure drop between the MPA and RPA was higher than that between the MPA and the LPA.

CONCLUSION

We have calculated the pressure drop and energy loss in the PA over the cardiac cycle of a normal subject using non-invasively measured 4D PC MRI data. Based on our result, we believe that the pressure drop and the energy loss in the PA is a viable parameter for evaluating the PA hemodynamics of a subject that may be differentiate the stages of late post-operative RV-PA dysfunction. Our future work will focus on extending this technique to post- operative tetralogy of Fallot.

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