An Optically-Coupled System for Quantitative Monitoring of MRI-Induced RF Currents into Long Conductors

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Introduction: MRI employs high-power RF fields which can induce RF currents in long conductors found in interventional devices, causing RF heating effects and posing safety risks during the clinical use of MRI in the presence of these devices [1]. The MRI community lacks reliable methods and systems to predict and monitor this dangerous RF heating. The uncertainties of RF safety leads to unpredicted risks of adverse events in unsafe settings, to the disqualification of entire patient populations from receiving any form of MRI scan (even in situations where it might be safe), and to limitations in the development and use of interventional MRI devices. To overcome these uncertainties, we have designed and built an optically-coupled system that independently and quantitatively detects RF currents/heating in long conductors external to the patient, and we have tested it with cable-traps [2] and Q-spoiling loads.

Material Methods: The system consists of an electro-optical transmitter and an opto-electrical receiver. The electro-optical transmitter includes an improved toroid-cavity, single-turn coil connected to the input parallel resistance of an OPA690 operational amplifier in unity-gain buffer configuration and power-matched at its output to a low-cost IFE99 light-emitting-diode (LED) biased through a bias-tee. The coil is built by wrapping a flexible piece of copper tape on a toroidal Teflon core with 1.55mm inner diameter. Any long conductor fed through the core of this sensor inductively couples to the coil, just as the primary circuit of a transformer couples to the secondary circuit. The toroid thus produces AC currents proportional in amplitude to the MRI-induced RF currents of a guidewire fed through its core. These AC currents are eventually converted by the LED into optical signals that are sent via optical fiber to the opto-electrical receiver, where they are converted to AC voltages by a low-cost IFD91 photodiode (PD) connected to a two-stage amplifier employing an OPA847 and an OPA843, the first stage being a low-noise transimpedance amplifier and the second stage being an inverting voltage amplifier. The electro-optical transmitter is powered by a custom-made 7.5V battery with 540mAh capacity that allows 3hrs of continuous safety monitoring. Figure 1 and Figure 2 illustrate the various parts of the system. We calibrated this system on the test bench for 64MHz wire current levels between $10mA_{rms}$ to $400mA_{rms}$. We then used it on a previously developed birdcage RF safety test platform that replicates the heating patterns seen within an MRI scanner to study the resonance properties of a guidewire and their dependence on the wire's length. We also investigated the idea of spoiling the resonant Q of the guidewire by inserting resistance in series with its high current regions using a custom-made balun-style RF trap, and by sliding a lossy dielectric over the free end of the wire. We studied the RF trap experimentally and as a function of its geometry. We studied the efficiency of the lossy dielectric experimentally, investigating the effects of several solutions and of their quantities. Figure 3 illustrates the setup of our experimental investigations on the birdcage RF safety test platform.

Results: Figure 4 presents the results of our investigation about the dependence of the resonant RF current/heating on the length of the guidewire and on the presence of a lossy dielectric (a 2M NaCl solution) connected to the end of the wire. We compared the electrical signals measured by our system (top) with the heating effects detected by a Luxtron fiber optic thermometer (bottom) when the birdcage RF safety test platform operates at a fixed RF power, and from this comparison we demonstrated that our system provides a real-time, accurate measure of the RF current/heating. The free guidewire was resonant at a length of 185cm; we observed that the Q-spoiling lossy dielectric changes this resonant length and reduces the RF currents/heating significantly for any length of the wire. In particular, at the resonant length, the Q-spoiler reduces the RF power of the guidewire current to <14% of its value in the free wire. Figure 5 confirms that a properly tuned balun-style RF trap has a similar effect and is capable of reducing the RF power of the resonant-guidewire current to <23% of its value in the free wire, for any level of intensity of the RF signal driving the birdcage. The comparison between the electrical signals measured by our system (top) with the heating effects detected by the Luxtron thermometer (bottom) again validates our newly-designed system for quantitative measurement of the RF currents/heating.

Conclusion: We have successfully designed, built and validated a low-cost, optically-coupled system to quantitatively measure the resonant RF current/heating induced in long conductors during MRI exams. Our experiments confirm that the amplitude of the AC voltages produced by our calibrated system provides a quantitative measure of wire current amplitude during the MRI exam. At peak heating levels, we estimate $350mA_{rms}$ currents that should be easily detectable by MRI B1 mapping methods. We have also demonstrated simple and effective devices and methods to reduce the RF current/heating. Since these system and devices are able to monitor in real time and reduce, respectively, the RF current/heating, they are significant instruments towards a much safer use of MRI in presence of long conductors, and are therefore beneficial in a number of applications including but not limited to interventional MRI procedures.

References: [1] R. Venook et al, ISMRM. 2037, 2006. [2] C.M. Hillenbrand et al, Proc 13th ISMRM, 2005.

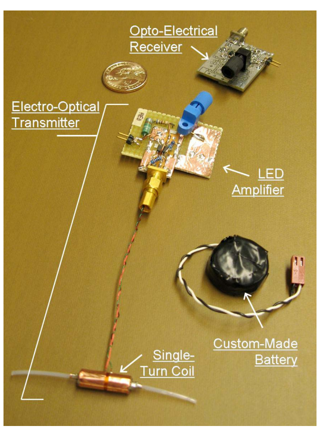


Figure 1 (above): Picture of system for measuring RF guidewire currents.

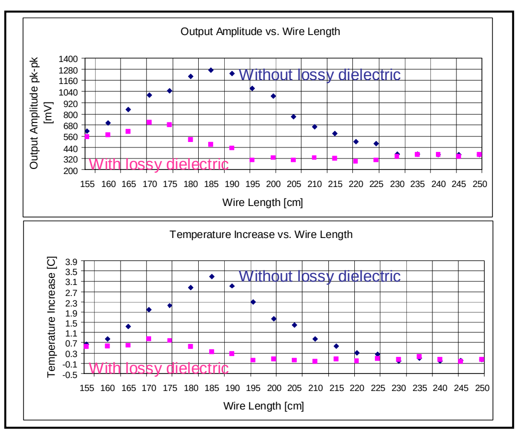


Figure 4 (above): Effects on the guidewire currents (top) and heating (bottom) by a lossy dielectric, at several different lengths of the wire

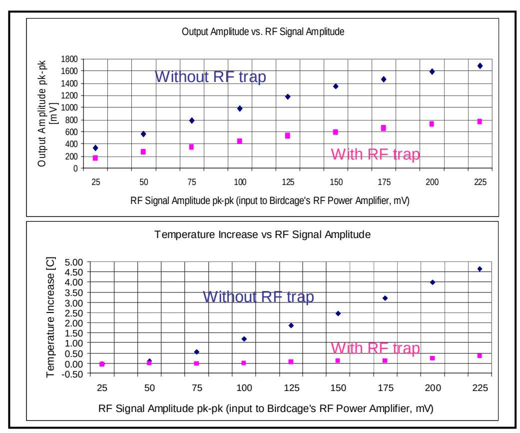
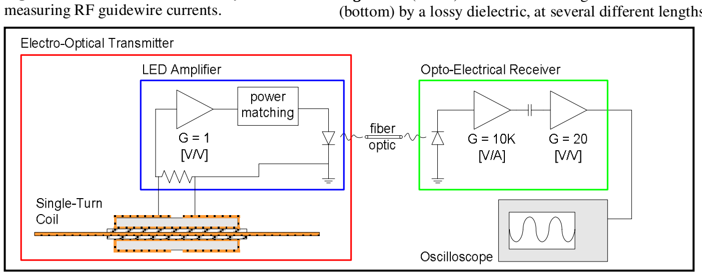


Figure 5 (above): Effects on the guidewire currents (top) and heating (bottom) by a RF trap, at several different values of the MRI RF signal



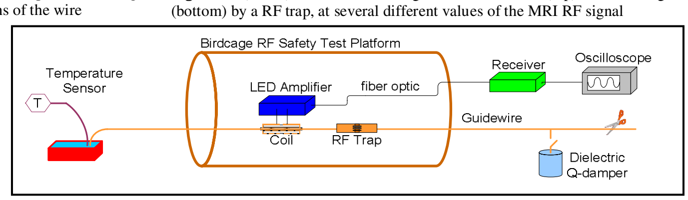


Figure 2 (left): Schematic of the optically-coupled system for measuring RF guidewire currents.

Figure 3 (above): Setup on the birdcage RF safety test platform for measuring guidewire currents and validating the effectiveness of devices realized to reduce them.