Estimation of Cardiac Elastance and Compliance from Pressure-Volume Tracing During Inflow Occlusion Using Real Time Cardiac Imaging Technique

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Introduction:
MRI-based estimation of preload and afterload independent indices of cardiac contractility and hemodynamic function are limited by the inadequate true temporal resolution of cine MRI. To address this problem we validated a real-time imaging technique that achieves a temporal resolution of 30 ms. This method combines a previous approach with golden angle radial k-space sampling and KWIC filtering [1] with an iterative SENSE reconstruction [2]. Left ventricular volumes were measured during SVC/IVC occlusion using automated LV segmentation and the resulting pressure-volume loops were utilized for measurement of the end-systolic pressure volume relationship (ESPVR), end-diastolic pressure volume relationship (EDPVR), preload recruitable stroke work (PRSW), and the zero-pressure volume (V_0).

Methods:
Animal Preparation: A Yorkshire male swine weighing approximately 60 kg was used in an IACUC approved study. After sedation, a posterolateral infarction was created by ligation of circumflex artery. The animal was allowed to recover twelve weeks after which a second terminal MRI study was performed. Pressures were recorded with an intraventricular pressure transducer (Millar Instruments, Houston TX) .

Imaging Protocol: The MR imaging protocol consisted of short-axis, cine-bSSFP and golden angle radial bSSFP MRI performed on a clinical 3 T MRI scanner (Tim Trio Model, Siemens Healthcare). A custom bSSFP, golden angle radial acquisition was run with a TE/TR = 1.25/2.5 ms, fov = 280 mm, bw/pixel = 500 Hz/pixel. The Nth radial spoke of the golden angle radial acquisition was oriented along an azimuthal angle θ=NG, where the golden angle G= (3-√5) / 2π. The scan was coordinated with an inflow occlusion to capture baseline and occluded heart beats. Coil sensitivity maps were obtained immediately following using a cine-FLASH sequence and derived from image data using an adaptive coil combine algorithm [3]. LV pressure was obtained from the placed in the LV cavity. Cardiac volumes were segmented from cine-SSFP images in ITK-Snap and a slice-to-volume ratio was determined to estimate real time cardiac volumes. This ratio was applied to the real-time short axis area to estimate a ventricular volume.

Reconstruction: The golden angle radial acquisition was reconstructed using KWIC-filtered iterative SENSE (kwicSense) using custom software on a GPU workstation [2]. The KWIC filter consisted of a central core of 12 spokes and two additional rings (36 spokes total) whose radii were determined to satisfied the Nyquist Criteria [1]. After creating an encoding matrix the linear system of equations was solved using an LSQR algorithm (conjugate gradient type) adapted to run on a GPU (nVIDIA Tesla C2050).

Results:
Baseline (i.e. prior to occlusion) pressure-volume loops derived from short axis CINE images and real-time kwicSense images were in close agreement (Fig. 1). The end-diastolic volume for the kwicSense loop was found to be lower than the CINE data resulting in a decreased stroke volume (SV), 36.9 mL vs. 44.1 mL, and an increased ejection fraction (EF), 22% vs. 19%. PV relationships during inflow occlusion computed from rt-kwicSense images resemble those obtained using standard conductance catheterization methods (Fig. 2, [4]): ESPVR (0.607 mmHg/mL), V_0 (5.6 mL) and EDPVR (0.0617 mmHg/mL). The end-diastolic points are combined with the stroke work to estimate PRSW (15.1 mmHg). Figure 3 shows the ventricular region of each occluded loop at end-systole. The segmented volumes show a marked reduction as the occlusion proceeds to decreased end-systolic pressure values.

Discussion:
rt-MRI based measurements of ventricular compliance have the potential to characterize LV performance in a wide range of heart disease states. Moreover, unlike conductance catheter, rt-MRI has the potential to characterize regional and right ventricular elastance. In this study, the animal had chronic MI in which the posterolateral wall (20% of the total LV endocardial surface area) was compromised by dense, noncontractile.scar tissue and also possible ischemic mitral regurgitation (MR). Therefore the poor regional performance and possible regurgitant volume could distort the shape of the pressure-volume relationship, ESPVR, V_0 and EDPVR compared to healthy animals [5]. It is well known for example that there is a large increase in V_0 due to increased scar compliance compared to normal myocardium. More study is required to understand how regional LV elastance is changed in these animals and humans. It was observed that underestimation of the end-diastolic volume may be attributed to the effect of varying image contrast, resolution and lower SNR of rt-MRI on the automated segmentation method. Figure 2 illustrates how the pressure-volume loop shifts along the ESPVR and EDPVR during an inflow occlusion. The estimated measures of cardiac performance agree with the severely impaired cardiac function of the twelve-week post-infarct animals.

Conclusion:
This work shows real-time non-gated free breathing cardiac images can be acquired during an inflow occlusion study to estimate the several preload and afterload independent measures of cardiac contractility.

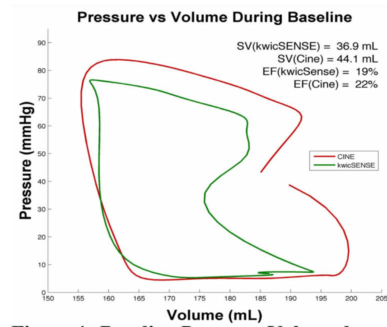

Figure 1: Baseline Pressure-Volume loop for CINE and Golden Angle kwicSense Reconstruction. The difference in end-systolic volume results in small changes in SV and EF.

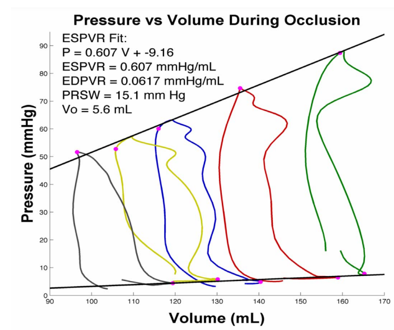

Figure 2: Baseline Pressure-Volume Loop for CINE and Golden Angle kwicSense Reconstruction. The difference in end-systolic volume results in small changes in SV and EF. Pink dots indicate end-systolic and end-diastolic points.

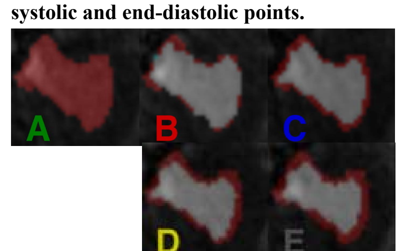

Figure 3: Segmented short-axis end-systolic images during varying points along inflow occlusion. Labels indicate with pressure-volume loop from Figure 2 correspond to the end-systolic image. A marked decrease in volume as the occlusion progresses is expected and observed.

References:
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