

Measurement of Implant Electrode Leads using Time-Domain Reflectometry to Predict the Resonant Length for MRI Heating

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Abstract—Magnetic Resonance Imaging (MRI) machines can generate hazardous RF heating of patients with implanted neurostimulation leads. Consequently, most patients with these implants are contraindicated from having MRI scans. The level of RF heating has a strong dependence on lead length and is most severe when the length is close to a specific resonant length. Recent studies have shown that simple modifications to the lead construction and insulating material can alter the resonant length and significantly ameliorate this heating hazard, achieving MRI safety. We propose a technique using time domain reflectometry (TDR) to find the resonant length of an arbitrary lead such to minimise the amount of MRI machine time needed to find the length of highest heating. The results are compared with temperature measurements made in a 3-Tesla MRI machine and with a CW dipole radiator in the lab.

Keywords—Pulse measurements, reflectometry, biomedical electrodes, medical diagnostic imaging, electrical stimulation, electromagnetic modeling, specific absorption rate, heating, safety.

I. INTRODUCTION

Implant leads such as those found in pacemakers, Spinal Cord Stimulators (SCS), and Deep Brain Stimulators (DBS), can be hazardous to a patient undergoing a Magnetic Resonance Imaging (MRI) scan. Fig. 1 shows a typical implant lead for SCS. The RF field generated by a 3 T MRI machine can deliver peak pulses exceeding 30 kW in power at 128 MHz. [1] This can induce significant heating of patient tissue at the distal electrodes [2], [3], well beyond the 1–2 °C safety limits recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in [4]. This has lead engineers to develop implant leads that are insusceptible to RF heating from MRI. [5]–[8]

An implant lead is most hazardous at a specific resonant length, l_{res} , a parameter which can be exceedingly difficult to calculate and resource intensive to simulate. Typically it is found through measurement in an MRI machine or in the lab with dipole radiators, where heating tests are made on several implant leads varying by length [9]. We present an alternative approach that employs Time Domain Reflectometry (TDR) to allow simple and rapid extraction of l_{res} from a single measurement.



Fig. 1. Distal end of a 62 cm SCS “Octrode lead”. Eight platinum electrodes, each 3 mm long and 1.3 mm in diameter, are separated by 4 mm insulating spacers. Electrode numbering starts from ‘1’ (left-most electrode) to ‘8’ (right-most electrode).

II. DISTAL HEATING

An implanted lead can behave as a resonant dipole to the incoming RF field from an MRI machine. [10] Stored energy is transferred along the length of the dipole and can permeate out into the surrounding tissue, especially around the bare electrodes. This gives rise to joule heating and in some circumstances, can reach hazardous levels. Works by [3] and [11] have shown that peak heating occurs when the lead length is about $0.41\lambda_{Pn}$, where λ_{Pn} is the wavelength along the lead, largely determined by the tissue composition and lead design. Calculation of λ_{Pn} is possible but is limited to simple coaxial-like lead structures. [10] Simulation can provide predictions when the complexity is higher but demands considerable resources and impractical computation run times.

Fig. 2 shows the simulated heating induced by an implanted wire within an MRI birdcage. The birdcage was calibrated to deliver a whole-body Specific Absorption Rate (SAR) of 1 W/kg. The three-dimensional simulation took 5 hours in COMSOL Multiphysics 4.4 running on a 3.5 GHz quad-core Intel CPU and consumed more than 60 GB of memory. Additional simulations were also needed in order to confirm the worst-case length for highest heating. For further simulation details refer to [11].

Experimental measurements are usually performed within a torso-shaped phantom inside of an MRI machine. Fig. 3 shows our phantom on the bed of a 3T MRI machine. The phantom is comprised of saline gel with electrical and thermal properties similar to that of human tissue. [12], [13] An implant lead under test is positioned within the gel and a fiber-optic based thermometer is aligned to the distal electrode where the heating is expected to occur.

As λ_{Pn} varies significantly with insulation thickness, permittivity, and geometry, its value is often unknown and is

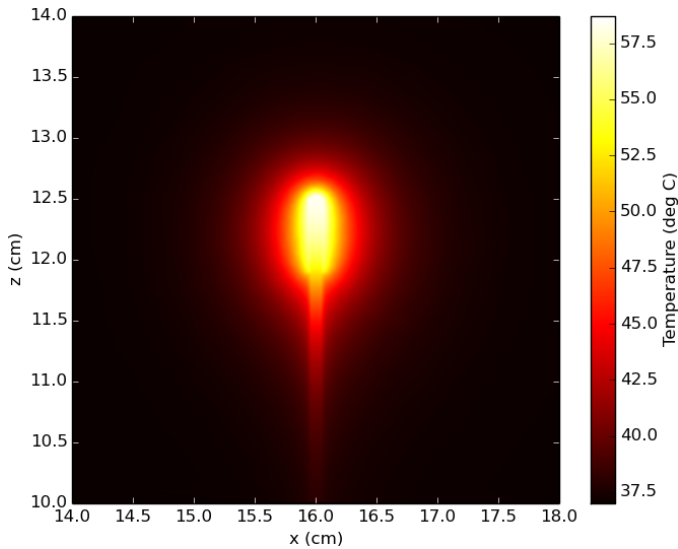


Fig. 2. Simulated heating generated at the 6 mm bared end of an insulated wire after 5 minutes of excitation from an MRI birdcage antenna. The 800 μm diameter wire was $0.41\lambda_{P_n} = 25$ cm in length, coated with plastic insulation 350 μm thick. Blood perfusion was included in the phantom model.



Fig. 3. Operators preparing a wire sample for testing within a gelled saline phantom in a 3T MRI machine.

usually found by individually measuring the distal heating of several wires differing only in length (≥ 10 cm), and looking for the length at which maximal heating occurs. A typical test set as shown in Fig. 4 contains 10 or more samples for a given lead type. The set-up and scan time to measure a single wire sample can easily exceed 30 minutes.

III. TDR TECHNIQUE

In addition to antenna effects, an implanted lead behaves as an unbalanced transmission line to RF currents. [10] The conductive tissue along the surface of the lead jacket forms the return path for currents, like a shield to a coaxial cable, with the tissue surrounding the distal electrode forming the dissipative load.

TDR is a well established technique for measuring the propagation of signals along transmission lines [14]. Similarly, TDR can be applied to implanted electrode leads. The phase

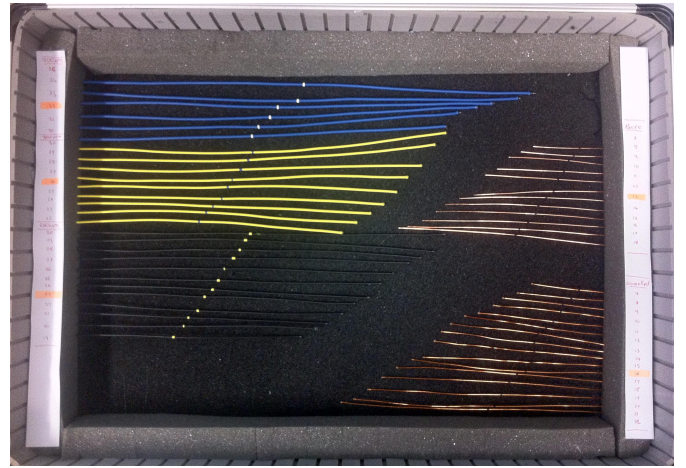


Fig. 4. Briefcase containing a range of wire samples to be tested.

velocity v_p for an implant lead of arbitrary length can be determined by measuring the time taken t_D for a voltage pulse to propagate to the end electrode and reflect back again:

$$v_p = \frac{2l_i}{t_D} \quad (1)$$

where l_i is the length of the insulated portion of the implant lead conductor. As the phase velocity is independent of length, the resonant length, l_{res} , of an implant lead at the MRI RF frequency f_{MRI} is therefore:

$$l_{res} = 0.41\lambda_{P_n} = 0.41 \frac{v_p}{f_{MRI}} \quad (2)$$

The RF frequency of MRI is proportional to the strength of the static magnetic field. In a 3T machine, the RF frequency is 128 MHz. When immersed in a gelled saline phantom from [12], a typical implant lead will have a λ_{P_n} in the order of tens of centimeters [9].

A phantom comprising 28 L of gelled saline in the shape of a torso-and-head was built from clear acrylic after [12]. The ratio of NaCl and polyacrylic acid (PAA) to distilled water was 1.32 g/L and 10 g/L, respectively, with an overall conductivity of 0.47 S/m.

To facilitate TDR measurements of implant leads, the test fixture in Fig. 5 was constructed. A thin aluminium disc rests on the surface of the gelled phantom, providing an electrical path from the shield of the coax cable to the gel. A screw terminal secures the implant lead under test and provides electrical connection to the inner conductor of the coax cable. The implant lead is immersed within the gel, uncoiled, and with the distal electrode unobstructed. Close up views of the fixture are shown in Fig. 6.

Measurements of various wire samples representative of implant leads, were captured with an Agilent 54754A TDR with 40 ps system rise time. The reflection produced by a 29 cm wire sample with 6 mm distal electrode is shown in Fig. 7. The initial sharp change corresponds to the impedance mismatch between the 50Ω SMA connector and the characteristic impedance of the wire sample. The reflection from the end of the wire sample can be identified by the second discontinuity, where the electrode comes into contact with the dissipative

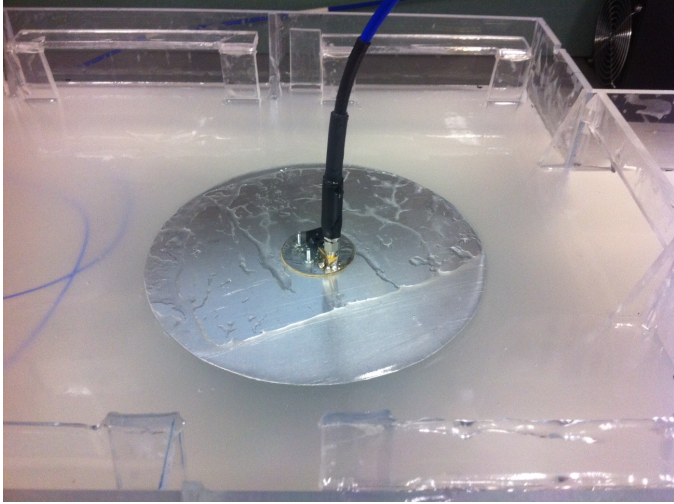
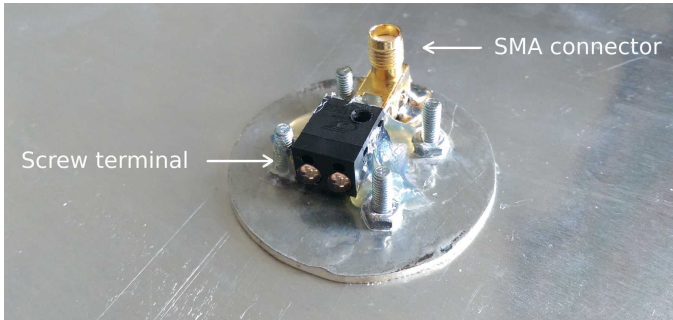
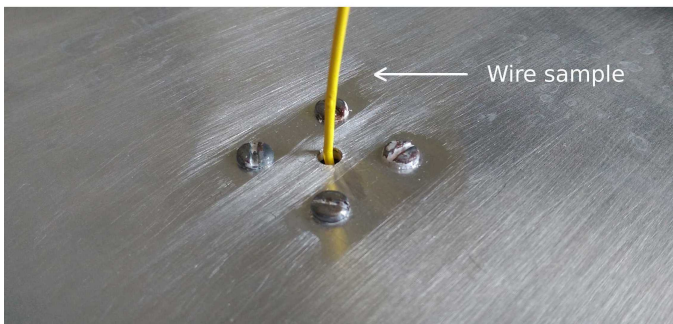


Fig. 5. An aluminium disc with a 20 cm diameter provides electrical connection from the coax cable shield to the gelled saline. Immersed within the gel, a wire sample is connected to the coax cable inner conductor via a small hole in the center of the disc and secured in place with a screw terminal.



(a)



(b)

Fig. 6. Close up view of the disc (a) topside (b) underside.

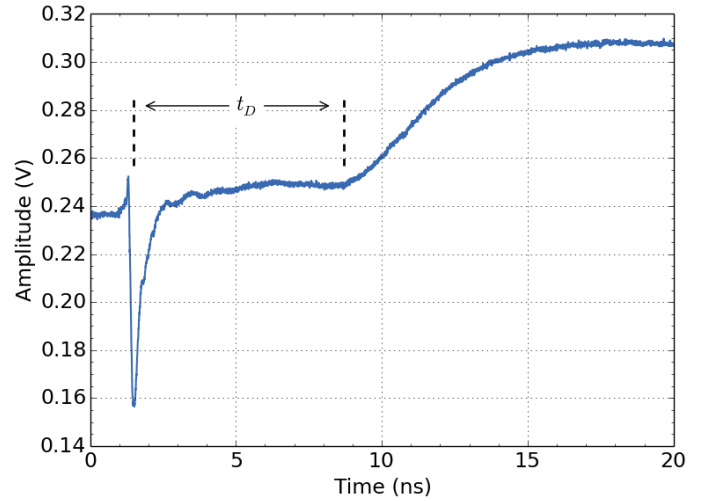


Fig. 7. Reflected TDR signal from a wire sample 29 cm in length, with insulation $350\ \mu\text{m}$ thick. The time delay for a TDR pulse to propagate to and from the distal electrode is 7.18 ns.

gel. Inserting a time delay of 7.18 ns into (2) yields a resonant length of 25.9 cm. Verification of this result is provided in section V.

IV. VERIFICATION TECHNIQUE

Recent work in [9] demonstrated a lab technique for predicting the level of RF heating induced by an implant lead from MRI, without requiring high energy RF pulses from an MRI machine. A dipole antenna driven by a low-power CW is used to provide excitation of the implant under test, with a fiber optic probe to monitor the distal temperature.

The same experimental set-up from [9] was used and is shown in Fig. 8. A dipole antenna was made from rigid 2.1 mm diameter copper wire with $350\ \mu\text{m}$ of insulation covering the entire 32 cm length. A close up view is shown in Fig. 9. A wire sample under test is spaced 6 cm from the dipole antenna and is centered about its midpoint. Temperature of the distal electrode is monitored with a GaAs-based fiber-optic temperature probe with $0.1\ ^\circ\text{C}$ resolution.

Calibration of the experiment is achieved by scaling the result 1.5 times, such that the reference wire sample generates equivalent heating when exposed to the RF field from the 3 T MRI machine in Fig. 3. The reference measurement along with simulated predictions is shown in Fig. 10.

V. MEASURED RESULTS

A range of wire samples varying in insulation thickness from 21–700 μm were tested. Each sample consisted of an 800 μm diameter copper core, with plastic insulation covering all but 6 mm from one end. Epoxy resin insulated the opposing end. The reflected TDR waveforms were captured for each wire sample using the test fixture in Fig. 5. The time delay t_D as measured from each waveform are listed in Table I along with the associated resonant length l_{res} , calculated using equations 1 and 2.

Heating tests using the dipole radiator for excitation were performed on each wire sample including several additional

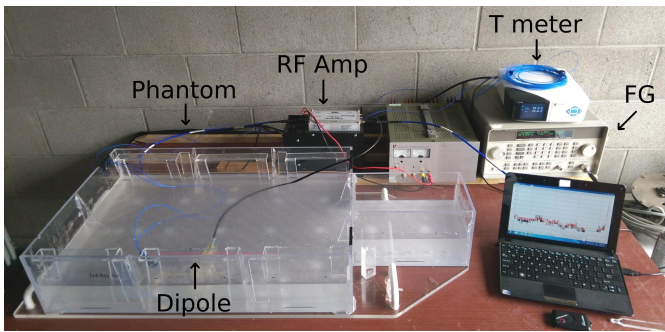


Fig. 8. Set-up for testing the RF heating of implant leads in the lab. A dipole antenna is immersed in the phantom alongside the wire sample with a function generator and 30 W RF power amplifier supplying excitation. A fiber optic thermometer monitors the temperature of the distal electrode.

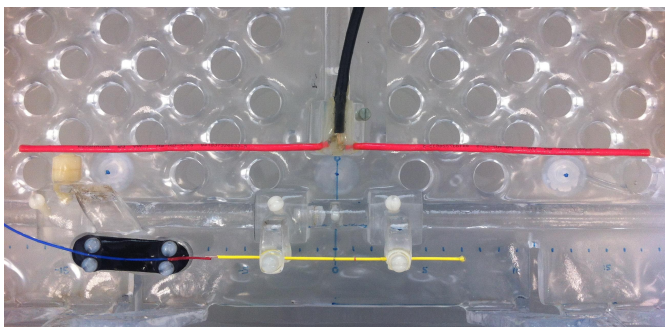


Fig. 9. Close-up view of the temperature probe aligned to the bared end of the wire sample (yellow) before immersion within the gelled saline. The dipole antenna (red) is spaced 6 cm away from the wire sample.

lengths. The change in temperature ΔT was recorded for each sample after 5-minutes of applied RF stimulus. The results shown in Fig. 11 are consistent with [3] and [11]. The lengths for peak heating as extracted from the same figure are summarised in Table I. The TDR-measured values are within 3% of expected values.

TDR measurements were also performed on the electrodes of the SCS lead shown in Fig. 1. The predicted resonant length for electrodes 1 and 8 are twice that of the 700 μm and 350 μm wire samples, respectively. This is owing to the much smaller 100 μm diameter filars that comprise the lead. Heating tests on the SCS lead were not performed.

VI. CONCLUSION

We explain a measurement technique that predicts the length an implanted lead will experience peak heating during MRI, without an MRI machine. We show this is possible through a TDR measurement of a single lead of arbitrary length.

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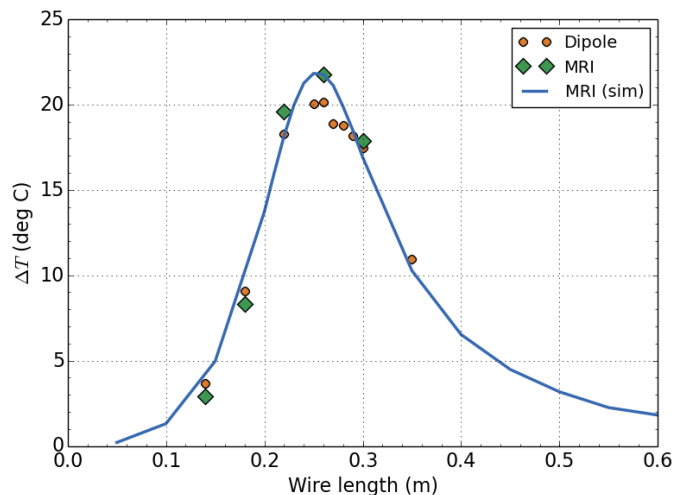


Fig. 10. Distal heating generated near the distal electrode of a reference wire sample coated with 350 μm of insulation, after 5 minutes of CW excitation from a dipole antenna. Measurements of the same wire sample in a 3T MRI machine are also shown along with simulated predictions.

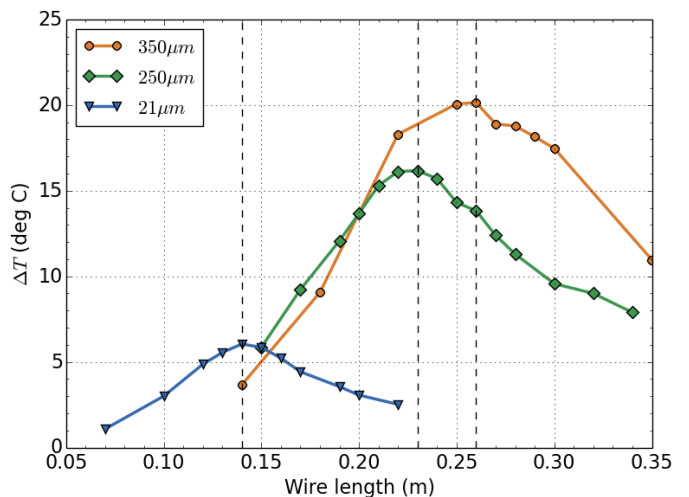


Fig. 11. Distal heating generated for wire samples varying by insulation thickness. Extraction of $0.41\lambda_{P_n}$ and ΔT_{pk} for a given lead type is achieved by measuring several lead lengths.

REFERENCES

- [1] R. Caverly, G. Breed, W. Cantrell, M. Eron, J. Garcia, N. Kondrath, D. Myer, M. Ruiz, and J. Walker, "Advancements at the lower end: Advances in HF, VHF, and UHF systems and technology", *IEEE Microwave Magazine*, vol.16, no.1, pp.28-49, Feb. 2015.
- [2] J. A. Nyenhuis, P. Sung-Min, R. Kamondetdacha, A. Amjad, F. G. Shellock and A. R. Rezaei "MRI and implanted medical devices: basic interactions with an emphasis on heating", *IEEE Transactions on Device and Materials Reliability*, vol.5, no.3, pp.467-480, Sept. 2005.
- [3] S. McCabe and J. Scott, "Electromagnetic techniques to minimize the risk of hazardous local heating around medical implant electrodes during MRI scanning," *European Microwave Conference 2015*, Paris, 7-10 Sept. 2015.
- [4] "ICNIRP statement on: Medical magnetic resonance (MR) procedures: protection of patients", International Commission on Non-Ionizing Radiation Protection (ICNIRP), *Health Phys.*, vol.87 no.2, pp.197-216, Aug. 2004.
- [5] S. McCabe and J. Scott, "New MRI-safe implant electrode design," *International Microwave Symposium 2016*, San Francisco, 22-27 May. 2016.

TABLE I. RESONANT LENGTHS OF VARIOUS IMPLANT LEADS: EXPECTED AND TDR-MEASURED VALUES.

Insulation Thickness	Conductor Length (cm)	t_D (ns)	l_{res} from TDR (cm)	l_{res} from ΔT_{pk} (cm)
21 μm	21.2	9.74	13.9	14
250 μm	29.8	8.55	22.3	23
350 μm	29.0	7.18	25.9	26
700 μm	34.3	7.42	29.6	30
Octrode (electrode 1)	61.8	6.68	59.3	-
Octrode (electrode 8)	54.8	7.12	49.3	-

- [6] S. O. McCabe and J. B. Scott, "Implant conductor assembly with improved radio frequency properties", New Zealand provisional patent 714212, Filed on Nov 16, 2015.
- [7] J. B. Scott and S. O. McCabe, "Implant conductor with improved radio frequency properties", New Zealand provisional patent 708633, Filed on May 29, 2015.
- [8] *MRI and SCS, SureScan system* Medtronic, USA, Implant Manual, 2013. <http://www.mrisurescan.com/au/for-radiologists/spinal-cord-stimulators/mri-and-scs/index.htm#tab2> retrieved Aug 2014.
- [9] S. McCabe and J. Scott, "Technique to assess the compatibility of medical implants to the RF field in MRI," *Asia-Pacific Microwave Conference 2015*. Nanjing, 6-9 Dec. 2015.
- [10] R. W. P. King and G. S. Smith, "Antennas in matter: fundamentals, theory, and applications", *The MIT Press*, Cambridge, MA, 1981.
- [11] S. McCabe and J. Scott, "Cause and amelioration of MRI-induced heating through medical implant lead wires," *Proceedings of the 21st Electronics New Zealand Conference*, Hamilton, 20-21 Nov. 2014, pp.34-40.
- [12] *F2182-11a Standard test method for measurement of radio frequency induced heating on or near passive implants during magnetic resonance imaging*, ASTM International, West Conshohocken, PA, USA, 2010.
- [13] A. T. Mobashsher and A. M. Abbosh, "Artificial human phantoms: Human proxy in testing microwave apparatuses that have electromagnetic interaction with the human body", *IEEE Microwave Magazine*, vol.16, no.6, pp.42-62, Jul. 2015.
- [14] S. O. McCabe, "Impulse TDR and its application to characterisation of antennas", MPhil thesis, The University of Waikato, 2011.