The Effects of Patient Orientations, Landmark Positions, and Device Positions on the MRI RF-Induced Heating for Modular External Fixation Devices

Author:

Meiqi Xia

Jianfeng Zheng

Rui Yang

Shuo Song

Jian Xu

Qi Liu

Wolfgang Kainz

Stuart A. Long

Ji Chen

Correspondence:

Ji Chen,

Department of Electrical and Computer Engineering, University of Houston

N308 Engineering Building 1

4726 Calhoun Rd

Houston, TX 77204-4005

Email: jchen18@uh.edu

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Abstract:

Purpose: This paper studies the radio frequency (RF)-induced heating for modular external fixation devices applied on the leg regions of the human bodies. Through numerical investigations of RF-induced heating related to different patient orientations, landmark positions, and device positions under 1.5 T and 3 T magnetic resonance imaging (MRI) systems, simple and practical methods to reduce RF-induced heating are recommended.

Methods: Numerical simulations using full-wave electromagnetic solver based on the finite-difference time-domain (FDTD) method were performed to characterize the effects of patient orientations (head-first/feet-first), landmark positions (the scanning area of the patient), and device positions (device on left or right leg) on the RF-induced heating of the external fixation devices. The G32 coil design and three anatomical human models (Duke model, Ella model and Fats model) were adopted to model the MRI RF coil and the patients.

Results: The relative positions of the patient, device and coil can significantly affect the RF-induced heating. With other conditions remaining the same, changing device position or patient orientation can lead to a peak 1 gram (g) averaged spatial absorption ratio (SAR_{1g}) variation of a factor around 4. By changing the landmark position and the patient orientation, the RF-induced heating can be reduced from 1323.6 W/kg to 217.5 W/kg for the specific scanning situations studied.

Conclusion: Patient orientations, landmark positions, and device positions influence the RF-induced heating of modular external fixation devices at 1.5 T and 3 T. These features can be used to reduce the RF-induced heating during MRI simply and practically.

KEYWORDS: modular external fixation devices, patient orientation, landmark position, device position, magnetic resonance imaging (MRI), RF-induced heating

1. Introduction

Although magnetic resonance imaging (MRI) scanners do not use the harmful ionizing radiation like X-rays and computed tomography (CT) scanners, there are still some safety issues related to medical devices that are fully or partially implanted in a human body undergoing MRI scan (1,2,3). One of these is the heating due to the interactions between the RF field and gradient field from the MRI system and the devices (4). For the fully implanted devices or partially implanted external devices in the human body, they usually do not have planar conductive surfaces and the gradient-induced heating is ignorable (5). Thus, the safety concerns mostly come from the RF-induced heating. The RF field will lead to high heating near the device, especially for metallic devices, and may result in the burn of tissue. Research about RF-induced heating of medical devices has been widely conducted, particularly for implanted wires or leads used for pacemakers or neurostimulators (6,7,8,9), implanted stents (10,11), and implanted plates and screws used for trauma system (12). For external fixation devices, some research has been conducted to study the RF-induced heating in a phantom using numerical simulations (13,14,15). However, the situations studied are limited and further study in the human models is still needed.

External fixation devices are typically used to immobilize the broken bone segments and generally include screws, clamps, and rods (16,17). Different from internal implants, external fixation devices can be quite large and very close to the RF coils. These factors can lead to more severe RF-induced heating concerns, and the overall system can become very sensitive to the relative positions of the RF coil, patient and external implant. The common factors affecting the relative positions are the different patient orientations, landmark positions, and device positions. Here, the patient orientation means the way that patients enter the MRI coil (head-first or feet-first), landmark position indicates the scanning area of the patient, and device position denotes the location of the device (device on left or right leg in this study). Since these factors can significantly affect RF-induced heating, such heating in the human body related to the external device may be mitigated by carefully considering these external factors during imaging. In order to find simple and practical methods to control the RF-induced heating near the external fixation devices, the influence of patient orientations, landmark positions and device positions on RF-induced heating needs to be studied.

Related research has suggested that head-first and feet-first can result in different RF-induced heating for a fully implanted device (18). But the study for the external fixation device is still needed. In addition to the patient orientation, the landmark position of the human model in the coil also significantly affects the RF-induced heating (19,20,21). The different landmark positions were modeled by moving the human model in the axial direction of the coil with a series of distances in this paper (21). The different landmark positions will lead to varying field distributions (21) then can influence the RF-induced heating.

In this study, firstly, a typical external fixation device used on the leg was simplified and modeled (22,23). Secondly, numerical simulations were performed to reveal the relationships between the RF-induced heating and imaging conditions. Specifically, the devices with different screw lengths and rod lengths were deployed in the Duke model and simulated under different patient orientations, landmark positions, and device positions at both 1.5 T and 3 T. Further, the Ella model and the Fats model with a specific device were also simulated to study the influence of patient population. Here, the MRI RF coils were represented by the G32 model. All the simulated results for different loading directions, loading positions, and device positions were compared in terms of peak SAR_{1g} near the device. Then a strategy was developed to manage the RF-induced heating by choosing the appropriate imaging conditions.

2. Methods

2.1 Device introduction

The modular knee bridge studied in this paper is a modular external fixation device used on the leg region for connection and fixation (24). The device mainly consists of rods, clamps, and screws as shown in Figure 1A. An example of device placement on the human body is shown in Figure 1B.

Generally, the screws and the clamps are made of metallic materials and the rods can be made of metal, carbon fiber or plastic glass (13). In this study, the rods of the devices were all chosen as carbon fiber and other parts were set to be perfect electrical conductors (PEC). To validate the PEC assumption, the conditions for PEC material and stainless-steel material were simulated. The relative errors of peak SAR_{1g} and highest temperature rises near the device do not exceed 0.5 % at 1.5 T and 3 T for the simulated situations. Thus, the contribution of the Joule heating in the clamps and screws can be neglected and using PEC is reasonable. In the simulations, some typical lengths of the screws and rods were chosen as (23): 140 mm,150 mm,160 mm, and 170 mm for screws and 200 mm, 250 mm, and 300 mm for rods.

2.2 Human models and coil

The three human models used for simulations (Duke model, Ella model and Fats model) are representative human models from the Virtual Family (25). The Duke and the Ella model have the world-average weights and heights for males and females respectively, and the Fats model is a typical obese male with high BMI. The Duke model was used for simulations for all sizes of the device. Then the Ella model and the Fats model were simulated with a specific device configuration (250 mm rods and 150 mm screws) to investigate the influence of different human models.

In order to get a circularly polarized and uniformly distributed $\vec{B}_1$ field inside the coil which can represent the field inside the physical MRI RF coil, the G32 coil was chosen for simulations to balance the complexity and accuracy of the modeling (26). The G32 coil design used in this study is a generic 32 port coil with 650 mm height and 740 mm diameter as in Figure 2A and Figure 2B. The coil has 32 sources on the rings (16 in the upper ring and 16 in the lower ring) and does not have any lumped elements. The sources are voltage source with 1 V amplitude and 50 Ω resistor in series. There is a successive phase delay of 22.5 degrees between adjacent sources. For any two sources on the top and bottom rings at the same azimuthal position, the source on the top ring is advanced 180 degrees in phase. The $\vec{B}_1$ field distribution of the unloaded G32 coil used for simulations is shown in Figure 2C: the blue arrow is the polarization direction of $\vec{B}_1$ field at the center of the coil (the element of $\vec{B}_1$ field along z axis is neglectable for z=0 cross-section), and $\vec{B}_{1+}$ and $\vec{B}_{1-}$ components in the coil at z=0 cross-section are also plotted. As shown in Figure 2C, the $\vec{B}_{1+}$ is the principal component, and it is the same as that used in the clinical setting.

2.3 Simulation setup

All numerical simulations were conducted with the SEMCAD X (V14.8 SPEAG) software based on the Finite-Difference Time-Domain (FDTD) method. The operating frequency is 64 MHz at 1.5 T and 128 MHz at 3 T. Boundaries for all six directions were set as absorbing boundary conditions (ABC) to reduce simulation domains. The simulation time was all set to be 30 periods for assuring convergence with the affordable computational burden. In order to make sure that the simulations were converged, the currents, voltages, and E/H field signals of the sensors versus time were checked after the simulations. The maximum mesh steps were 2.5 mm for the human models, 2 mm in the *x* direction and 1 mm in the *y* and *z* directions for screws and clamps, and 2 mm for other parts of the device with the adaptive meshing used. The human models were loaded in a series of positions along the z-direction as in Figure 3A. The initial position would have the device at the center of the coil along the z-axis. Then the human models with the device were moved along the z- direction (–z direction for head-first and +z direction for feet-first) for distances of 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm, respectively. To investigate the impact of the patient orientation (head-first/feet-first shown in Figure 3B) and device position (device located on the left leg or on the right leg), four scenarios, as shown in Figure 3C, were studied. All the results were normalized to a whole-body average SAR of 2 W/kg.

3. Results

To quantify the RF-induced heating, the spatial averaged specific absorption rate over one gram (SAR_{1g}) was proposed as a standard (6,27,28,29,30). The SAR is calculated as (29):

$$\mathrm{SAR} = \frac{\sigma|E|^2}{\rho}\ (W/kg)$$

where σ is the conductivity of the tissue, ρ is the mass density, and E is the root mean square of the electric field strength. The SAR averaged over one gram is denoted as SAR_{1g}. The simulation results of the peak SAR_{1g} near the device are shown as following and examples of SAR distributions over the three human models are shown in Supporting Information Figure S1. An uncertainty analysis has been conducted to consider the uncertainty of the human tissue, mesh resolutions, absorbing bounding conditions and temporal convergence, which shows the combined standard deviation uncertainties are 10.0% at 1.5 T and 6.5% at 3 T.

3.1 Simulation results of the Duke model at 1.5 T

From the results in Figures 4 and 5, the values of peak SAR_{1g} near the device are influenced by the length of the rods and screws at 1.5 T. For all sizes of the studied device, the values of peak SAR_{1g} near the device at 1.5 T always decrease with the human model moving away from the center of coil along z-direction for all four situations (feet-first with device on the left leg, feet-first with device on the right leg, head-first with device on the left leg and head-first with device on the right leg). For the four situations, the peak SAR_{1g} near the device are different for different patient orientations (head-first or feet-first) and device positions (device on left or right leg). Although the difference is not significant, patient orientation and device position still influence the RF-induced heating for the studied external fixation device. At 1.5 T, the influence of landmark position on RF-induced heating is the most dominant factor. Therefore, the most efficient way to control the RF-induced heating is to select appropriate imaging landmarks. At 1.5

T, the value of highest peak SAR_{1g} near the device for the Duke model is 1472.7 W/kg. The worst case (highest peak SAR_{1g} near the device) at 1.5 T occurs when the Duke model entered the coil by head-first and landmark position at 0 mm with device on right leg and the lengths were 300 mm for rods and 170 mm for screws. Thermal simulation was conducted by continuous RF exposure for 900 s for the worst case and the maximum temperature rise is 82.7 K.

3.2 Simulation results of the Duke model at 3 T

The results of the RF-induced heating vs landmark position, patient orientation, and device position are shown in Figures 6 and 7 for the 3 T system. Similar to the results shown for 1.5 T, the sizes of the device (lengths of the rods and screws) will affect the values of peak SAR_{1g} near the device. The peak SAR_{1g} values near the device at 3 T are obviously lower than that at 1.5 T with the same size, patient orientation, landmark position, and device position. Also, the values of peak SAR_{1g} near the device will decrease with the human model and the device moved out of the coil. The SAR_{1g} value at the landmark position of 200 mm is much lower than that at the landmark position of 0 mm. The values of peak SAR_{1g} near the device for different device positions or patient orientations are obviously different, especially for landmark positions of 0 mm and 100 mm. From the simulation results at 3 T, the value of peak SAR_{1g} near the device on the right leg can be 4.1 times as that of the device on the left leg with head-first, 300 mm-rod, 160 mm-screw and 0 mm-landmark position. For different patient orientations, the maximum ratio of the value of peak SAR_{1g} near the device for head-first to the value of peak SAR_{1g} near the device for feet-first is about 3.8. It occurs for the device on the right leg, 300 mm-rod, 140 mm-screw and 0 mm-landmark position. For the landmark position at 0 mm and 100 mm, the values of peak SAR_{1g} for head-first are always lower than those for feet-first with the device implanted on the left leg. With the device implanted on the right leg, the values of peak SAR_{1g} for head-first are always higher than those for feet-first. At 3 T, patient orientation and landmark position both influence the RF-induced heating significantly, so both of them can be used to control the RF-induced heating effectively. The worst case at 3 T for the Duke model is the head-first, landmark position at 0 mm and device on right leg with 300 mm rods and 160 mm screws. The highest peak SAR_{1g} near the device is 589.3 W/kg at 3 T and the maximum temperature rise is 35.1 K from the thermal simulation under continuous RF exposure for 900 s.

3.3 Simulation results of the Ella model and the Fats model

As shown in Figure 8, for the Ella model and the Fats model, the effects of patient orientations, landmark positions, and device positions on the RF-induced heating are similar to those for the Duke model. Generally, the peak SAR_{1g} near the device will decrease with human models and device pulled out of the coil at 1.5 T and 3 T. The patient orientations and device positions both affect the RF-induced heating at 1.5 T and 3 T, but the influence is more obvious at 3 T for all studied human models. Thus, for the studied three human models with different gender or size, the landmark positions at 1.5 T or the landmark positions and patient orientations at 3 T can be adjusted to effectively get lower RF-induced heating.

3.4 RF-induced heating management

From the results, the imaging conditions in this study (patient orientation, landmark position, and device position) affect the RF-induced heating near the studied external fixation device. Table 1 shows the ratios of the values of peak

SAR_{1g} near the device for different patient orientations and landmark positions normalized to the highest peak SAR_{1g} near the device at the same device position. In Table 1, the length of the rods is 250 mm and the length of the screws is 150 mm for the three human models. At 1.5 T, the landmark position has the most significant influence on the RF-induced heating and moving the human models and device from landmark position at 0 mm to landmark position at 100 mm will lead to a much lower RF-induced heating as shown in Table 1. For the landmark position at 300 mm, the values of peak SAR_{1g} near the device will be reduced to around 13.3% − 22.5% compared with landmark position at 0 mm for the three human models at 1.5 T. For landmark position larger than 300 mm, the influence of landmark position on RF-induced heating will be slight for 1.5 T MRI system. At 3 T, the landmark position and patient orientation both have obvious influence on the RF-induced heating for the three studied human models from Table 1. For landmark position at 0 mm and the device implanted on the left leg, the value of peak SAR_{1g} near the device for head-first is only 37.9% of that for feet-first for the Duke model. The same ratios are 28.1% for the Ella model and 34.8% for the Fats model. While for the device on the right leg and the same landmark position, the values of peak SAR_{1g} near the device for feet-first are only 37.0% (Duke model), 37.2% (Ella model) and 41.6% (Fats model) of those for head-first. Similar to 1.5 T, the values of peak SAR_{1g} near the device will decrease to 10.9% − 50.9% with the landmark position changed from 0 mm to 300 mm for the three human models. After 300 mm the variation of the peak SAR_{1g} near the device with landmark position will also be tiny at 3 T. Given that the quality of the imaging will not be affected, the doctor can thus choose that the patients to enter the MRI bore by either a head-first or feet-first manner for different device positions at 3 T, or the patients can be moved out of the coil at an appropriate distance for 1.5 T and 3 T to get lower heating. Although the existence of external fixation device in the field of view during MRI may disturb the B_{1+} field and affect the imaging quality, there are some new techniques that can be used to improve the image quality such as carefully choosing the imaging parameters or using newly developed sequences (31).

4. Discussion

For different landmark positions, because the electric and magnetic field is mainly confined within the coil, with the device moving out of the coil, the incident electric field around the device will be weaker so the less RF energy will be absorbed. Thus, the peak SAR_{1g} near the device will decrease.

The incident E-field distribution around the device is different for different patient orientations or different device positions. That leads to various absorbed RF energy, so the RF-induced heating is different. The different incident E-field distribution may come from the asymmetry of the human models (the human models have different dimensions along the x and the y directions). The distributions of the root-mean-square of electric field strength (E_{RMS}) on a x-y surface at 1.5 T and 3 T without and with the Duke model loaded were extracted as shown in Figure 9. Without the Duke model, the distributions of E_{RMS} are mirror-symmetrical about the y = 0 plane at both 1.5 T and 3 T. With the Duke model loaded, the distributions of E-field become close to a rotational symmetry with a 180° rotational angle. Thus, for different patient orientations or device positions, the device will be in regions with different incident electric fields, which leads to different RF-induced heating. What's more relevant is the fact that the incident electric field for left and right sides of the human model is more different at 3 T than at 1.5 T, as shown in Figure 9. The distribution of the incident electric field is consistent with the simulation results that the difference of peak SAR_{1g} near the device for different patient orientations or device positions is more obvious at 3 T.

5. Conclusions

The modular external fixation devices investigated here are shown to have different RF-induced heating for different landmark positions, patient orientations, and device positions at both 1.5 T and 3 T MRI systems for all studied human models. Also, the RF-induced heating will be affected by the configuration parameters of the devices. As the device moves out of the coil, the RF-induced heating near the studied device will decrease. For different patient orientations (head-first or feet-first) or different device positions (device on left leg or right leg), the RF-induced heating is different, especially for the 3 T system where the difference can be as high as four times. All the difference comes from the different incident electric field. Future research related to RF-induced heating of medical devices under MRI exposure may need to consider the landmark positions, patient orientations, and device positions. In addition, the significant difference of peak SAR_{1g} near the studied modular external fixation device for different patient orientations at 3 T can be used to decrease the RF-induced heating in clinical settings. Under the circumstance that the imaging will not be affected, the doctor can direct that the patients enter the MRI equipment head-first or feet-first for different implant positions to get less heating for the 3 T MRI system. Also, for both 1.5 T and 3 T, moving the human and the device with a 100 mm − 300 mm distance from the center of coil along the axial direction can effectively result in much lower RF-induced heating as indicated by the simulation results. Moving patient and device more than 500 mm away from the center of coil with the device basically entirely out of the RF coil will leads to negligible RF-induced heating near the device. Clinically less heating can result if the patient can be moved out of the coil at an appropriate position without influencing the imaging.

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References

1. Woods TO. Standards for medical devices in MRI: present and future. *J Magn Reson Imaging*. 2007;26:1186–1189.
2. Dempsey MF, Condon B, Hadley DM. MRI safety review. *Semin Ultrasound CT MR*. 2002;23:392-401.
3. Shellock FG, Woods TO, Crues JV III. MR labeling information for implants and devices: explanation of terminology. *Radiology*. 2009;253:26–30.

4. Shellock FG. Radiofrequency energy-induced heating during MR procedures: A review. *J Magn Reson Imaging*. 2000;12:30-36.
5. ISO/TS 10974 (2018). Assessment of the safety of magnetic resonance imaging for patients with an active implantable medical device. https://www.iso.org/standard/65055.html
6. Park SM, Kamondetdacha R, Amjad A, Nyenhuis JA. MRI safety: RF-induced heating near straight wires. *IEEE Trans Magn*. 2005;41:4197-4199.
7. Nordbeck P, Weiss I, Ehses P, et al. Measuring RF-induced currents inside implants: Impact of device configuration on MRI safety of cardiac pacemaker leads. *Magn Reson Med*. 2009;61:570-578.
8. Mattei E, Triventi M, Calcagnini G, et al. Complexity of MRI induced heating on metallic leads: Experimental measurements of 374 configurations. *Biomed Eng Online*. 2008;7:11.
9. Park S, Kamondetdacha R, Nyenhuis JA. Calculation of MRI-induced heating of an implanted medical lead wire with an electric field transfer function. *J Magn Reson Imaging*. 2007;26:1278-1285.
10. Ji X, Zheng J, Chen J. Numerical evaluation of RF-induced heating for various esophageal stent designs under MRI 1.5 tesla system. *Electromagnetic biology and medicine*. 2017;36:379-386.
11. Song T, Xu Z, Iacono MI, Angelone LM, Rajan S. Retrospective analysis of RF heating measurements of passive medical implants. *Magn Reson Med*. 2018;80:2726-2730.
12. Zheng J, Ji X, Kainz W, Chen J. Study on search strategies for assessing the worst case RF-induced heating for multi-configuration implant system under MRI. *IEEE Trans Electromagn Compat*. 2018.
13. Liu Y, Shen J, Kainz W, Qian S, Wu W, Chen J. Numerical investigations of MRI RF field induced heating for external fixation devices. *Biomed Eng Online*. 2013;12:12.
14. Huang X, Zheng J, Wu X, et al. MRI heating reduction for external fixation devices using absorption material. *IEEE Trans Electromagn Compat*. 2015;57:635-642.
15. Yang R, Zheng J, Kainz W, Chen J. Numerical investigations of MRI RF-induced heating for external fixation device in TEM and birdcage body coils at 3 T. *IEEE Trans Electromagn Compat*. 2018;60:598-604.
16. Murray WM. External fixation device. US Patent 4,483,334[P]. November 20, 1984.
17. Fischer DA. External fixation device. US Patent 4,308,863[P]. January 5, 1982.
18. Martinez JA, Serano P, Ennis DB. Patient orientation affects lead-tip heating of cardiac active implantable medical devices during MRI. *Radiology: Cardiothoracic Imaging*. 2019;1:e190006.
19. Murbach M, Neufeld E, Samaras T, et al. Pregnant women models analyzed for RF exposure and temperature increase in 3T RF shimmed birdcages. *Magn Reson Med*. 2017;77:2048-2056.
20. Guo R, Zheng J, Chen J, Kainz W. RF-induced heating comparison between in-vivo and in-phantom for 1.5 T MRI. *2016 IEEE International Symposium on Electromagnetic Compatibility (EMC)*. 2016:121-125.
21. Liu Y, Li D, Min X, Sison S, Mouchawar G, Chen J. Evaluation of electromagnetic field distributions under 1.5 T MRI scanning within human models of a virtual family. *Computing in Cardiology 2014*. IEEE. 2014:117-120.
22. Dell'Oca AF. External fixation using simple pin fixators. *Injury*. 1992;23:S1-S54.

23. Hoffmann-Clair ML, Mazzio MC. Multipin clamp and rod attachment. US Patent 7,875,030[P]. January 25, 2011.
24. Johnson & Johnson Medical Devices Companies. http://synthes.vo.llnwd.net/o16/LLNWMB8/US%20Mobile/Synthes%20North%20America/Product%20Support%20Materials/Technique%20Guides/DSUSTRM10161175_LgExFix_ModKnee_TG_150dpi.pdf
25. Gosselin M, Neufeld E, Moser H, et al. Development of a new generation of high-resolution anatomical models for medical device evaluation: The virtual population 3.0. *Physics in Medicine & Biology*. 2014;59:5287.
26. Lucano E, Liberti M, Mendoza GG, et al. Assessing the electromagnetic fields generated by a radiofrequency MRI body coil at 64 MHz: Defeaturing versus accuracy. *IEEE Transactions on Biomedical Engineering*. 2016;63:1591-1601.
27. Shellock FG. Radiofrequency energy-induced heating during MR procedures: A review. *J Magn Reson Imaging*. 2000;12:30-36.
28. Baker KB, Tkach JA, Nyenhuis JA, et al. Evaluation of specific absorption rate as a dosimeter of MRI-related implant heating. *Journal of Magnetic Resonance Imaging: An Official Journal of the International Society for Magnetic Resonance in Medicine*. 2004;20:315-320.
29. Adair ER, Petersen RC. Biological effects of radiofrequency/microwave radiation. *IEEE Trans Microwave Theory Tech*. 2002;50:953-962.
30. Zeng Q, Wang Q, Zheng J, Kainz W, Chen J. Impacts of RF shimming on MRI induced heating of implantable medical lead in 3T birdcage coil. *2017 IEEE MTT-S International Microwave Symposium (IMS)*. 2017:1239-1241.
31. Stradiotti P, Curti A, Castellazzi G, Zerbi A. Metal-related artifacts in instrumented spine. Techniques for reducing artifacts in CT and MRI: State of the art. *European Spine Journal*. 2009;18:102-108.

FIGURE 1 A, Simulated model of the modular external fixation device; B, An example of the studied device implanted on the human body.

FIGURE 2 A, The height of the coil is 650 mm and the diameter of the coil is 740 mm. B, The 32 sources (red arrows) are on the rings and the lumped elements (blue arrows) are zero (no lumped elements). C, The $\vec{B}_1$ field distribution of the G32 coil.

FIGURE 3 A, Different landmark positions: the human model with the device was moved long the z-direction at distances of 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm. B, The human model can enter the coil in two directions: head-first and feet-first. C, Four scenarios of head-first/feet-first and device on left/right leg. (The human model in the figure is the Duke model while the situations for the Ella model and the Fats model are the same.)

FIGURE 4. Peak SAR_{1g} near the device (W/kg) at 1.5 T for different lengths of rods.

FIGURE 5. Peak SAR_{1g} near the device (W/kg) at 1.5 T for different lengths of screws.

FIGURE 6. Peak SAR_{1g} near the device (W/kg) at 3 T for different lengths of rods.

FIGURE 7. Peak SAR_{1g} near the device (W/kg) at 3 T for different lengths of screws.

FIGURE 8. Peak SAR_{1g} near the device (W/kg) for the Ella model and the Fats model at 1.5 T and 3 T.

FIGURE 9. Electrical field distributions in V/m at 1.5 T (top) and 3 T (bottom) without and with the Duke model loaded.

Supporting Information Figure S1 Top: the SAR distributions at 1.5 T for three human models. Bottom: the SAR distributions at 3 T for three human models. (In this Figure, the human models were loaded as feet-first with landmark position at 0 mm and device on left leg. The length of rods are 250 mm and the length of screws are 150 mm. The red cubes are the locations of peak SAR_{1g} near the device.)