Experimental and Theoretical Analysis of the Induced Voltage along Implant Leads due to Gradient Fields

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Introduction:

Magnetic resonance imaging (MRI) is an important imaging technique to diagnose various diseases. However, patients with an implanted medical device, e.g. pacemakers, cannot benefit from this diagnostic modality. To analyze the adverse effects of MRI on patients with implants, various experimental studies have been performed [1]. It is observed that due to radiofrequency pulses, heating at the tip of the implant lead can occur and due to gradient fields, undesired stimulation can be observed. The harmful effects of gradient and static magnetic fields on the pacemaker also include asynchronous pacing, inhibition of pacing output, damage at the pacemaker circuitry causing changes at the program, or movement of the device [1]. In this study, we present a mathematical formulation that shows the risk of undesired stimulation due to the induced electric field by the gradient fields. During MRI, it is known that gradient fields induce an electric field inside the conductive medium. In this study, to analyze the safety aspect of the induced electric field on the implant lead, we use the simplified analytical electric field expressions obtained for a homogenous body model [2]. With the help of these expressions for *x*, *y* and *z* gradient coils, approximate voltage values to occur on the lead are derived analytically and these values are compared with the values obtained from realistic experiments. Experimental results show that, if we know the path of the implant lead we can determine the voltage induced on it using the simplified expressions.

Theory and Method:

The simplified electric field expression for a homogenous cylindrical body model was found with the assumption of the uniform gradient field distribution [2]:

$$\vec{E}(x,y,z,t) = G_x'(t)\left\{0.5xy\hat{a}_x + 0.25\left(-\rho_0^2 + y^2 - x^2\right)\hat{a}_y - yz\hat{a}_z\right\} + G_y'(t)\left\{0.25\left(\rho_0{}^2 + y^2 - x^2\right)\hat{a}_x - 0.5xy\hat{a}_y + xz\hat{a}_z\right\} + G_z'(t)\left\{0.5yz\hat{a}_x - 0.5xz\hat{a}_y\right\}.$$

Here ρ_0 is the radius of the cylindrical volume, $G_x'(t)$, $G_y'(t)$ and $G_z'(t)$ are the first order time derivatives of the gradient fields, and $\hat{a}_x$, $\hat{a}_y$, and $\hat{a}_z$ are the unit vectors in x, y and z directions, respectively. Inside the uniform region of the gradient field, the field distribution obtained with this simplified expression is similar to that of given in study [3]. From this expression, it is clear that the curl of the electric field is different than zero (i.e., $\nabla \times \vec{E} \neq 0$, which means field is not conservative) in the uniform region, so the induced voltage between the two selected points depends on the choice of path. Therefore the induced voltage on the implant lead can only be calculated if the position of the lead is known. By defining the path of the lead and using the relation between the voltage and the electric field (i.e., $V = -\int \vec{E} \cdot d\vec{l}$), the voltage induced on the lead is calculated approximately.

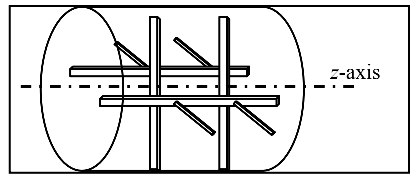
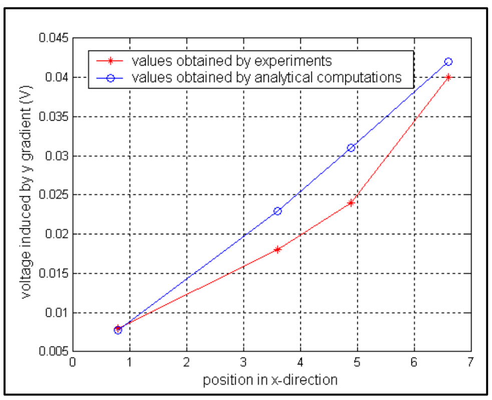


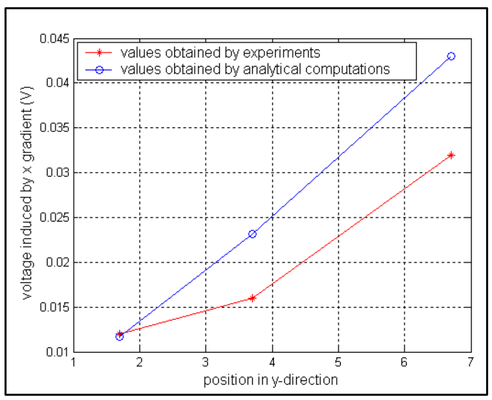
Figure 1: Cylindrical phantom with 18 cm diameter.

Experiments are performed by using a cylindrical phantom with a diameter of 18 cm (Figure 1). We use a dipole probe with 7.6 cm length (Figure 2), and perform the calculations using the path of this lead. Oscilloscope is used to measure the voltage. In the MRI sequence, RF is zero, gradients have 133T $m^{-1}s^{-1}$ slew rate, the duration of the gradient pulse is 5 s, and there is 5 s between each gradient.

Figure 2: A dipole probe.



Graph 1: The voltage change induced by *y*-gradient for different x positions when probe is located at the z-axis.



Graph 2: The voltage change induced by *x*-gradient for different y positions when probe is located at the z-axis.

Results and Discussion:

During the experiments, for different probe positions, voltage values are measured and compared with the results obtained with the analytical approach. To determine the exact position of the probe, MR images are used. Probe path is changed in x, y and z directions. Graph 1 and Graph 2 shows the comparison of the analytical results with the experimental observations. In both graphs we observe that the analytically computed voltage values form a tight upper bound for the experimentally observed values, hence the analytical results can be used for safety analyses. The differences between the two curves can be attributed to the assumptions made during the definition of the electric field (infinitely long phantom) and the limitations in the sensitivity of the probe and the oscilloscope.

Conclusion:

By using simplified electric field expressions, voltages induced on the lead are calculated analytically and by realistic experiments voltages induced on the lead are measured. Comparison of these results shows that, if the path of the implant lead is known, induced voltage on the lead can be determined analytically and with the obtained result the risk of the stimulation can be examined for patients with implants prior to MRI.

References:

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Acknowledgements:

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