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Three-Dimensional Brain MRI for DBS Patients Within Ultra-Low Radiofrequency Power Limits

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ABSTRACT

Background: For patients with deep brain stimulators (DBS), local absorbed radiofrequency (RF) power is unknown and is much higher than what the system estimates. We developed a comprehensive, high-quality brain magnetic resonance imaging (MRI) protocol for DBS patients utilizing three-dimensional (3D) magnetic resonance sequences at very low RF power.

Methods: Six patients with DBS were imaged (10 sessions) using a transmit/receive head coil at 1.5 Tesla with modified 3D sequences within ultra-low specific absorption rate (SAR) limits (0.1 W/kg) using T₂, fast fluid-attenuated inversion recovery (FLAIR) and T₁-weighted image contrast. Tissue signal and tissue contrast from the low-SAR images were subjectively and objectively compared with routine clinical images of six age-matched controls.

Results: Low-SAR images of DBS patients demonstrated tissue contrast comparable to high-SAR images and were of diagnostic quality except for slightly reduced signal.

Conclusions: Although preliminary, we demonstrated diagnostic quality brain MRI with optimized, volumetric sequences in DBS patients within very conservative RF safety guidelines offering a greater safety margin. © 2014 International Parkinson and Movement Disorder Society

Key Words: conditional magnetic resonance imaging; deep brain stimulation; low specific absorption rate; radiofrequency heating; Parkinson's disease

The advantages of magnetic resonance imaging (MRI) for mapping deep brain stimulation (DBS) lead position¹ or postoperative function² have already been demonstrated. However, local absorbed radiofrequency (RF) power during routine MRI (specific absorption rate [SAR]) at the electrodes is several times more than that from whole-head SAR,^{3,4} creating significant risks for such patients.⁵⁻⁷ DBS manufacturers⁷ have labeled their devices as magnetic resonance (MR) conditional by specifying a limit to head SAR of 0.1 W/kg at 1.5 Tesla (T) and RF exposure limited only to the head by using a local (transmit/receive) head coil. The main reason for heating concern is due to the "critical length" of DBS leads (odd multiples of half wavelengths at 1.5 T or 3 T), producing unknown local heating⁸ that varies with implantation techniques, including lead geometry, patient posture in the MRI bore, chosen MR sequences, and scanner hardware.

Given the increasing number of patients being treated with such devices, a high-quality, low-SAR brain MRI could be valuable, although it is not currently available. For MRI of patients with DBS, some centers have chosen to reduce the applied SAR by restricting imaging volume or sequence types,^{9,10} whereas others have used high-SAR MRI on DBS patients based on the low-incidence track records.¹¹⁻¹⁴ Three-dimensional (3D) fast spin echo (FSE) sequences using reduced angle refocusing pulses are promising and require one-third the SAR of 2D FSE while preserving most of the tissue contrasts.¹⁵⁻¹⁸ In this work, we modified a recent work that resulted in ultra-low-SAR 3D MRI for normal volunteers¹⁹ and developed a comprehensive brain MRI protocol that included T₁, T₂, and fluid-attenuated inversion recovery (FLAIR) imaging at 10-fold to 30-fold lower SAR for DBS recipients.

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Patients and Methods

Two authors (A.J.M. and R.F.B.) who are employees of GE Healthcare were involved in providing the research pulse sequences that were prospectively modified on healthy volunteers and applied on DBS patients in compliance with a retrospective institutional review board.

Patient Selection and Preimaging Requirements

In total, 12 patients (6 women; age range, 45–81 years) were included in this study. Of these, six were DBS recipients (4 with Parkinson's disease, 2 with essential tremor), and six were age-matched controls without DBS. All patients were screened by earlier MRI to exclude deep brain pathology. Prior to MRI, the pulse generators were inactivated and set to bipolar settings at 0 volts to minimize lead heating or potential device re-activation. The indications for MRI were assessment of targeting accuracy, postoperative complications, or other neurologic conditions; whereas the control patients were free of acute symptoms or space-occupying lesions and underwent routine MRI at high SAR (range, 2.2–3.0 W/kg) using more efficient eight-channel head array coils.

Imaging Sequences and SAR Reduction Steps

The details of MR sequences are as follows (Table 1): (1) 2D FSE T_2 (control group, SAR = 2.2 W/kg) and 3D FSE T_2 (DBS group, SAR $\leq$ 0.1 W/kg); (2) 2D FLAIR (control group, SAR = 1.5 W/kg) and 3D FLAIR (DBS group, SAR $\leq$ 0.1 W/kg); and (3) 3D inversion-recovery spoiled gradient recalled-echo (IR-SPGR) (T_1 identical for both groups: SAR $\leq$ 0.1 W/kg). 3D FSE T_2 and 3D FLAIR sequences were modified from 3D-Cube research FSE sequence (GE Healthcare, Milwaukee, WI) by stretching refocusing RF pulse widths and reducing refocusing flip angles and by linear-modulation view

ordering with skipping corners of k-space. The average SAR for each sequence was verified at the research interface before applying to patients, and the gradient slew rate was maintained below 16 T per meter per second.

Objective Signal-to-Noise Ratio, Relative Tissue Contrast, and Statistical Tests

The noise regions of interest were drawn along the frequency direction in air background for computing the signal-to-noise ratio (SNR). Ten cerebral tissue regions (frontal and parietal gray matter, adjacent white matter, subthalamic nucleus, cerebral peduncle, putamen, globus pallidus, ventricular fluid, and adjacent white matter) were selected from the right hemisphere for computing the tissue SNR and contrast-to-noise ratio (CNR) ($CNR = [SNR_a - SNR_b]$). A two-tailed Wilcoxon rank-sum test was used to compare tissue SNR as well as tissue CNR for the control and DBS groups. Because SNR is proportional to pixel area, the SNR for 3D T_2 sections (256×256 matrix) was scaled down by a factor of 1.56 to compare with 2D slices that had smaller pixels (resolution, 320×320). In addition, the scan time normalized SNR was computed defined by $SNR/\sqrt{(\text{scan time})}$.

Subjective Quality Assessment Relative to an Implant-Free "Reference" Patient

One of the six implant-free control patients who had a tissue SNR matching that of the control group average was used as reference (assigned score = 0) for comparing image quality. Two senior neuroradiologists (D.B.H., R.A.B.) with over 25 years' experience subjectively evaluated the image appearance and signal characteristics based on SNR, cerebrospinal fluid intensity, gray/white matter contrast, and artifacts on

TABLE 1. Scan parameters for routine high-specific absorption rate (control group) and low-specific absorption rate (implant group) MRI sequences at 1.5 Telsa

Sequence Type	TR/TE/TI/Matrix/Total Scan Time	Echo Train Length/ Band Width, kHz	Refocusing Pulse Width/ Refocusing Flip Angles	Average Whole Head SAR, W/kg
High-SAR 2D FSE T_2	4.4 s/90 ms/—/320 × 320/1:40 min	16/±25.0	1.6 ms/150°–170°	2.2–3.0
Low-SAR 3D T_2	4.4 s/75 ms/—/256 × 256/5:00 min	80/±62.5	1.2 ms/first, 120°; minimum, 20°–25°; center, 35°; last, 50°–60° (all pulses nonselective)	≤ 0.1
High-SAR 2D FLAIR	9 s/125 ms/2.2 s/256 × 224/4:00 min	10/±17.9	1.6 ms/150°–170°	1.5
Low-SAR 3D FLAIR	6 s/125 ms/1.9 s/256 × 224/5:50 min	50/±25.0	1.8 ms/first, 110°; minimum, 15°–20°; center, 30°; last, 50°–60° (all pulses nonselective)	≤ 0.1
3D IR-SPGR T_1 ^a	10 s/3 s/550 ms/256 × 224/5:30 min	—/±19.8	Excitation pulse angle, 12°	≤ 0.1

^aFor 3D IR-SPGR, the slice thickness was 1.1 mm; the radiofrequency coil was a body transmit/8-channel head receive device (for control patients) or a head transmit/head receive (T/R) device (for deep brain stimulation patients); and the field of view was $22 \times 18 \text{ cm}^2$. For all FSE sequences, the slice thickness/gap was 5/1.5 mm for 2D images and 5/0 mm for 3D images.

Abbreviations: TR, repetition time; TE, echo time; TI, the time between inversion and excitation pulses; SAR, specific absorption rate; 2D, two-dimensional; FSE, fast spin echo; 3D, three-dimensional; FLAIR, fluid-attenuated inversion recovery; IR-SPGR, inversion-recovery spoiled gradient recalled-echo.

a 5-point scale (−2, −1, 0, +1, and +2, with −2 indicating the worst and +2 indicating the best).

Results

All low-SAR imaging studies were completed without any complications. Figure 1 compares images from typical DBS patients with images from controls. From top to bottom, the rows show 3D FLAIR, 3D T_2 -weighted, and 3D T_1 -weighted images at ultra-low SAR (0.1 W/kg) (Fig. 1, left column) and images for a clinical reference patient at routine clinical SAR (range, 2.2–3.0 W/kg) (Fig. 1, right column).

Objective Assessments

Compared with high-SAR 2D FLAIR, the scan time normalized SNR from low-SAR 3D FLAIR was 47% for gray matter, 45% for white matter, and 47% for deep nuclei. Similarly, the scan time normalized SNR for low-SAR 3D T_2 was 67% for gray matter, 63% for white matter, and 48% for deep nuclei compared with high-SAR. The T_1 -weighted 3D IR-SPGR sequence produced an SNR of 58% to 68% for DBS compared with controls. The SNR reduction for all three low-SAR sequences compared with high SAR was statistically significant ($P < 0.05$), whereas the tissue contrasts were basically the same for both methods.

Subjective Assessment of Implant Group: Quality Scores and Specific Features

The overall image-quality scores were as follows: Both readers rated the low-SAR FLAIR and IR-SPGR T_1 sequences with overall scores close to that of the reference control (DBS group, −0.3; reference control, 0), whereas the low-SAR T_2 sequence produced a slightly lower rating compared with the control (DBS group, −0.8; reference control, 0). Overall, the conclusion was that the low-SAR images were adequately diagnostic (score range, −1 to +1). Although a comparison of high and low SARs for various brain pathologies was beyond the scope of this work, pathologies, including infection, infarcts, and subdural hematoma, were observed with low SARs.

Discussion

Whole-head MRI heating when scanning within the conditions of the DBS product label (≤ 0.1 W/kg) should be 20-fold to 30-fold lower than heating from routine MR sequences according to calorimetric principle. In vitro testing that demonstrates an acceptable temperature rise according to American Society for Testing and Materials testing standards is approved by the US Food and Drug Administration, although it does not address the uncertainty in local heating by a “critical length” implant like DBS, nor does it guarantee safety for issues other than RF heating (personal

FIG. 1. Low-specific absorption rate (SAR) images of deep brain stimulation (DBS) are shown in the left column, and high-SAR images from control patients are shown in the right column, including images from (A) a DBS patient who had a recent cardiovascular accident (arrows indicate the DBS leads; three-dimensional [3D] fluid-attenuated inversion recovery [FLAIR] image; score, −0.5); (B) a representative control patient (2D FLAIR; score, 0); (C) a DBS patient (arrows indicate bilateral substantia nigra pars compacta leads; 3D T_2 -weighted image; score, −1); (D) another representative control patient (high-SAR; 2D T_2 -weighted image; score, 0); (E) another DBS patient (arrows indicate the DBS leads; 3D T_1 -weighted inversion-recovery spoiled gradient recalled-echo [IR-SPGR] coronal reformat image; score, 0); and (F) a representative control patient (3D T_1 -weighted IR-SPGR image; score, 0). Note that 3D T_1 -weighted images for both DBS patients and control patients were from identical sequences (SAR, 0.1 W/kg), except that, for the implant group, we applied a local transmit/receive coil, which was approximately 60% as sensitive as the eight-channel multi-element coil with body coil excitation that was used for the control group.

communication, Wolfgang Kainz, PhD, Center for Devices and Radiological Health, US Food and Drug Administration, Silver Spring, MD, USA).

Currently, a number of groups use low-power 3D magnetization-prepared rapid gradient echo (MPRAGE) for assessing DBS lead placements without directly identifying DBS targets, which can be identified in our approach even at thick slices with T_2 or FLAIR sequences. However, adopting a frame-based correction should improve surgical efficacy further.²⁰ Two-dimensional

imaging produces imperfect slice profiles that overlap (cross-talk), whereas 3D sections are sharp with no overlaps between adjacent slices and, thus, localize electrodes better than 2D for identical slice thicknesses.

Our work was aimed to develop a full range of MR sequences within a very conservative SAR guidance to provide brain imaging for the growing population of DBS patients and to compare the advantages and drawbacks in diagnostic quality for this group compared with routine MRI on implant-free patients at high SAR. Note that, although absolute MR safety cannot be guaranteed, based on calorimetric principles, a 20-fold to 30-fold reduction in applied RF power compared with a conventional high-SAR MRI, as demonstrated here, would lead to a proportional decrease in local tissue temperature and may be preferred when MRI is absolutely needed for an implant patient. It should be noted that the whole-head SAR is an approximate estimate of the energy delivered to the tissue, and there are additional concerns, including gradient-induced effects or open circuits in case of a fractured lead. At present, adverse events, including permanent neurological injury with high-SAR, are rare,¹³ although a recent report²¹ has expressed concern that MRI at routine power might have caused neurologic deficits in some cases that previously were attributed to surgery.

Low-SAR images had a lower SNR partly due to lower sensitivity (65%) of the transmit/receive coil,²² whereas the tissue CNR matched well with that of the control group. However, these results should be considered preliminary because of the small sample size. Currently, our quadrature coil does not allow parallel imaging, which could have helped imaging speed and further SAR reduction. ■

Conclusion

In this preliminary work, by conforming to the strictest MR hardware and RF safety requirements, we have developed a set of brain T₁, FLAIR, and T₂ MRI sequences for DBS patients at very-low-SAR levels (≤ 0.1 W/kg) that produce acceptable image quality comparable to high-SAR sequences. With further in vitro testing and regulatory approvals, this approach has the potential for reducing, although not completely eliminating, RF heating risks for some of the urgently desired MR procedures that are currently not recommended by DBS manufacturers.

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