# Deep brain stimulation lead design to reduce radio-frequency heating in MRI

Changqing Jiang, Xiaolong Mo, Jianqi Ding, Yantao Dong, Feng Zhang, Hongwei Hao and Luming Li

Radio-frequency (RF) induced heating at the electrodes of the deep brain stimulation lead is a major concern when used in magnetic resonance imaging (MRI). A novel lead design is proposed to address this problem. By adopting a coil with non-uniform diameters, the maximal temperature rise measured in a standard phantom is reduced from 4.6 to 2.0°C, with an average reduction of 59%. The suppression of RF heating is probably achieved because of the alteration of the transmission line parameters of the lead by the novel design. The details of the design, experiment validation and discussion of the mechanisms are presented.

*Introduction:* Deep brain stimulation (DBS) has now become a widely accepted surgical therapy in treating a variety of refractory disorders such as Parkinson's disease [1]. The therapy incorporates an implantable pulse generator to generate a pulsed current, and then transmits it to a specific brain nucleus through an extension cable and a lead with its electrodes implanted therein. The abnormal functionality of the brain could then be restored. So far there are more than 100 000 patients worldwide who have received the therapy.

In the meantime, magnetic resonance imaging (MRI) has become one of the most important diagnostic means in clinics because of its multiple merits [2]. Along with the ongoing popularisation of DBS, there is a growing demand for the patients to perform MRI examinations. Furthermore, MRI/functional MRI (fMRI) is also a powerful tool in neuroscience research. There are emerging studies combining MRI/fMRI with DBS to explore brain network responses after stimulation. It could not only shed a new light on the mechanisms of DBS, but also help to understand the functionality of the brain network. However, currently there are safety concerns limiting the patient with DBS to perform MRI, especially high-field MRI. The radio-frequency (RF) field-induced heating at the electrodes of the lead is the most important issue [3].

MRI inherently employs an RF magnetic field to excite the water protons within the body, producing signals to reconstruct the image. The frequency is proportionally associated with the main static magnetic field according to Larmor's law, with a gyromagnetic ratio of 42.58 MHz/T. Elongated conductive objects like the DBS leads would interact with this RF field and pick up energy as an antenna [4]. Owing to the concentrated power deposition, excessive ohmic heating could be resulted in the vicinal tissue around the electrodes at the end of the lead. A temperature rise as high as 23.5°C was measured in a phantom study [5]. Patients might suffer severe injury if precautions were not properly taken.

There are a number of factors affecting RF heating, such as transmitting power, device configuration, scan setup and wavelength effect [6]. These factors are complicated, making the heating amount difficult to predict and control in clinics. Therefore, safe-by-design devices are required.

In this Letter, we present a novel lead design that adopts helical coils with non-uniform diameters. By partially enlarging the coil diameter, the transmission line properties of the lead under RF could be altered. As a result, the induced RF heating at the electrodes could be diminished and the safety of patients could be enhanced.

*Materials and methods:* The traditional lead design (model L301, PINS Medical Inc., Beijing, China) and the novel design are schematically shown in Fig. 1. The traditional lead (Fig. 1*a*) consisted of a helical quadrifilar platinum–iridium (Pt–Ir) alloy coil inside a polyurethane sheath. The coil wires were 0.1 mm in diameter and coated with fluoropolymer. The outer diameter of the coil was 0.8 mm. The sheath had an outer diameter of 1.3 mm and a wall thickness of 0.2 mm. Four 1.5 mm long Pt–Ir electrodes and four 2.5 mm long MP35N connectors were attached at two ends of the lead, respectively. Spacing between the electrodes and connectors were 0.5 and 2.0 mm, respectively. The total length of the lead was 400 mm. The novel lead (Fig. 1*b*) was the same as the traditional one, except that a non-uniformly diametered coil was used, part of which had an enlarged outer diameter of 1.3 mm near the electrodes. The length of the enlarged section was ~50 mm.

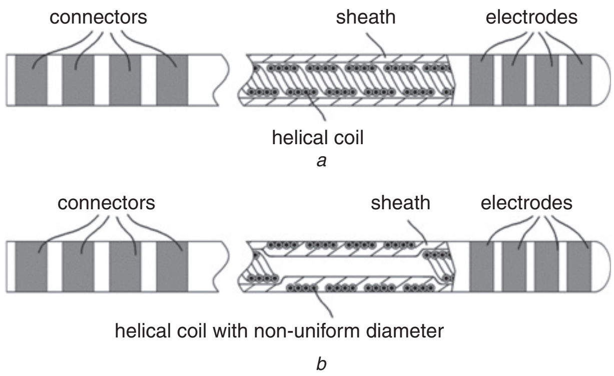


**Fig. 1** *Schematics of lead structures*

*a* Traditional lead
*b* Novel lead

The test scheme was adopted from the ASTM standard F2182-11a [7]. A polymethyl methacrylate (PMMA) phantom mimicking the head and torso of the human body was built with inner dimensions as shown in Fig. 2*a*. A gelled medium was prepared containing 1.32 g/l of NaCl and 10 g/l of polyacrylic acid in water. The medium had a conductivity of ~0.47 S/m at room temperature, similar to that of human body tissue, and its viscosity was great enough to prevent convective heat transport. The height of the medium was 10 cm. The leads were suspended straight in the medium along the main field direction with a set of PMMA frames. They were placed 1.5 cm to the lateral wall of the phantom, 4 cm deep down from the surface of the medium and with the middle on the centre line of the phantom torso. A photograph of the setup is shown in Fig. 2*b*.

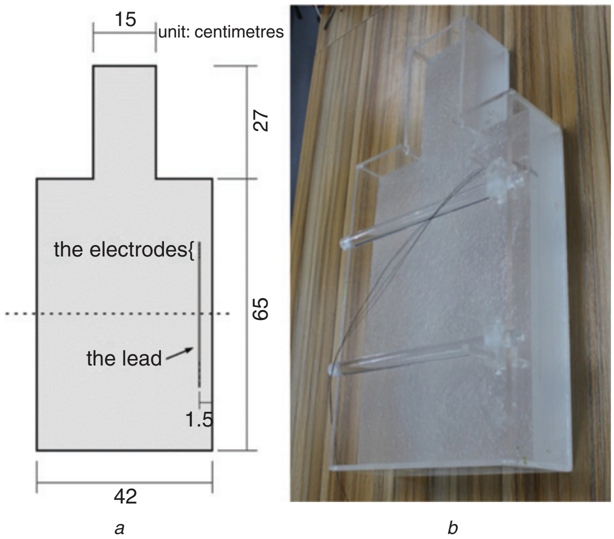


**Fig. 2** *Setup of RF heating measurement*

*a* Dimensions of phantom and placement of lead
*b* Photograph of phantom setup

Fluoroptic probes (STB probes connected to a four-channel FOT Lab Kit, both Luxtron/Luma Sense Technologies, Santa Clara, CA, USA) were used to measure the temperature rise. The four probes were placed at the surfaces of the four electrodes, respectively.

A Philips Achieva 3.0 T TX MRI scanner (Philips Healthcare, The Netherland; Software version: Achieva 3.2.1) featuring a maximal gradient strength of 40 mT/m and maximum slew rates of 200 T/m/s was used to perform the scans. The nominal frequency of the RF system was 127.7 MHz. The Q-body coil was used for both RF excitation and signal detection. A turbo spin echo (TSE) protocol was applied. The parameters were set as follows: TE = 5 ms, TR = 3736 ms, FOV = 400 × 400 mm, voxel size = 2.3 mm, slice thickness = 4 mm with default gap, TSE factor = 20 and NSA = 6. The total scan time was 6 min. The whole body averaged specific absorption rate was 1.7 W/kg. The landmark was located at the middle of the lead.

Both the baseline temperature before the scan and the maximal temperature rise used a ten-point average.

*Results:* The temperature elevation profiles measured at the four electrodes (E1–E4) are shown in Fig. 3. A significant reduction in RF heating was achieved by the novel lead design. Compared with a maximal temperature rise $\Delta T_{max}$ of 4.6°C for the traditional lead design, it was only 2.0°C for the novel one. On average, the $\Delta T_{max}$ was reduced by 59% by adopting the new design. The measured $\Delta T_{max}$ had little variance among the four electrodes of the same lead, not greater than 0.3°C for the novel lead and 0.4°C for the traditional one. Owing to the discrepancy in heat dissipation conditions, the temperature elevations at electrodes E2 and E3 were expected to be slightly higher than those at the other two. The precision of the thermometer and deviation in probe placement might also have contributed to the temperature measurement variance.

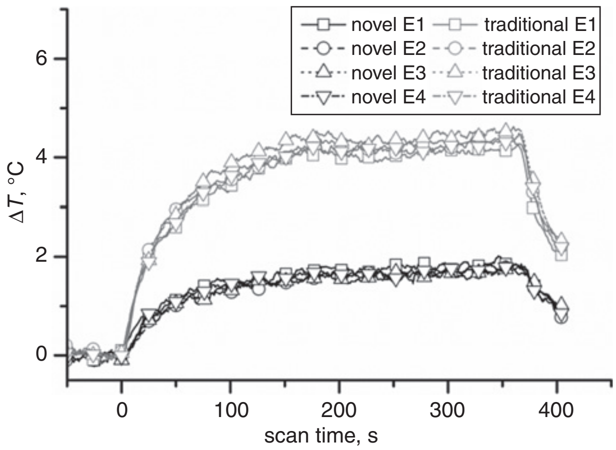


**Fig. 3** *Measured temperature elevation at electrodes*

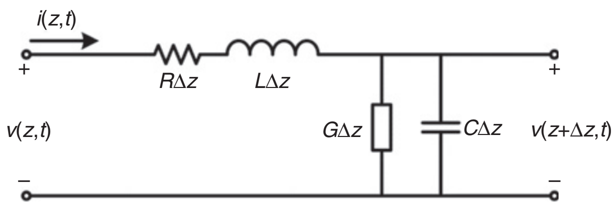


**Fig. 4** *Transmission line model representation of lead*

The behaviour of the lead wires under the RF field of MRI could be depicted using a transmission line model as shown in Fig. 4 [4]. *R*, *L*, *G* and *C* denote the distributed serial resistance, serial inductance, parallel conductance and parallel capacitance, respectively. By changing the diameter of the coil, these parameters were altered. The parallel capacitance *C* between the lead wires and the surrounding medium increased because of the reduction in the thickness of the insulation. It facilitated the bypass of the induced currents in the lead wires into the medium along the lead body. The serial inductance *L* of the helical wires increased as the inductance was approximately proportional to the square of the radius of the solenoid. Therefore, the impedance under RF increased, which could reduce the amplitude of the induced currents. The serial resistance *R* also increased slightly as the length of the wires increased, but this should be a minor effect.

*Conclusion:* By adopting a novel design, the RF heating at the electrodes of the DBS lead in MRI could be significantly reduced. The reduction was achieved through an alteration of the transmission line parameters towards the less concentrated electric field near the electrodes.

*Acknowledgments:* This work was supported by the National Natural Science Foundation of China (nos. 51077083, 51125028, 51407103) and the Tsinghua University Initiative Scientific Research Program. The MRI experiments were accomplished on the MRI platform provided by the Center for Biomedical Imaging Research, Tsinghua University.


*26 September 2014*
doi: 10.1049/el.2014.3482
One or more of the Figures in this Letter are available in colour online.

Changqing Jiang, Xiaolong Mo, Jianqi Ding, Yantao Dong, Feng Zhang, Hongwei Hao and Luming Li (*National Engineering Laboratory for Neuromodulation, School of Aerospace Engineering, Tsinghua University, Beijing, People's Republic of China*)

E-mail: lilm@tsinghua.edu.cn

**References**

1 Benabid, A.L., Chabardes, S., Mitrofanis, J., and Pollak, P.: 'Deep brain stimulation of the subthalamic nucleus for the treatment of Parkinson's disease', *Lancet Neurol.*, 2009, **8**, (1), pp. 67–81
2 Fox, M.D., and Raichle, M.E.: 'Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging', *Nat. Rev. Neurosci.*, 2007, **8**, (9), pp. 700–711
3 Bronstein, J.M., Tagliati, M., Alterman, R.L., Lozano, A.M., Volkmann, J., Stefani, A., Horak, F.B., Okun, M.S., Foote, K.D., Krack, P., Pahwa, R., Henderson, J.M., Hariz, M.I., Bakay, R.A., Rezai, A., Marks, W.J., Moro, E., Vitek, J.L., Weaver, F.M., Gross, R.E., and DeLong, M.R.: 'Deep brain stimulation for parkinson disease: an expert consensus and review of key issues', *Arch. Neurol.*, 2011, **68**, (2), pp. 165–171
4 Nitz, W.R., Oppelt, A., Renz, W., Manke, C., Lenhart, M., and Link, J.: 'On the heating of linear conductive structures as guide wires and catheters in interventional MRI', *J. Magn. Reson. Imaging*, 2001, **13**, (1), pp. 105–114
5 Rezai, A.R., Finelli, D., Nyenhuis, J.A., Hrdlicka, G., Tkach, J., Sharan, A., Rugieri, P., Stypulkowski, P.H., and Shellock, F.G.: 'Neurostimulation systems for deep brain stimulation: in vitro evaluation of magnetic resonance imaging-related heating at 1.5 Tesla', *J. Magn. Reson. Imaging*, 2002, **15**, (3), pp. 241–250
6 Nyenhuis, J.A., Park, S.M., Kamondetdacha, R., Amjad, A., Shellock, F. G., and Rezai, A.R.: 'MRI and implanted medical devices: basic interactions with an emphasis on heating', *IEEE Trans. Device Mater. Reliab.*, 2005, **5**, (3), pp. 467–480
7 ASTM F2182-11a: 'Standard test method for measurement of radio frequency induced heating on or near passive implants during magnetic resonance imaging', 2011