IS MAGNETIC RESONANCE IMAGING SAFE FOR PATIENTS WITH NEUROSTIMULATION SYSTEMS USED FOR DEEP BRAIN STIMULATION?

KEY WORDS: Deep brain stimulation, Magnetic resonance imaging, Neurostimulation, Parkinson’s disease

In this article, we report to the neurosurgical community important safety concerns related to the use of magnetic resonance imaging (MRI) in patients with neurostimulation systems used for deep brain stimulation (DBS). The significance of these concerns is underscored by our case report in this issue and another published recently (19). The alarming report of a patient with a DBS implant experiencing adverse effects in association with an MRI examination emphasizes the crucial importance of strictly following safety recommendations. Any attempt to generalize or trivialize these safety aspects may result in serious temporary or permanent injury to the patient.

The DBS-Magnetic Resonance (DBS-MR) Safety Cooperative Group includes a consortium of experts in the fields of MR safety, biomedical engineering, radiology, and neurosurgery who have systematically studied MRI safety for neurostimulation systems for the past 4 years. In this issue, our group presents a report of a patient who underwent MRI with adverse effects and report the latest findings with respect to DBS and MRI safety. Of note is that the Food and Drug Administration recently issued a warning regarding the use of MRI in patients with neurostimulation systems (23).

The therapeutic use of electrical stimulation to treat neurological disorders is rapidly growing. There are more than 100,000 implanted neurostimulation devices consisting of DBS, motor cortex stimulation, spinal cord stimulation, vagal nerve stimulation, and peripheral nerve stimulation devices. The number of patients with neurostimulation implants is increasing, clinical indications are evolving, and an increasing number of manufacturers are providing Food and Drug Administration-approved, or -pending, systems.

The focus of this Special Commentary is DBS. With more than 30,000 DBS implants worldwide and Food and Drug Administration-approved indications for treating Parkinson’s disease, essential tremor, and dystonia, DBS is one of the most rapidly growing areas in the field of neurosurgery (12, 20, 22). In addition, a number of clinical trials are underway to assess the role of DBS in treating epilepsy, chronic pain, cluster headaches, obsessive-compulsive disorder, major depression, and other related conditions.

Despite rapid growth in neurostimulation technology and clinical application, there have been few studies directed at assessing the safety of performing MRI procedures on patients with DBS implants. The neurosurgery, neurology, and radiology communities have not, for the most part, addressed the safety factors of DBS and MRI. The use of MRI procedures for patients with DBS involves various approaches. Certain centers routinely scan patients with DBS devices based on the premise that there have been no problems in those scanned in the past. In other centers, MRI examinations of patients with DBS implants is strictly prohibited, as it is with patients with cardiac pacemakers (1, 14–16). Other centers use various approaches and policies in between.

Importantly, the necessity of using MRI examinations in these patients is implicit (3, 4, 12, 13). MRI is important for the diagnosis of hemorrhage, stroke, and other intracranial lesions; for the assessment of the progression of neurodegenerative disorders; and for the evaluation of spinal disorders. In addition, MRI is beneficial for determining postoperative DBS lead location, crucial for the evaluation of patients with suboptimal results or side effects,
as well as for targeting in revision or additional DBS or other cranial surgeries. Furthermore, functional MRI is proving to be greatly beneficial in helping us to understand the mechanisms of DBS, as well as the pathophysiology of the disorders.

In general, MRI is regarded as an extremely safe, noninvasive diagnostic technique (14, 16). However, experimental data must be obtained for patients with implanted devices, particularly devices that are conductive and electronically activated (4–6, 10, 14–16). The necessity for MRI in patients with DBS has prompted other groups and the DBS-MR Safety Cooperative Group to systematically study these safety concerns (2–7, 10–12, 20–22). Investigations were conducted to define specific recommendations to permit the safe use of this imaging modality in patients with implanted DBS and other neurostimulation systems. Notably, these studies have resulted in the current manufacturer’s guidelines for the use of MRI in a patient with a neurostimulation system used for DBS (7, 18).

The principal MR safety concerns for electrical stimulation devices include heating, magnetic field interactions, induced electrical currents, and functional disruption of the operational aspects of these devices (1, 2, 4–6, 9–17, 20–22). To date, only a small number of studies have addressed MR safety issues for DBS electrodes, implanted pulse generators (IPGs), and other neurostimulation devices. We have performed thousands of in vitro experiments involving a phantom model and direct measurement of heating, induced currents, magnetic field interactions, and the assessment of device functionality before and after scanning. The details of the in vitro testing techniques used to establish safe MR conditions and their parameters have been previously described (2, 4, 11–13).

Our overall results showed that the most compelling and problematic safety issue for DBS is that of MRI-related heating of the DBS electrode. Accordingly, caution must be exercised, and steps similar to those that exist for other implants and devices that have components made from conductors or with an "elongated configuration" (e.g., pacemaker leads, electrocardiographic cables and leads, guidewires, etc.) must be taken to safely perform MRI procedures (9, 14–16).

Radiofrequency (RF) fields are routinely used for MRI and can induce currents in the body (17). It is well known that electrically conducting implants can locally increase these currents and, under certain MR operational conditions, generate excessive heating of biomedical devices. For example, Achenbach et al. (1) reported a temperature increase at the tip of a pacing electrode, unattached to a cardiac pacing pulse generator, of up to 63.1°C within 90 seconds of MRI. More recently, Finelli et al. (4) and Rezai et al. (11) have performed in vitro heating measurement experiments. The landmark position selected for MRI in these experiments was either through the IPG or the tips of the DBS leads. These investigations demonstrated that MR procedures conducted at various whole-body averaged specific absorption rates (SAR) using a transmit/receive body coil generated the greatest temperature increases at the lead tips that ranged from 2.5 to 25.3°C (highest temperature recorded for IPG landmark position), whereas using a transmit/receive head coil produced temperature changes that ranged from 2.3 to 7.1°C (highest temperature recorded for the DBS lead landmark position). These data indicate that substantial heating occurs for certain conditions, whereas others produce relatively minor, physiologically inconsequential, temperature increases. Of greater concern, perhaps, is the rate at which the temperature increased, with most of the heating occurring within the first minute of scanning and reaching a steady-state within 15 minutes (Fig. 1).

Heating is poorly tolerated in the central nervous system, with irreversible lesions occurring at temperatures ≥45°C. Serious examples of heating in the central nervous system associated with DBS leads have been reported in a patient undergoing diathermy (8) and in another patient undergoing cardioversion (24). The amount of heat generated in a neurostimulation system used for DBS is dependent upon multiple factors related to the specific type of implanted device and various aspects of the MRI procedure (Table 1). These factors

![FIGURE 1. Examples of temperature changes recorded during assessment of magnetic resonance imaging-related heating for bilateral neurostimulation systems used for deep brain stimulation. A, graph corresponds to the use of a transmit/received body radiofrequency coil, a whole-body averaged SAR of 3.90 W/kg, and imaging location through the IPGs. The leads took direct routes from the IPG to the deep brain positions. Note the rapid increases in temperatures recorded by fluoroptic thermometry probes on the right and left leads. B, graph corresponds to the use of a transmit/received body radiofrequency coil, a whole-body averaged SAR of 0.98 W/kg, and imaging location through the IPGs. Each lead was placed with two small loops (approximately 2.5 cm in diameter) in an axial orientation at the top of the head portion of the phantom. Figure reprinted with permission from Reference 11.](image-url)
include the electrical characteristics of the particular neurostimulation system; the field strength of the MR system; the orientation of the IPG, extension (the extension is the cable that connects the IPG to the implanted lead), and lead relative to the source of RF energy; the lengths and routing of the extension and lead; the type of RF coil used (e.g., transmit/receive body coil, transmit body coil with receive-only head coil, transmit/receive head coil); the anatomy imaged (e.g., the landmark position, or the anatomic site undergoing MR imaging, that is associated with heating depends on the geometry of the RF coil and the amount of the DBS lead contained within this coil); the amount of RF energy delivered (i.e., the SAR); and how the SAR is calculated by a given MR system (2, 4, 11, 13).

Notably, the calculation of SAR may vary based on the model of the MR system (e.g., older versus newer model) and the software version running on the scanner (2), and there are inherent differences that have been observed on a manufacturer by manufacturer basis (unpublished observations, F. Shelley, March 2005). MR system manufacturers use proprietary and evolving models of the human body on which to base their SAR calculations (2). In general, the actual source of discrepancy for the determination of SAR for a given MR system is unclear, but it is likely a combination of hardware- and software-related factors (2). With respect to hardware issues, the largest contribution probably derives from differences in the design of the transmit RF body coils. From the software perspective, different algorithms (e.g., body modeling) used to estimate whole-body averaged SAR plays a large role (2).

This is of particular concern insofar as safety information determined for a given scanner may not be applicable to another, even from the same MR system manufacturer. Furthermore, estimates of SAR implicitly assume that no conductive materials, such as those associated with metallic implants, are present in the patient. These issues are currently areas of active investigation (2). Thus, attempting to generalize the data across MR system platforms, whether within or across manufacturers, is inappropriate.

Unfortunately, the two case reports underscore the serious consequences of heating at the DBS tip in an MRI. In the case reported by Spiegel et al. (19), the transmit/receive head coil was used, and the scan was performed at 1.0 Tesla (not the recommended 1.5 Tesla) with the leads externalized and unconnected to implanted pulse generators. As such, these conditions greatly deviated from the manufacturer’s MR safety information and recommendations for this neurostimulation system used for DBS (7, 18). The authors speculated that this side effect was the result of induced current in the implanted leads that caused heating and consecutive thermal tissue damage (19). In the second case reported in this journal, the patient, with one IPG implanted in the abdomen and the other infraclavicularly, underwent MRI of the spine at 1.0 Tesla using a transmit/receive body coil.

Importantly, both incidents occurred with scanning that was performed outside the guidelines provided by the device manufacturer (Table 2) and should further emphasize the danger of generalizing or trivializing the safety recommendations. The manufacturer’s current safety information and recommendations should be followed because these are known to be safe MR practices (7, 18). Notably, with careful adherence to these specific safety recommendations, there have been no injuries or incidents reported to date.

Overall, the neurostimulation systems and the resultant heating seems to be sensitive to intrinsic as well as extrinsic factors. The configuration and/or geometry of the individual system (electrode, extension, and the IPG), lengths and routing of the extension and leads, the impedance of the wires, and wire breakage all are expected to result in heating variances. Extrinsic factors such as transmit/receive body versus transmit/receive head RF coils, the landmarking site, and the amount of RF energy used for imaging (i.e., the whole-body averaged SAR) are crucial considerations in the heating equation. Additionally, testing on externalized systems with percutaneously exiting leads has revealed potential hazards of heating at higher SARs used for MRI, with sensitivity to the routing of the extension cable (unpublished observations, Rezai et al., 2004).

At this time, considerable research is needed to provide a more comprehensive evaluation of heating, movement, induced current, and device functionality. A number of centers are performing MRI with neurostimulation devices and scenarios not previously tested, whereas others are trivializing these safety issues. It is imperative to remember the inherent risks posed to the patients and to undertake the responsibilities to fully explore these issues. As such, we urge the neurosurgery, neuromodulation, and MR healthcare communities to take a cautious approach in the use of MRI in patients with

### Table 1. Safety variables for magnetic resonance imaging and neurostimulation systems used for deep brain stimulationa

<table>
<thead>
<tr>
<th>Variable Description</th>
<th>Notes</th>
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<tr>
<td>Field strength and RF frequency of the MR system</td>
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<tr>
<td>Type of transmit RF coil</td>
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<td>Transmit/receive body coil</td>
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<td>Transmit body coil/receive-only head coil</td>
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<td>Transmit/receive head coil</td>
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<td>The amount of RF energy delivered-RF power level SAR</td>
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<td>Technique used to calculate or estimate SAR by the MR system</td>
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<td>The anatomy imaged</td>
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<td>The landmark positionb</td>
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<td>Specific type of neurostimulation system used</td>
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<td>Electrical characteristics of the specific neurostimulation system</td>
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*a RF, radiofrequency; MR, magnetic resonance; SAR, specific absorption rate; IPG, implantable pulse generator.

b The anatomic site undergoing MRI that is associated with heating depends on the geometry of the RF coil and the amount of the DBS lead contained within this coil.

Notably, the calculation of SAR may vary based on the model of the MR system; the field strength of the MR system; the orientation of the IPG, extension (the extension is the cable that connects the IPG to the implanted lead), and lead relative to the source of RF energy; the lengths and routing of the extension and lead; the type of RF coil used (e.g., transmit/receive body coil, transmit body coil with receive-only head coil, transmit/receive head coil); the anatomy imaged (e.g., the landmark position, or the anatomic site undergoing MR imaging, that is associated with heating depends on the geometry of the RF coil and the amount of the DBS lead contained within this coil); the amount of RF energy delivered (i.e., the SAR); and how the SAR is calculated by a given MR system (2, 4, 11, 13).

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neurostimulation systems and to help maintain the excellent safety record for MRI procedures. It is important to have a rigorous, critical, and standardized scientific approach toward MR safety with DBS and all neurostimulation devices.

In consideration of the multitude of variables known to affect MRI-related heating, it is apparent that the determination of safety information for a neurostimulation system used for DBS is not trivial. Despite the complexity of the problem, the need to provide MRI capabilities to the growing group of patients with these implants is implicit. These serious incidents emphasize the fact that, although MR examinations may be performed in patients with DBS devices under specific, well-controlled conditions, the generalization of these conditions to other neurostimulation system-positioning schemes, other MR systems, and other imaging scenarios, is potentially dangerous.

**REFERENCES**

The authors address a crucial issue for surgeons, radiologists, and patients with implanted stimulation systems. For clinicians facing the practical question of whether or not to image a patient, however, many unresolved questions remain. The current guidelines for the Medtronic Activa system (Medtronic, Minneapolis, MN) preclude any application where a body transmit coil is necessary, and report testing on only a limited number of magnetic resonance (MR) systems. Furthermore, the reported specific absorption rates (SAR) guidelines are admittedly flawed and, therefore, may or may not be appropriate to a particular setting. Clinicians should heed the reported adverse events, and it is prudent to take steps towards reducing patient risk. Consideration must be given to the benefit that the patient will receive from an MR examination. If an MR exam is deemed necessary, then several practical steps can be taken, as reported by the authors. For centers with substantial experience scanning patients with deep brain stimulation (DBS) electrodes without incident, adjustments to their present practice are warranted. Surgically, practices that result in MR-friendly lead and extension geometries should be adhered to, and we hope that the authors will provide us with more specific information on recommended device geometries. It seems prudent to avoid long lead extensions. MR protocols that may have been run without incident should still be modified to the lowest possible SAR levels.

For centers with limited or no previous experience imaging patients with neurostimulators, the problem is even more difficult. Ideally, they would be working with an MR system that has already been tested for MR-induced heating of neurostimulators, and could then follow the neurostimulator manufacturer’s guidelines. If working with an MR system that has not been tested, or if a body transit coil is necessary for the imaging application, then the way forward is less clear. The ultimate solution is, of course, implantable devices that are designed to be safe in the MR environment under conventional imaging conditions. There are clearly technical challenges to this endpoint, but the benefits offered by both neurostimulators and MR imaging justify its exploration.

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I}s MR imaging safe for patients with neurostimulation systems used for DBS? The answer is obviously yes, but with the provision that appropriate precautions must be used to ensure safety. There have been thousands of patients with deep brain stimulators who have been scanned with no adverse effects. Those of us who routinely perform MR imaging after the placement of the DBS do so knowing the safety issues and are confident our neuroradiologist can perform these studies in a manner that is safe and effective. Almost all of the reported cases of MR-related injuries have been the result of failure to follow safety guidelines or the use of outdated information related to the safety aspects of the biomedical implants and devices. The Medtronic guidelines for MR imaging of DBS implants, discussed in Table 2 of the article, are quite reasonable and easy to comply with to obtain essential information. This is the key point to take away from this article.

The concern relates to the potential for thermal injury. We know from long-term experience that the DBS lead does not move and the implanted pulse generators do not change parameters. The induction of thermal energy especially at the tip or at a fracture may be a source of problems. The heat that is generated can be trivial to potentially deadly (5, 8, 12). Overall, I am less concerned about routine MR imaging of the postoperative brain than I am of MR imaging of the body, use of diathermy, or the potential problems from cardioversion (11, 16, 20). Although the SAR is a good perimeter to follow, it is clear that the SARs will vary with the particular MR manufacturer system and therefore the recommendations must be applied carefully as they may be unreliable depending on which MR manufacturer is being used (1). Temperatures tend to increase linearly in relation to the SAR’s value. Keeping the SARs below 0.4W/kg in the head is a reasonable perimeter (5). The SAR’s calculation varies considerably with each MR system platform both within manufacturers and across manufacturers. Thus, generalizations are somewhat difficult. The database is also incomplete. I performed hundreds of postoperative MR procedures on an 1.5 T Philips Gyroscan (Philips Medical Systems, Eindhoven, The Netherlands) without incident, but it is not on the “tested” list in Table 2 of the article.

It is unknown whether the SAR was exceeded in the two cases that reported consequences from heating of the DBS tip during an MR procedure. In the first case, there was a lead externalization that was unconnected to an implanted device and this deviation is clearly a problem (17). It is also not clear that tissue damage was experienced, as the affect was transient. In the second reported case that sparked the interest for this Special Commentary, spinal MR imaging was performed with an implanted pulse generator located in the abdomen. This, unfortunately, resulted in thermal tissue damage and permanent neurological injury. However, it should be emphasized that both of these incidents were performed outside of the guidelines provided by the manufacturer. There is no example of an injury that has occurred within those guidelines. In addition to postoperative imaging studies, DBS leads can be placed within the MR environment as well as used in the performance of functional MR imaging (3, 6, 7). Even electroconvulsive therapy for depression can be performed in the presence of bilateral subthalamic nucleus DBS (2). These two incidences, however, clearly demonstrate the need for caution and expertise in performing postoperative MR imaging, whether of the head or of the body.

It is important to remember that postoperative MR imaging is extremely essential in neurosurgery to advance the field and understand problems that develop postoperatively. Questions of documentation of electrode localization in comparison to planned preoperative imaging localization verses post- and interoperative electrophysiological localization are important topics and that can safely be studied.
postoperatively (4, 15, 18). That there have been rare problems with postoperative MR imaging performed outside of the guidelines should not restrict the use of these studies when performed properly. The knee-jerk response of not conducting any studies because there could be some problem is unwise, unethical, and the worst form of intellectual slough. Neurosurgeons have seen this before with aneurysm clips and other forms of hardware. It is clearly important to perform studies and narrow the potential risks.

I have advocated that this should be the responsibility of the manufacturer with the introduction of any new device or any new imaging platform (19). Why should we do their research for them? It should be the Food and Drug Administration’s policy to require any new mechanical device to be tested in the MR environment to know exactly what potential risks there are before release. These studies should be no different than toxicity studies that would be performed for safety evaluation. Similarly, any new MR platform should be tested to exactly determine its safety in relation to routinely used devices. In this regard, the restriction on MR imaging of patients with pacemakers has recently taken a new turn. Once prohibited from MR suites, modern pacemakers and implantable cardioverter/defibrillator systems are safe in the MR environment (9, 10, 13, 14). It is interesting to note that, even though temperatures may be markedly increased (up to 20° C), pathological and histological studies could not demonstrate thermal damage in chronic experiments (9). Thus, the situation in vivo may be very different than a plastic-saline head. There is local cooling that can occur quite quickly from blood flow, which is not accounted for in the models. The modeling may need rethinking.

The authors have attempted to make a careful evaluation of the safety of DBS devices in the MR suite. It is clear that there are certain restrictions that must be followed but it is also clear that postoperative MR imaging is essential and should not be restricted except for clear safety indications. With concerns now highlighted, the Food and Drug Administration will be following very carefully the interactions between MR and DBS devices. It should be the objective of both the neurosurgeon and the neuroradiologist to perform these studies effectively and safely in the postoperative period.

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infer generalized risks. Both injuries occurred with lower field (1 Tesla) magnets, which one might intuitively have assumed to be safer. Clearly this is not the case. Additionally, complications have occurred both with the body transmit/receive coil and the head transmit/receive coil, as well as with the DBS leads connected to external wires or to an implanted pulse generator. It becomes clear that the complexity of these interactions defy simple generalizations.

Using in vitro models to assess electrode heating, the authors have, in previous publications, described several factors that may contribute to MR injury. These are summarized in the table listing the manufacturers’ recommendations for a limited number of imaging equipment pairings. Extrapolation to other MR systems, as the authors point out, is not reliable given our current understanding of these interactions. Therefore, caution is necessary and appropriate. The authors have performed a service by raising awareness of this increasingly important issue.

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An overview of biomechanical tools used to study deformation patterns in the brain during inertial loading that leads to diffuse axonal injury. A, physical model using the skull of a pig filled with a silicone gel that simulates the properties of brain tissue. Once accelerated from rest, the original rectangular grid pattern embedded within the gel (left), distorts severely (right) in response to the acceleration. B, Computer-based models (left), developed from results of the physical modeling tests, can more accurately represent the gray matter (green) and white matter (pink) of the brain, as well as the enveloping cerebrospinal fluid (blue) and encasing skull (cyan). Using accelerations known to produce injury in animals, these models predict the distribution of shear stress (right: red, high shear stress; blue, low shear stress) throughout the brain. C, The motions, when transferred to the in vivo brain, suggest that the brain distorts within the skull during the inertial loading. D, Inertial brain injury in the pig results in a distribution of axonal pathology throughout the white matter shown in the schematic illustration (red, most severe axonal pathology; blue, moderate axonal pathology; yellow, mild axonal pathology). (From, Smith DH, Meaney DF: Axonal damage in traumatic brain injury. The Neuroscientist 6:483–495, 2000).