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Electrical Noise in the Intraoperative Magnetic Resonance Imaging Setting

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Abstract

Background—Intraoperative magnetic resonance imaging (iMRI) is a tool now commonly used in neurosurgery. Safe and reliable patient care in this (or any other) operating room setting depends on an environment where electrical noise (EN) does not interfere with the operation of the electronic monitoring or imaging equipment. In this investigation, we evaluated the EN generated by the iMRI system and the anesthesia patient monitor used at this institution that impacts the performance of these 2 devices.

Methods—We measured the EN generated by our iMRI-compatible anesthesia patient monitor as detected by the EN analysis algorithm in our iMRI system. We measured the EN generated by our iMRI system during scanning as detected in the electrocardiogram (ECG) waveform of our patient monitor. We analyzed the effects on EN reduction and signal quality of the ECG noise filters provided in our iMRI-compatible anesthesia patient monitor.

Results—Our patient monitor generated EN that was detectable by the iMRI EN analysis algorithm; however, this interference was within the iMRI manufacturer's acceptable limits for an iMRI scan (<10% more than background system level noise). In the clinical case analyzed, the iMRI generated a narrow-band low-frequency (20Hz) relatively high-energy EN that interfered with the ECG signal of our patient monitor during an iMRI scan. This EN was correlated with the acoustic noise from the iMRI system during the scan and was associated with the radio frequency and magnetic gradient pulsations of the iMRI system. The integrity of the ECG waveform was nearly entirely lost during a scan. The filters of the ECG monitor diminished but did not entirely eliminate this 20Hz interference. We found that the filters alter the morphology of the ECG signal, which may make it difficult to identify clinically relevant ECG changes.

Conclusion—The EN generated by our anesthesia patient monitor is within acceptable limits for the iMRI system. The iMRI generates EN which renders the ECG unreadable in the most commonly used filter mode. The monitor's filters diminish this noise but also alter the morphology of the ECG waveform. The anesthesiologist must be cognizant of these technical compromises and recognize that adjusting the ECG filters on the monitor is required to obtain a useful ECG signal

for patient monitoring during the iMRI scan but that the diagnostic value of the ECG will be reduced.

Introduction

Intraoperative magnetic resonance imaging (iMRI) in neurosurgery presents new challenges for operating room (OR) personnel and particularly for the anesthesiologist in monitoring the neurosurgical patient. Essentially all electronic devices in the OR today are microprocessor-based. These devices can emit spurious low-energy electrical noise (EN) in the megahertz or gigahertz region of the radio frequency (RF) spectrum that can interfere with the operation of other electrical equipment, including an electrically-sensitive iMRI system. One of the largest challenges for the anesthesiologist is coping with the high-energy iMRI-generated EN. An iMRI system, by design and function, generates pulsating high-energy RF signals and pulsating magnetic field gradients in order to capture a useful anatomic image (1). The RF generator operates in the megahertz region of the RF spectrum and, by itself, can emit EN in the form of electromagnetic energy that can interfere with the operation of electronic patient monitors. The RF signal and the magnetic gradients of an iMRI system are pulsed, during a scan, at a frequency dependent on the specific imaging pulse sequence type and the variables used. The sequences used for iMRI typically apply gradient and RF pulses at rates $<100\text{Hz}$, but pulsing in some rapid imaging sequences can exceed 1000Hz (2). These pulsations can generate a second EN component in the frequency bandwidth of most monitored physiologic signals. In the neurosurgery suite that uses an iMRI system, the anesthesiologist must be able to effectively monitor a patient in the presence of EN from the iMRI when he/she does not have direct visual contact with the patient for an extended period of time.

This experiment was designed to evaluate the EN generated by both the patient monitor and the iMRI system and determine the manner in which the noise generated by each device affects the other.

Materials and Methods

Clinical Equipment

We use a PoleStar N-20 iMRI system (Olin Medical Technologies, Inc./Medtronic Navigation Systems, Louisville, CO, USA) in our neurosurgical OR. This device is a low-field, 0.15T , iMRI unit. The technical specifications of the unit are given in Table 1.

Our iMRI system includes a portable extendable EN shield (StarShield, Medtronic Navigation Systems, Louisville, CO, USA) that accords over and completely encloses the patient during a scan and retracts during surgery. The EN shield is designed to prevent externally radiated EN energy from disturbing the iMRI scan, in a functional manner similar to a Faraday cage. It is also intended to shield external electronic equipment from the high-energy (5KW) RF and magnetic gradient pulses generated by the iMRI system during an imaging scan.

We use a Veris MR (MEDRAD, Inc., Indianola, PA, USA) iMRI-compatible anesthesia patient monitor for iMRI neurosurgical cases. This monitor is designed for use with iMRI units up to 3T field strength. This unit monitors a 5-lead electrocardiogram (ECG), pulse oximetry (plethysmograph), 2 invasive arterial blood pressures, a noninvasive arterial blood pressure, respiratory carbon dioxide, respiratory oxygen, nitrous oxide and the inhaled anesthetic drugs and 2 body-surface temperatures. The monitor uses fiberoptic leads to transmit the ECG, pulse oximetry and body temperature signals to the monitor. For the ECG, however, the Veris MR monitor requires short electrical leads to connect the electrodes on the patient to a battery-powered fiberoptic converter box located immediately adjacent to the patient. The Veris MR monitor has both a main and slave unit. Each unit displays virtually identical patient waveforms and metrics.

The Veris MR monitor uses 4 EN ECG filters pairs, for a total of 8 possible filter settings. The filters in each pair have similar electrical characteristics with the exception that one filter in each pair has a t-wave suppression component to prevent an elevated t-wave from being counted in a heart rate calculation. Table 2 discloses the characteristics and usage of the filters as specified by the monitor manufacturer.

Testing Procedures

We measured the EN generated by the Veris MR main and slave monitor as detected by the PoleStar iMRI system noise analysis algorithm. We attached ECG electrodes and the pulse oximeter finger probe to a volunteer who then laid on the OR table with the iMRI magnet, receiving antenna, associated hardware and EN shield in place for scanning. The volunteer was not scanned in these tests. Each noise measurement trial consisted of powering on the main and slave monitors in random mode succession: Mode 1=both monitors powered off and disconnected from the electrical power source; Mode 2=main monitor powered on; Mode 3=main and slave monitors powered on. For each mode of each trial, we made 20 noise measurements with the iMRI system noise analysis algorithm. Ten trials were performed. The 20 noise measurements for each mode in each trial were averaged and then the corresponding average mode measurements were averaged across the 10 trials. We tested the resulting data for normality and analyzed the data with an ANOVA statistic and appropriate *post hoc* testing (SigmaStat, Systat Software, Inc., Point Richmond, CA, USA) with the alpha error set *a priori* at $p=0.05$.

We measured the noise generated by the PoleStar iMRI system during a scan procedure as detected by the Veris MR patient monitor. With institutional approval and written informed patient consent, we recorded the analog waveforms from the Veris MR monitor just prior to and during an iMRI scan on patients undergoing craniotomies for tumor resection. We attached to the patient the Veris MR monitor probes and electrodes for the parameters of interest in this study: ECG, one invasive blood pressure, pulse oximeter, and respiratory CO₂. The patient was anesthetized, positioned and prepped for surgery in the normal clinical manner. The iMRI magnet and EN shield were positioned for a scan. Just prior to scanning, we recorded all analog waveforms from the Veris MR monitor. We repeated these recordings during the scan. In our analysis, we compared prescan and scan data to establish the EN content of the data contributed by the iMRI system. This included fast Fourier transform

(FFT) analysis of the ECG waveforms to delineate the magnitude and frequency of the noise. In addition, we recorded the acoustic noise in the OR during the scan. Patient data were recorded in all 8 ECG filter modes (Table 2).

We examined the 8 ECG filtering modes (Table 2) on the Veris MR monitor by connecting a signal generator (Model 184, Wavetek, San Diego, CA, USA) to the left leg lead (positive) and right arm lead (negative) and recording the sinusoid input and output waveform from lead II of the Veris MR monitor over a 0.1Hz through 60Hz frequency range for each filter. The outputs were then normalized to the input signal. The amplitude frequency response of each filter was constructed from the resulting data.

Additionally, we connected a simulated 60 bpm ECG signal from an ECG simulator (Medsim 300, Dynatech Nevada Inc., Carson City, NV, USA) to the Veris MR patient monitor and recorded the input ECG signal along with the resulting output ECG signal from each monitor filter. We cross-correlated the output signals with the input signal in order to delineate the effect of the filters on the morphology of the ECG signal.

In these experiments 8-second long analog waveforms (1,024 samples/waveform) were recorded with a USB-compatible analog-to-digital converter (USB-6008, National Instruments Corporation, Austin, TX, USA), sampling at 128Hz, and a custom software program written in LabVIEW (Version 8.2, National Instruments Corporation). All frequency analyses of these signals were performed after removing the mean amplitude value from the signal and after windowing the signal with a Hanning (cosine square) window function. Acoustic noise was recorded using Microsoft Windows XP sound recorder, sampling at 22kHz, and analyzed with a custom LabVIEW program. All signal manipulations and FFT analyses were performed in Microsoft Excel. Cross-correlation analyses were also performed in Microsoft Excel.

Results

EN Generated by the Veris MR Monitor

Figure 1 discloses the EN generated by the Veris MR monitor as detected by the iMRI noise analysis algorithm. According to the manufacturer, the iMRI acceptable noise limit is 10%. This noise figure is calculated by the algorithm as the percent difference between the measured noise and the typical iMRI internal system noise. Any interference above the typical internal system noise level is assumed to be emanating from sources external to the iMRI system. The manufacturer, in its testing, has set 10% as the noise upper limit for an acceptable quality clinical image. The overall noise contributed cumulatively from all sources other than the Veris MR monitor (Mode 1) was within the manufacturer's 10% specifications (Figure 1). The Veris MR monitor main and slave units added to the cumulative noise figure (Mode 2 and 3) measured by the iMRI noise algorithm, but the total magnitude of the noise was within the iMRI manufacturer's specifications and therefore not likely to unacceptably reduce image quality.

EN Generated by the iMRI During Scanning

There was no iMRI system-generated EN measurable in the Veris MR monitor's blood pressure, plethysmographic, respiratory CO₂ or agent signal during an iMRI scan. Our analyses, therefore, concentrated on the ECG signal. The iMRI added a substantial amount of EN to the ECG signal. The description and characteristics of this interference are detailed below.

Figure 2a discloses the EN generated by the iMRI system, in the time domain, as detected in the Veris MR monitor's ECG waveform during the scan of 1 of our patients undergoing a T1 3.5min 4mm scan. Figure 2b shows these signal tracings in the frequency domain after FFT analysis. These figures show 8-second time-domain tracings and corresponding frequency-domain representations of a patient's ECG signal just prior to the iMRI scan (prescan) and during the scan for all filter modes. For the case shown, the iMRI generated a high-amplitude narrow-band noise component with a 20Hz fundamental frequency and with a measurable harmonic at 40Hz (see the tracing in the Monitor and MR4 filter modes). The harmonic was filtered out by the MR1-MR3 and MR5-MR7 filters but the 20Hz fundamental component remained as a contaminating component of the ECG signal. This EN was detectable in all ECG leads, but its amplitude varied from lead to lead and from filter to filter. In the worst case, the noise masked all but the ECG r- and s-waves. The sound recording of the iMRI scanning process correlated with the EN seen in the ECG waveform. There was a measurable 20Hz signal component in the acoustic sound recording (Figure 3).

Black-Box Analysis of the Veris MR ECG Filters

The exact ECG filter designs used in our monitor are proprietary. However, we measured the amplitude frequency response of the Veris MR filters in order to establish some understanding of the filters' effects on the ECG signal. Figure 4a discloses the amplitude frequency response (gain) of the filters without t-wave suppression (Monitor mode and MR5-MR7). MR6 and MR7 filter modes are relatively similar and have the narrowest pass band: most amount of filtering. Monitor and MR5 both show a wider frequency response with Monitor having the widest passband: least amount of filtering. Their corresponding filtering modes with t-wave suppression (MR1-MR4), in Figure 4b, have similar passbands as their non-t-wave suppression partners. The filters with narrower frequency responses, MR1, MR2, MR6 and MR7, exhibit a recording with relatively higher amplitude. The t-wave is a relatively low frequency component of the ECG signal. We see that the t-wave suppression filters (MR1-MR4, Figure 4b) have a higher low-frequency cutoff point than the equivalent filters with no t-wave suppression (Figure 4a).

Figure 5 discloses the effect of the ECG filters on a simulated 60 bpm ECG signal in the absence of EN from the iMRI, viewed in the time domain. We see that the filters change the relative morphology of the ECG waveform, particularly in the t-wave suppression filter modes. As expected, the t-waves are diminished in these filter modes. Quantitatively, the filters' morphology effect is evident in Figure 6 which discloses the cross-correlation of the filter signal outputs with the simulated signal input. The output signals from the non t-wave suppression filters are not well correlated with the input signal, which indirectly indicates that rhythm of the filtered signals vary to some degree from the rhythm of the input signal.

Discussion

EN is an important factor for the anesthesiologist to consider when using an iMRI system and anesthesia monitoring equipment because EN adversely affects the operation of these devices. The first section of this study shows that EN from our patient monitor adds to the total noise measured by our iMRI system but that with properly designed shielding to separate the patient from external noise sources, this EN is well within the iMRI manufacturer's specifications for producing a quality image.

We have demonstrated that EN generated by the iMRI system during a scan interferes with the ECG signal of our patient monitor. The iMRI system generates 2 pulsating signals during a scan. The first signal is an RF pulse which functions to orient protons in the subject's body, which are aligned in the static homogeneous field of the permanent magnet, so that they are perpendicular to the receiving coil of the iMRI. In the neurosurgery setting, the receiving coil is located on the head of the patient undergoing a craniotomy. This coil receives the signals from which the anatomical image is constructed. The second pulsating signal is a dynamic magnetic field gradient that is superimposed on the static permanent magnetic field. This pulsating gradient controls the frequency of proton oscillation (2). These RF and gradient pulses are typically applied at a rate of <100Hz, which is within the frequency range of most monitored physiologic signals, including the ECG signal. These pulses are the source of the EN seen in the ECG signal described in this paper.

The acoustic noise delineated in this study is a well-known unavoidable phenomenon of a MRI system, including the iMRI system (3,4). The acoustic noise is generated by Lorentz forces produced by the pulsing magnetic gradients. These forces cause vibrations in the gradient coils, which surface as periodic audible broadband chatter (4).

We can speculate on the entrance point of the EN into the ECG monitoring system. It is possible that the pathway taken by the heart's electrical signals traveling to the peripheral ECG electrodes are being affected by the pulsed change in proton orientation in the heart caused by the pulsating RF energy. The EN then would be in the signal detected by the ECG electrodes. Since our iMRI is focused on the patient's head and is not a whole-body imaging system, this is probably not the explanation for the EN. A more likely entrance point of the EN into the ECG signal is through the short electrical wires connecting the ECG electrodes to the fiberoptic converter box in our monitoring system. These wires act as receiving antennas. The magnetic field gradient pulsations will induce an EN current in these electrical leads that will propagate to the patient monitor.

Our results show that the ECG filters have different effects on the ECG waveform during iMRI scanning that both help and hinder the integrity of the ECG signal. None of the filters in our monitor completely eliminate the EN. All filters affect the morphology of the ECG signal. Although a clinical investigation would need to be conducted to determine how this change in ECG morphology affects the identification of cardiac anomalies such as ischemia, bundle branch blocks or atrial fibrillation, we suspect that the morphology would be changed enough to make these diagnoses more difficult. However, without the use of filters during an iMRI scan, virtually all information in the ECG rhythm is lost to the anesthesiologist.

iMRI presents a unique challenge for the anesthesiologist in his/her clinical practice. It constitutes one of the few situations in which the anesthesiologist completely loses visual contact with an anesthetized patient for an extended period of time (often >15 minutes), when the patient is enclosed in the EN shield during a scanning procedure. During this period, the anesthesiologist must rely entirely on monitored physiologic variables to evaluate the status of the patient. The anesthesiologist must be cognizant of this monitoring challenge and adjust the filtering of the ECG signal to achieve the best compromise between minimized EN and maximized signal quality to achieve an acceptable level of anesthesia patient monitoring safety in the iMRI environment.

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Implication Statement

Electrical noise during intraoperative magnetic resonance imaging interferes with electrocardiographic (ECG) monitoring. Filters can reduce the impact of the interference on the ECG but diagnostic features may still be obscured.

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Figure 1.

Noise generated by the Veris MR patient monitor as detected by the intraoperative magnetic resonance imaging (iMRI) noise algorithm.

Figure 2.

Electrocardiographic (ECG) tracing of a patient's lead II ECG waveform data prior to (prescan) and during a T1 3.5 min at 4mm iMRI scan in each of the eight Veris MR ECG filtering modes (Monitor, MR1-7). a) time-domain tracings; b) associated frequency-domain representation of the signals. The data show a predominant 20Hz signal that is induced on the ECG leads by the iMRI system.

Figure 3.

Acoustic record of the intraoperative magnetic resonance imaging (iMRI) T1 scan depicted in Figure 2. The data show an audible 20Hz sound component which is readily heard during an iMRI scan.

Figure 4.

Results of amplitude frequency analysis of the Veris MR monitor filters. a) output from Monitor and MR5-MR7 filters with no t-wave suppression; b) output from MR1-MR4 filters with t-wave suppression. The filters with t-wave suppression filter out low-frequency components of the electrocardiographic (ECG) signal.

Figure 5.

Electrocardiographic (ECG) time-domain tracing of a simulated 60 beat/minute lead II ECG waveform. The data demonstrate the relative change in ECG signal morphology caused by the monitor's filters.

Figure 6. Electrocardiographic (ECG) monitor filter output crosscorrelations with a simulated 60 bpm ECG input signal.

Table 1

Medtronic Navigation Systems PoleStar N-20 iMRI System Specifications.

Variable	Description/Value
Magnet Type	Permanent, open, portable and compact
Aperture	27cm
Field of view (FOV)	20×16cm
Magnetic field strength	0.15T
5 Gauss line	7.2ft
Gradient Strength	25mT/m
RF transmission power	5kW

RF = radio frequency

Table 2

MEDRAD Inc. Veris MR ECG Filter Characteristics. There are 4 pairs of filters, giving a total of 8 possible filter settings. The filters in each pair have similar characteristics except that 1 filter in each pair has a t-wave suppression component.

MEDRAD Suggestion for Filter Use	* T-Wave Suppression	No T-Wave Suppression
General Filter	MR4	Monitor
** Light Grass Filter	MR3	MR5
Spike Filter	MR2	MR6
Heavy Grass Filter	MR1	MR7

* T-wave suppression should be used as necessary

** Spike Filters and Heavy Grass Filters may also be adequate