Fast Gated EPR Imaging of the Beating Heart: Spatiotemporally-Resolved 3D Imaging of Free Radical Distribution during the Cardiac Cycle

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Abstract. Electron paramagnetic resonance imaging (EPRI) is a powerful technique for determining the in vivo spatial distribution of free radicals and other paramagnetic species. However, cardiac and pulmonary EPRI is limited by physiological motion. Gated EPRI remains challenging due to long acquisition times and hardware limitations. Previous reports of gated EPRI have had poor spatial or temporal resolution. Recent hardware and software advances have enabled the development of fast EPR acquisitions with individual projections acquired as quickly as every 10 – 20 ms. In this work, we report fast gated EPRI of the complete cardiac cycle of the beating heart with submillimeter spatial resolution in as little as 2 to 3 minutes. Reconstructed images display the temporal and spatial variations of the free radical distribution, anatomical structure, and contractile function of a rat heart during the cardiac cycle.

Introduction. An important long term goal in EPRI has been to develop rapid gated imaging with high temporal and spatial resolution. This goal has been difficult to achieve in CW EPRI due to the limited signal to noise ratio in individual projections, the large number of projections required for 3D reconstruction, and instrumentation challenges (e.g., maintaining bridge frequency lock on a moving object). Prior work with gated cardiac EPRI [1, 2] was very slow because the main magnetic field could not be cycled fast enough to acquire even one entire projection during each cardiac cycle. Instead, a complete projection was indirectly acquired over multiple cardiac cycles, taking only one data point for each cardiac frame during the cycle. This indirect acquisition had an effective temporal resolution of approximately 20–25 seconds per projection, and total acquisition time was 64 minutes [2]. Recent advances have enabled a much faster acquisition with high spatial and temporal resolution.

Methods. We developed a fast EPR acquisition scheme using adaptive heterogeneous clocking (AHC), which significantly reduces communication between the host computer and gradient hardware by using different clocks to pace the A/D and D/A functions of our acquisition cards [3]. Projections containing up to 4096 points can be acquired in as little as 10–20 ms using AHC. In direct gated cardiac EPRI, data I/O is grouped into multiple batches. Each batch corresponds to one cardiac cycle, as depicted in Figure 1 which illustrates the gradients, field sweeps, and pacing waveforms for direct fast gated EPRI acquisition. The main magnetic field is swept 10 times per cardiac cycle, corresponding to 10 projections. In the current implementation, these projections share the same gradient angle, and one cardiac image frame is reconstructed from each of them. In the next cardiac cycle, another set of multiple projections are acquired with another gradient angle, and so on. In addition to outputting gradients and field sweep waveforms, the EPR acquisition computer also outputs waveforms for pacing a phantom or isolated heart, and the pacing waveform is synchronized with all other waveforms to ensure correct acquisition. During the acquisition, the rat heart was paced at 2.5 Hz, the EPR projection acquisition time was 40 ms. Ten projections of the same gradient angle were obtained during each cardiac cycle (400 ms). A total of 10240 projections were acquired during continuous 1024 cycles over a total acquisition time of 8 minutes, resulting in ten 3D cardiac frames and 1024 projections for each frame. The acquired image sequences were post-processed with dynamic range compression, interpolation, smoothing, thresholding and color mapping for better visualization.

Results. The total data acquisition time for ten 3D frames was 8 minutes. Figure 2 shows a frame sequence of the coronal view of a paced heart during a cardiac cycle. The images show cyclical contraction and relaxation of the paced isolated heart. The effective spatial resolution is about 0.5 mm after deconvolution. During systole the left ventricular cavity contracts, and the left ventricular wall expands.

Discussion. In conclusion, direct gated cardiac EPRI has been successfully achieved with the fast EPR acquisition enabled by adaptive heterogeneous clocking. A sequence of 3D images depicting the motion of the beating heart during the cardiac cycle can be acquired in minutes, as compared to hours reported in previous work. The fast gated EPRI technique not only enables the study on how free radical distribution and organ functions evolve during the cardiac cycle, but also provides sharper images without the temporal blurring caused by cardiac motion. Future work will include measurement of myocardial contraction, regional metabolism, and spectral-spatial acquisitions, which have the potential to depict spatially localized changes in oxygen, pH, and redox state.

References and Acknowledgements. [1] Testa et al. Phys Med Biol 1993;38:259–266. [2] Kuppusamy et al. MRM 1996;35:323–328. [3] Chen et al. ISMRM 2011;19. This work is supported in part by NIH grants EB0890 and EB4900. The third author was supported by NIH training grant F32 EB012932.

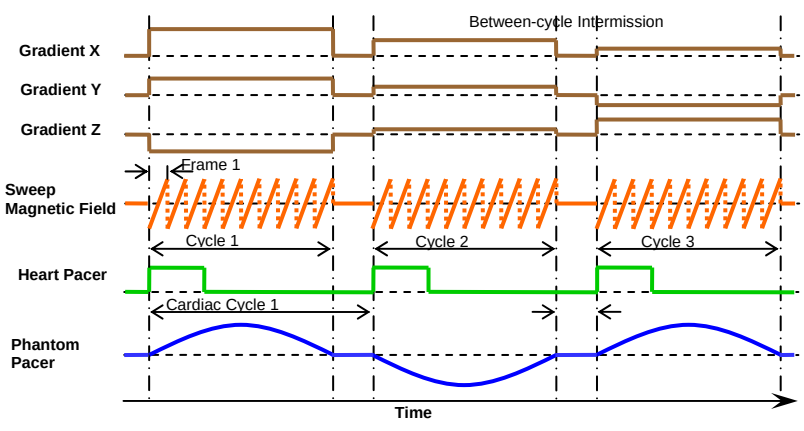

Fig. 1. Gradients, field sweep, and pacing waveforms for direct fast gated EPR acquisition

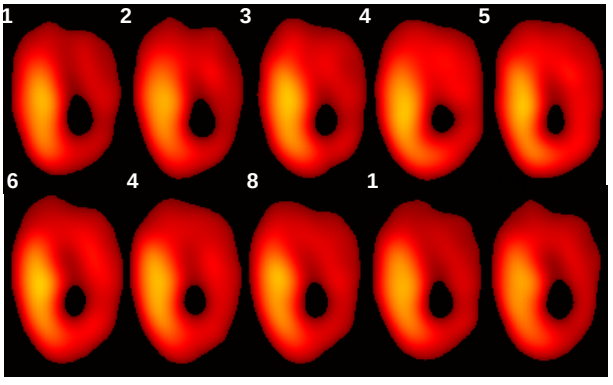

Fig. 2. A frame sequence of the coronal view of a paced isolated heart in a cardiac cycle