Low Latency Reconstruction of Free-breathing Real-time Cardiac Cine with VISTA and SENSE

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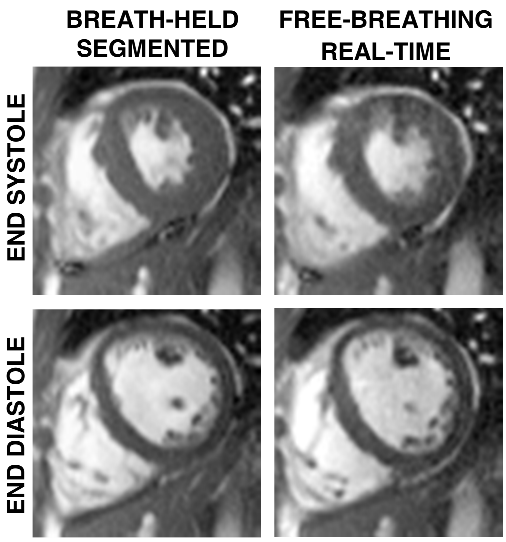

Figure 1: Example **breath-held** segmented (**left**) and **free-breathing** real-time (**right**) images at end systole (**top**) and end diastole (**bottom**).

Purpose: The combination of Variable density Incoherent Spatiotemporal Acquisition (VISTA, [1]) with 3D spatiotemporal regularization has been shown to achieve comparable image quality relative to conventional segmented cine techniques when combined with a SPIRiT reconstruction [2]. We combine these techniques with an iterative SENSE [3] reconstruction to achieve further speed improvements, allowing an avenue for highly accelerated real-time, free-breathing cardiac cine imaging with minimal reconstruction latency. We achieve < 10 second reconstruction times using a GPU-based implementation of the Fast Iterative Shrinkage Thresholding Algorithm (FISTA, [4]) and demonstrate a clinically practical implementation of real-time free-breathing cine meeting target guidelines for temporal and spatial resolution (< 40 ms and < 2x2 mm^2, respectively) with sufficient diagnostic quality compared to segmented cine.

Reconstruction: SENSE reconstruction was implemented within the Gadgetron framework [5] with coil sensitivity maps estimated using a method by Walsh et al. [6]. The VISTA sampling pattern was used to provide sufficient spatiotemporal incoherence for subsequent reconstruction. Spatiotemporal ℓ_1-regularization within the 3D wavelet domain was implemented to take advantage of this sampling. Forward and backward wavelet transforms were applied to a single coil-combined channel, significantly reducing per-iteration computation time compared to coil-by-coil reconstruction methods. An efficient GPU-based wavelet transform implementation eliminated the need to perform an initial FFT in the readout direction for reduction of computation time, allowing us to take advantage of sparsity within all three spatiotemporal dimensions. FISTA enabled highly efficient iterative optimization by eliminating the need for a line search along the gradient direction, both reducing per-iteration computation time and improving convergence [7]. All real-time data were reconstructed using an Intel Core i7 workstation with 64GB system memory and an NVIDIA GeForce GTX Titan with 6GB memory. No coil compression or image cropping was used to reduce computation time. The zero-filled k-space data was used as an initialization. A minimum change in the cost function of 1e-6 was used as a stopping criterion.

Volunteer Study: Short axis (10-12 slices), 2 chamber, and 4 chamber views were acquired at rest from 5 healthy volunteers (Siemens, Avanto, 1.5T, 12 channels) using our real-time technique (free-breathing, 40 phases, rate 12) as well as a conventional segmented technique (breath-held at end-expiration, 40 phases, GRAPPA rate 2 with 28 reference lines). Common parameters between the two techniques were as follows: FOV: 287 x 340 mm^2, slice thickness: 8 mm, matrix size: 156 x 192, spatial resolution: 1.8 x 1.8 mm^2, BW: 1447 Hz/Px, TE/TR: 1.1 / 2.5 ms, FA: 70 - 79, temporal resolution: 32.5 ms. A respiratory bellows signal was used to acquire real-time short axis stacks during end-expiration. Reconstruction time for real-time data was automatically recorded from the time all acquired data was received until the time images were sent back to the scanner. Datasets were visually scored by two qualified readers for image quality (1: nondiagnostic, 2: poor, 3: adequate, 4: good, 5: excellent), temporal fidelity of wall motion (1: nondiagnostic, 2: poor, 3: adequate, 4: good, 5: excellent), and artifact level (1: nondiagnostic, 2: severe, 3: moderate, 4: mild, 5: minimal). Scores greater than or equal to 3 indicated diagnostic quality. Argus (Siemens) was used to estimate end diastolic volume (EDV), end systolic volume (ESV), stroke volume (SV) and ejection fraction (EF).

REAL-TIME			
EDV (mL)	ESV (mL)	SV (mL)	EF
102.8 ± 19.2	44.8 ± 13.2	58.0 ± 8.3	57.2% ± 7.4%
SEGMENTED			
102.4 ± 19.8	45.0 ± 14.4	57.3 ± 8.6	56.9% ± 8.1%
p = 0.557	p = 0.861	p = 0.463	p = 0.663

Table 1: Summary of volumetric parameters (mean ± std. dev.). P-values show no significant difference between breath-held segmented data and breath-held real-time data.

Results: Figure 1 shows example images from one volunteer for the short-axis view at both systole and diastole. Mean reconstruction time for SENSE was 7.8 seconds for each 40-frame image series, or 194 ms per frame. Even with a six-fold reduction in scan time and under free-breathing conditions, paired t-test results show no significant differences in EDV, ESV, SV, and EF between real-time and segmented data (Table 1). Table 2 shows mean image scores across all volunteers for all views. While paired t-test results indicated significant differences in scoring metrics between real-time and segmented data for both readers ($p < 0.004$ for all comparisons), all scores were at least adequate for real-time data, with the exception of three 2 chamber views in which a single reader gave a score of 2. In each of these cases, significant field-of-view wrapping was apparent, which introduces errors in coil sensitivity map estimation.

	READER 1		READER 2	
	SEGMENTED	REAL-TIME	SEGMENTED	REAL-TIME
IMAGE QUALITY	4.20 ± .077	3.33 ± 0.49	4.87 ± 0.52	3.53 ± 0.83
TEMPORAL FIDELITY	4.33 ± 0.82	3.27 ± 0.46	4.67 ± 0.82	3.60 ± 0.74
ARTIFACT LEVEL	4.67 ± 0.62	3.07 ± 0.59	4.87 ± 0.52	3.60 ± 0.51

Table 2: Scoring of artifact level, temporal fidelity, and image quality (mean ± std. dev.) for all volunteers.

Conclusion: Combined with VISTA and 3D spatiotemporal regularization, the FISTA implementation of SENSE within the Gadgetron framework provides a clinically practical avenue for highly accelerated, real-time, free-breathing cardiac imaging in terms of overall image quality, quantification of volumetric parameters, and low-latency reconstruction time.

References: [1] Ahmad et al., to appear in MRM, DOI: 10.1002/mrm.25507. [2] Ting ST. et al. Proc. ISMRM, 2014. p. 4385. [3] Pruessmann K. et al. MRM 1999; 42(**5**):952-62. [4] Beck A. et al. SIAM J Imag. Sci. 2009; 2(**1**):183-202. [5] Hansen MS, et al. MRM 2013; 69(**6**):1768-76. [6] Walsh, DO. et al. MRM 2000; 43(**5**):682-90. [7] Ting ST. et al. Proc. ISMRM, 2013. p. 3813.