

# Models of pulmonary vascular resistance in pulmonary hypertension from pulse wave analysis of MRI measurements in the main pulmonary artery

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**Purpose:** This work demonstrates the potential of the MR flow and anatomical image based mathematical models of wave reflection and impedance to probe the physiology of the pulmonary vasculature in healthy volunteers and patients with pulmonary hypertension (PH).

**Introduction:** PH is clinically defined as a disorder characterised by increased values of the mean pulmonary arterial pressure (mPAP>25 mmHg), typically measured at rest using invasive right heart catheterisation (RHC)<sup>1</sup>. One cause of PH is increased pulmonary vascular resistance (PVR) from narrowing of distal vessels and decrease of the vessel compliance (C) than leads to the increase in the right ventricular afterload and ultimately right heart failure and death. The overall system resistance ( $R_{total}$ ) and compliance (C) are expected to change with the disease state<sup>2</sup> and a 0D- distributed model of impedance (fig. 1.a) could be used to determine their values from synchronised flow (Q) and pressure, (p) measurements from MRI at the input - the main pulmonary artery (MPA).

A 1D model of a straight elastic vessel (fig. 1.b) can add supplementary information to the 0D model findings. After the right ventricle contracts, and the blood flow is ejected through the pulmonary valve the pressure wave that builds up starts traveling along the system, exchanging energy with the blood flow and vessel wall. Any impedance discontinuity in the system will cause part of the wave to be reflected back. With an increased distal PVR ( $R_d$ ), more reflections are expected at the periphery (fig1.c).

**Materials and Methods:** 32 subjects: 24 suspected PH patients (separated in 3 groups according to  $PVR < 4WU$ ,  $PVR \geq 4WU$  and NoPH-PH suspected patients with  $mPAP < 25mmHg$ ) and 8 healthy volunteers underwent flow (phase contrast- PC) and anatomical cine imaging (bSSFP) of the main pulmonary artery (MPA) on a GE HD x1.5T scanner. The wave reflection quantification requires simultaneous and accurate measurement of  $Q(t)$  and  $p(t)$  in the same physical position over the entire cardiac cycle. Due to the high SNR and better vessel - blood delineation, a bSSFP sequence was chosen for imaging dynamic radius change,  $R(t)$ , which is a pressure surrogate. PC MR was used to measure the flow waveform in the PA with a velocity encoding,  $venc$  of 150 cm/s. The two sequences were registered spatially in the same slice, pixel size (256x 128 matrix dimensions, 480x 288 mm FOV) and temporally using the same number of cardiac images (40) with the same retrospective gating during breath-hold, 8 views per gate and 10% arrhythmia rejection.

Post-processing was done using Matlab (R2011b, The MathWorks Inc.) and ShIRT<sup>3</sup> for: rigid registration to account for any movement between the acquisitions. The cross sectional area of the MPA was automatically segmented at every time step in the cardiac cycle in order to extract  $Q(t)$  and  $R(t)$ .  $p(t)$  was determined using a linear relationship between pressure and radius in the pulmonary artery ( $p(t) = \frac{E_p}{1-\nu^2} \left( \frac{1}{R_{diastolic}} - \frac{1}{R(t)} \right) + p_{diastolic}$ ), where Peterson's elasticity module( $E_p$ ) and  $p_{diastolic}$  are adapted using in-vivo measurements reported in the literature. From<sup>4</sup> we plot area change vs.  $E_p$ , respectively,  $p_{diastolic}$  and used the mathematical relationship predicted by a power-line fit to infer the  $E_p$  and  $p_{diastolic}$  for our subjects.

After determining the waveforms,  $Q(t)$  and  $p(t)$ , the  $R_c$ , C and  $R_d$  parameters of the 0D model (Fig 1a) were obtained using the Genetic Algorithm function from the Matlab optimisation toolbox. The components of the forward and reflected travelling waves were determined using Fourier analysis. The ratio of the distal resistance to the total resistance ( $R_d/R_{total}$ ) and the ratio of the power of the reflected wave to the power of the total wave ( $W_{pb}/W_{ptotal}$ ) were used as quantitative metrics for comparison between the two PH subgroups, the No-PH and healthy volunteers.

**Results and discussions:** The 0D model parameters showed significant statistical difference ( $p < 0.001$ ) between the healthy volunteer group and each of the PH sub-groups. Significant difference ( $p < 0.05$ ) was found between the No-PH and the severe PH group. The 1D model indicated on that average 12% of the power was contained in the reflected wave in the healthy volunteer group, 20% in the No-PH group and up to 40% in the group with  $PVR \geq 4WU$ . The preliminary results indicate that 1D model is able to distinguish between healthy volunteers and the other groups. Additionally, the  $W_{pb}/W_{ptotal}$  metric can distinguish between the No-PH and the severe PH group, and between the 2 PH groups.

**Conclusions:** We have showed that wave reflection quantification from MR measurements in the pulmonary artery has the potential to distinguish healthy from diseased PH patients consistent with the clinical stratification derived from right heart catheter. The method offers a new non-invasive means of sensing distal pulmonary vascular resistance, which cannot currently be accessed with direct imaging techniques or catheter measurements.

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