Effect of Linear Phase Electric Field Variation on Implant Lead Heating

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Introduction

The relationship between the electric field distribution and implant heating was investigated in many studies [1,2]. In one of these studies, [2] it was shown that the worst case heating occurs when the phase of the electric field changed linearly along the implant lead. From a similar point of view, varying the phase distribution along the implant lead can minimize tip heating [2]. In this study, it is shown that a helical lead geometry experiences a linear phase electric field when it is placed inside a quadrature birdcage coil. In this situation, heating is maximized at one tip and is minimized at the other one.

Theory

A straight wire connecting points A1 and B1 (Figure 1) experiences a constant phase electric field inside a birdcage coil. As a result of symmetry, points A1 and B1 have equal SAR. On the other hand a helical lead connecting the points A2 and B2 experiences an electric field whose phase is varying linearly along the lead. The local SAR at the tip of a lead which is exposed to a linear phase electric field was calculated in a previous study [1]. In that study, the wire was divided to number of segments and excitation of each segment was assumed to have an arbitrary phase. It was shown that a linear phase variation with a slope equal to the wave number k would cause maximum constructive interference at a single tip. This causes maximum charge density increase at that tip. Since the local SAR near the implant tip is directly proportional to the square of the tip charge density, heating was maximized. Similarly the segment excitations interfere destructively at the other tip and cause minimal heating. The effect of maximal and minimal heating is valid when the slope of linear phase variation is non zero.. The phase of the field of a quadrature birdcage coil varies linearly with respect to angular direction. The electric field along a helical lead which is placed inside a birdcage coil, connecting points A2 and B2, will also have a linear phase variation. For a phase increasing in counter clockwise direction and a right handed helical lead maximum tip heating is expected at point A2 and minimal tip heating is expected at point B2. For a left handed helical lead B2 is expected to heat more than A2.

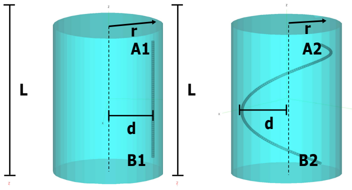

Figure 1 Straight and helical lead geometries

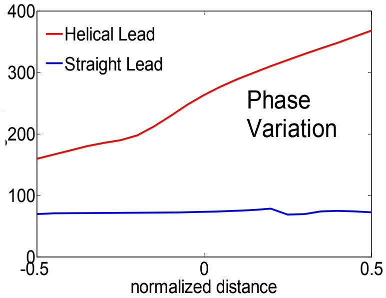

Figure 2 Phase variation along the straight and helical leads

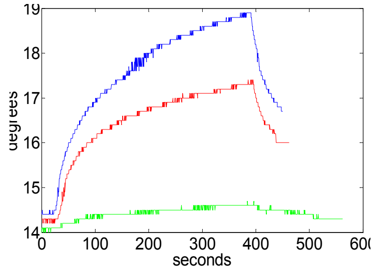

Figure 3 Temperature data for straight lead (blue),maximum heating tip(red),and minimum heating tip(green) of helical lead is shown

Methods and Results

The helical and straight leads in Figure 1 are simulated. Leads are assumed to exist in a cylindirical head model of radius 7.5 cm and length 22 cm The conductivity and relative permittivity of the body are assumed as 0.5 S/m and 70 respectively. For excitation, the field of a birdcage coil is simulated by assuming linear current elements around the head model. The phase of each line current element is varied linearly with respect angular location of the element. The phase of the tangential component of the electric field along the straight lead and the helical lead of radius 6 cm can be seen in Figure 2. For the helical lead phase varied linearly with a slope of 500 deg/m which is equal to 8.8 rad/m. For both the straight and the helical leads, two sets of simulations are performed by choosing the lead-center distance as d=1 cm and d=6 cm. The charge densities at the tips of straight wire, and helical lead are calculated. For local SAR, square of the charge densities are compared. The local SAR at the tip of the straight wire is defined as **1a.u**. Rest of the results were defined with respect to this value. For d=1 cm helical lead, the SAR at the tips A2 and B2 were calculated as **1.5 au** and **0.34 au**, respectively. Since d is very small when compared to lead length, the magnitudes of the electric field experienced by the helical and straight lead are approximately equal. The reduction and increase of the local SAR at the A2 and B2 tips are results of constructive and destructive phase cancellation. On the other hand the SAR values for tips of the d=6 cm helical lead were obtained as **0.5 au** and **0.11 au**. Both of the SAR values were reduced when compared to a straight wire. In addition to the effect of linear phase electric field variation, the helical lead of radius 6 cm experiences an electric field with lower magnitude. This is another reason for SAR reduction at both tips. For the tip A2 two effects are combined where for the tip B2 they have opposite effect to local SAR. In order to verify the simulation results, gel phantom experiments were performed. A phantom with a straight lead (Phantom 1), and another with a helical lead of 6 cm radius (Phantom 2) are prepared. The dimensions and the locations of the leads were chosen as shown in Figure1. Fiber optic temperature probes (Neoptix,Quebec) were placed at the tip of straight helical leads in both phantoms. GE Signa 1.5 T scanner and its T/R head coil is used to scan the two phantoms with a SPGR sequence. The sequence parameters were TR=6.25 msec,flip angle=90 deg,scan time=400 sec. First, phantom 1 is scanned, then phantom 2 was scanned twice to demonstrate results for maximum and minimum tip heating.. After the first scan the phantom 2 was reversed in z direction. Then a 30 minute waiting interval.is inserted in between the scans for the lead temperatures to reach steady state. Then phantom 2 was scanned again. The temperature variations at the lead tips are shown in Figure 3. Maximum heating was observed as 4.7 degrees in the straight wire tip. For the two tips of the helical lead, maximum temperature rise was obtained as 3 degrees and 0.4 degrees. The local SAR values were calculated from slopes of temperature variation graphs as 1, 0.61,0.07 a.u. for the 3 cases. The SAR values were calculated from the initial slopes of the temperature data in the first 20 seconds. These values are vey close to the ones obtained by the simulations.

Discussion

For helical wire geometries it was shown that the tip heating is amplified at one tip while it is reduced at the other one. A candidate application for this result is deep brain stimulator (DBS) leads. For most cases DBS leads are placed similar to straight wire where the lead experiences no phase variation and maximum electric field magnitude. For a helical lead geometry If the maximum heating tip is terminated with the IPG- pulse generator, that tip will not heat. Since at the other tip the heating will be reduced, a helical lead will be safer. However the orientation of the helical lead with respect to phase variation in the birdcage coil should be known prior to scan. Besides the heating problem, due to electric field induced by the gradient fields, stimulation can occur, when there is an implant. To investigate this risk, voltage induced on the implant in helical geometry is calculated using the electric field expressions given in [3]. Stimulation risk is not observed for this path of the lead.

Conclusion

In this work the local SAR at the tips of helical and straight lead wires are compared. It is shown that a helical lead which experiences a linear phase electric field variation has less local SAR near its tips. The SAR reduction was 10 and 2 respectively at two tips compared to a straight wire. DBS leads can be implanted with a helical geometry around the head to ensure local SAR reduction.

Reference [1] C.J Yeung RF heating due to conductive wires during MRI depends on phase distribution of the transmit field.Mag Resin Med 48:1096-1098[2] E. Abacı, E. Kopanoğlu, V. B. Ertürk, and E. Atalar, “Simple analytical equation of the induced field”, ISMRM Toronto, 2008