A Comparison of the Two and Three Element Windkessel Models in the Non-Invasive Evaluation of Pulmonary Artery Pressure by MRI

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OBJECTIVE. We seek to improve non-invasive quantification of pulmonary artery pressure by MRI by application of the three element Windkessel model through addition of a characteristic impedance term estimated by MRI, as well as by increasing the temporal resolution of the MRI flow wave form though post-processing interpolation. We will compare the three element Windkessel and the two element Windkessel with up-sampled flow input to the two element Windkessel with raw flow input measured by phase contrast MRI.

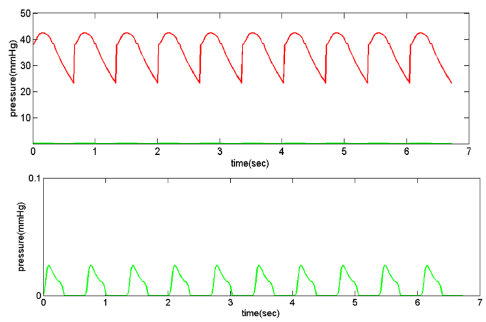
BACKGROUND Local area compliance, the ratio of changes in vessel cross section and pressure between systole and diastole (C_A=dA/dP), can be estimated from MR images (1). Assuming pulmonary artery flow and pressure waves in early systole to be unidirectional and reflectionless , we can express area compliance independently of pressure change, in terms of known blood density and parameters measurable by MRI, as $C_A = (((\Delta A)^2 * A)/((\Delta Q)^2 * \rho)$, where ρ is the density of blood, A is vessel cross-section at diastole, Δ A change in area and ΔQ change in flow between systole and diastole. Area compliance is multiplied by vessel length to obtain volume compliance (C) Under the same assumptions, characteristic impedance can be expressed as $Z_c = (\rho /(A\ C_A))^{1/2}$ (1).

MATERIALS AND METHODS

__**Pulse Sequence**__ Three pulmonary hypertension patients (female, age range 32-67,mean age 47) had phase contrast flow images acquired in the main, right and left pulmonary arteries (orientation orthogonal to the pulmonary arteries, FOV 285 x 380, matrix size 101 x 192, TE 3.2 ms, TR 37.5 ms, slice thickness 6 mm), on a 1.5 T Avanto scanner. PVR and mPAP by MRI were determined based on a retrospective study of 16 patients (1 male, 15 female, mean age 51, age range 30-79), who underwent cardiac TrueFisp CINE short axis imaging at 1.5T (FOV 309x 380, matrix size 109x 192, TE 1.13 ms, TR 56.1 ms, slice thickness 6 mm) for the measurement of volumetric parameters(2).

__**Analysis**__ __Compliance, pulmonary vascular resistance(PVR) and pulmonary artery pressue (mPAP)__ were calculated from MRI measurable parameters by a method we presented previously(3).

__The pulmonary artery pressure wave__ was computed from the flow wave in the main PA measured by MRI and the parameters above, by direct convolution in MatlabR2009a (Mathworks, Natick, MA). The relative pressure obtained by convolution was normalized by mean arterial pulmonary artery pressure estimated by linear regression of right heart catheter (RHC) pressures on MRI volumetric parameters, to obtain the absolute pulmonary artery pressure wave. We repeated this calculation with re-sampled flow wave forms, and with the addition of a Zc term calculated from area compliance, as above.



$$P_{diastole}(t) = P_{es} e^{-\frac{t}{C \cdot PVR}}$$

$$P_{systole}(t) = \frac{1}{C}(Q(t) \otimes e^{\frac{-t}{C \cdot PVR}}) + P_s e^{-\frac{t}{C \cdot PVR}} + Z_c e^{-\frac{t}{C \cdot PVR}}$$

Figure 1 Three element Windkessel pressure curve (red) and the impedance term of the systolic pressure equation (green) .

__Input flow wave resampling__ Our previous results displayed poor resolution of the systolic pressure peak. We sought to improve our method by interpolation of the flow wave form and Fourier space de-convolution with a boxcar function of width set at the desired temporal resolution.

RESULTS __Compliance, pulmonary vascular resistance, pulmonary artery pressure (mPAP) and Zc__ values from MRI and RHC are summarized in Table 1 below. There was a statistically significant difference between PVR by RHC and MRI (p<0.02).

__Pressure wave forms from the three element Windkessel model__ The addition of the impedance term to form a three element windkessel model resulted in less than 0.1% change in the pressure measured by MRI, even when the input impedance modulus was used as a proxy for characteristic impedance (Figure 1).

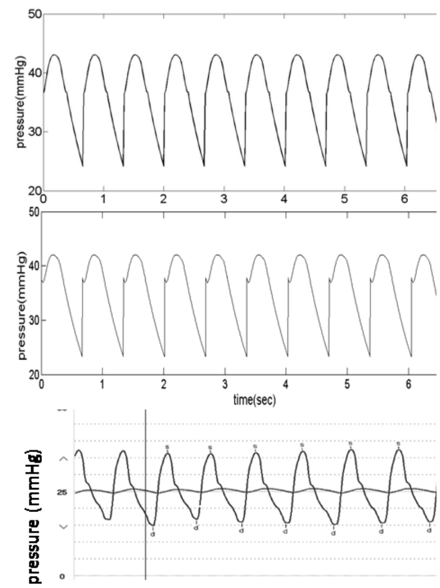


Figure 2. MRI Pressure waveform with no flow resampling (top), with 5 fold up-sampling (mid) and from RHC (bottom)

__Pressure wave forms with resampled flow input__ Up-sampling of the flow input resulted in a 1 mmHg increase in systolic pressure from MRI (Figure 2).

CONCLUSIONS The use of up-sampled flow wave forms brought about a modest improvement in the systolic and diastolic values of pressure measured by MRI. The use of the three-element Windkessel had no effect. These findings show that improved quantification of the pressure wave forms relies on accurate measurement of volume compliance C and PVR, as well as mPAP by MRI. Calculation of mPAP and PVR by MRI in by linear regression of RHC mPAP and MRI volume parameters in a large cohort of patients with similar degree of pulmonary arterial hypertension will improve quantification of pressure.

	mPAP mmHg MRI	**mPAP** mmHg RHC	**C** ml/mmHg MRI	**C** ml/mmHg RHC	**PVR** mmHg*min/l MRI	**PVR** mmHg*min/l RHC	**PVR*C** s MRI	**PVR*C** s RHC	**Zc** mmHg*min/l MRI
Mean	33.453	38.000	2.237	2.510	6.744	4.248	0.900	0.587	0.42
stdev	1.140	12.530	0.895	1.016	0.545	1.312	0.335	0.095	0.17
p-value	**0.573**		**0.560**		**0.034**		**0.199**		

1.Vulliemoz S et al Magn Reson Med. 2002;47(4):649-54.
2. Kuehne T et al.Circulation. 2004;110(14):2010-6.
3.Biris O et al. ISMRM 19th Annual Meeting and Exhibit; 2011; Montreal, Canada