Quantitative Assessment of Left Ventricular Function Using Cardiac Phase-Contrast and Cine Magnetic Resonance Imaging Comparison with Pressure-Volume Loops Analysis: *In Vivo* Validation on a Swine Model

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OBJECTIVE: To compare and correlate cardiac outputs obtained from segmented cine magnetic resonance imaging (MRI), phase-contrast (PC) velocity measurement and invasive pressure-volume (P-V) relation for evaluation of left ventricular (LV) function

INTRODUCTION: Noninvasive velocity measurement using PC-MRI has been recognized as a valuable and accurate technique to evaluate the change of hemodynamics and impaired heart function in a wide spectrum of cardiovascular pathologies (1,2). PC-MRI provides unique advantages for noninvasive diagnosis with no radiation exposure, high reproducibility, and integrated assessment with cardiac MRI protocols providing both anatomic and functional information for patients with heart diseases. In contrast with noninvasive PC-MRI, P-V loops obtained by conductance catheter intervention provide an alternative method to assess intrinsic ventricular diastolic and systolic characteristics of the heart (3,4). Dynamic P-V loops analysis is a reliable physiological indicator that is significantly beneficial to quantitative understanding of the passive relationship between myocardial contractile state and cardiac function independent of loading conditions. Previous clinical studies suggest that evaluation of passive relaxation properties of LV serves as a useful indicator of quantitative LV contractility and function without influence of relative ventricular load. To our knowledge, the correlation of LV function obtained from PC-MRI, cine MRI and invasive P-V loops relation has not been investigated and reported previously. The aim of this study was to determine the validity of PC-MRI, cine MRI in the assessment of LV function compared with P-V loops analysis.

METHODS: Eight domestic pigs weighing 45-50 kg were anesthetized with 2% isoflurane before intravascular intervention and MRI examinations. **P-V loops:** The left carotid artery of each subject was isolated for introduction of a 5-F/7-electrode conductance catheter. The latter was advanced into the LV to perform *in vivo* P-V loop measurements. A 2-in incision was made on the abdomen for access to the inferior vena cava to control the cardiac pre-load. All hemodynamic signals (LV pressure, LV volume, heart rate, and peak rate pressure development, dP/dt_{max}) were recorded using a commercial P-V loops system (MPVS Ultra system, Millar Instruments, Inc., Texas, USA). **MRI:** All imaging experiments were performed on a 3.0 Tesla scanner (Trio, Siemens Healthcare, Erlangen, Germany) with prospective electrocardiography-signal gating. Through-plane velocity measurements using segmented PC gradient-echo sequence were used on an imaging plane perpendicular to subjects' descending aorta. Acquisition parameters of PC-MRI were: matrix=256x144, flip angle=20°, spatial resolution=2.18x2.18 mm^2, Venc = 150 cm/s and TE/TR/temporal resolution = 2.6/7.1/42.0 msec. A quantitative evaluation of the cardiac output (CO) using PC-MRI was done by multiplying stroke volume (i.e., the area under flow curve within one cardiac cycle) and heart rate. Additionally, noninvasive measurements of CO using segmented cine sequence (TE/TR=2.6/6.8ms, matrix=256x144) on multiple short-axis slices were acquired with the standard post-processing to validate and compare the results from P-V loops and PC-MRI.

RESULTS: Figure 1 shows P-V loops and cine MRI results from two out of eight subjects. End-systolic pressure-volume relations (ESPVR) and end-diastolic pressure-volume relations (EDPVR) indicate the myocardial contractile state of Subject A (Figure 1a) is superior to Subject B (Figure 1b). One frame of a cine loop at end-systole (Figure 1c and e) and end-diastole (Figures 1d and 1f) demonstrate consistent findings from P-V loops relation (Figures 1a and 1b). The mean CO was calculated as 3.23 ± 0.49 L/min by PC-MRI, 3.45 ± 0.51 L/min by cine MRI, and 3.39 ± 0.28 L/min by P-V loops. The CO measurement from all subjects by using PC-MRI and P-V loops agreed relatively closely ($y=0.49x+1.78$, $R^2 = 0.77$) with a mean difference (bias) of 0.16 L/min or 4.9% of CO (Figure 2a). The upper and lower limits of agreement (bias ± 2 SD of the difference) were 0.41 and -0.73. A good correlation was observed as well between cine MRI result and P-V loops analysis ($y=0.52x+1.6$, $R^2 = 0.88$) with a mean difference of 0.079 L/min or 2.3% of CO and upper and lower limits of 0.59 and -0.43, respectively (Figure 2b).

CONCLUSIONS: The correlation between both PC-MRI and cine MRI, and P-V loops analysis of assessment of LV function studied suggests that cardiac MR imaging could be a reliable noninvasive method for assessing LV function. MRI has great potential to serve an alternative modality to characterize physiologic reaction without any complication from current invasive procedures.

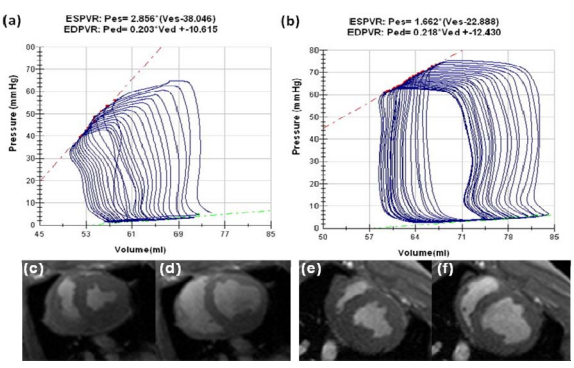

Figure 1. Sample plot of LV P-V loops of two out of eight pigs with normal (a) and impaired heart conditions (b). The slops of end-diastolic pressure volume relation (EDPVR) and end-systolic pressure volume relation (ESPVR) were determined. Figures c and d show the corresponding MR images at end-systole and end-diastole from the same subjects, respectively. The corresponding MR images from the same subject (as shown P-V loops in figure b) were displayed in Figures e and f.

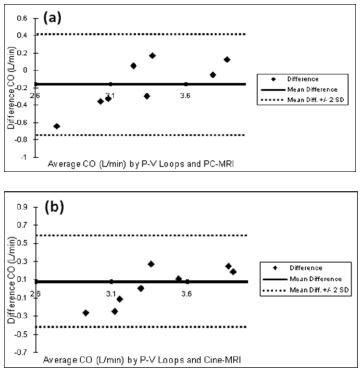

Figure 2. Bland-Altman analysis of agreement for CO correlations (a) PC-MRI vs. P-V loops, (b) MRI cine vs. P-V loops. The difference is plotted as a function of the average of the result from two methods. The lines in the graphs indicate the upper and lower limits of agreement, mean ± 2 SD.

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