Accelerated Four-dimensional, multiphase, steady-state imaging with Contrast Enhancement (MUSIC) using Parallel Imaging and Compressed Sensing

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Purpose: Recently, a 4D non-breath-hold multiphase, steady-state imaging technique (MUSIC) was proposed using ferumoxytol as an intravascular contrast agent[1] to address the issue of poor intra-cardiac definition and the necessity of breath holding in conventional CE-MRA. MUSIC supports simultaneous anatomical and functional assessment of the heart and related blood vessels using a single scan without breath holding in children with congenital heart disease (CHD). In its current format, MUSIC incorporates parallel acquisition with GRAPPA and typical acquisition time is on the order of 6-10 mins. In this study, with the goal of further increasing acquisition speed and temporal resolution, we develop and evaluate an accelerated MUSIC strategy using Parallel Imaging and Compressed Sensing [2] with clinically acceptable image reconstruction time.

Methods: The original MUSIC sequence was modified in such a way that center ky-kz region is fully sampled while the outer k-space is under-sampled using a variable-density Poisson-Disk distribution (Fig.1d). The net acceleration rate is 7x compared with fully sampled k-space and 2x compared with original MUSIC with Partial Fourier and GRAPPA[1]. Images were reconstructed separately for each cardiac phase by minimizing the following cost function:

$$\arg min_x \, ||DFSx - y||_2 + \mu||Wx||_1,$$

where S is the coil sensitivity map estimated using ESPIRiT[3], F and D are Fourier transform and under-sampling operations. x and y represent the reconstructed image and k-space measurement. Randomized shifting wavelets W were used as the regularization term. The algorithm was implemented in C/C++ based on the Berkeley Advanced Reconstruction Toolbox[4] (BART). Total reconstruction time for one 4D dataset (512x300x150x8) was less than 5 minutes on a conventional PC with GPU.

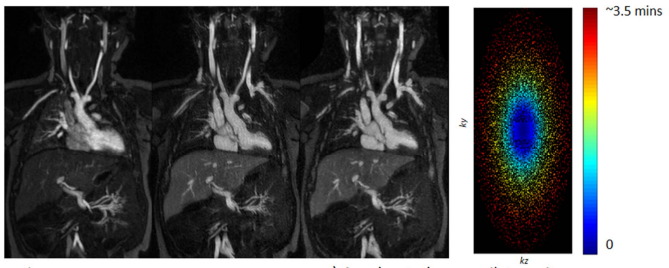

Figure 1 Selected slices of first-pass a) CE-MRA under VCBH; b) MUSIC and c) accelerated MUSIC on a 3 m.o. girl. The intra-cardiac structures (e.g. cardiac chambers, aortic root and valves) are much better defined using MUSIC and accelerated MUSIC. d) Variable density Poisson-Disk k-space sampling pattern used in accelerated MUSIC. The fully sampled center k-space and under-sampled outer k-space result in net acceleration factor of 7x. The trajectory is depicted with samples colored based on the temporal sampling order.

Nine pediatric CHD patients were scanned under general anesthesia and controlled ventilation. The breath-held CE-MRA was first performed under ventilator-controlled breath-holding (VCBH) during the first-pass of a ferumoxytol bolus injection (4 mg-Fe/kg). Subsequently, the original MUSIC[1] and the proposed accelerated MUSIC sequences were performed during the steady-state distribution phase of ferumoxytol without VCBH using the regular airway pressure signal for respiratory gating. Sequence parameters included: TR/TE: 2.9/0.9ms, FA: 25°, matrix size: 500x300x150, isotropic resolution: 0.8-1.0mm without interpolation, 6-9 cardiac phases, scan time: 8±2 min for MUSIC, 4±1 min for the accelerated MUSIC. Subjective image quality scores (1=poor, 2=fair, 3=good, 4=excellent) in five different anatomical regions were visually assessed on both original MUSIC and accelerated MUSIC images by a board certified radiologist. In one patient, a supplemental accelerated MUSIC acquisition was performed incorporating 17 cardiac phases with 41ms temporal resolution.

Table 1 Subjective image quality score

	Coronary Origins	Aortic Root	Myocardium	Pulmonary Trunk	Descending Aorta
MUSIC	2.67±0.5	3.56±0.5	3.33±0.5	3.56±0.5	3.89±0.3
Accelerated MUSIC	2.67±0.5	3.78±0.4	3.44±0.5	3.89±0.3	4.0±0.0

Results and Discussion: Fig.1a-c compares first pass VCBH CE-MRA, MUSIC and accelerated MUSIC on a 3 m.o girl. Both MUSIC and accelerated MUSIC provide vastly better definition of intra-cardiac structures than first pass CE-MRA by eliminating cardiac motion. Subjective image scoring (Table 1) of accelerated MUSIC is similar to the original MUSIC, although acquisition time was halved. Fig. 2a shows reformatted cardiac four-chamber view of MUSIC and accelerated MUSIC where both images provide equally clear myocardium-blood boundary which is important for accurate chamber segmentation and ventricular volumes measurement. In the patient where high temporal resolution MUSIC was performed, both global and regional wall motion were clearly visualized with isotropic resolution as shown in Fig. 2b.

Conclusion: We have successfully incorporated compressed sensing into 4D MUSIC with a doubling of acquisition speed while preserving image quality with clinically acceptable reconstruction times. The complete 4D dataset can be reconstructed in less than 5 minutes, suggesting the feasibility of inline image reconstruction on the MR host computer. As always, the acceleration can be either used to shorten the scan time or increase the temporal/spatial resolution.

References: [1] F Han et al, MRM 2014. [2] M Lustig et al, MRM 2007. [3] M Uecker et al, MRM 2014. [4] BART: v0.2.04.

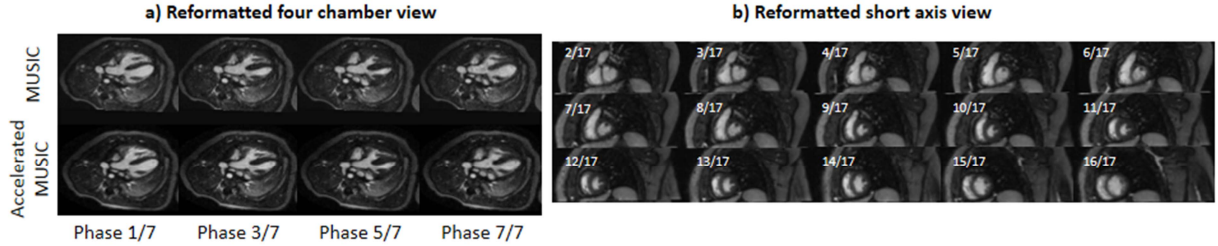

Figure 2 a) Reformatted cardiac four chamber views based on MUSIC and accelerated MUSIC on a 6 m.o. boy. Sharp myocardium and clear myocardium-blood contrast is demonstrated on both cases. b) Selected 15 cardiac short axis views from total 17 cardiac phases on a 6 y.o. girl. Cardiac phase number is shown at upper left corner.