Improved ECG triggering with the *T-wave Terminator*

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INTRODUCTION. MR imaging of the heart and thoracic vessels requires ECG gating to compensate for cardiac motion. Triggering is accomplished by synchronizing the image acquisition pulse sequence to the R-wave of the ECG. However, the magnetic fields within the bore of the scanner can cause artifacts in the ECG waveform which result in gating errors. In addition, small variations in electrode position on the thorax can result in an unusable ECG signal.

Despite recent technical advances that have improved ECG signal quality, including fiber-optic cables, radiofrequency filtering, and carbon fiber electrodes, establishing reliable gating in the clinical realm is often problematic. In particular, patients with congenital heart disease, ischemic or hypertrophic cardiomyopathy, or who have undergone thoracic surgery, often manifest alterations in the directions and relative magnitudes of the R and T waves that yield high voltage T-waves once placed inside the bore of the magnet (Figure top and middle).

In order to improve ECG gating reliability, we designed and constructed hardware to selectively suppress the T-wave in the ECG waveform and evaluated it in human subjects. We call the device the *T-wave Terminator (TwT).*

METHODS. The *TwT* was designed by modeling the effect of varying filtering circuits on the ECG waveform using simulated data and simulated noise from blood flow artifacts. Analysis was performed with ICAP/4 software program (Intusoft Inc., San Pedro, CA). Based on the results of this software simulation, a standard ECG bandpass filter (bandpass range of 0.67Hz to 40Hz) was combined with an additional single pole high pass filter which preferentially suppresses frequencies below 10 Hz (3dB down). This combined filter was inserted into a fiber optic transducer FOX™ module (Magnetic Resonance Equipment Corp., Bay Shore, NY). The output signal was fed back into the MR system signal processor.

We prospectively recorded ECG strips on 12 consecutive patients (ages 4 - 51 years) while on the gurney under 4 conditions: inside and outside the magnet bore, with and without the *TwT*. All patients were undergoing cardiac MRI at our institution for clinical evaluation of congenital heart disease. The patients were imaged with a torso phased array coil on a 1.5T Horizon LX (GEMS). In addition, 3 normal adults volunteers underwent cardiac MRI with ECG leads placed high on the left chest to simulate elevated T-waves. The volunteers were scanned with ECG gating with the FOX™ module with and without the *TwT*, with a spin echo pulse sequence with respiratory compensation (256 x 192 matrix; 2 NSA; TR = 1 RR; TE = 20ms). Gating accuracy was assessed by counting the number of false positive (triggering on the T-wave) and false negative (missed beats) events. The additional time (beyond calculated time) required to complete the scan was recorded.

For the 12 patients, the R-wave height and the height of the highest peak other than the R-wave (T-wave) above the ECG baseline were measured in three consecutive beats and a mean R-wave to T-wave ratio was calculated. The baseline was determined from the tracing outside the bore of the magnet. Mean R-wave to T-wave ratios were compared using the two-tailed, paired student t-test.

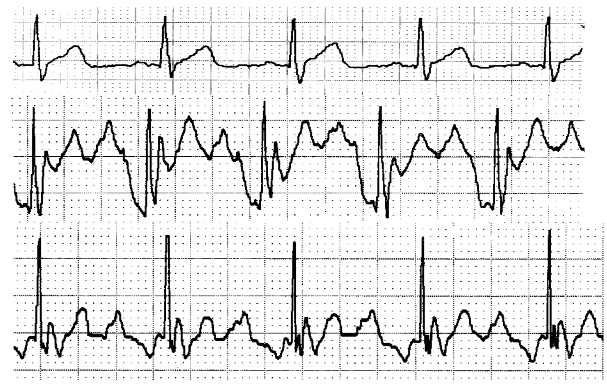

Figure 1: ECG from patient with congenital heart disease in the MR scanner, outside of magnet bore (top), inside the magnet bore with standard FOX™ module (middle), and inside the magnet bore with TwT (bottom).

RESULTS. While in the magnet bore, the R-wave to the T-wave ratio was significantly greater with the T-wave terminator (4.0 versus 2.3, $p = 0.01$). In fact, in all patients the *TwT* reduced the ratio. Using the *TwT*, gating was successful and diagnostic quality images were obtained in all patients. In 4 of 12 patients the T wave was greater than 70% of the R wave with the standard FOX™, versus in none of the patients using the *TwT*. No additional adjustments of the ECG electrode positions were required after switching to the *TwT.*

The *TwT* performed better than the standard filter in all three volunteers with altered lead placement to simulate tall T waves. In the 3 volunteers with the standard FOX™ the mean false positive rate was 46.3 beats versus 5 beats with the *TwT.*

DISCUSSION. Use of the *TwT* resulted in a significant increase in the R/T ratio and was necessary for successful gating in at least 2 patients. Moreover, its use in volunteers with simulated increased t waves, clearly resulted in superior gating.

Frequently 10 to 20 minutes of technician and physician time are required at the beginning of a cardiac MR study to optimize the ECG signal and ensure that the gating is adequate. This optimization process often involves changing the electrode positions, which requires moving the patient out of the scanner and readjusting the coils and the landmarks, further delaying the start of the exam. Consequently, use of the *TwT* may significantly reduce the total exam time as well as the associated frustration of the technicians and the physicians. Moreover, the improved ECG signal from the *TwT* should reduce the number of false positive and false negative triggers leading to shorter scanning time and improved image quality by eliminating artifacts from unsynchronized heartbeats.

Further improvements in triggering may be accomplished by using a more sophisticated R-wave detection algorithm. This may reduce the delay from the actual R-wave to the creation of the trigger pulse, which may enable images to be acquired closer to end diastole.

CONCLUSION. A new bandpass filter was added to a fiber optic ECG gating circuit which significantly improves the ECG waveform and subsequent gating during cardiac imaging.