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Origin of the Radio Frequency Pulse Artifact in Simultaneous EEG-fMRI Recording: Rectification at the Carbon-Metal Interface

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Abstract

Simultaneous electroencephalograph-functional magnetic resonance imaging (EEG-fMRI) recording has become an important tool for investigating spatiotemporal properties of brain events, such as epilepsy, evoked brain responses, and changes in brain rhythms. Reduction of noise in EEG signals during fMRI recording is crucial for acquiring high-quality EEG-fMRI data. The main source of the noise includes the gradient artifact, the radio frequency (RF) pulse artifact, and the cardiac pulse artifact. Since the RF pulse artifact is relatively small in amplitude, little attention has been paid to this artifact, and its origin is not well understood. However, the amplitude of the RF pulse artifact fluctuates randomly even if a very high EEG sampling rate is used, making it more salient than the gradient artifact after postprocessing for noise removal. In this paper, we investigate the cause of the RF pulse artifact in EEG systems that use carbon wires.

Index Terms

Carbon; electroencephalography; electromagnetic radiative interference; magnetic resonance imaging (MRI)

I. INTRODUCTION

Simultaneous EEG-fMRI recording is a method for measuring electrophysiological and hemodynamic activities in the brain from the same experimental runs. It has become an important tool for investigating spatiotemporal properties of brain events, such as epilepsy [1], event-related brain activities [2], and changes in brain rhythms [3] (see [4] for a review). Reduction of noise in EEG signals during fMRI recording is crucial for acquiring high-quality EEG-fMRI data. The main sources of the noise include rapidly changing gradient

fields, radio frequency (RF) pulses, and pulsative flow of the blood in synchrony with the cardiac cycle. The waveforms of the gradient and RF pulse artifacts have been assumed to be regular, repeating a near identical waveform for each image acquisition. Therefore, gradient and RF pulse artifacts are often removed by the average waveform removal method and its variants [5]–[7].

Since the RF pulse artifact is relatively small in amplitude compared to the gradient induced artifacts, little attention has been paid to this noise source, and the origin of the artifact has not been previously studied. However, the amplitude of RF pulse artifact fluctuates randomly, making it more salient than the gradient artifact after post-processing for noise removal [8]. In this paper, we investigate the cause of the RF pulse artifact in EEG systems that use carbon wires. Carbon materials are suited for use in high field MR compatible EEG systems because they cause less imaging artifacts [9] and RF heating [10] than metallic components. Since the frequency of the RF pulse is much higher than usual EEG sampling frequency, it is not clear how the RF pulse artifact is recorded in the EEG after sufficient low-pass filtering. Some researchers suggested that nonlinearity in the EEG recording system transforms the RF pulse into lower frequency artifacts [11]. In this paper, we present the results of testing the hypothesis that a particular form of nonlinearity, namely a rectification property at junctions between carbon and metallic components, causes the RF pulse artifact.

II. METHODS

To test the carbon–metal interface, a carbon wire (CPVC4050, World Precision, Inc., Sarasota, FL) loop and a copper wire loop were affixed to the top of a spherical water phantom placed in a head coil of a 3T MR (magnetic resonance) scanner (Trio, Siemens Medical, Erlangen, Germany). Each loop was of a 4 cm × 4 cm square shape and consisted of a single turn of wire. The carbon loop was connected to the rest of the circuit by two copper crimps, whereas the copper wire was connected by solder. The carbon loop had a resistance of 35 Ω . The purpose of the first measurement was to obtain the amplitude of the RF signal at the wire loops without low-pass filtering. For this measurement, outputs from the wire loops were connected to an oscilloscope (maximum 500-MHz measurement, Tektronix TDS 3052, Beaverton, OR) using coaxial cables (50 Ω) routed through a wave guide from the MR scanner room to outside. A gradient-echo pulse sequence was used (TR/TE=100/34 ms, 1 slice/volume, FA=130, BW=1371 Hz, no fat saturation). The dominant frequency of the RF pulse was 123.2 MHz.

The next experiment was conducted to observe the RF pulse artifact. Two kinds of MR sequences were used: one was the gradient-echo imaging sequence used in the first experiment, and the other was an RF pulse-only sequence with a rectangular envelope waveform (TR = 101 ms, FA = 180; pulse duration = 1 ms) that was not accompanied by any magnetic gradients. In this experiment, a 1-k Ω metal sheet resistor was serially inserted to each loop, and the output of each loop was connected to a coaxial cable (Fig. 1). The coaxial cables were connected to a patch panel filter (310-pF low-pass, 56-375-001, Spectrum Control, Fairview, PA). The outputs from the patch panel filter were optionally connected to 10.7-MHz low-pass filters (BLP-10.7, Mini-Circuits, Brooklyn, NY) and were then connected either to an oscilloscope or to bipolar inputs to an EEG recorder (SynAmps1, Compumedics, El Paso, TX). The EEG sampling frequency was set to 1 kHz, and the EEG filtering parameter was set to dc-to-70 Hz (12 dB/oct). Since a carbon wire must be connected to metal elements on both ends, there inevitably are two carbon–metal interfaces of opposite directions, possibly reducing the rectification effect. During preliminary measurements, it was found that the RF pulse artifact was larger when one of the carbon–metal interfaces was firmly attached by a crimp, and the other was more loosely connected

(e.g., by using a copper hook). To examine both firmly and loosely connected conditions, we first measured generated voltages when the carbon wire was crimped on one side and hooked on the other side, and next with both ends of the carbon wire firmly crimped.

III. RESULTS

Voltages at the RF peak of the gradient-echo sequence measured from the carbon and the copper wire loops in the first experiment, without any filtering, were 14 and 16 V, respectively. Fig. 2 shows the averaged waveforms ($N=50$) recorded on the oscilloscope from the wire loops in the second experiment using the gradient-echo sequence. The waveforms correspond to an initial part of a gradient-echo sequence that includes the RF pulse and associated slice-select gradient magnetic-field changes. The zero in the time (horizontal) axis corresponds to the trigger pulse from the MR scanner indicating the beginning of the RF pulse. Waveforms in the upper row [Fig. 2(a), (b)] were recorded only through a patch panel filter, whereas waveforms on the bottom row [Fig. 2(c), (d)] were recorded through a patch panel filter and a 10.7-MHz low-pass filter. Waveforms in the left column [Fig. 2(a), (c)] were recorded from a carbon wire loop with one end firmly crimped and another end hooked, whereas waveforms in the right column [Fig. 2(b), (d)] were recorded from the copper wire loop. It can be seen that the recording without the 10.7-MHz filters showed sinc-function-like waveforms representative of the RF pulse waveform, with higher amplitude from the copper wire than from the carbon wire. Recording with the 10.7-MHz filter from the carbon wire loop [Fig. 2(c)] initially showed a voltage deflection whose waveform was analogous to the envelope of the RF pulse, followed by a shorter positive peak at 2.7 ms and a noisy and narrow negative peak at 3.3 ms. The two narrow peaks correspond to the beginning of the gradient artifact pattern. The average peak amplitude of the deflection was 2.7 mV, and the standard deviation (std.) was 0.81 mV. By contrast, recording with a 10.7-MHz filter from the copper wire loop [Fig. 2(d)] did not show a deflection corresponding to the RF pulse, but showed the beginning of the gradient artifact. When the other sequence, an RF-only MR sequence, was used, a square-wave deflection was observed from the carbon wire, whereas no deflection was observed from the copper wire (not shown).

When both ends of the carbon wire were firmly crimped to metal wires, no deflection could be observed on the oscilloscope, but deflection was observed on the EEG recorder (Fig. 3), which has a better sensitivity than the oscilloscope. The top plot in Fig. 3 was recorded from the carbon wire loop using the RF-only MR sequence with a 10.7-MHz low-pass filter. Average absolute baseline-to-peak amplitude was 34.8 μ V (std. 24.4 μ V). The bottom plot was recorded from a copper wire loop under the same conditions. No RF-related signal changes were observed regardless of whether the copper loop was hooked or soldered to the coaxial cable.

IV. DISCUSSION

The results from the experiments contrasting carbon wires and copper wires indicate that the use of carbon wire resulted in signals corresponding to the RF pulse, whereas no such signals were observed when all-metal wiring was used. The hypothesis that the deflection is caused by a rectifying effect is consistent with the facts that the waveform of the deflection is analogous to the envelope of the RF pulse and that the deflection is sensitive to the conditions at the ends of the carbon wire.

The possibility that this artifact is caused by a distortion in the RF pulse itself or control signals in the MR system is ruled out by the fact that metal wire did not pick up this artifact. Deflection was also detected in an additional experiment conducted outside of the MR

environment using a UHF pulse generator (Hewlett-Packard 3200 B, Palo Alto, CA) as the RF source, providing further evidence that the artifact was not caused by MR control signals. To make sure that the deflection was not caused by a digitization artifact, we also confirmed the deflection by observing the signal from a carbon wire with an analog oscilloscope (Tektronix 2230, Beaverton, OR) using a gradient-echo sequence.

It has been known for a long time that boundaries between two different materials often have rectifying properties, including some metal–metal and metal–electrolyte boundaries [12]. During World War II, soldiers made what was called a fox-hole radio [13], in which a rectifier was implemented by a pencil (carbon) lightly touching the surface of a shaving blade (iron). Carbon nanotube–metal junctions have rectifying properties caused by the Schottky effect [14], but rectification has not been reported for larger scale (micron-level) carbon filaments.

In our system, the RF pulse artifact was eliminated by using copper wires and using 10.7-MHz low-pass filters. It was reported that the copper wires caused more artifacts in MR images than carbon, but the amount of artifact was in an acceptable range at 1.5 T and was smaller than artifacts caused by some other components in the EEG recording system, such as the electrolyte [9]. Alternatively, the RF pulse artifact may be eliminated by using a nonmechanical carbon–metal interface. For example, such an interface can be implemented using a capacitor constructed with a conductive carbon sheet as one electrode and a metal sheet as another.

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Fig. 1.
Schematic diagram of a circuit used for the RF pulse artifact measurement.

Fig. 2.

Waveforms corresponding to the initial part of a gradient-echo MR sequence recorded on an oscilloscope from the following conductor loops. (a) Carbon wire loop with only a patch panel filter. (b) Copper wire loop with only a patch panel filter. (c) Carbon wire loop with a patch panel filter and a 10.7 MHz low-pass filter. (d) Copper wire loop with a patch panel filter and a 10.7-MHz low-pass filter.

Fig. 3.
RF pulse artifact recorded from carbon (top) and copper (bottom) wire loops.