Gradient-Induced Voltages on 12-lead ECGs during High-Duty-Cycle MRI Sequences and a Theoretically based Method to Remove Them

HuaLei Zhang[1], Zion Tsz ho Tse[2], Charles L. Dumoulin[3], Ronald Watkins[4], Wei Wang[1], Jay Ward[5], Raymond Kwong[1], William Stevenson[1], and Ehud J. Schmidt[1]
[1]Brigham and Women's Hospital, Boston, MA, United States, [2]University of Georgia, Georgia, United States, [3]Cincinnati Children's Hospital Medical Center, Cincinnati, United States, [4]Stanford University, CA, United States, [5]E-TROLZ, Inc, Andover, MA, United States

Target Audience Cardiologists and scientists interested in high-fidelity 12-lead ECGs for gating and physiological monitoring during diagnostic or interventional MRI.
Purpose ECG traces inside MRI bore are highly distorted by both the magnetohydrodynamic effect and by strong (~1000 mV) MRI gradient- induced electric fields. An MRI-compatible 12-lead ECG platform, equipped with hardware blocking and software magneto-hydrodynamic voltage removal [1], was previously applied to physiological monitoring and synchronization of cardiac imaging of patients inside MRI. This approach had limited success for high-duty-cycle MRI sequences, such as Steady State Free Precession (SSFP), Short-TR Gradient Echo (GRE), and Short-TR Fast Spin Echo. The study goal is to measure and develop a method to restore high fidelity 12-lead ECGs during high-duty-cycle MRI sequences, by way of canceling induced electric field noise [2], while avoiding strong low-pass filtering of the traces.
Methods A theoretical system response function for the gradient-induced voltages on each ECG electrode (S_k) was derived based on Maxwell's equations [3] and the concomitant fields equation [4], $S_k(t) = p_{1k}\frac{\partial G_x}{\partial t} + p_{2k}\frac{\partial G_y}{\partial t} + p_{3k}\frac{\partial G_z}{\partial t} + p_{4k}G_x + p_{5k}G_y + p_{6k}G_z + p_{7k}\frac{\partial G_x}{\partial t}G_x + p_{8k}G_x^2 + p_{9k}\frac{\partial G_y}{\partial t}G_y + p_{10k}G_y^2 + p_{11k}\frac{\partial G_z}{\partial t}G_z + p_{12k}G_z^2 + p_{13k}\frac{\partial G_x}{\partial t}G_z + p_{14k}G_x\frac{\partial G_z}{\partial t} + p_{15k}G_xG_z + p_{16k}\frac{\partial G_y}{\partial t}G_z + p_{17k}G_y\frac{\partial G_z}{\partial t} + p_{18k}G_yG_z + C_k$, where $p_{1k} \ldots p_{6k}$ and $p_{7k} \ldots p_{18k}$ are 1st- and 2nd- order coefficients, respectively, G_x, G_y, G_z, $\frac{\partial G_x}{\partial t}, \frac{\partial G_y}{\partial t}, \frac{\partial G_z}{\partial t}$ are the three gradient waveforms and their time-derivatives, and C_k is a DC-offset term related to the ECG amplifier response. The ECG traces were collected through a modification of the hardware in [1] to enable measuring the gradient-induced voltage over a 24 KHz frequency-range within +/-10V, or through a commercial CardioLab system (GE, Waukesha, WI) equipped with 100Hz low pass filters. ECGs were measured in 9 volunteers at 3T (Siemens Skyra), while simultaneously recording the gradient waveforms. The 19 sequence-specific equation coefficients were obtained during an accelerated training versions (3-4 sec, GRAPPA = 6-8) of each sequence, which was followed by 3 cardiac cycles without imaging. A clean ECG template obtained during the non-imaging period was aligned and subtracted from ECG traces acquired during imaging, resulting in net gradient-induced voltages, which together with gradient waveforms was used to obtain the 19 coefficients for each ECG electrode. Full resolution imaging (GRAPPA=2) was then performed, with real-time subtraction of the computed gradient-induced voltages based on the 19 coefficients and simultaneously-recorded gradient waveforms. **Results** Measured induced voltages during SSFP imaging with the heart at isocenter were ~0.8V peak to peak in the left leg electrode (Fig. 1A), close to theoretical predictions [3]. Applying the response function during GRE, 3D FSE and multi-slice SSFP imaging (Fig. 2A-C) restored ECG traces with the majority of gradient induced voltages removed. Equation coefficients varied by subject, sequence and slice orientation (Fig. 3).

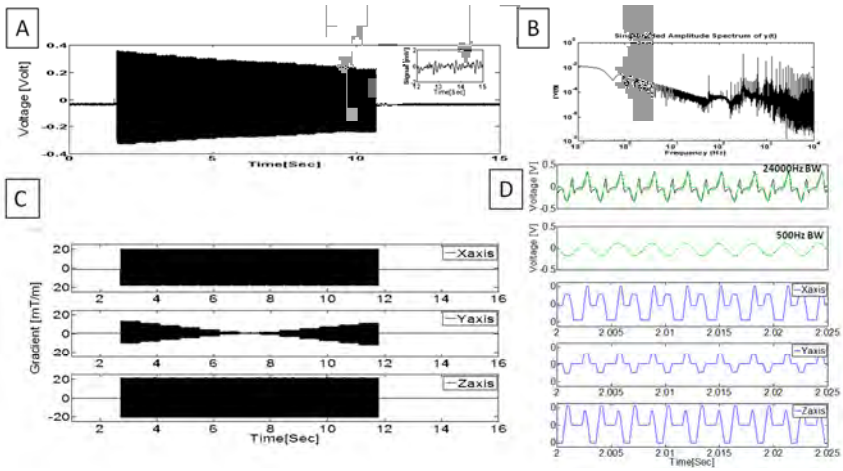

Figure 1 Full spectrum ECG traces recorded at a rate of 48 kHz during an axial bSSFP scan. (A) Voltages measured from the left leg limb lead. Inset showed 30Hz low-pass filtered ECG (in mV). (B) Spectral analysis from 0.1-10KHz. (C) Gradient waveforms recorded simultaneously. (D) Expanded induced voltages filtered below noted frequencies (black traces), overlaid on data fitted to the 19-parameter equation (green traces), and corresponding gradient waveforms (blue traces).

Discussion We have shown, for the first time, the complete amplitude and frequency spectrum of the induced voltages in 12-lead ECGs. The theoretically derived equation for the gradient-induced electric field closely fitted the observed induced voltages for the tested pulse sequences. The calculated 19 parameters varied among ECG electrodes, as predicted by the response function, and 2nd order coefficients playing a greater role in the electrode farther from magnet isocenter (data not shown).
Conclusion A system response function was derived for gradient-induced voltages observed in 12-lead ECGs during high-duty-cycle MRI sequences. A rapid training sequence permitted computing equation-coefficients, followed by real-time gradient-induced voltage removal during imaging.

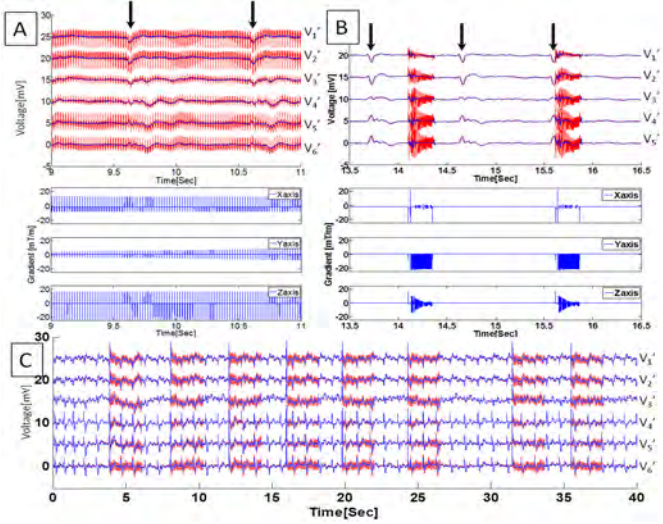

Figure 2 (Left) ECG signals acquired in volunteers recorded with CardioLab system during (A) a 20ms TR transverse GRE sequence , (B) a coronal 3D FSE sequence and (C) a multi-slice bSSFP full resolution acquisition right following leg exercises inside the scanner with heart rate dropping from 90 to 70 BPM. The top panel displays recorded traces (red) and restored traces using 19-parameter fit (blue) for the pre-cordial leads V_1'-V_6', and bottom panel shows the gradient waveforms recorded during the MRI acquisition. Black arrows indicate the QRS complex locations.

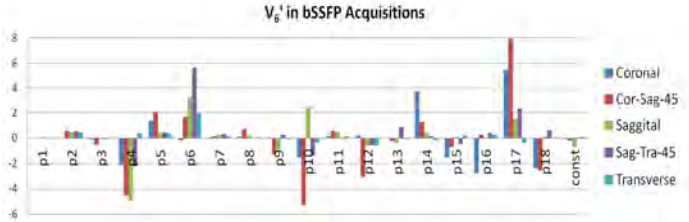

Figure 3. Variation of 19 fit parameters during bSSFP acquisitions along different slice planes in a volunteer. Cor-Sag-45 and Sag-Tra-45 designate 45-degree oblique angles between the Coronal and Sagittal, and Sagittal and Transverse orientations, respectively.

References [1] Tse, TH. *et al*, MRM '13, [2] Felblinger, J. *et al*. MRM , '99, [3] Bowtell R. *et al*, MRM. '00, [4] Bernstein MA.*et al*, MRM. '89.