Highly-accelerated, single breath-hold 3D Cine b-SSFP MRI with a combination of compressed sensing and parallel imaging

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Introduction: Cardiac cine MRI using balanced steady-state of free precession (b-SSFP)[1] provides excellent myocardium-to-blood contrast and is considered the gold standard for imaging left ventricular function (LV). Typically, cine MRI is performed with parallel imaging with moderate acceleration rate (R) on the order of 2-3 and requires multiple breath-holds to cover the entire LV. The need for multiple breath-holds, however, increases the examination time and likelihood for patient exhaustion from repeated breath-holds. One approach to eliminate the need for multiple breath-hold acquisitions and speed up the examination time is to perform a single breath-hold 3D cine MRI. Several acceleration methods [2-5] have been used to perform single breath-held 3D cine MRI, with R on the order of 5 and 10 using standard [2-3] and 32-element [4-5] coil arrays, respectively. We sought to develop a single breath-hold 3D b-SSFP cine MRI pulse sequence with R =12 using a standard coil array, by employing a combination of compressed sensing [6] and parallel imaging that exploits joint sparsity among all component coil datasets (k-t SPARSE-SENSE)[7], and compare its performance against multi-slice 2D b-SSFP cine MRI for LV function quantification.

Methods: We modified a 3D cine b-SSFP MRI pulse sequence to employ a "Poisson disk" sampling pattern (Fig. 1) to provide incoherent aliasing artifacts while conserving relatively uniform distance between sampling points [8]. The pulse sequence was implemented on a 3T MRI system (Tim Trio, Siemens) equipped with a standard coil array (12 elements total). The relevant imaging parameters for 3D cine MRI with prospective electrocardiogram (ECG) triggering included: FOV = 340mmx340mm, matrix = 192x192x20 (4 slices, 2 on each end, discarded after reconstruction to avoid aliasing artifacts), slice thickness = 6 mm, TE/TR = 1.4/2.8ms, flip angle = 25°, BW=1000 Hz/pixel, number of k-space lines per cardiac phase = 16, temporal resolution = 45ms, R =12, one partition per cardiac cycle, and breath-hold duration = 22 cardiac cycles (including 1 cardiac cycle for coil sensitivity pre-scan and 1 cardiac cycle for dummy scan to achieve steady state of magnetization). The standard 2D protocol with retrospective ECG triggering used similar imaging parameters, except reconstructed cardiac phases = 25. We performed the accelerated image reconstruction off-line using customized software developed in MATLAB (MathWorks, MA), using the k-t SPARSE-SENSE formalism [7] with two orthogonal sparsifying transforms: temporal Fourier transform and temporal total variation, where the weight for the former was ten times smaller than for the latter. Coil sensitivity maps were calculated using the adaptive array combination method, as previously described [9,10]. Both 2D and 3D protocols were performed in 3 volunteers (1 female and 2 males, age range = 22-34 years), to cover the entire LV. The pooled short-axis stacks of cine data (n=6, including both 2D and 3D cine data sets) were randomized and blinded for quantitative evaluation. Specifically, one adult cardiologist and one pediatric cardiologist independently calculated the end-diastolic volume (EDV), end-systolic volume (ESV), stroke volume (SV) and ejection fraction (EF) for each dataset, using a CMR[42] software workstation (Circle Cardiovascular Imaging). Global function measurements between 3D and multi-slice 2D cine MRI pulse sequences were compared using the Bland-Altman and coefficient of variation (CV) analyses.

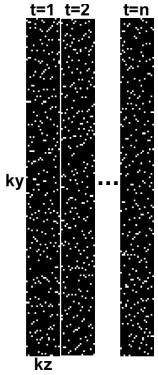

Fig. 1 k_y-k_z-t undersampling pattern with 12-fold acceleration (white: sampled).

Results: Fig. 2 displays representative sets of 2D and 3D cine MR images in one volunteer. The 3D protocol produced comparable image quality in all 3 subjects. According to the Bland-Altman and CV analyses (Table 1), all four global function measurements, averaged over 2 readers, were in good agreement, with CV ranging from 6-12%.

Conclusions: Our results demonstrate that it is feasible to obtain high quality 3D b-SSFP cine MR images in a single breath-hold of approximately 20s. This study demonstrated that the proposed 3D protocol produces relatively accurate global function measurements in healthy human volunteers. Compared with the retrospectively ECG triggered 2D protocol, our prospectively ECG triggered 3D protocol underestimated EDV, SV, and EF values, because in prospective ECG triggering it is difficult to obtain true end diastole. This discrepancy can be minimized by increasing the acceleration to achieve even higher temporal resolution with a 32-element cardiac coil array. Nevertheless, a 3D protocol provides several advantages over a 2D protocol, including: i) suitable for volumetric segmentation of cardiac contours, ii) suitable for reformatting into different cardiac views, and iii) decreasing the acquisition time.

Grant Sponsor: AHA 0730143N, NIH-5R01 HL092439, NIH-2R01DK063183-06, NIH-5R01DK088375-02.

References: [1]. Carr JC, et al. Radiology 2001; 219:828-34. [2]. Kozerke S, et al. MRM 2004;52:19-26. [3] Mascarenhas NB, et al. AJR 2006;187:1235-39. [4]. Kellman P, et al. ISMRM 2005; p.2432. [5]. Xu J, et al. ISMRM 2011; p. 576. [6]. Lustig M, et al. MRM 2007;58:1182-1195. [7]. Otazo R, et al. MRM 2010; 64:767-776. [8] Glassner, A. Morgan Kauffman, 1989. [9]. Walsh DO, et al. MRM 2000;43(5):682-690. [10]. Griswold MA, et al. ISMRM 2002; p. 2410.

Table 1. Bland-Altman and CV analyses of 4 global function measurements between 2D and 3D cine MR protocols.

Measurement	Mean	Mean Difference	Upper 95% Limit	Lower 95% Limit	CV
EDV	113 ml	-31 ml	-18 ml	-44 ml	6 %
ESV	51 ml	2 ml	9 ml	-5 ml	7 %
SV	62 ml	-33 ml	-18 ml	-47 ml	12 %
EF	54%	-14 %	-7 %	-21 %	7 %

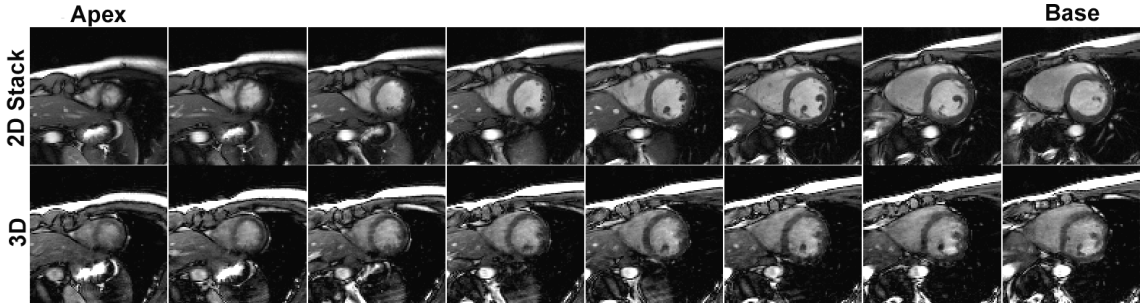

Fig. 2. Representative sets of (top) 2D and (bottom) 3D images of one volunteer, covering the LV from apex to base (left to right). Note that 2D images (8 mm thick) are not contiguous and have 1.6 mm gaps between adjacent slices, whereas 3D images (6 mm thick) are contiguous and have no gaps.