Isotropic Cardiac MR Functional Imaging with 3D Variable Density Spiral and Non-Cartesian Through-time GRAPPA

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TARGET AUDIENCE: Those interested in Cardiac MRI.

PURPOSE: To assess the feasibility of volumetric coverage of the left ventricle (LV) within a single breathhold at isotropic reconstructed resolution for cardiac MR functional imaging. Such a scan would allow multi-planar reformatting to generate any clinical imaging plane without image registration at a fraction of the total scan time for the 2D-based clinical standard scans. Despite the large volume to be covered, a high temporal resolution is maintained (<50ms) by taking advantage of the encoding efficiency of the 3D Stack-of-Spirals trajectory and parallel imaging via 3D through-time non-Cartesian GRAPPA reconstruction

METHODS: Ten healthy volunteers provided written consent to participate in this IRB approved study. All imaging was performed on a 3.0T MR scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) using a body and spine array combination (up to 32 channels). The gold-standard ECG-gated 2D segmented cine bSSFP sequence used one breathhold per acquired slice (TE 1.43ms, RF spacing 2.86ms, thickness 8mm, gap 0mm, FOV 284x340mm^2, matrix 174x208, GRAPPA R=2, BW 960Hz/pix, temporal resolution 39ms per cardiac phase, in-plane resolution 1.63x1.63 mm^2). Note that two slices per breathhold are typically acquired, where the worst-case patient might only tolerate holding their breath for one slice at a time. ECG-gated 3D cine volumes were collected with a 3D Stack-of-Spirals trajectory bSSFP sequence [1] (RF spacing 4.52ms, partition thickness 4.94mm, FOV 300x300mm^2, 8 out of 48 spiral arms for matrix 128^2, temporal resolution 32ms per cardiac phase, in-plane resolution 2.47x2.47 mm^2). Due to SAR limits, the flip angle varied across the cases: [40°, 57°] for 2D and [20°, 45°] for 3D [min, max]. Ten repetitions of an ungated, free breathing, fully-sampled (48 spiral arms) acquisition with the same basic 3D spiral sequence parameters were used for 3D through-time spiral GRAPPA calibration (8x1 segment size) [2]. Following the parallel imaging reconstruction, two-fold partition-wise zero-filling yielded data with isotropic resolution of 2.47mm^3, where each partition was gridded using NUFFT [3] in Matlab (R2011b, The Mathworks, Nattick, MA). Note that slice coverage was nearly identical for the 2D and 3D scans (2D: 12 slices at 8mm, or 96mm of coverage; 3D: 20 partitions at 4.94mm, or 98.6mm of coverage, plus 40% oversampling) where the complete scan times for both scans (including rest periods for 2D and calibration for 3D) were recorded for comparison. Multi-planar reformatting (cvi^{42}, Circle Cardiovascular Imaging, Inc.) of the 3D cine volumes was performed along the short-axis, 2-chamber and 4-chamber planes.

RESULTS: The 2D-based LV functional short-axis scan required 12 breathholds over 335.3±37.8sec (mean±SD) including rest periods to cover the same 96mm as the 3D scan, where every additional imaging plane would require a separate acquisition with even more breathholding for a patient. The 3D scan required one breathhold of 23.7±3.8sec (mean±SD) plus a fixed calibration time of 60.7 sec, where the typical total scan time of 84.4sec represents a 3.97-fold reduction of examination time versus the clinical standard in this experiment. Figure 1 shows two cases of 3D reformatted images, where good blood-myocardium contrast is maintained throughout the entire cardiac cycle, papillary muscles are well-resolved, and volumetric coverage extends beyond the level of the valves in one of the displayed cases (Fig. 1b, arrows). Figure 2 shows a comparison of 2D vs. 3D imaging. In this case, an additional 2D slice in the 2-chamber orientation was acquired, where the image is partly obscured by flow artifact (Fig. 2a), whereas the same 3D short-axis volume could be reformatted to a similar plane (Fig. 2b), or through the mitral valve to assess patency (Fig. 2c) or along the length of a papillary muscle to capture a long segment of the anatomy within one image plane (Fig. 1d).

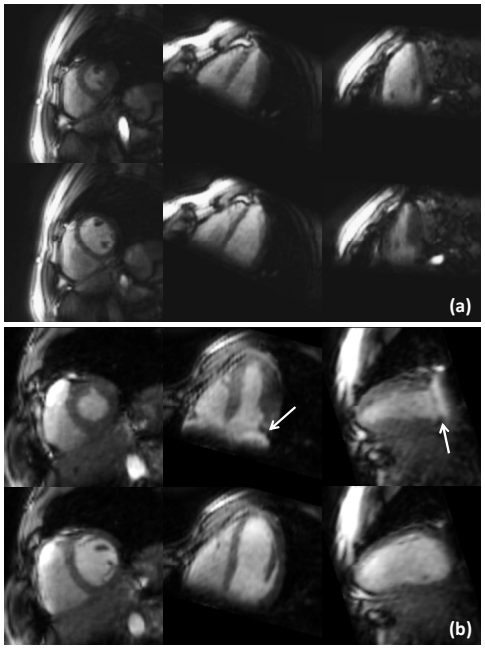

Figure 1: Reformatted 3D examples. End-systole (top) and end-diastole (bottom) in short-axis (left), 4-chamber (middle) and 2-chamber (right) reformatted planes from the same source data are shown for two cases (a,b). Image contrast is good, papillary muscles are well-resolved, and coverage exceeds the level of the valves (b, arrows). Reformat thickness 2.47mm.

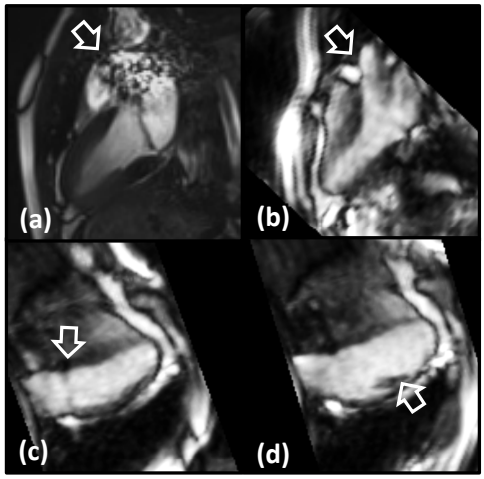

Figure 2: 2D vs. 3D imaging. Flow artifact at end-systole for 2D (a) is not present in 3D reformatted 2-chamber plane (b) allowing artifact free visualization of outflow into the aorta. Reformatting the same data along different planes, for example, allows patency of the mitral valve (c) and large segments of papillary muscles (d) to be evaluated. Reformat thickness 2.54mm.

DISCUSSION: This work demonstrates that undersampled dynamic volumetric data can be acquired within one breathhold and reconstructed using 3D through-time spiral GRAPPA to achieve isotropic spatial resolution of the LV for 3D cine imaging. This combination enables functional imaging of the LV and valves along arbitrary slicing planes at nearly 4-fold less total time than 2D-based short-axis LV functional imaging alone. Note that accelerating the partition direction of the 3D scan is needed to achieve whole-heart coverage at isotropic resolution, whereas a 2D scan can either increase the slice gap – which exacerbates non-contiguous coverage – or add more slices and breathholds – which can lead to fatigue in patients with cardiomyopathy [4]. In addition to saving total scan time versus the 2D-based sequence, the combination of this 3D-based approach with modern image display software has the unique capacity to generate 4D cine images in any plane. This could, for example, enable imaging of the papillary muscle anatomy along its entire length, which is relevant in clinical conditions like hypertrophic cardiomyopathy. Also, isotropic 4D imaging could be invaluable for assessing ventricular anatomy prior to placement of interventional devices such as left ventricular partitioning devices.

REFERENCES: [1] Seiberlich N, et al. MRM 2011. 66(6):1682-1688; [2] Seiberlich N, et al. JCMR 2012. 14(Suppl 1):P279; [3] Fessler JA. JMR 2007. 188(2):191-195; Gay SB, et al. Invest Radiol 1994. 29(9): 848–851

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