Adaptive Filter Optimization of ECG Recordings during MRI-Guided Cardiovascular Interventions

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Introduction

MRI guided cardiac catheterization procedures offer a distinct advantage over traditional X-ray guided interventions due to an increase in soft tissue contrast and reduced patient exposure to ionizing radiation[1]. However, due to a hostile electromagnetic environment created by the rapid switching of magnetic gradients, hemodynamic signals are difficult to monitor and record accurately.

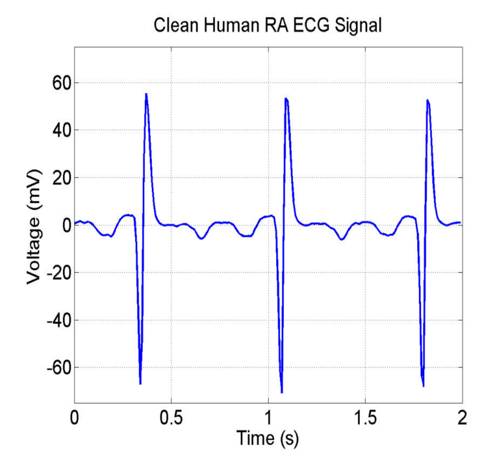

Figure 1. Clean right arm (RA) signal for a human ECG taken outside the bore of the magnet.

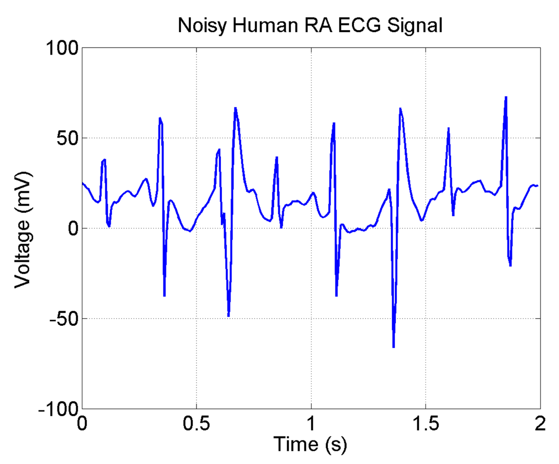

Figure 2. Noisy RA signal for a human ECG taken during a Real-Time MRI sequence with diffusion saturation.

These signals, including the ECG and invasive blood pressures, are important markers of patient health and provide valuable diagnostic information. Also, the QRS complex of the ECG is used to trigger some MRI sequences. Therefore, a system that can effectively eliminate noise induced from MRI sequences is necessary to allow for safe operations[2].

Objectives

- Reduce ECG noise through hardware and software solutions
- Identify noise present in different types of MRI sequences.
- Optimize the ability of a least mean squares adaptive filter to remove gradient induced noise through consideration of quality metrics.

Experimental Setup

ECG data was gathered from healthy volunteers and from anesthetized pigs undergoing experimental procedures. Electrodes were placed on the patients' chest to provide nine leads.

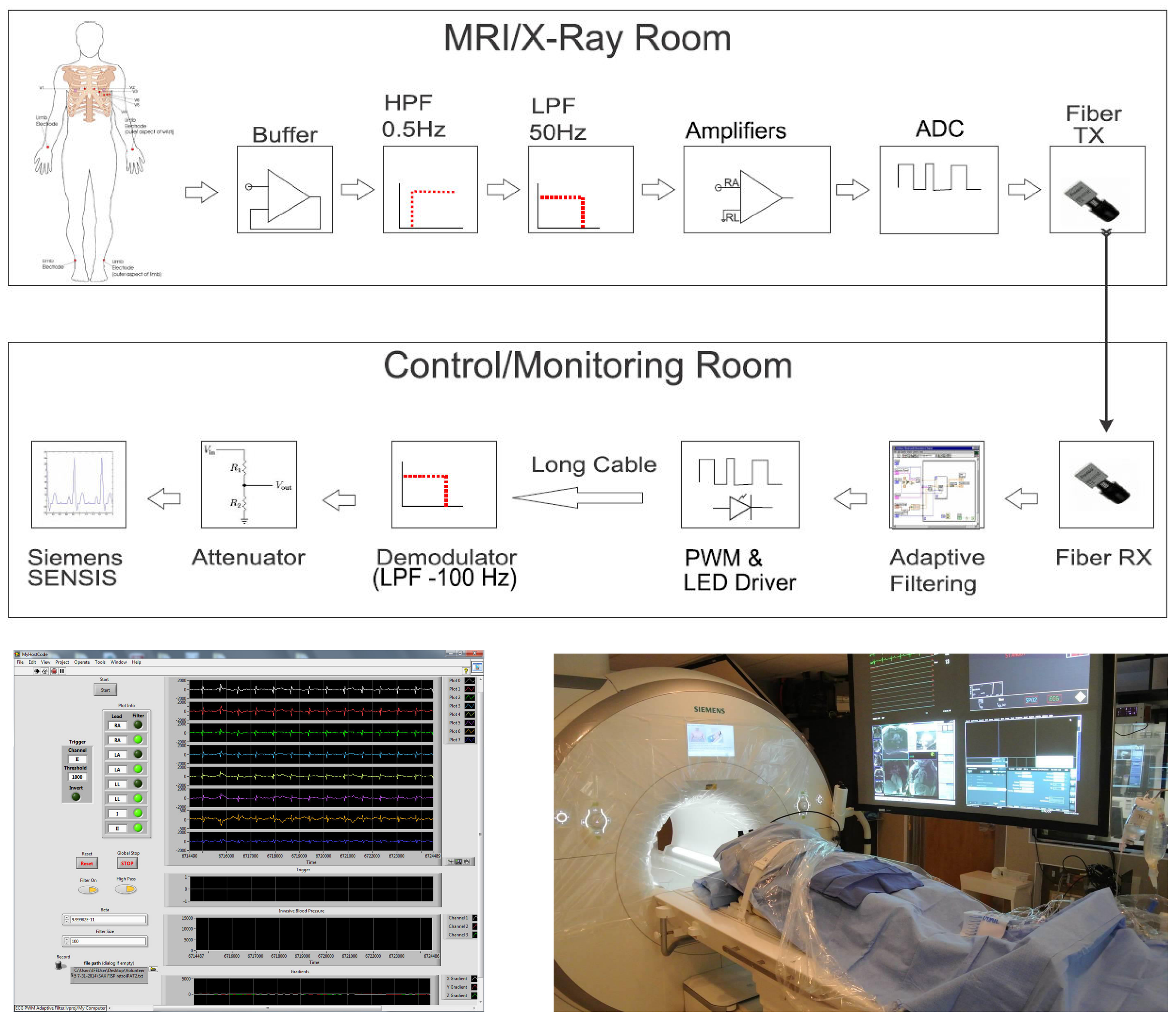

Figure 3. MRI/X-Ray room components were contained in a transmitting box that digitized the signal and sent it by fiber optic cable to a receiving box in the control room. Analog adaptively filtered signals were sent back from Labview to the Siemens SENSIS in the MRI room, which is a standard set of equipment for hemodynamic display during interventions.

Methods

- A series of different hardware solutions were attempted to reduce MRI generated noise. These included: moving the position of the transmitting box relative to the MRI bore, changing the gain on the input channels, and tuning the resistance to ground of the right leg electrode.
- A series of sequences common during cardiovascular interventions were recorded to evaluate the noise induced on the ECG. These included: Real-Time, Cardiac Cine, 3D Radial Whole Heart, HASTE, Flow, FLASH, and Cardiac Function sequences.
- Various quality metrics were examined to quantify the noise and optimize filter parameters. These included: Signal-to-Noise Ratio, QRS Power Ratio, Baseline Power Ratio, Cross Correlation Ratio, Coherence Ratio, Kurtosis, and Skew.

Results and Discussion

Hardware Changes

Noise present on the signals varied in magnitude corresponding to a change in the gain on the input channels. Additionally, increasing the resistance to ground on the right leg electrode reduced the DC voltage offsets that were apparent with each of the different gradient orientations.

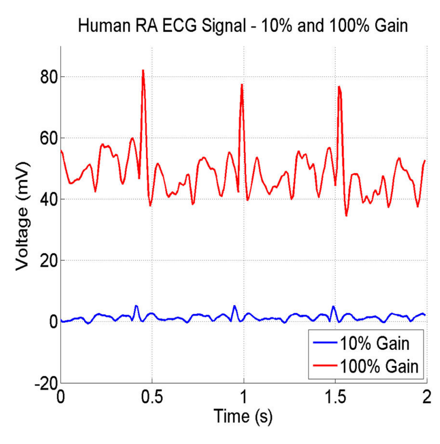

Figure 6. RA signals for a human ECG taken during a cine MRI sequence. Noise induced by the signal correlates to the value of the gain.

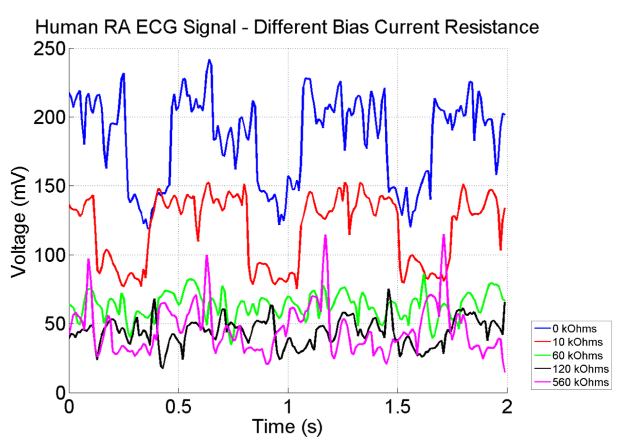

Figure 7. RA signals for a human ECG taken during a Real-Time MRI sequence. Noise induced by the gradients correlates to the resistor value for the right leg bias current to ground.

Induced Noise From Different Sequences

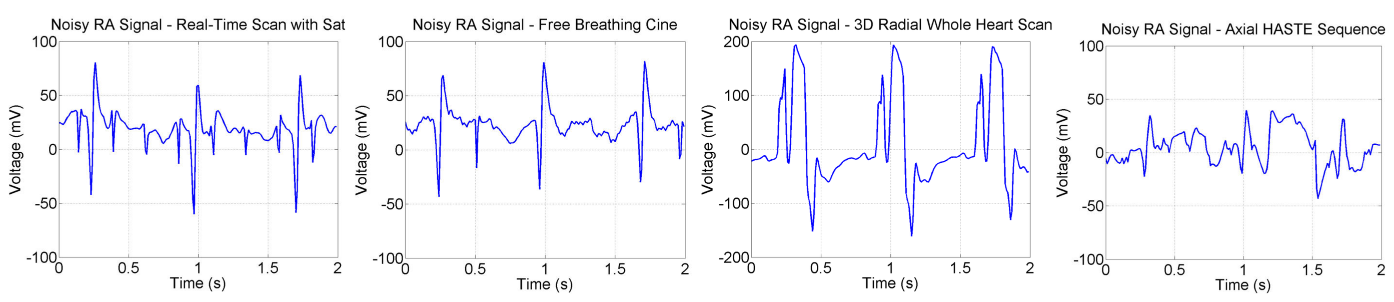

Figure 8. Noisy RA ECG signals during different MRI sequences are shown. Most commonly, the Real-Time sequence is run during catheterization to allow for visualization of catheter motion and position as it changes.

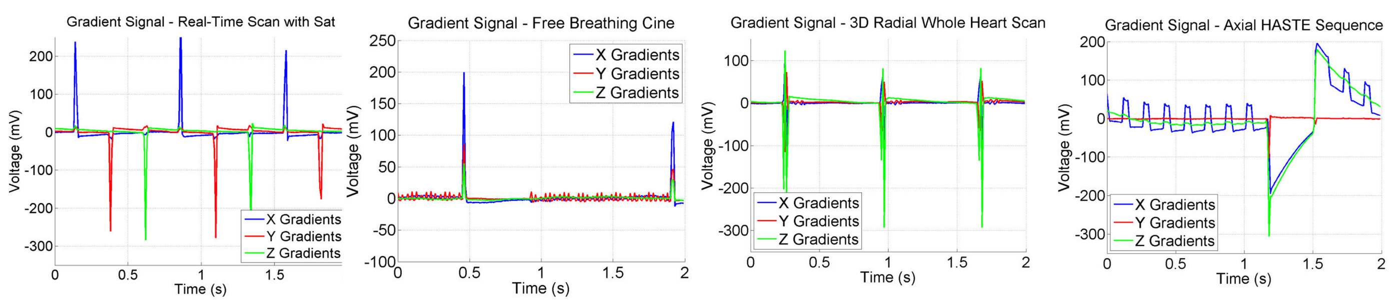

Figure 9. Gradient signals used by the different MRI sequences. Temporal positioning of spikes and rapid changes on the gradient signals correlate strongly with the temporal position of noise induced on the ECG signals. The magnitude of the induced noise makes identification of the QRS complex for triggering and heart rate monitoring difficult.

Quality Metrics

Different weighting values and filter sizes were tested for each signal to determine what parameters were optimal for the peak performance of the adaptive filter.

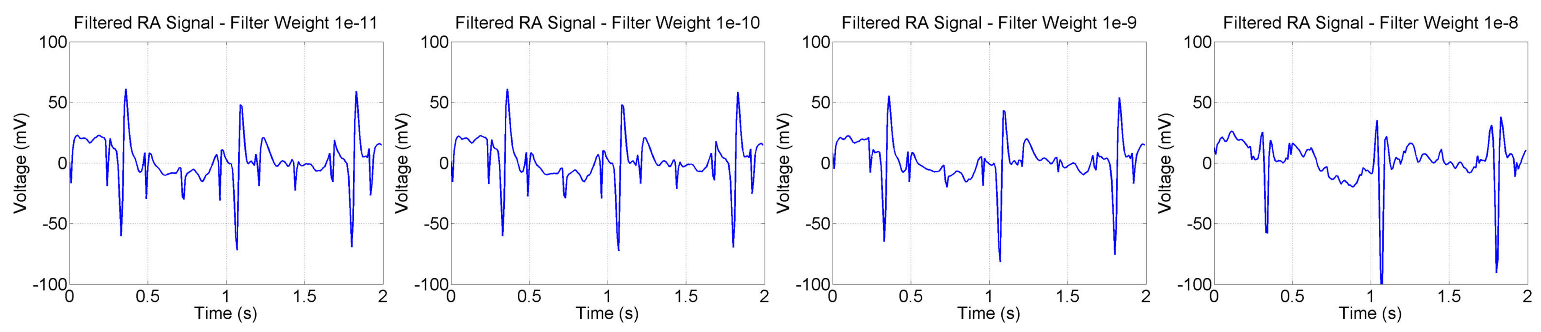

Figure 10. Filtered RA ECG signals with different filter weights during the adaptive filtering step while the Real-Time Sequence is running. Noise spikes from the magnetic gradients are reduced to a greater degree with higher weights. Too much weighting can cause the filter to remove actual signal and distort the waveform.

Seven different quality metrics were tested for each sequence with the best indicators of quality decided as Signal-to-Nosie Ratio, QRS Power Ratio, and Cross Correlation Ratio of the signals. Different metrics used in concert help choose a specific value for each parameter based on inflection points and peaks.

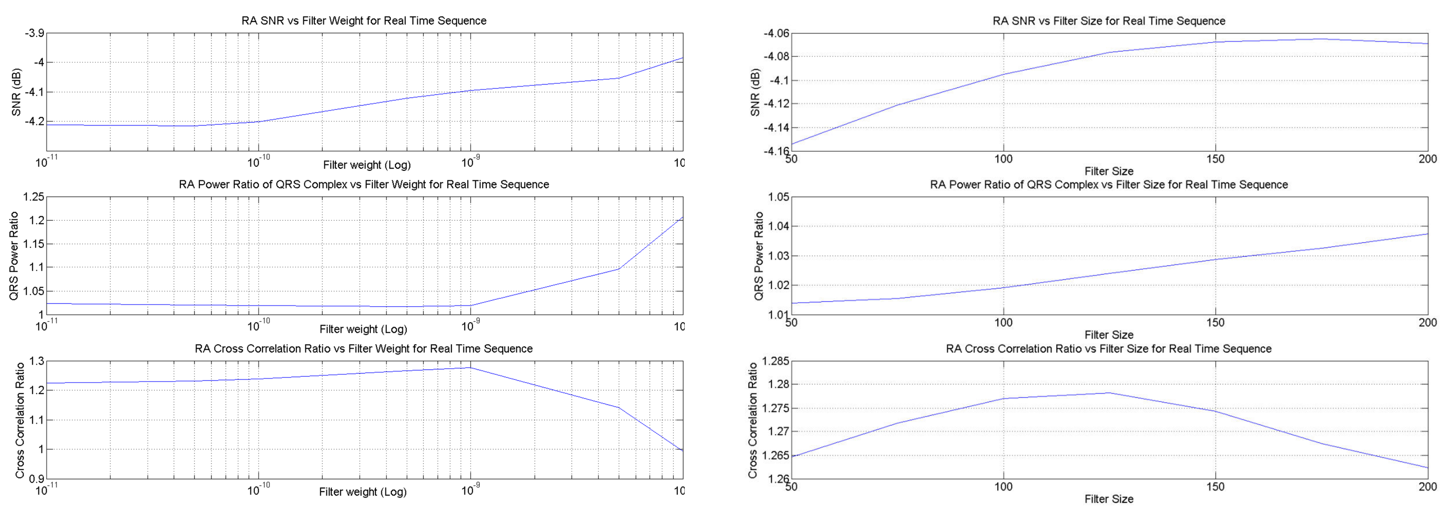

Figure 11. Quality metrics plotted vs filter weights and filter sizes. Weighting value of 5e-9 and filter size of 125 were chosen as most effective.

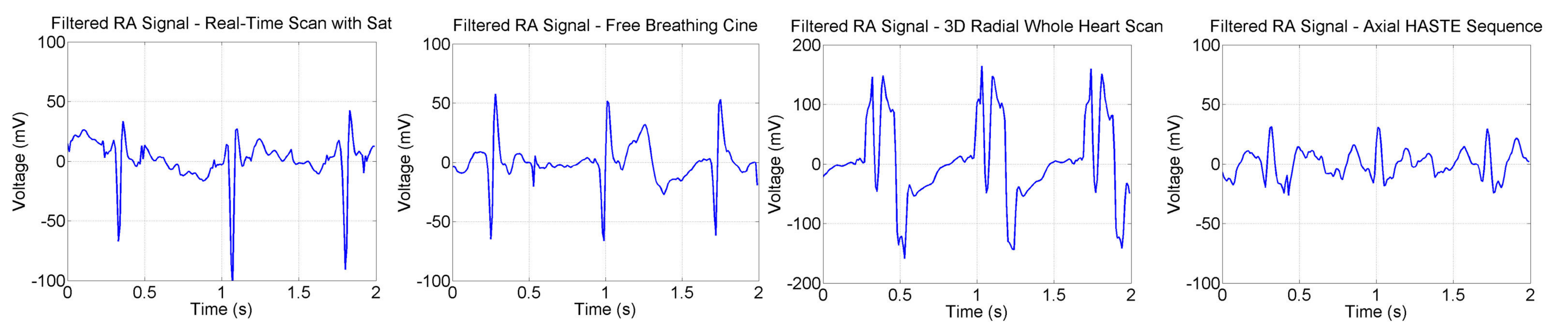

Figure 12. Filtered sequences from Figure 8. Adaptive filtering was effective in removing noise from most sequences (Real-Time Scan, Free Breathing Cine, and Axial HASTE Sequence), though the some of the signals are still distorted by the gradients (3D Radial Whole Heart Scan).

Conclusions and Future Work

- Hardware setup for initial measurement of noisy ECG signals was improved with higher resistance to ground and longer leads to keep transmitting components away form MRI bore.
- Because of the noise amplitude change when the gain changed, it was evident that the gradients were primarily inducing noise on the inputs, making the noise a filtering issue rather than a shielding issue.
- Amount of noise generated by different sequences was examined, with the 3D Radial Whole Heart Scan inducing the most noise according to SNR.
- Real-Time sequence noise was successfully reduced to allow for reliable recognition of QRS complex.
- Future studies will compare induced noise across patients and implement the hardware setup at a second testing site.

Acknowledgements

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1.Saikus, Christina E., and Robert J. Lederman. "Interventional cardiovascular magnetic resonance imaging: a new opportunity for image-guided interventions." *JACC: Cardiovascular Imaging* 2.11 (2009): 1321-1331.
2.Ratnayaka, Kanishka, et al. "Real-time MRI-guided right heart catheterization in adults using passive catheters." *European heart journal* 34.5 (2013): 380-389.