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Experimental and simulated distribution of the RF electrical field inside a birdcage coil

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Synopsis

High-field MR systems bring additional safety issues regarding the patient. One of main concern is the heating effect caused by the high-frequency and high-power signals that can be picked up by the conductors. It is thus required to identify these regions and to quantify the electrical E -field knowing that it is proportional to the square of the temperature elevation. For a direct measurement, an optical probe was used to perform a mapping of the E -field distribution inside a birdcage of a preclinical MRI. Experiments and simulations were found similar with E -field concentrations mainly located close to the capacitors.

Introduction

The spatial resolution of MR images could be improved by developing sophisticated radiofrequency (RF) transceiver coils or by increasing the static magnetic field B_0 -strength¹. However, the fast and successful progresses of MR scanners could be the reason for additional safety issues regarding the patient²⁻³. The specific absorption rate (SAR) is proportional to the square of B_0 thus local heating is caused by the transmission of high-frequency and high-power electrical E -field along conductors or passive components e.g. capacitors. This requires a fast and an accurate assessment of the E -field concentrations in order to control the SAR-parameter during MRI exam. Detecting of the distribution of the E -field inside MRI or near metallic implants was already evaluated by dipole-based probes inserted in a phantom^{4,5} and numerical simulations⁶. But, the metallic structure of the dipole probe may alter the electromagnetic fields and thus limits the accuracy of the measurements. In this study, we propose an optical-based probe for E -field measurements and we present a comparison between the simulated E -field distribution and the experimental map of the E -field using an optical-based probe inside a MRI birdcage.

Methods

A finite element method simulation was performed using COMSOL Multiphysics. The birdcage consists of two circular conductive loop (end rings) where the capacitors are placed and nineteen conductive elements referred to as rungs (Fig 1). The capacitors of the coil are defined using lumped elements. The birdcage is linear thus only one lumped port boundary is used for RF excitation ($P = 138\text{W}$). The birdcage was placed inside a cylindrical RF shield. The experimental measurement of the E -field was performed in a 4.7-T preclinical MRI (Bruker) using an optical-based probe. The E -field probe operates based on Pockels effect; it consists of isotropic crystal that changes its optical proprieties according to the variation of the E -field. A laser diode was simultaneously applied to the crystal. The polarization of the laser changes with the applied E -field. Optoelectronic devices were used to analyze the modulation of the polarization and insure the optical-to-electrical conversion of the signal to be then visualized by a spectrum analyzer. The probe measures the radial component of the E -field. It was calibrated outside the MRI to determine the proportionality factor between the EO signal and the E -field. The proximal side of the birdcage corresponds to the plane $Z=0$. On this plane, we have chosen nine measurement points as shown in Fig 2. For these nine points, we have measured the E -field every 1cm by moving the probe along z-axis. The measurements points have been used to plot 2D maps of the E -field using Matlab language. For these experiments, a FLASH sequence with hermite shape RF pulse was used.

Results

The simulated results show that the E -field is not uniform within the birdcage. Figure 3 exhibits clearly the positions of the E -field concentrations regarding the geometry of the birdcage. The high-concentrations areas (around 1900 V/m) are mainly located near the lumped port and the capacitors. The concentrations-value gradually decreases along the copper rungs to have the lowest value (100 V/m) in the middle of the birdcage rungs/legs. Experimental maps are shown in the Fig 4. The E -field high-concentrations are located at Z-values equal to 5 cm and 11 cm for all the slices. The E -field was measured with a factor of proportionality equal to 417714.9 m^{-1} . The maximum value was around 1900 V/m and decreases progressively by approaching to the center.

Discussion

The E -field measurements and simulations were performed in air in order to determine the distribution of the E -field inside a birdcage and specifically near its walls without any limitations due to the dimensions of a phantom^{4,5}. The experimental maps of the E -field are very close to the simulation in terms of distribution and value. The high concentrations of the E -field are in proximity of the birdcage wall and the weakest concentrations are in the center. The simulation shows that the E -field high-concentrations are located near lumped port and capacitors. The distance between the two rings is 56 mm, therefore the high-concentrations in the experimental maps corresponds exactly to the locations of the capacitors.

Conclusion

We proved that the optical-based probe has the ability to measure in air the E -field inside a birdcage within picoseconds. This probe would also be used inside a phantom or a biological tissue to control the SAR-parameter and could definitely replace thermal sensors commonly used as an alternative method for SAR assessment but cause additional measurement errors due to the convection and the diffusion of the temperature in the medium nearby.

Acknowledgements

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Figures

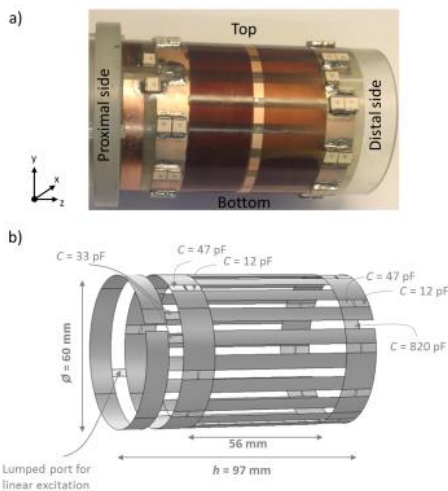


Fig 1. a) A photograph of the birdcage used. The birdcage was put inside the 4.7-T MRI as shown in the photograph. b) The design of the birdcage modelled by COMSOL Multiphysics. The RF excitation is linear and transmitted along the x-axis. A lumped port was used to simulate the coaxial cable that transmits the excitation pulse.

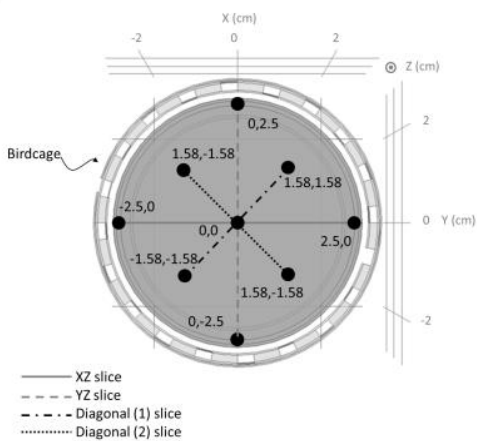


Fig 2. The black dots indicate the locations of the nine measurement points in xy-plane. Each point is referenced by a (X, Y) coordinate-values (in cm). The E-field was measured every 1cm by moving the probe along the z-axis. The points are used to plot four slices: (2.5,0), (0,0) and (-2.5,0) points are used to plot XZ slice, (0,2.5), (0,0) and (0,-2.5) points are used to plot YZ slice, (1.58,1.58), (0,0) and (-1.58,-1.58) points are used to plot diagonal(1) slice and (1.58,-1.58), (0,0) and (-1.58,1.58) points are used to plot diagonal(2) slice. The spatial resolution of the probe is 5mm.

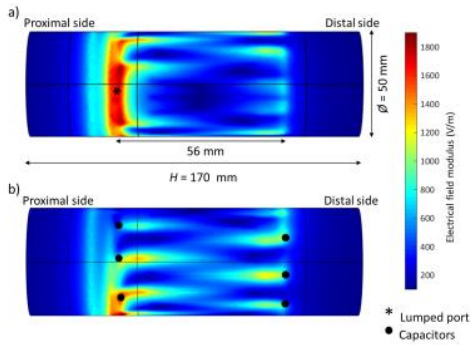


Fig 3. Simulated three-dimensional maps of the E -field distribution within the birdcage (E -field mapping on the surface of a 50 mm-diameter cylinder of air inside the birdcage). a) The E -field concentrates principally near the lumped port modelling the coaxial cable. b) The simulation demonstrates that the E -field concentrates as well close to the capacitors put at the proximal and distal sides of the birdcage. The asterisk and the black dots are used to mark the positions of the lumped port and the capacitors, respectively.

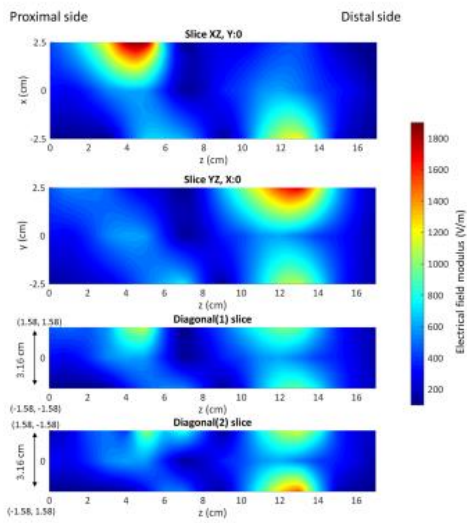


Fig 4. Experimental two-dimensional maps of the E -field inside the birdcage using an optical probe. For the four maps, the distance between the high-concentrations along the z -axis is around 60 mm which corresponds exactly to the locations of the capacitors. Referring to the simulation, the high-concentration at the point ($X=2.5, Z=5$) of XZ slide is due to the coaxial cable.