A Novel Method for MRI Safe Lead Design

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Target audience: This study is beneficial for MRI safe implant designers and RF safety researchers.

Purpose: In this study a novel method using Modified Transmission Line Method (MoTLiM)[1] for designing MRI safe implant leads is explained. Resistance and of a multilayer wound lead can be increased using proximity effect. Also, inductance of a multilayer wound lead can be increased by ensuring that the magnetic fields of different layers will not cancel each other. It is shown that resistance and inductance can be increased into a level that the implant lead tip heating is no longer a significant problem.

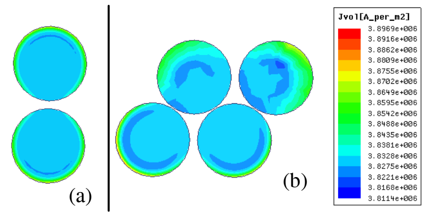

Figure 1: Current distribution in the cross-sectional area of conductive wires with a diameter of 1mm. Finite element method simulation results are shown for RF current at 123MHz. (a) 2 wires are adjacent to each other. (b) 4 wires are adjacent to each other.

Introduction: People with active implantable medical devices such as pacemakers are denied from MRI scanning because of the possible high induced currents on the lead and excessive heating at the tip of it[2]. This effect has been investigated earlier in depth and various solutions have been proposed by modifying the winding of the pacemaker leads[3]. Here we propose a new method of reducing induced current.

Theory: Using Modified Transmission Line Theory[1] (MoTLiM) a linear relationship with the SAR at the tip of the electrode[1] can be formulated. In MoTLiM leads were characterized with two parameters: impedance per length, $Z = R + j\omega L$ and wave number along lead, $k_t = \sqrt{-ZY}$. Then the relationship between currents and the incident field was defined as in Eq. 1[1]. Solving Eq. 1 under uniform incidence electric field (E-field), the induced currents along the lead can be found as in Eq. 2[1]. Also, from MoTLiM a hypothetical voltage which is a scaled version of the charge distribution along the lead can be defined as in Eq. 3[4]. For a lead without an electrode by applying the boundary condition that the currents are zero at both ends of the lead to Eq. 2, induced current can be found as in Eq. 4. Then, the square of the hypothetical voltage can be found as in Eq. 5. Here, it is assumed that the scattered electromagnetic field from the lead decays fast due to the loss in the medium (tissue) then the square of the hypothetical voltage has linear relationship with the SAR at the tip of the electrocde[4]. Eq. 4 implies that k_t is dominant parameter in tip heating. Value of the k_t both determines the location of the resonance length and the SAR at the tip. So by increasing the k_t SAR can be reduced significantly.

$$I(s) + \frac{1}{k_t^2}\frac{d^2 I(s)}{ds^2} = \frac{E^i(s)}{Z} \quad (1)$$

$$I(s) = Ae^{-jk_t s} + Be^{jk_t s} + \frac{E_i}{Z} \quad (2)$$

$$V(s) = \frac{-jZ}{k_t}(Ae^{-jk_t s} - Be^{jk_t s}) \quad (3)$$

$$I(s) = \frac{E_0}{Z} - 2\frac{E_0}{Z}\frac{\sin(k_t \frac{l_w}{2})}{\sin(k_t l_w)}\cos(k_t s) \quad (4)$$

$$|V(s = l_m/2)|^2 = |\frac{E_0}{k_t} tan(k_t l_w/2)|^2 \quad (5)$$

k_t can be increased by both increasing the inductance of the lead and resistance of the wire. It is known that by multilayer winding inductance of the lead can be increased. Another benefit of multilayer wound leads is the proximity effect. It is very well known that when radiofrequency (RF) current is induced to a single conductor; the current will flow in a thin layer close to the surface of the conductor due to the skin effect. However, when two or more adjacent conductors carry the RF current, it will be restricted to flow in a much smaller cross-sectional area due to proximity effect as shown in Figure 1. This is due to the magnetic force generated by the current on conductive wire, acting on the charges on the other conductive wire. This phenomena result in a drastic increase in the series resistance of the wire.

	R(kΩ/m)	L(μH/m)
1 layer	5.94	43.4
2 layers	29.93	212.1
3 layers	41.01	284.7

Table 1: Resistance per length and Inductance per length values of windings at 123MHz.

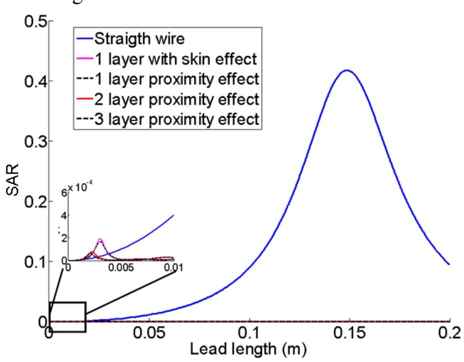

Figure 3: Square of hypothetical voltage with respect to lead length.

Method: To show the effect of the proximity effect and increased inductance on tip heating of the lead, an enameled copper wire with radius 0.7mm winded around a 4mm diameter rod as one, two and three layered windings. Resistances and inductances of these windings were measured using Agilent E5061A network analyzer at the frequencies 123MHz. Then resistance and inductance per length of wire was found for each of the windings. Resistance per length due to skin depth was calculated for the enameled wire. First the skin depth was found for copper as $\delta = 1/\sqrt{\pi f \mu \sigma}$. Then AC resistance per length of a round wire was calculated by defining an effective area, where most of the current is flowing, as: $A_e = \pi r_c^2 - \pi(r_c - \delta)$, then the AC resistance per length was found by $1/A_e\sigma$.

Then the tip heating analyses of leads with both windings were carried out using MoTLiM[3]. In order to characterize the tip heating, k_t and Z of lead wire must be found including the resistance due to the proximity effect. Detailed derivation of k_t and Z parameters were explained in Reference 1 for straight leads. However, these parameters were not derived for helix. To find the parameters of wound wires, Method of Moment (MoM) simulations were used. Induced currents were solved inside a medium with ε_r=60 and σ=0.17S/m for a perfect electrical conductor (PEC) helical wire with length of 20cm and helix diameter of 4mm using MoM simulations without considering losses in the conductor including the proximity effect. Eq. 4 was fitted to this solution to find k_t and Z of the helical wire In MoTLiM losses due to the conductors are included in impedance per length as: $Z_p = Z + R_p$, where Z is the impedance per length of lossless helical as it is found by MoM, R_p is the resistance per length due to conductivity of the wire including the proximity effect and Z_p is the overall impedance per length. Similarly, increased inductance is added as: $Z_p = Z + j\omega L$. Then, the wavenumber, k_t, is modified using: $k_{tp} = k_t\sqrt{1 + R_p/Z}$ for resistive losses and $k_{tp} = k_t\sqrt{1 + j\omega L/Z}$ for inductance. After finding the k_{tp} and Z_p of helical wire, Eq. 5 is used to estimate SAR at the tip of the electrode as a function of lead length.

Results: In Table 1 measured resistance due to the proximity effect and inductance of 1, 2 and 3 layers winded leads is shown. Resistance due to skin effect is found as 2.56Ω/m. Resistance per length of windings increases with the frequency and but more importantly it increases drastically with increase in number of layers. In Figure 3 normalized SAR is shown to show the effect of increase inductance and proximity effect on the tip heating. Winding of the wire results in reduction of SAR more than 100 times compared to SAR of a straight wire with radius 0.09mm.

Discussion and Conclusion: It is shown that MoTLiM is promising method to design MRI safe leads. MoTLiM can also be used for analysis of currently existing lead designs. This design may also be suitable for interventional MRI applications such as the design of the guidewires and catheters. In this study it is shown that SAR decreases with the increased number of winding layers drastically. **References:** **1**DOI:10.1118/1.3662865 **2**DOI: 10.1002/mrm.10037**3**DOI:10.1118/1.3439590 **4**V.Acikel,ISMRM 21thAnn.Mtg.Proc.2013