Validation of Real Time MR Imaging Using Pressure-Volume Loops

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Introduction: Measurement of load-independent LV parameters is paramount to determine post-infarct contractility and assess surgical and medical therapy efficacy. An MRI sampling and reconstruction strategy with sufficient spatiotemporal resolution is required to ascertain these parameters. We hypothesize that sub-Nyquist MRI sampling and reconstruction strategies that utilize non-Cartesian radial data sampling, linear inversion of k-space signal data, and joint estimation of coil sensitivities provide the sufficient spatiotemporal resolution [1,2], but these methods have not been validated with concurrent measurement of left ventricular (LV) pressure to determine LV pump function via pressure-volume (PV) loops. We sought to validate here a real time (i.e. no cross-beat view sharing or temporal regularization) method using regional (a single tomographic slice) PV relations in an animal model across a range of normal and post-infarct ejection fractions (EF) and stroke volumes (SV) at intermediate heart rate (100 bpm). We further demonstrate for the first time that MRI can be used to characterize beatwise alterations in regional PV relations during an LV inflow occlusion (i.e. to reduce preload) to measure regional wall stiffness (end-systolic PV relation – ESPVR).

Methods: *Animal Preparation:* Yorkshire male swine (N=9, mean weight = 45 kg) were used in accordance to IACUC guidelines. Myocardial infarction (MI) was induced by direct ligation of the circumflex artery to create a posterolateral infarct and MRI was performed at 1-week (N=3), 3-weeks (N=5) and 4-weeks (N=1) weeks post-infarction [3]. In a subset of animals (N=4), an occlusion balloon catheter was threaded from the jugular vein into the superior vena cava (SVC) to limit venous return; this experiment estimates the regional maximum elastance (E_{max}), ESPVR and volume-axis intercept (V_0) [4]. The slice position was chosen to intersect post-infarction scar, identified by signal enhancement on a late gadolinium enhanced scan. Additional scans were performed at a remote (i.e. no visible infarct on LGE) slice location (N=1) and during dobutamine infusion (N=1). *Imaging Protocol:* The MR imaging protocol consisted of short-axis, balanced SSFP cine and golden angle radial bSSFP MRI performed on a clinical 3 T MRI scanner (Tim Trio; Siemens Healthcare) with an 18 ch Rx array. Golden angle radial bSSFP was acquired with TE/TR = 1.25/2.5 ms, FOV = 280 mm, bw/pixel = 500 Hz/pixel. The Nth radial spoke was oriented along an azimuthal angle θ=NG, where the golden angle θ =111.25°. Intraventricular pressure (femoral cath.; Millar Instrum., Houston TX) was digitized and synchronized in real time with radial views to generate a PV loop. *Reconstruction:* Images (N=30k) were reconstructed using sliding window (1 image frame per radial view), KWIC-filtered iterative SENSE [5]. 34 spokes were utilized to reconstruct each frame. Slice volumes were segmented from real time and cine image frames with a user-guided level set algorithm resulting in ~30k and ~60 frames of segmented data, respectively [6]. Volumes were estimated from the binary mask. Statistical analysis was performed by paired t-test and linear regression.

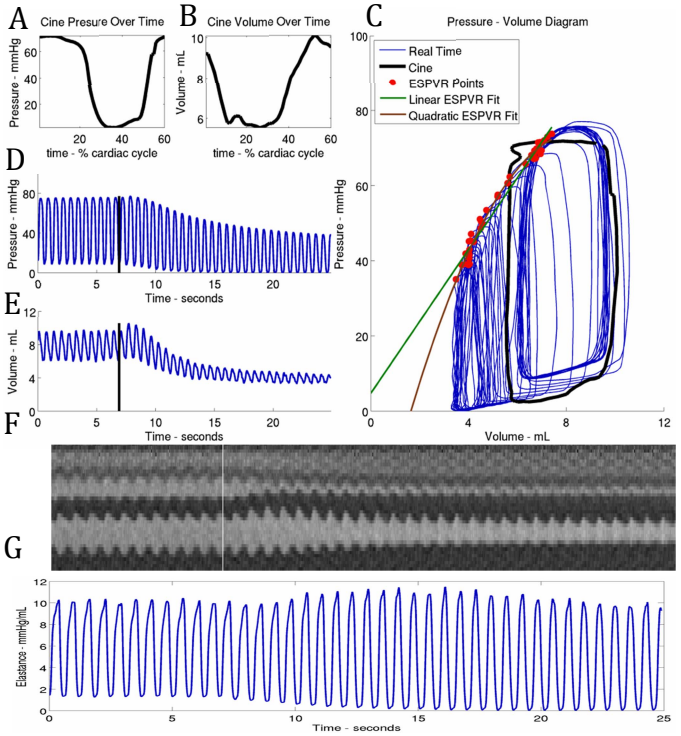

Figure 1: Representative PV relations in a X-week post-infart swine. Baseline (a) pressure and (b) volume timecourse used to map loops in the PV domain (c) (black curve). continuous (d) pressure and (e) volume using real time image . Inflow occlusion begins 7 seconds into recording The vertical black line indicates the start of the inflow occlusion. The right panel illustrates the corresponding PV loops. The red dots indicate end-systolic PV points. Two fits (linear and quadratic) of the ESPVR are shown. A projection (F) of the real time dataset and an estimate of elastance (G) are shown during the occlusion.

	1-week (N=3)		3-week (N=5)		4-week (N=1)	
	Cine	RT	Cine	RT	Cine	RT
EF (%)	48 ± 10	37 ± 3	46 ± 6	42 ± 8	33	23
SV (single slice) (mL)	3.59 ± 0.83	2.68 ± 0.78	5.39 ± 0.37	4.79 ± 0.36	2.71	1.86

Results: Although we found close agreement between the cine and real-time MR at baseline (Figure 1, i.e. prior to the inflow occlusion), there were small increases in ESV and small decreases in EDV, EF and SV ($p<0.05$, Table 1). Infarct size was about 18% (estimated endocardial circumferential LV on LGE). Linear regression of the two methods results in the following results. For EF, slope = 0.79, y-intercept = 0.02, and R = 0.77 ($p < 0.05$). For SV, slope = 1.07, volume-axis intercept = -1.03, and R = 0.97 ($p < 0.05$). For the animal shown in Figure 1 (1 week post-infarct), a linear and quadratic fit are shown to illustrate non-linearity under low loading conditions. The end-systolic stiffness measured is 21.57 mmHg/mL and the volume-axis intercept is 1.65 mL. In a 1-week post-infarct animal, dobutamine infusion resulted in an increase in end-systolic stiffness from 7.76 to 14.56 mmHg/mL. There was an increase in both end-systolic stiffness (36.81 vs. 12.96 mmHg/mL) and volume-axis intercept (3.99 vs. -0.22 mL) in the infarct slice location compared to a remote slice location in a 4-week post-infarct animal

Discussion: We found that sub-Nyquist MRI with radial data sampling, linear inversion, and joint estimation of coil sensitivities closely follows single-beat (cine) PV relations in swine at intermediate heart rates. Small deviations in EF (~12% reduction) are a complex result of interview blurring (Tres = 23 ms (cine) vs. ~100 ms (real time)), papillary muscle longitudinal motion (through-plane), and LV longitudinal motion and torsion, and intensity thresholding in the level-set algorithm. There are tradeoffs between image quality, reconstructed view number and accuracy, which are under investigation. We showed for the first time that it is possible to characterize beatwise volume changes during inflow occlusion using MRI to measure regional measures of post-infarction myocardial stiffness. This is important in ischemic heart disease where ventricular shape, ischemic mitral regurgitation and parallel conductance of myocardial tissue each compromise conductance catheterization (gold-standard). Single-slice PV loops enable assessment of regional contractile function and stiffness; this information cannot be obtained with conductance catheter. We detected significant changes in regional, post-infarct contractile function and during stress testing. Therefore, it may be more sensitive to scar and borderzone dysfunction than the gold-standard, which assesses global LV function. These results might be validated with limited window conductance catheter (i.e. recording signal from a single catheter antenna limits the measured volume). Diagnosis of heart dysfunction is challenging because alterations in loading conditions and myocardial contractile state result in variations in function, but MRI PV loop analysis may provide important regional, load-independent measure of contractile state.

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