Free Breathing Cardiac Cine Imaging with Self-Gated Dual-Echo SSFP

D. A. HERZKA[1], E. R. MCVEIGH[1], S. L. LEE[1], P. KELLMAN[2], R. J. LEDERMAN[3], AND J. A. DERBYSHIRE[3]

[1]BIOMEDICAL ENGINEERING, JOHNS HOPKINS UNIVERSITY SCHOOL OF MEDICINE, BALTIMORE, MD, UNITED STATES, [2]LABORATORY OF CARDIAC ENERGETICS, NHLBI, NIH, DHHS, BETHESDA, MD, UNITED STATES, [3]TRANSLATIONAL MEDICINE BRANCH, NHLBI, NIH, DHHS, BETHESDA, MD, UNITED STATES

INTRODUCTION: Recently, self-navigation has become an alternative to breath-holding and respiratory navigators for cardiac MR scans {1-6}. Current self-navigated sequences can acquire a high spatial-resolution navigator projection every cardiac phase {i.e. 4}, acquire a much lower resolution navigator every TR {i.e. 5}, or acquire a complete image with lower temporal resolution {2}. In all cases, either temporal or spatial resolution is sacrificed to minimize the loss of imaging efficiency. Unfortunately, to perform high-resolution imaging with effective cardiac and respiratory navigation, high temporal and spatial resolution projections are needed. Previous approaches to high temporal and spatial resolution have acquired varying radial projection angles, making motion detection difficult {3}. In this work, we propose and balanced SSFP-based imaging sequence that acquires a constant navigator projection during every TR. The sequence is specifically designed to obtain high spatial and temporal resolution navigators for both cardiac and respiratory gating.

THEORY: With the intention of acquiring a high spatial and temporal resolution navigator projection combined with the standard constraints of maintaining balanced SSFP, we propose the pulse sequence in Fig 1d. The sequence acquires two complete imaging readouts, similar to "flyback SSFP" {7}, with a navigator projection between the two. The nav orientation, given by angle θ relative to the readout direction, is independent of the readout direction. To minimize TR, an efficient gradient waveform design technique such as Hardware Optimized Trapezoid Pulses (**HOT**) pulses can be applied {8,9}, minimizing the transition periods between RF excitation, readouts and nav projection. For an additional reduction in TR, a partial Fourier factor (**PFF**) was used. The images from each imaging echoes can be reconstructed separately combined using root-sum-squares.

METHODS: MRI: Two normal human subjects were scanned on a 1.5 Espree system (Siemens Medical Systems, Erlangen, Germany) with max gradient amplitude of 33 mT/m and max slew rate of 100 mT/m/ms using a cardiac phased array. Imaging was approved by the local IRB and informed consent was given. Short-axis and long-axis cardiac image data were acquired during free breathing over periods ranging from 80-90s per slice. Imaging parameters were: α=45°, TR=5.7 at 977 Hz/pixel bandwidth, 8mm slice thickness, 256x256 sampling matrix, for final resolutions of 1.17x1.17 mm^2 to1.32x1.32mm^2 to with a PFF 5/8. The navigator projections had either 128 or192 points, yielding a resolution equivalent to that in the phase encode direction. For comparison a breath-held single-echo SSFP sequence (TR/TE = 3.8-4.2/1.9-02.07ms, ~20s breath-hold). The sequence was also simulated to determine minimum TRs possible. Post-Processing: Respiratory self-navigated images were generated offline using MATLAB. The cardiac gating signal was obtained from the scanner's own recorded timing and used for cardiac binning of the data, though the acquisition was ungated and free-breathing. For simplicity, the best respiratory gating signal was identified as the point in the nav profile with the highest power at the respiratory frequency (for any coil). The respiratory intervals were manually identified on this signal. 18 cine phases were reconstructed for each of 4 respiratory phases.

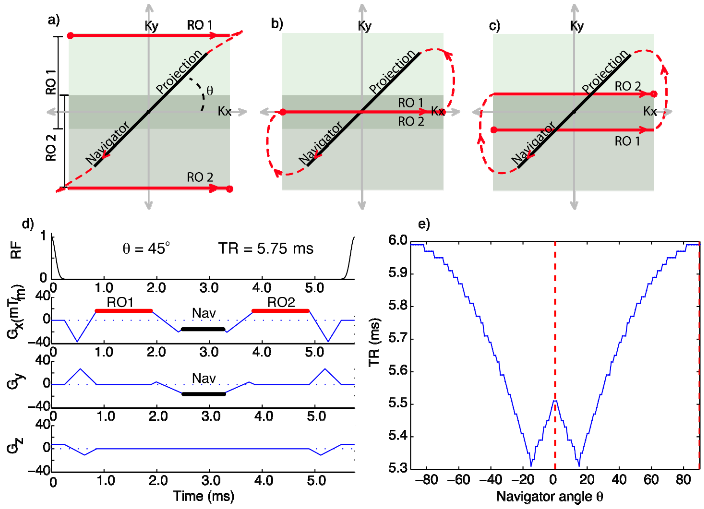

Figure 1: (**a-c**) k-Space trajectories for the proposed dual-echo self-navigated sequence using a 5/8 k-space acquisition, demonstrating the maximum, zero, and minimum PE steps and a nav projection angle θ=45°. Two full resolution readouts (256 pts) and one nav projection (192 pts) are acquired. Note that the nav projection stays constant throughout all PE steps and that θ is completely independent of the readout direction but may be used to decrease TR. Also, RO1 and RO2 acquire different fractions of k-space. (**b**) Pulse sequence diagram demonstrating HOT pulse design for efficient transitions. (**c**) Plot of minimum TR vs. nav projection angle for a transverse slice using a PFF=5/8. The shortest TR is obtained with θ = 15°. The curve is symmetric since TR for the negative nav angle acquisitions can be minimized by changing the k-space ordering.

RESULTS: Figure 1 (c) shows a simulation of the minimum TRs obtained with the sequence for an axial plane. By changing which portions of k-space are acquired, the TRs for negative θ nav projection angles are minimized. The use of PFF = 5/8 reduced the TR by ~300-400µs. Figure 2a displays a trace of the high-resolution nav projection over a 90s acquisition which acquired over 14,000 projections at image resolutions. Note the level of detail, which includes both cardiac and respiratory information. Figure 2b-c displays two LAX slices from a normal volunteer, acquired using the self-gated technique and standard breath-hold.

DISCUSSION AND CONCLUSIONS: We present a pulse sequence specifically designed for high-resolution imaging, with a constant navigator projection acquired every TR and with resolution equivalent to phase encoding. The navigator direction is independent of readout direction, though certain directions minimize TRs by reducing the distances traversed in k-space in transitions. Neither image or navigator orientation was specifically chosen to align with the lung-liver interface: there is sufficient information in the high-res projection trace to detect motion. In this work, the navigator projection was only used for respiratory gating though cardiac gating is certainly possible, making a viable approach for self-gated, free breathing cardiac- and respiratory-resolved cine imaging. The processing steps necessary to fully and automatically utilize such high-resolution projections remain to be explored. Nevertheless, this double-echo, self-navigated SSFP sequence provides a method for free-breathing cardiac cine imaging in high-resolution, with application in patient scans are not possible, or where the desired resolution makes a breath-hold untenably long.

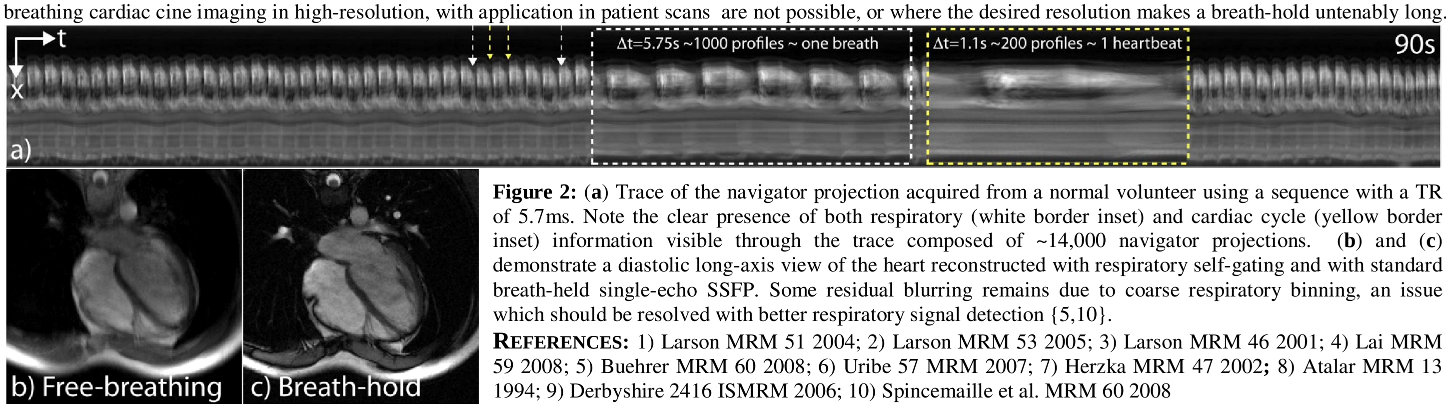

Figure 2: (**a**) Trace of the navigator projection acquired from a normal volunteer using a sequence with a TR of 5.7ms. Note the clear presence of both respiratory (white border inset) and cardiac cycle (yellow border inset) information visible through the trace composed of ~14,000 navigator projections. (**b**) and (**c**) demonstrate a diastolic long-axis view of the heart reconstructed with respiratory self-gating and with standard breath-held single-echo SSFP. Some residual blurring remains due to coarse respiratory binning, an issue which should be resolved with better respiratory signal detection {5,10}.

REFERENCES: 1) Larson MRM 51 2004; 2) Larson MRM 53 2005; 3) Larson MRM 46 2001; 4) Lai MRM 59 2008; 5) Buehrer MRM 60 2008; 6) Uribe 57 MRM 2007; 7) Herzka MRM 47 2002**;** 8) Atalar MRM 13 1994; 9) Derbyshire 2416 ISMRM 2006; 10) Spincemaille et al. MRM 60 2008