Validation of an ECG Restoration Method Using a Linear Time-Invariant Model of Eddy Currents in Tissue

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Introduction: Factors such as the electrohydrodynamic effect, radio frequency pulses, and time-varying gradients can corrupt ECG waveforms in an MR environment. However, the factor that causes the most severe interference on ECG signals in an MR environment is time-varying magnetic gradients. Because gradients produce dramatic noise on an ECG signal due to their inducement of eddy currents in tissue, this presents a challenge for patient monitoring and cardiac gating. It has been proposed[1] that this noise can be removed by modeling the effect of the gradients on the ECG signal as a linear time-invariant (LTI) system. For a system to be considered LTI, it must demonstrate the properties of homogeneity and time-invariance and obey the superposition principle. Theory states that LTI systems are fully characterized by their responses to input delta functions. Therefore, if the impulse response of the system is known, any noise superimposed on the ECG as a result of the gradients can be predetermined and removed. The impulse response of the system is determined by the following:

$$H_x[n] = IFFT\left(\frac{FFT\ (S_{MR,x}[n])}{FFT\ (G_x[n])}\right) \quad \text{Eq. 1}$$

where $S_{MR,x}[n]$ is the digitized ECG signal recorded right after the gradient is applied, $G_x[n]$ is the digitized gradient waveform, FFT and IFFT are the fast Fourier Transform and inverse FFT, respectively, and $H_x[n]$ is the pulse response function of the system. This pulse response needs only to be computed once for each of the three orthogonal directions to account for the x, y, and z gradients for a given position of electrodes. The pulse response of the system ($H_x[n]$) is convolved with an arbitrary time-varying gradient ($G_x[n]$) to obtain the output signal contribution ($S_{MR,x}$) on the ECG waveform as a result of the applied gradient. This output signal is subtracted from the ECG waveform to remove the noise caused by this particular gradient. This process is repeated for each of the three orthogonal gradients used in a typical MR pulse sequence. Since the system is assumed LTI, the influence of one gradient can be removed independently from another orthogonal gradient. The goal of this paper is to verify the fundamental assumption of this technique: that the effect of the magnetic gradients on ECG waveforms can be modeled as a LTI system.

Methods: We simulated a delta function by applying a single short-duration trapezoidal gradient. The triggered gradient is applied during late diastole, an isoelectric interval in the heart cycle. Applying the gradient at this time allows for the isolation of eddy current effects on the ECG signal apart from the actual ECG signal itself. The resulting ECG signal recorded during this interval along with the time dependent gradient shape allows for the calculation of the impulse response by Eq. 1.

To verify the assumption that the system is LTI, we must verify the following properties: the output amplitude scales with the input amplitude (scalability), the output shifts in time with the input (time-invariance), and the principle of superposition holds. To test for scalability we applied triggered x-gradient pulses of amplitudes 4 mT/m and 8 mT/m, respectively. Taking the ration of peak values of the two waveforms should yield the ratio of gradient amplitudes if the output scales linearly with the input. To determine if the system is time-invariant, we applied two identical gradients with delay times of 400 and 450 msec, respectively from the onset of the R wave. The waveform acquired with the 450 msec gradient delay should be a time-shifted version of the waveform acquired with the 400 msec gradient delay. We subtracted the two waveforms and computed the mean and standard deviation of the result. The superposition principle holds for this system if the output waveform corresponding to two gradients close together in time equals the sum of individual waveforms acquired by applying single gradients. To test this we applied two triggered, short-duration x-gradients with a 50 msec interval between them. The corresponding ECG waveform should equal the sum of waveforms acquired with single applied x-gradients once the waveforms are properly registered in time and summed. All ECG signals were recorded using Siemens software built into the Avanto system and all waveform analysis was done using MATLAB.

Results/Discussion: Figure 1 shows three waveforms recorded when single gradients of different amplitudes were applied. The solid line represents an isoelectric waveform acquired with a gradient amplitude of zero, while the dotted and dashed lines were recorded after gradients of amplitude 4mT/s and 8mT/s were applied, respectively. These waveforms show the influence of eddy currents on the ECG caused by the gradients. It is evident that larger gradient amplitudes will induce stronger eddy currents and produce more noise on an ECG waveform. The scalability property seems to hold as the ratio of peak values in the two waveforms yields (1.63±0.34). The expected value of this ratio is two (the ratio of the input gradient amplitudes). Figure 2 shows the subtraction of two ECG waveforms with gradients applied at different times relative to the R wave. The system demonstrates time-invariance since the subtraction yields (0.00026± 0.04), which means the waveforms are equal, time-shifted versions of each other. Figure 3 shows that the system obeys the superposition property since the result of the subtraction is (0.05± 0.05).

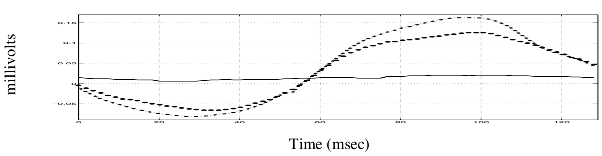

Figure 1–The solid line, dotted line, and dashed lines correspond to ECG waveforms acquired when the gradient amplitude was 0, 4 mT/m, and 8 mT/m, respectively.

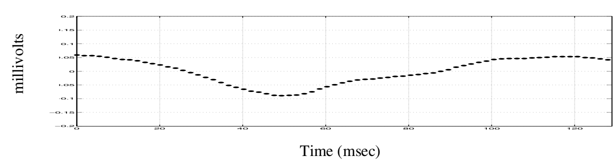

Figure 2- Time-invariance property test: The waveform acquired when the gradient was applied at 400 msec minus the waveform when the gradient was applied at 450 msec.

Conclusion: Our results show a strong indication that the superposition and the time-invariance properties hold for this system. There was strong evidence that the scaling property holds for this system, but we speculate that by performing a baseline correction to remove the true ECG signal in the waveform, the ratio of the peak values in the waveforms may closer resemble the ratio of the gradient amplitudes. Because this technique offers a promising way of removing gradient interference in ECG signals, it was important to verify its most fundamental assumption. We have evidence that modeling the system as LTI is appropriate and we wish to explore this technique further for use during our interventional MR procedures.

Reference: Felblinger J., Slotboom J., Kreis R., Jung B., Boesch C. Restoration of Electrophysiological Signals Distorted by the Inductive Effects of Magnetic Field Gradients during MR Sequences. Magnetic Resonance in Medicine 41: p 715-721 (1999).

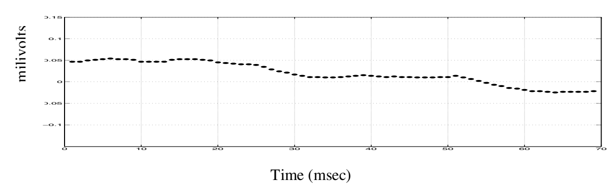

Figure 3- Superposition property test: The waveform acquired when two gradients were applied 50 msec apart minus the sum of individual waveforms acquired by applying single gradients.