APPLICATION OF A GTEM CELL TO DETERMINE RF INDUCED CURRENTS IN ELECTRODES OF MEDICAL IMPLANTS
An Alternative to Measurements in MRI Birdcages

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Abstract: RF induced currents in elongated electrodes of medical implants can cause hazardous tissue heating during MRI scans. In this paper we introduce an experimental setup to investigate the influence of the geometrical electrode design on the magnitude of the RF induced current. A Vector Network Analyser (VNA) was connected to a Gigahertz Transverse Electromagnetic (GTEM) cell containing the electrode under test. The forward power gain (S_{21} scattering parameter) was measured by the VNA, whereof the magnitude of the current at the electrode tip could be derived. Furthermore, calculations via transmission line theory were done to describe the present mechanism of current induction. These calculations show good agreement with the results of the performed measurements.

1 INTRODUCTION

Medical implants used to electrically stimulate nerves or muscles (e.g. cardiac pacemakers, cochlear implants or deep brain stimulation) find widespread application in therapeutic medicine. Some of these implants are contraindicated with magnetic resonance imaging (MRI). If these implants contain comparatively long metallic electrode leads, these electrodes couple with the radiofrequency field of the MRI scanner, which can cause serious burns of tissue specifically in the vicinity of the electrode contacts (Nitz et al., 2001). A current is induced along the axis of the electrode lead, which is prone to create a high current density in the tissue at the electrode contact. The electrical energy is absorbed and converted into thermal energy in the tissue, which has a much higher specific ohmic resistance than the electrode material. Therefore the amount of heating depends on the induced current, which in turn depends on the geometric design of the electrode. Other authors have, for instance, investigated tissue heating of different solenoidal electrode designs (Gray et al., 2005). Such changes in the electrode geometry may be capable of avoiding hazardous tissue heating.

In this paper we present an experimental setup to investigate the influence of electrode design on tissue heating. Instead of a temperature measurement of the tissue in a MRI birdcage, however, measurements of scattering parameters were performed by a Vector Network Analyser (VNA), connected to a Gigahertz Transverse Electromagnetic (GTEM) cell containing the electrode.

It is important to mention that the exciting electromagnetic field in the GTEM cell differs from the one in the MRI birdcage. Therefore, the presented GTEM setup is not proper for safety measurements of certain electrodes, but allows comparative investigations of induced RF currents in differently designed electrodes.

2 METHOD

The different electrode geometries were investigated under two different circumstances: with an alignment of the electrode perpendicular to the electric field and parallel to it. The experimental setup and the transmission line theory for the former alignment are described in the following paragraphs. The latter situation, which is more realistic in comparison to the situation in the MRI birdcage, will be subject of future experiments.

2.1 Experimental Setup

A LA19-13-02 3GHz VNA (LA Techniques, UK)

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was connected to a GTEM cell (Model 5402, ETS-Lindgren, USA) as it is shown in Figure 1. The output power of the VNA from port 1 was used to generate a homogeneous transverse electromagnetic field inside the GTEM cell. The electrode was positioned inside a medium and connected to port 2 via a BNC-connector at one end and left in contact to the medium on the other end. Several different media were investigated: air, silicone and a phantom muscle. The latter was a mixture of the gelling agent TX151 (Brunschwig Chemie, Netherlands), distilled water and sodium chloride (Chou et al., 1995). The electrode axis was in a horizontal orientation and thus perpendicular to the electric field, which is vertically aligned. The electric field was measured with an electric field probe (D.A.R.E.!! Instruments, RadiSense, LP1001A, Netherlands).

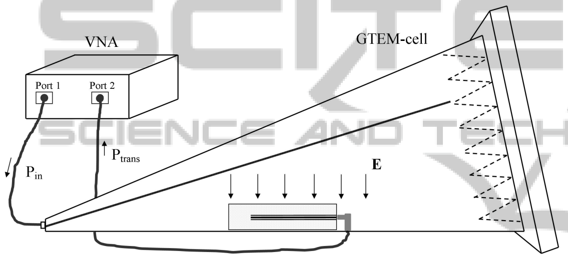

Figure 1: Connection of the VNA and the GTEM cell. The electrode under test is horizontally positioned and surrounded by a medium.

The Network Analyser measures the amplitude and phase of the four scattering parameters in a frequency range from 3 MHz to 300 MHz. Only the reverse (S_{12}) or forward (S_{21}) power gain – both are equal (reciprocity theorem) – are relevant in our investigation. The S_{21}-parameter is defined as the ratio of the transmitted power at the matched port 2 to the input power at port 1. We compared the amplitudes of the S_{21}-parameter of different electrode geometries (straight wires, completely and partially solenoidal wires) over the complete frequency range in air and silicone and at 64 MHz and 128 MHz in the phantom material, which are the RF frequencies for the 1.5 T and 3 T MRI-scanners, respectively.

The electrodes tested in viscous materials (e.g. silicone) were moulded into these materials to provide a perfect contact between the tip of the electrode and the medium.

2.2 Transmission Line Theory

A part of the equivalent circuit of the electrode being excited by the electric field of the GTEM cell is shown in figure 2. It is important to note that a theoretical description of the electrode as a transmission line must include environmental parameters in addition to intrinsic parameters of the electrode (Konings et al., 2000). In the presented setup, the electrode is

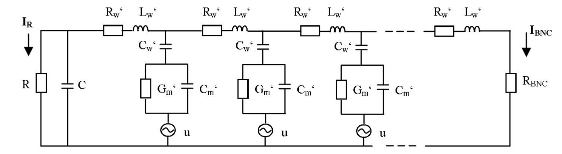

Figure 2: The equivalent circuit of the electrode in a perpendicular electric field inside the GTEM cell.

considered to be the inner conductor and the housing of the GTEM cell the outer conductor of the transmission line. The field perpendicular to the electrode axis induces a voltage u between the electrode and the GTEM housing. The equivalent circuit is a cascade connection of n consecutive quadripoles (three of them are shown in figure 2). Each quadripole is characterized by two complex impedances, one along the wire, consisting of a resistance R'_w in series with an inductance L'_w, another between the inner and outer conductor, consisting of C'_w in series with a parallel connection of G'_m and C'_m. R'_w and L'_w are the resistance and inductance of the wire per quadripole length, respectively, C'_w is the capacitance along the insulation layer between wire and medium per quadripole length, G'_m and C'_m are the conductance and capacitance between the surface of the insulation and the outer conductor per quadripole length. R_{BNC} is the resistance of the BNC-connection (=50Ω). For simplicity, the lead tip is described as a hemisphere, with surface area of the lead tip's real contact area, and thus representing the capacitance C of a hemisphere and an analogous resistance R. The total resistance and capacitance of the wire were also calculated by geometric considerations and checked by low frequency measurements and then divided by the number of quadripoles to yield the values per quadripole length. A calculation of R'_w and C'_w is trivial for any wire with concentric insulation. L'_w was estimated via well known inductance formulas for solenoids and straight wires. To determine G'_m and C'_m we considered the transmission line to be a coaxial line, with the radius of the outer conductor being equal to the distance between electrode and cell housing, while the radius of the inner conductor is equal to the wire radius for straight wires and equal to the coil radius for solenoid wires.

The equivalent circuit is a linear network with n voltage sources and described by 3n+2 independent first-order differential equations. They can be written in state space representation:

$$\dot{x}(t) = A \cdot x(t) + B \cdot u(t), \qquad (1)$$

where A and x(t) are the state matrix and state vector, B and u(t) are the source matrix and source vector, respectively. In the case of harmonic time dependence $e^{j\omega t}$, the equation simplifies such that x(t) can be easily calculated from u(t) within parts of a second using a commercial mathematical tool even for networks of 40 quadripoles and more. The vector x(t) contains the current and voltage along every element of the equivalent circuit including I_{BNC}. The power absorbed in R_{BNC} is $P_{trans} = I_{BNC}^2 \cdot R_{BNC}$. The amplitude of the S_{21}-parameter is then given by:

$$|S_{21}| = \sqrt{P_{trans}/P_{in}}, \qquad (2)$$

where $P_{in} = 1mW$.

For *in vivo* experiments the amount of tissue heating is most appropriately characterized by the specific absorption rate (SAR) (Yeung and Atalar, 2001). The SAR value can be derived from the current density by $SAR = J^2/(\rho \cdot \sigma)$, where ρ and σ are the mass density and electric conductivity of the tissue, respectively. In our model the current density is maximal at the electrode contact, where it is equal to I_R divided by the area of the electrode contact.

3 PRELIMINARY RESULTS

The model was checked by a rough comparison over the whole frequency range of measured and calculated S_{21}-parameters of solenoidal and straight copper wires with a diameter of 0.77mm. Figures 3 and 4 show good qualitative agreement of measurement and calculation of these electrodes in media with different relative permittivity ε_r, which was air ($\varepsilon_r = 1$) and silicone ($\varepsilon_r = 3$), respectively. A comparison of our model and a measurement of the electrode in the phantom muscle were not yet possible; a better definition of the relative permittivity and conductivity of the phantom material over the whole frequency range is required.

Excessive heating effects at the electrode contacts occur due to resonating RF waves (Konings et al., 2000), which depend strongly on the length of an electrode and the surrounding medium. The latter makes it difficult to exactly predict resonances, which is important for MRI safety aspects, however.

4 DISCUSSION & OUTLOOK

The presented experimental setup provides a possibility to determine currents induced in electrodes by RF fields. It measures the power received by the electrode, which represents an antenna, and verifies the validity of the equivalent circuit by comparison of the S_{21}-parameter over a wide frequency range. The current along the electrode as well as the current density at the electrode tip (which is relevant for SAR and thus the temperature rise estimation) can be derived by a state space analysis of the equivalent circuit. It has not escaped our attention that this approach contains uncertainties. The correct determination of the induced currents relies strongly on the accuracy of a theoretically derived equivalent circuit. Furthermore, the equivalent circuit correctly describing the situation of the electrode in the MRI birdcage differs from the one in the GTEM cell. Thus it is questionable to what extent one can conclude from the results in the presented setup to tissue heating in a MRI birdcage. The validity of such a conclusion must be confirmed experimentally and theoretically. This can be

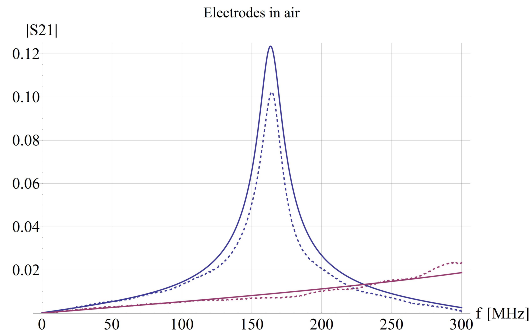

Figure 3: Comparison of the amplitude of the measured (dashed lines) and calculated (solid lines) S_{21}-parameter of a solenoid (blue) and a straight wire (magenta) in air. The parameters of the solenoid were: #turns = 54, pitch = 2mm, solenoid radius = 2.5mm, length of the solenoid = 0.1m. The length of the straight wire also was 0.1m.

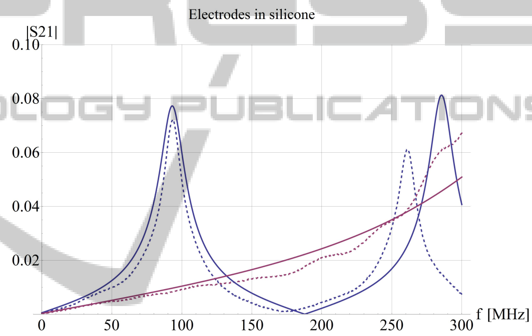

Figure 4: Comparison of the amplitude of the measured (dashed lines) and calculated (solid lines) S_{21}-parameter of a solenoid (blue) and a straight wire (magenta) in silicone. The parameters of the solenoid and the straight wire were the same as in figure 3.

achieved by comparing results of our setup to results of temperature measurements in a MRI birdcage or verifying the equivalent circuit via numerical computer simulation techniques. This will be a future challenge.

Nevertheless, already at the present stage the setup allows fast and uncomplicated measurements over a wide frequency range including several RF frequencies of present commercial MRI scanners. Such a broadband current measurement allows a better insight in the mechanism of RF induced currents in electrodes than temperature measurements at a single frequency in MRI scanners.

Further work will be done to investigate different electrode geometries and materials with electrode axis parallel to the electric field.

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