Circuit Model for Implant Electrode and Lead-Electrode Impedance Matching

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Target audience: This study is beneficial for MRI safe implant designers and people who studies safety analysis of active implantable devices.

Purpose: Up to 50-75% of patients with active implants need MRI examinations during their lifetime[1]. Also there are reported cases about MRI related deaths[1] and therefore it is dangerous to scan these patients with MRI unless all the related issues are completely understood and solved. In our previous studies[2] we modeled the lead of the implant using Modified Transmission Line Method(MoTLiM) as shown in Figure1(b) and solve the Radio Frequency(RF) induced currents on the leads. In this study we propose an electrode model that completes our electromagnetic model of active implants and enables us to calculate the SAR gain and analyze the tip heating properties of the implants. Also with this model electrode and lead impedances are defined considering their RF scattering and tissue interaction properties. Correctly defined impedances of leads and electrodes clarify the matching of electrode impedance to lead impedance concept.

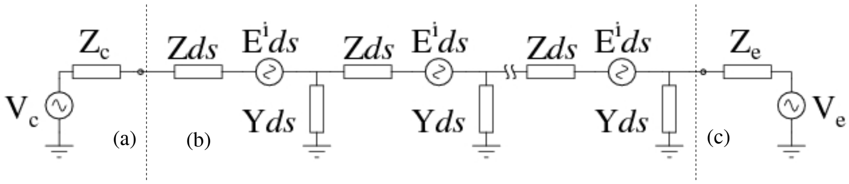

Figure 1: (a)Case Model, (b)Modified Transmission Line Model and (c)Electrode Model

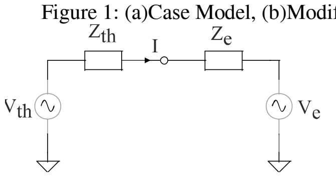

Figure 2: Thevenin equivalent of lead and electrode model. **I** is the current flowing through electrode.

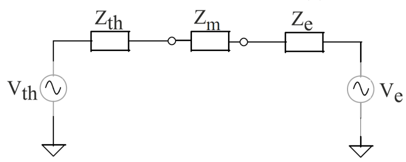

Figure 3: Matching the electrode impedance to the Thevenin impedance of the lead

Theory: In MoTLiM, implant leads are modeled by adding a series electric field (differential voltage) source to the lumped element model of the transmission lines. In MoTLiM RF induced currents along the leads were calculated by solving the differential Eqn 1 where $\boldsymbol{k_t}$ is the wavenumber along the lead, $\boldsymbol{Z}$ is the impedance per unit length, $\boldsymbol{E^i}$ is the incident tangential electric field (E-field) and $\boldsymbol{s}$ is the position along the lead. Under uniform E-field exposure the solution of the equation is can be found as in Eqn2. Using the Modified Transmission Line Model, a hypothetical voltage along the lead can be defined as in Eqn3. Unknowns $\boldsymbol{A}$ and $\boldsymbol{B}$ depend on the boundary conditions (the electrode and the case). Eqn2 and 3 will be useful for calculation of electrode parameters.

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

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

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

Modeling of pulse generator case[3] and electrode of an active implant can be done by using a voltage source and impedance as shown in Figure 1(a) and 1(c). The voltage source shows the effect of the incident RF field and its value is normalized to the magnitude of the incident E-field. The impedance models the interaction with the surrounding tissue. To find the values of the electrode model parameters, electromagnetic simulations and MoTLiM used together. Using EM simulations two leads with different lengths were connected to the electrode then the current at the connection point was found. Later Thevenin equivalents of the leads, which are used in EM simulations, were found. Using the Eqn2 and 3 open circuit voltage (Thevenin voltage) and short circuit current were found at one end while other end was open. Finally the ratio of open circuit voltage to the short circuit current gave the Thevenin equivalent of the electrode impedance. Using the equivalent circuit shown in Figure 2, Kirchoff voltage equations were written for both leads and solved for the electrode parameters. Also using the equivalent circuit in Figure 2 the power dissipated around electrode can be calculated.

Method: To test the accuracy of the model, electromagnetic simulations using FEKO (EM Software & Systems Germany, Böblingen, GmbH) and MoTLiM calculations were conducted. Throughout the study a spherical electrode with radius 1mm was used and all analysis were done inside a uniform medium with σ=0.42S/m ε_r=81. To find circuit model parameters of the electrode two leads (1mm radius) with lengths 10cm and 40cm were used under 1V/m E-field incidence. After the electrode parameters were found they tested under different conditions. First, the electrode was connected to the leads (radius 0.5mm) with lengths 25cm, 35cm and 45cm and using MoTLiM current distribution along the leads with electrode connection was solved for 1V/m and 2V/m E-field incidences. These solutions were also compared with the EM simulation results as shown in Figure 4. Second, the electrode was connected to the lead with length 25cm and radius 0.1mm via matching impedance as shown in Figure 3. By changing the value of the matching impedance dissipated power, which is the dissipated power on Z_e, around the electrode was calculated using Figure 3 and these results were compared with EM simulations as shown in Figure 5.

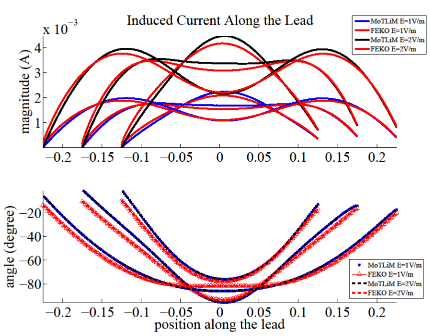

Figure 4: Induced currents along the lead with electrode connection

Results: Electrode impedance was found as 126-j135 Ω and electrode voltage was found as -57+j18 mV. In Figure 4, induced current on lead was solved for the leads with lengths 25cm, 35cm and 45cm and radius 0.5mm and for incident fields with magnitude 1V/m and 2V/m. For all situations, leads were connected to the spherical electrode with radius 1mm. For solved situations, mean square error was less then 8%. Then the Thevenin equivalent of the lead with length of 25cm and radius of 0.1mm was found as; 37.7+j4.88Ω and connected to the electrode via matching impedance. Value of the matching impedance was varied from 0 to j200Ω. The dissipated power was calculated using Figure 3 and compared with the EM simulations as shown in Figure 5. The dissipated power reaches its maximum when the imaginary part of the $Z_{th}+Z_m+Z_e$ is equal to zero as shown in Figure 5.

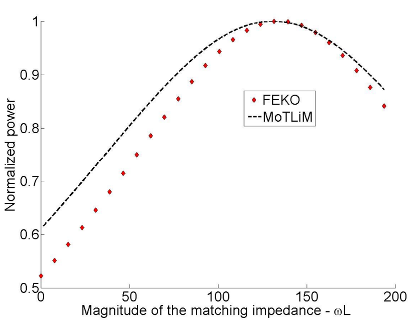

Figure 5: Black line is the normalized dissipated real power on the electrode impedance and calculated using the MoTLiM and the electrode model. Red dots are normalized SAR at the tip of the electrode calculated using FEKO.

Discussion and Conclusion: Electrodes of active implants are modeled with an impedance and voltage source. So the EM interaction of active implants inside the tissue can be analyzed using the MoTLiM with the proposed electrode model. Also the matching of electrode to the lead concept is clarified with the defined electrode impedance and lead Thevenin impedance. Putting series inductance to prevent heating[4] is a working technique but the inductance value must guarantee a high mismatch. Failure in choosing inductance value can cause increase in the heating.

References: **1**DOI:10.1111/j.1540-8159.2005.50024.x **2**DOI:10.1118/1.3662865 **3**V.Acikel,ESMRMB,29th Ann.Mtg. Proc.2012 **4**DOI 10.1002/mrm.10088