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Model for Calculating the Magnetic Field and the Current Density in the Vicinity of a Hemitoroidal Coil for Transcranial Magnetic Stimulation

M Traad, PP Tarjan, ED Smith[1] and JW Levy[2]
Departments of Biomedical Engineering and Neurosurgery[2], University of Miami, and SciBuTec, Inc.[1]

ABSTRACT-- Presently-used magnetic stimulators use multiturn round coils. The self-inductance of the coil increases with the square of the number of turns in the coil. The self-inductance can be reduced without any loss in focalization by a coil that is shaped as a half toroid ("Slinky"). A computational technique was developed to model this configuration and to predict the magnetic field and current densities in the resistive tissues of the brain.

Magnetic stimulation must produce current densities of high intensity and short duration to stimulate the motor cortex. A time-varying magnetic field produces an electric field according to Maxwell's Equations which results in a current distribution in a conductive medium such as the brain. The conductivity of the brain is relatively low, hence the current density may be evaluated without considering its effect on the primary source. Presently-used magnetic stimulators generate their magnetic field via multiturn round coils. As the turns of the typical coil are close to one another, the self-inductance of the coil is roughly proportional to the square of the number of turns in the coil.

The strength of the coil's magnetic field is greatest in its immediate vicinity. The biological effect of the field is maximal if the induced current in the tissue is perpendicular to the fibers to be stimulated. Based on these considerations, it is necessary to orient the coil with respect to the target tissues for stimulation in such a way that a segment of the coil with maximum ampere-turns be near the tissue. As the rest of the coil is not involved in the process, the turns of the coil need not be tightly bunched except in the critical sector. The simplest configuration to improve upon the round multiturn coil is offered by a "figure eight" or butterfly coil configuration. In this configuration, the current directions in the two adjacent loops are opposite and the current elements are additive at the point of intersection. This configuration should reduce the self-inductance for the butterfly coil by about 50 percent with respect to the same number of turns in a round coil, but without any reduction in the effect in the target tissues. As a consequence of the lower inductance, the magnitude of the supply voltage can be reduced significantly.

University of Miami,
Department of Biomedical Engineering
P.O. Box 248294
Coral Gables, FL 33124 USA

We have considered further design changes to reduce the coil's self-inductance without any reduction in focalization. The specific configuration presented in this communication is the geometric equivalent of a coil shaped as a "Slinky" toy bent into a half toroid. The model consists of N single loops in series, the planes of the individual turns are rotated by 180°/(N-1) with respect to each other. This configuration still maintains the current "bundle" at the point where all the turns merge, but reduces the mutual coupling between the turns. The self-inductance is expected to approach square root of the total number of turns because each of the N turns presents its self-inductance in the series configuration and this sum is enhanced by the mutual inductance due to the relatively loose coupling between adjacent turns.

The problem of calculating the current density in the tissue was addressed by our model using a combination of computational techniques. The magnetic field of a single circular current loop is given in cylindrical coordinates as follows:

$$B_R = \frac{2\mu_o\ I\ Z}{R[(a+R)^2+Z^2]^{1/2}}\ [-K(m)+\frac{a^2+R^2+Z^2}{(a-R)^2+Z^2}\ E(m)] \quad [1]$$

$$B_Z = \frac{2\mu_o\ I}{[(a+R)^2+Z^2]^{1/2}}\ [+K(m)+\frac{a^2-R^2-Z^2}{(a-R)^2+Z^2}\ E(m)] \quad [2]$$

where B_R and B_Z are the radial and axial components of the magnetic field, μ_o is the permeability of free space, I is the current in each loop of radius a. K and E are complete elliptic integrals of the first and second kind whose variable is m:

$$m = \frac{4aR}{(a+R)^2+Z^2} \quad [3]$$

The values of K and E are available in the form of a fourth order polynomial expansion in terms of m.

The equations were normalized with respect to the radius of the coil, the spatial variables of z=Z/a and r=R/a were substituted. This change does not affect the variable m in the elliptic integrals.

The magnetic field is now represented by

$$B_r = \frac{2\mu_o \ I \ z}{ar[(1+r)^2+z^2]^{1/2}} \left[-K(m)+\frac{1+r^2+z^2}{(1-r)^2+z^2} E(m)\right] \quad [4]$$

$$B_z = \frac{2\mu_o \ I}{a[(1+r)^2+z^2]^{1/2}} \left[+K(m)+\frac{1-r^2-z^2}{(1-r)^2+z^2} E(m)\right] \quad [5]$$

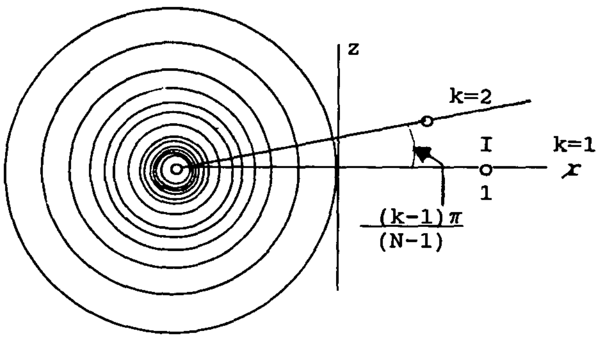
$$m = \frac{4r}{(1+r)^2+z^2} \quad [6]$$

The magnetic field of the first current loop, (k=1), may also be represented in phasor form as

$$\mathbf{B}_k = B_k \angle\alpha_k \quad \text{where } B = [B_r^2 + B_z^2]^{1/2} \quad [7,8]$$

$$\text{and } \alpha = \arctan [B_z/B_r] \quad [9]$$

The grid for the calculation of the B field is shaped like a spider web of M concentric circles and 2(N-1) radial spokes centered at unit distance from the origin. The radii of the circles in the grid increase as a geometric series. These radii are referenced as RG_i (i= 0..M). Each spoke is represented by the index j (1..2(N-1)). This grid is advantageous as the field intensities for each of the N rotated turns can be obtained from a single turn's computed field by simply adding an incremental angle to the appropriate phasor and summing N vectors for each point in the grid.



The current loops are referenced by the subscript k (1..N). The B field of the first current loop is computed for each grid point P(i,j) and these are stored as an array of values. The values are designated as

$$\mathbf{B}_{i,j,1} = B_{i,j,1} \angle \alpha_{i,j,1} \qquad [10]$$

however, $\mathbf{B}_{i,j,k} = B_{i,j+k-1,1} \angle \underline{\alpha_{i,j+k-1,1} \pm (k-1)\pi/N}$ [11]

therefore

$$\mathbf{B}_{i,j} = \sum_{k=1}^{N} B_{i,j+k-1,1} \angle \underline{\alpha_{i,j+k-1,1} \pm (k-1)\pi/N} \qquad [12]$$

These sums yield the amplitude and direction of the magnetic field of the "Slinky" model in the r,z plane. From these values the current density may be determined from the curl($\underline{B}$) in the same plane where the current distribution is uniformly orthogonal to the r,z plane.

Results of the calculations will be presented in graphic form.

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COMPARISON OF LINEAR AND NON-LINEAR METHODS IN THE ESTIMATION OF DEGREE OF COUPLING AND TIME DELAYS DURING SEIZURE SPREAD IN THE RAT

V.M.F. de Lima,F.H.L.da Siva,J.P.Pijn e C.N.Felipe

ABSTRACT -- Linear cross-correlation (r2) and the non linear association (h2) coefficients were applied to short epochs of epileptic activity recorded form both hippocampi in anaesthetized rats. When the major component of the signals were the high frequency population "spikes" coming different neural populations, only the non-linear coefficient detected coupling. When the signals in the epoch were dominated by the synaptic fields with low frequency components, both coeffficients detected coupling. A comparison was also made between the estimates of interhemispheric delays given by the maxima of the estatistical function and direct measurements of onset delays.