MRI Heating Reduction for External Fixation Devices Using Absorption Material

Xin Huang, Jianfeng Zheng, Ji Chen
ECE department
University of Houston
Houston, USA
{xhuang12, jchen18}@uh.edu

Xin Wu, Mari Kono, Hideki Hozono
Molex Inc.
Lisle, USA

Wolfgang Kainz
Food and Drug Administration
Silver Spring, US
wolfgang.kainz@fda.hhs.gov

***Abstract*— Using absorption materials to reduce RF heating during MRI procedure is studied in this paper. Materials with different electromagnetic absorption characteristics are used to alter the EM and current distributions on the device. Consequently, the RF induced heating behaviors of external fixation devices can be reduced. Numerical and experimental studies are provided to demonstrate the potentials of reducing the RF heating for external fixation devices of using lossy materials.**

Keywords—absorption material; RF heating reduction; external fixation

I. INTRODUCTION

Over recent years, magnetic resonance imaging (MRI) has become one of the most important imaging techniques. However, strong radio frequency (RF) fields generated by MRI systems can cause heating effects when patients are being scanned. This can be a significant issue when patients with metallic medical devices are scanned. Localized energy can be deposited near the tips of these medical devices. This is particularly true when patients with external fixation devices are being scanned since only a small portion of the metallic implants are inside the human body while major portion of the device is outside the human body. A typical external fixation device is made up of nonmagnetic metal to maintain its mechanical strength. When the device undergoes MRI, the metallic parts will interact strongly with the electromagnetic field and may produce very high local temperature increase inside human subjects. Luechinger et al. evaluated a group of nonmagnetic large external fixation clamps and frames in MR environment and found a maximum of 9.9 ºC temperature increase at the tip of metallic pin which was buried in human bodies [1]. Besides, Liu et al. studied the effect of insulated layer material, and found it a potential way to reduce the induced RF heating [2].

In this paper, a novel and efficient solution to reduce RF induced heating is proposed. The utilization of absorption material can help change the electric field distribution in the external fixation devices, make power consumed outside the human body, and thus reduce the heating effect. With current technology, the absorption characteristics of the material can be adjusted by needs. This approach makes absorption material practical in engineering.

The rest of this paper is divided into several parts. In section II, a numerical simulation framework will be introduced, including the device description and simulation setting. Section III will explain the simulation study and present numerical result. The usage of the absorption material is proved to change the distribution of RF fields, which ultimately affect the heating behavior. Section V will demonstrate an experimental result of the absorption material. Discussion and conclusion will be obtained in section VI.

II. NUMERICAL SIMULATION FRAMEWORK

Numerical simulations have always been widely used in RF heating evaluation. To mimic the real circumstances, the property of material, the CAD model for devices and tools, the environment and the methodology to evaluate heat should be specified in simulation setup.

A. *Absorption Material*

The absorption material comes from the concept of absorber in antenna engineering. In anechoic chamber, absorber is used to absorb the reflected wave on the wall of the chamber [3]. The absorber should be lossy so that the reflected EM waves can be eliminated. For single frequency RF heating evaluation, the absorption characteristics can be considered as electrical conductivity. In this paper, conductivity ranging from 10^{-4} to 10^{3} S/m is dedicatedly investigated.

B. *External Fixation Device and ASTM phantom*

An external fixation device is used for stabilization and immobilization of bones with open fractures. The device is generally composed of clamps, pins and connection bars. A generic external fixator model was developed to study the RF heating effects in MRI environment [4]. The model is shown in Fig. 1. It is comprised of three parts: 1) two metallic blocks to represent the clamps; 2) two connection bars between the clamps; and 3) four pins which are screwed into the bones during surgery. The metallic block has the dimension of 11.4 cm by 2 cm by 3.75 cm. The pin has a diameter of 0.5 cm and length of 16 cm. The connection bar has a diameter of 1.1 cm and a length of 41.5 cm. In this work, the 2 cm insertion depth is used for all studies.

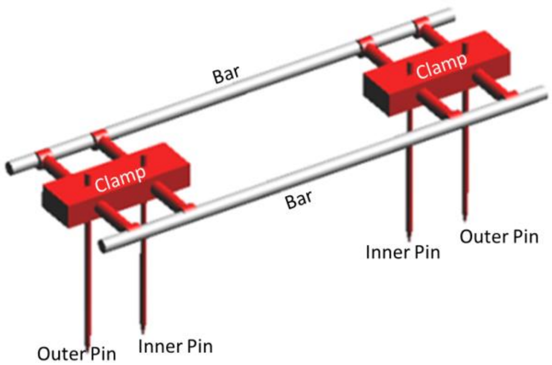


Fig. 1 Typical structure of external fixation devices

In this study, device is placed at a location where high incident tangential electric field is observed (see Fig. 2). The absorption material is modeled as a ring structure with inner diameter = 5 mm and outer diameter = 7 mm placed between the block and pin. Detailed structure for the device model is shown in Fig. 3. Electrical properties for materials are shown in Table 1.

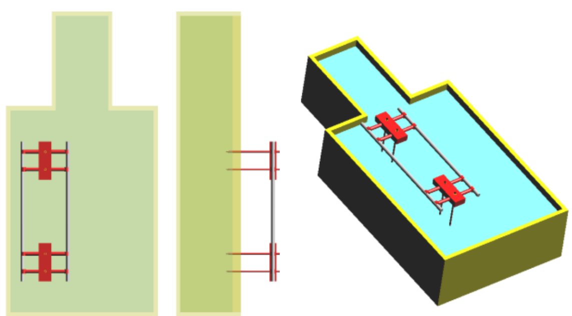


Fig. 2 relative location of external fixation and ASTM phantom

TABLE 1 ELECTRICAL PROPERTIES FOR MATERIALS (AT 64MHZ)

	Relative Permittivity	Electrical conductivity
ASTM Phantom Gel	80.38	0.448
ASTM Phantom Shell	3.7	0
Bar (Carbon fiber)	10	5700000
Device Clamp, Pin	PEC	PEC

C. *Heating Effect Evaluation*

Developed in 1948 by Pennes, the "Pennes Bioheat Equation" (PBE) with certitude is the most used model for thermal BioEM simulations. The formula is shown below:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T\right) + \rho Q + \rho S - \rho_b c_b \rho \omega \left(T - T_b\right) \qquad (1)$$

where k is the thermal conductivity, S is the specific absorption rate (SAR), ω is the perfusion rate and Q is the metabolic heat generation rate. ρ is the density of the medium, ρ_b, c_b and T_b are the density, specific heat capacity and temperature of blood.

From above equation, induced RF heating effects are commonly related to Specific Absorption Rate (SAR). It is commonly accepted to use SAR as a typical index of heating. Later in this paper, 1g average SAR value will be used to evaluate RF heating effects.

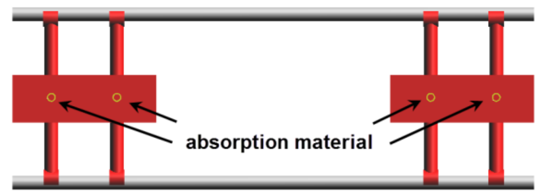


Fig. 3 Absorption material geometry on external fixation devices

III. SIMULATION STUDY

To study the effect of different absorption materials on induced RF heating of the device, 5 categories of materials with different absorption characteristic are numerically examined. Each category has its individual dielectric constant epsilon = 2, 3, 5, 7, 9, and the electrical conductivity varies from 10^{-4} to 10^{3} S/m. The electromagnetic properties of device bar, ASTM phantom gel, ASTM phantom shell are shown in Table 1. The other parts of the external fixation devices are modeled as perfect electric conductor (PEC). After the simulation, 1g averaged SAR along device pins can be obtained for further analysis.

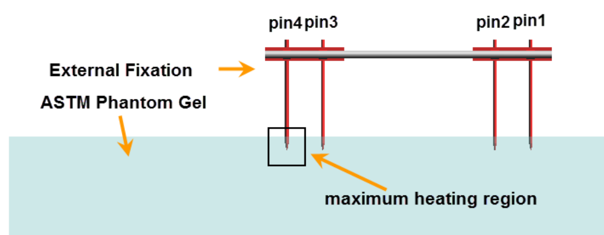


Fig. 4 Side view of external fixation geometry

A. *Typical examples of simulation*

The external fixation geometry is shown in Fig. 4. For simplicity, the four pins are named pin 1, pin 2, pin 3, and pin 4 from right to left. Two examples are chosen to illustrate typical SAR patterns.

The first example is shown in Fig. 5(a). The material has a dielectric constant $\varepsilon_r = 9$ and $\sigma = 0$. The maximum heating regions occur at the tip of the pins. Red square in this figure denotes the global maximum SAR value. To have a better view, the SAR along a horizontal line across the pin tip (the green line in Fig. 5(a)) is shown in Fig. 6. It is observed that the outer pins (pin 1 and pin 4) have larger SAR value than that at the inner pins (pin 2 and pin 3). The highest SAR can be as high as 1160 mW/g, which is located at tip of pin 4.

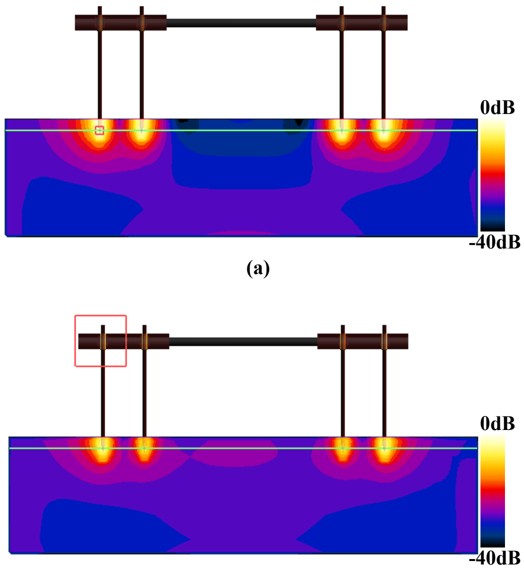


Fig. 5 1g average SAR distribution at cross-section plane of pins for case a) ε_r=9, σ=0 and b) ε_r=9, σ=0.1 S/m. All SAR values are normalized to 1160 W/kg

In the second example, which corresponds to $\varepsilon_r = 9$ and $\sigma = 0.1$ S/m, the SAR pattern is shown in Fig. 5(b). SAR pattern inside the phantom gel is nearly the same as before, but the global maximum SAR occurs at the layer between clamp and pin, as denoted by a red square. The SAR value along the same green line is plotted in Fig. 6. While the global maximum SAR goes up to 905mW/g, the max SAR inside the phantom is about 470mW/g. Since only inside the phantom is the region of interest, the max SAR is reduced by nearly 59.5% compared with pure insulating material.

Those field distributions in Fig. 5 are normalized to 1160 mW/g. No matter what the absorption material will be, the energy dissipation is found to be concentrated and decays rapidly around the tip of the pin. For case $\varepsilon_r = 9$ and $\sigma = 0.1$ S/m, the maximum SAR at the tip of the pin is smaller than the case $\varepsilon_r = 9$, $\sigma = 0$. This implies materials with absorption characteristics can possibly reduce heating effects.

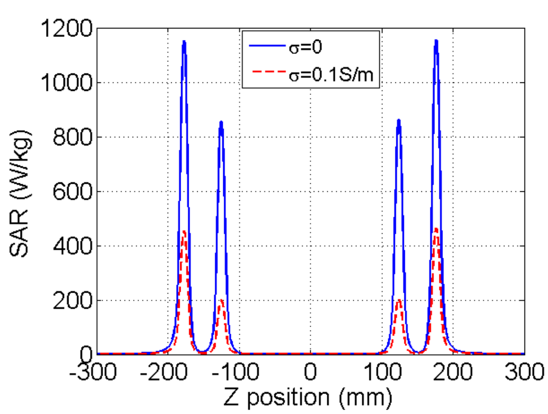


Fig. 6 SAR along green line that across the tips of pins (ε_r=9)

B. Maximum SAR vs. conductivity

As the conductivity of the material changes, external fixation device will have different thermal behavior. For $\varepsilon_r = 9$, the relationship between conductivity and the max SAR near pin is plotted in Fig. 7. There is a valley in the middle range (10^{-2} to 10^{0} S/m). The minimum value for max SAR at pin is 450mW/g. When conductivity goes lower (10^{-4} to 10^{-3} S/m) or higher (10^{1} to 10^{3} S/m), the max SAR increase to 1160mW/g and 645mW/g respectively. It should be pointed out that current optimal conductivity are acquired based on the thickness of 1mm lossy ring at 64 MHz. This optimal conductivity could change as a function of ring thickness.

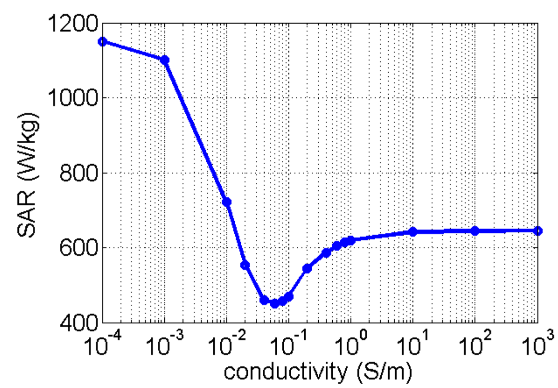


Fig. 7 Max SAR near pin vs. conductivity for ε_r=9

C. Max SAR-conductivity curves vs. permittivity

Various dielectric constants are tried to test the idea of using absorption material. From Fig. 8, the utilization of absorption material to reduce RF heating works for a large

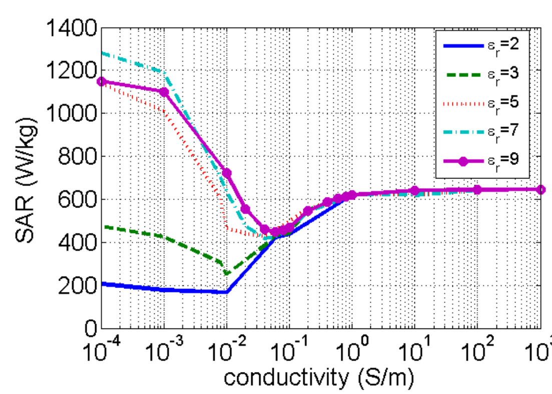


Fig. 8 Maximum SAR near pin vs. conductivity for different dielectric constant

permittivity range (from 2 to 9) for heating reduction. For smaller permittivity, the conductivity needed to reach the minimum SAR is smaller.

IV. DISCUSSION

The numerical results above can be concluded as follows: by using different absorption material, the RF induced heating effects may have different behavior. If properly chosen, the absorption material can reduce the RF induced heating effect. The reason why too high or too low conductivity result in higher SAR at pin can be explained by the definition of SAR.

TABLE 2 OPTIMUM CONDUCTIVITY FOR DIFFERENT PERMITTIVITY AND THEIR LOSS TANGENT AT 64 MHZ

Permittivity	Optimum Conductivity (S/m)	Loss Tangent
2	6e-3	0.8426
3	1e-2	0.9362
5	1.5e-2	0.8426
7	4e-2	1.6050
9	6e-2	1.872

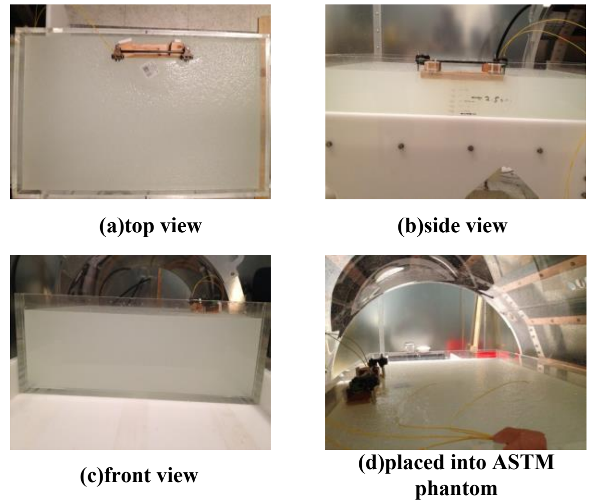
SAR is defined as $\sigma E^2/2\rho$. The received power for the external fixation can be assumed relative invariant. When conductivity is very close to 0, i.e. sigma approaches to zero, the SAR is zero. On the other side, when the conductivity goes high enough, the material acts like PEC, which means the electric field inside the material is zero. SAR is then zero as well. SAR represents the power loss in this position. Since there is no power dissipation in the absorption material, all energy enters into the phantom gel and thus higher SAR is expected. When conductivity is in the middle range (10^{-2} to 10^{0} S/m), neither conductivity nor E field approaches to zero. The power consumption in the material reaches the maximum. Energy that can enter the phantom becomes less.

When the minimum value for max SAR near pin occurs, the corresponding conductivity is called optimum conductivity. Table 2 lists the optimum conductivity for different dielectric constant. Also loss tangent is provided. When the loss tangent is near 1 or 2, the minimum peak SAR near pin can be achieved.

V. EXPERIMENTAL STUDY

To validate the heating reduction effect of absorption material, experiments are conducted in a MRI birdcage coil at 64 MHz. A MRI shielding room is employed to prevent leakage of RF field. Up to 4 temperature probes can be used to measure the thermal effect. Temperature recording platform is embedded with the probe system so that there is no need to do the reading manually.

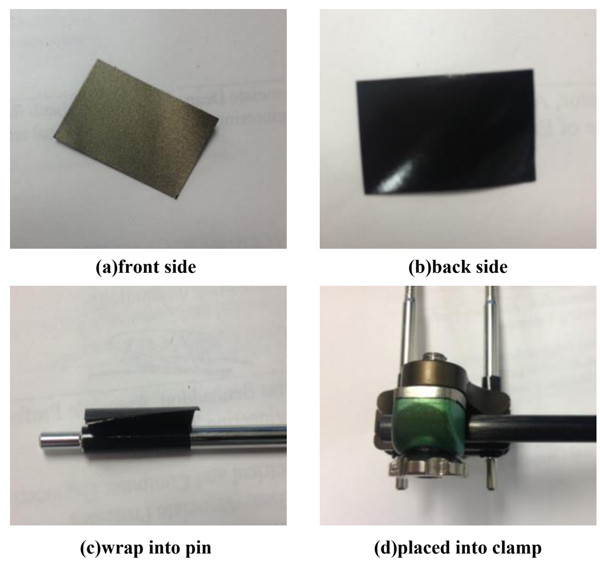
According to standard ASTM F2182 [5], device is put into phantom at about 2-3cm from the side (see Fig. 9). Phantom with device is loaded into MRI birdcage for 15 minutes. The temperature is recorded once the MRI coil is turned on.



(a)top view **(b)side view** **(c)front view** **(d)placed into ASTM phantom**

Fig. 9 Experimental setup for external fixation and ASTM phantom

The absorption material provided by Molex is shown in Fig. 10. For testing, the material is wrapped at connecting part between device components with 1mm thickness (see Fig. 10).



(a)front side **(b)back side** **(c)wrap into pin** **(d)placed into clamp**

Fig. 10 setup for absorption material

There are two kinds of connecting parts. One is covered between clamps and pins, while the other one is covered between clamps and bars. For convenience, these two configurations are named “pin cover” and “bar cover” respectively. Four cases are measured in the experimental study, which are listed below:

- No cover for device (no cover)
- Cover between pin and clamp (pin cover)
- Cover between clamp and bar (bar cover)
- Cover on both sides (both cover)

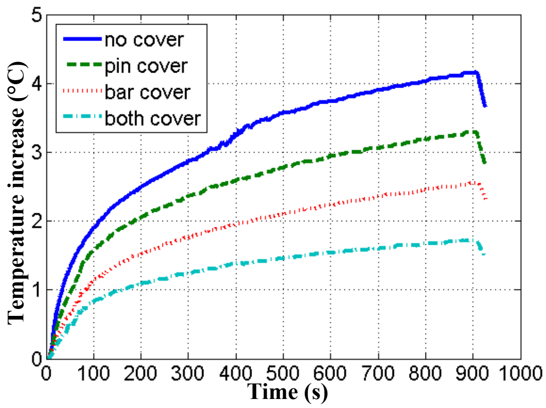


Fig. 11 Temperature increase measurement for all 4 cases

The temperature increase measurement for all 4 cases is plotted in Fig. 11. The device with no cover is observed to have the highest temperature increase, about 4.2 °C. As the pin cover or bar cover applied to the external fixation device, the heating effect becomes less significant (3.3 and 2.6 °C respectively). Device with cover on both sides will have temperature rise as low as 1.7 °C.

VI. Conclusions

The effects of using absorption material between the clamp and pin for external fixation device were numerically and experimentally studied in this paper. Choosing proper conductivity of the absorption material can potentially reduce the induced RF heating since some of the energy is consumed in the absorption material instead of entering the phantom.

References

[1] Luechinger R, Boesiger P, Disegi JA, "Safety evaluation of large external fixation clamps and frames in a magnetic resonance environment," J Biomed Mater Res B Appl Biomater 2007; 82:17-22

[2] Liu Y, Kainz W, Qian S, Wu W, Chen J, "Effect of insulating layer material on RF-induced heating for external fixation system in 1.5 T MRI system" Electromagnetic Biology and Medicine

[3] A. Hasnain, M. I. Imran, Z. S. Rohaiza, S. Roslan, A. A. Takiyuddin, A. Rusnani, A. A. H. Azremi, "Preliminary Development of Mini Anechoic Chamber," Asia Pacific Conference on Applied Electromagnetics (APCAE 2007), pp. 1–5, 2007.

[4] Liu Y, Shen J, Kainz W, Qian S, Wu W, Chen J, "Computational Study of External Fixation Devices Surface Heating in MRI RF Environment," IEEE Symposium on Electromagnetic Compatibility, Pittsburgh, Aug 2012

[5] ASTM International. Standard test method for measurement of radio frequency induced heating near passive implants during magnetic resonance imaging. ASTM standard F2182-11 West Conshohocken, PA: ASTM International: 2011. www.astm.org