Evaluation of Epidural and Peripheral Nerve Catheter Heating During Magnetic Resonance Imaging

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Background: Many epidural and peripheral nerve catheters contain conducting wire that could heat during magnetic resonance imaging (MRI), requiring removal for scanning.

Methods: We tested 2 each of 6 brands of regional analgesia catheters (from Arrow International [Reading, Pennsylvania], B. Braun Medical Inc [Bethlehem, Pennsylvania], and Smiths Medical/Portex [Keene, New Hampshire]) for exposure to clinical 1.5- and 3-T MRI. Catheters testing as nonmagnetic were placed in an epidural configuration in a standard human torso–sized phantom, and an MRI pulse sequence applied at the maximum scanner-allowed radiofrequency specific absorption rate (SAR) for 15 minutes. Temperature and SAR exposure were sampled during MRI using multiple fiberoptic temperature sensors.

Results: Two catheters (the Arrow StimuCath Peripheral Nerve and B. Braun Medical Perifix FX Epidural) were found to be magnetic and not tested further. At 3 T, exposure of the remaining 3 epidural and 1 peripheral nerve catheter to the scanner's maximum RF exposure elicited anomalous heating of 4°C to 7°C in 2 Arrow Epidural (MultiPort and Flex-Tip Plus) catheters at the entry points. Temperature increases for the other catheters at 3 T, and all catheters at 1.5 T were 1.4°C or less. When normalized to the body-average US Food and Drug Administration guideline SAR of 4 W/kg, maximum projected temperature increases were 0.1°C to 2.5°C at 1.5 T and 0.7°C to 2.7°C at 3 T, except for the Arrow MultiPort Flex-Tip Plus catheter at 3 T whose increase was 14°C.

Conclusions: Most but not all catheters can be left in place during 1.5-T MRI scans. Heating of less than 3°C during MRI for most catheters is not expected to be injurious. While heating was lower at 1.5 T versus 3 T, performance differences between products underscore the need for safety testing before performing MRI.

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With the increased use of epidural and peripheral nerve catheters in recent years, the question has arisen as to whether patients could retain those catheters during magnetic resonance imaging (MRI). Advantages of MRI include high soft-tissue contrast, imaging in any plane, lack of ionizing radiation, excellent visualization of vascular structures even without administration of contrast agents, and lack of beam-hardening artifacts from bone or dental amalgam that may arise with x-ray computed tomography.[1,2] In fact, MRI is the criterion standard for diagnosing epidural hematoma, which may occur following placement of an epidural catheter.[3–7] However, whether to remove epidural and peripheral nerve catheters during MRI or to leave them in place is uncertain because of potential concerns over device heating, movement, or interference with MRI during scanning.

Many epidural and peripheral nerve catheters contain coiled electrically conducting wire within a polyurethane casing that provides for greater maneuverability. However, there is some concern that the MRI scanner's radiofrequency (RF) applied fields might cause the wire to heat because of induced currents. The Arrow International, Inc (Reading, Pennsylvania), FlexTip Plus Epidural Catheter and the StimuCath Continuous Peripheral Nerve Block Catheter were reported as being "MR-conditional" according to MRIsafety.com, a commonly referenced Web site for information on safe scanning in the MRI environment.[8] This conditional rating is based on limited data and restricts the types of MRI that can be performed, but more often means that catheters are removed prior to MRI as a matter of practice. However, it would be preferable to avoid removal in situations where the catheter is providing effective pain relief to the patient, or where there are potential contraindications to extraction such as thrombocytopenia or anticoagulation, or in general, where discomfort and potential morbidity in replacement exist.

Our literature search identified only 1 article that addressed the safety of epidural and peripheral nerve catheters in the MRI environment.[9] This showed that the linear movement and torque of the Arrow International, Inc, FlexTip Plus Epidural Catheter was within the American Society for Testing and Materials International standard for MRI safety.[7,9] No published studies were found regarding epidural and peripheral nerve catheter heating during MRI. Thus, the goal of the present work was to study the effect of MRI on 6 of the most commonly used catheters for neuraxial and peripheral nerve anesthesia. Our studies were performed in 2 clinical MRI scanners operating at 1.5- and 3.0-T field strengths used for the vast majority of clinical examinations today.

METHODS

We measured catheter heating at the maximum RF exposure levels allowed by the scanner's inbuilt safety constraints for regular MRI. The local specific absorption rate (SAR), which is the US Food and Drug Administration (FDA) guideline metric for RF exposure during routine MRI,[10,11] was documented via calorimetry. The SAR is defined as the RF power deposited per unit mass in Watts per kilogram, which is typically averaged over the whole body, or defined locally in any 1- or 10-g of tissue. The SAR results from currents induced in the body by the scanner's RF excitation field, which is essential for producing images[11] and directly proportional to the temperature change per unit time when the effects of tissue perfusion and blood flow are excluded.[12,13]

To comply with FDA guidance, the scanner estimates the whole-body average and local peak SAR levels prior to every scan. However, because the SAR depends as much on the body's size and shape as it does on the amplitude of the applied RF field,

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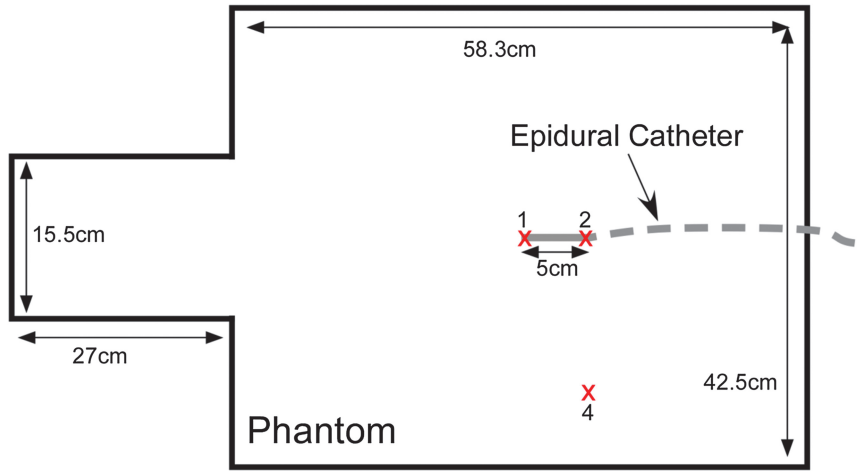


FIGURE 1. Planar view of phantom setup with thermal sensor locations (1, 2, 4) marked by red X's.

these estimates, which rely on prior or factory settings, are often overstated and erroneous when applied to actual patients.[14,15]

Moreover, in the presence of implanted conducting devices or leads including epidural or peripheral nerve catheters, the induced RF currents in the body can couple to the conductor, resulting in locally elevated SAR and heating.[11] This is not accounted for by the scanner's estimate of local SAR. Therefore, because heating and SAR are directly related, we used local temperature measurements recorded in the presence and absence of the catheters to determine, respectively, (i) the differential heating and local SAR associated with the catheter's presence and (ii) the true applied SAR exposure in the sample.[13]

The 6 catheters we studied included 3 from Arrow International, Inc (MultiPort Epidural with Flex-Tip Plus, Epidural with Flex-Tip Plus, and StimuCath Peripheral Nerve Catheter), 2 from B. Braun Medical Inc (Bethlehem, Pennsylvania) (Contiplex Polyamide PNC and Perifix FX Epidural), and 1 from Smiths Medical/Portex (Keene, New Hampshire) (Epifuse Nylon Epidural). These catheters were obtained from clinical supplies and were not provided specifically for testing by the manufacturers. Testing was performed on 2 catheters of each type (12 catheters in total). Each catheter was examined for defects before and after each test. The potential for magnetic forces imposed by the clinical 1.5- and 3-T MRI scanners to cause potentially hazardous catheter displacement due to the device's magnetic properties was first assessed, and devices presenting significant displacement risk were excluded from further testing. Each of the remaining catheters were tested for RF heating during MRI in 2 safety-test runs in both the 1.5- and 3-T clinical scanners, for a total of 4 runs with each catheter type at each MRI field strength.

A standard human torso MRI phantom with 40.5-L volume (total length = 85.3 cm, maximum width = 42.5 cm, height = 14 cm) was filled with saline that had electrical properties similar to those of human muscle at 128 MHz (dielectric constant, $\varepsilon = 80$; conductivity, $\sigma = 0.63$ S/m). It contained 0.8 g/L salt and 15 g/L polyacrylic acid to inhibit convection (higher viscosity but same thermal conductivity as water; Fig. 1).[12] This type of phantom has been used previously on multiple occasions for safety testing internal MRI probes and conducting leads.[11–13] To mimic routine clinical placement, the epidural catheters were placed 8 cm deep from the surface of the phantom and extended for 5 cm longitudinally parallel to the main magnetic field (Fig. 2).

The displacement and heating experiments were conducted inside a GE Signa 1.5-T scanner (GE Healthcare, Waukesha, Wisconsin) and a Philips Achieva 3-T MRI scanner (Philips Medical Systems, Cleveland, Ohio) (Fig. 3A) using the scanner's standard body coils for excitation. For heat testing, the MRI pulse sequences were adjusted to maximize RF exposure within the operating limits imposed by the scanners, for total scan times of 15 minutes (the FDA guideline for whole-body SAR exposure is 4 W/kg for 15 min).[10,11] The torso phantom was instrumented with fiberoptic temperature sensors (Neoptix, Inc, Québec, Québec, Canada) that were in tight contact with the catheters (sensor 1 [S1] at the catheter tip; sensor 2 [S2] at the bend; sensor 3 [S3] at the phantom entry point). The use of fiberoptic sensors is standard for these studies because the sensors are not affected by, nor interfere with, the MRI.[11–14] The phantom was placed at the isocenter of the MRI scanner's body coil, which was maintained at room temperature for all experiments. The temperature inside the phantom was monitored continuously at a 1-Hz sampling rate during RF (MRI) exposure.

The local applied SAR was measured by calorimetry based on reference temperature measurements acquired from the same phantom locations S1 to S3 in the absence of any

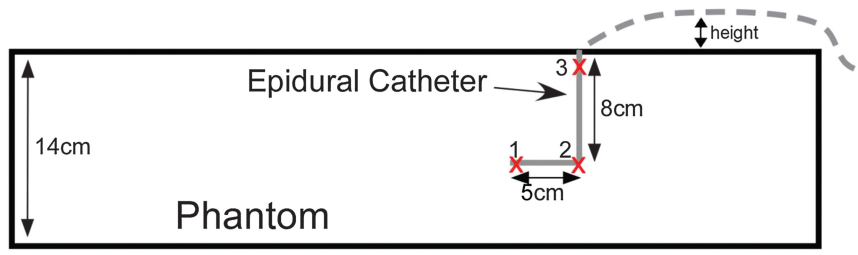
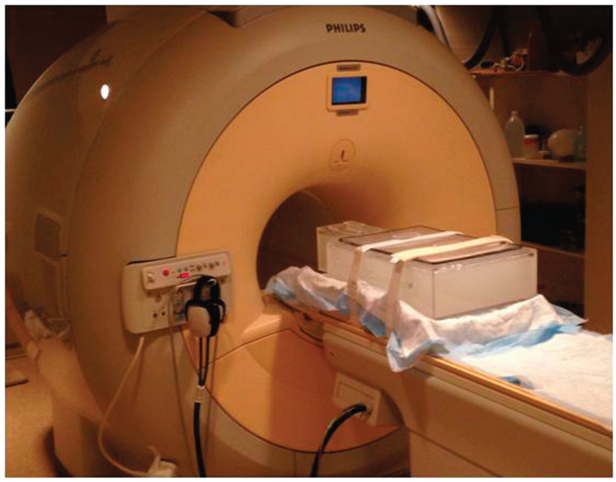


FIGURE 2. Side elevation of phantom setup with thermal sensor locations (1, 2, 3) marked by red X's.



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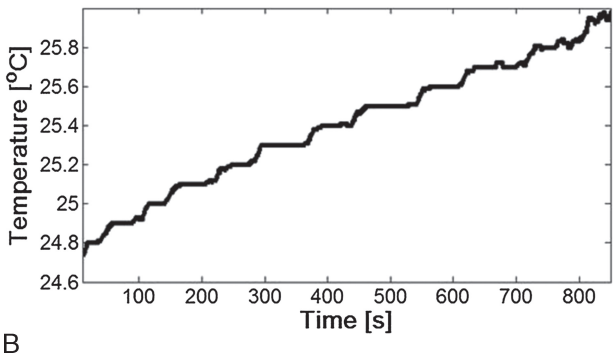

B

FIGURE 3. A, Torso-sized phantom and the 3-T MRI scanner. B, Temperature data at sensor location S2 next to the Arrow MultiPort Epidural T Flex-Tip Plus catheter at 3 T. The steps are due to the finite (0.1C) resolution of the temperature sensors.

catheters (reference R1-R3, respectively) and at a fourth remote location (sensor 4, R4). The local SAR at each location was then calculated from the following:

$$\mathrm{SAR} \approx c\,(\Delta T/\Delta t), \qquad (1)$$

where $c = 4180\,\mathrm{J/kg \cdot °C}$ is the specific heat of the saline gel, and $\Delta T/\Delta t$ is the temperature rise per unit time (°C/s). This approximation to the heat equation becomes true in the absence of thermal diffusion, perfusion, and media phase changes, and in the limit $\Delta t \rightarrow 0$. Because perfusion and diffusion reduce local heating, the approximation is considered conservative. The SAR computed from the temperature measurements at sensors R1, R2, and R4 was averaged to obtain a volume average SAR exposure during each study (the temperature rise at R3 was negligible).

The heating experiments were repeated 3 to 4 times at both field strengths with each of the catheters that tested as nonmagnetic. The temperature data were imported into Matlab software (Mathworks Inc, Natick, Massachusetts) for processing. Because SAR and temperature scale directly (Eq. 1), the temperature measurements at sensors S1 to S3 were also scaled for a whole-body average SAR exposure of 4-W/kg SAR over 15 minutes, based on the volume averaged SAR as determined from R1, R2, and R4. This exposure corresponds to the FDA guideline for MRI systems that generally limits whole-body average SAR to 4 W/kg over a 15-minute period.[10]

RESULTS

Examination of each catheter before and after each MRI test revealed no visible defects. However, 2 of the 6 catheters, the Arrow International, Inc, StimuCath Peripheral Nerve Catheter and the B. Braun Medical Inc Perifix FX Epidural, were found to be magnetic, exhibiting a significant attractive displacement force 1 m from the bores of the 1.5- and 3-T MRI scanners and were excluded from further testing. The remaining 4 catheters (3 epidural, 1 peripheral nerve catheter) underwent RF heat testing.

In tests with 2 of each type of catheter, none of the catheters had a mean temperature increase of more than 1.4°C in the 1.5- or 3-T scanners when subjected to the maximum scanner output over 15 minutes. However, at 3 T, the 2 Arrow catheters each showed heating of 4°C to 7°C at the catheter entry point (S3) but in only 1 of 4 runs (Tables 1 and 2; Fig. 3). At 1.5 T, the mean increase at the entry point close to the sample edge was indistinguishable from room temperature and is omitted from Table 1 (and Table 3, derived from Table 1).

In the absence of catheters, the volume average applied SAR at the temperature sensor locations never reached 4 W/kg, although the local SAR at R4 in the 3-T scanner did (Table 4). The temperature changes at R3 were negligible and are not listed. The projected temperature increases for a 15-minute volume average SAR exposure of 4 W/kg based on the R1/R2/R4 average are listed in Tables 3 and 5. At 1.5 T, the Arrow catheters warmed by 2.5°C or less at the S2 bend. At 3 T, greatest heating occurred at the entry point (S3) for all devices: the Arrow multiport catheter fared worst, with a maximum projected heating up to 14°C. The B. Braun catheter performed the best, with mean heating of 2°C or less. The Smith/Portex device also performed well, heating up to 2.6°C at the entry point, but only ~1°C or less elsewhere (Table 5).

DISCUSSION

Our experiments are the first we know of that assess the heating of epidural and peripheral catheters during MRI in clinical 1.5- and 3-T scanners. We evaluated 4 epidural and peripheral nerve catheters in a whole-body torso phantom exposed to scanning at the maximum SAR levels permitted by the scanners, albeit below body-average FDA SAR limits. The catheters were placed in what was considered a worst-case scenario for an epidural procedure with respect to length and depth in the body, with the catheter perpendicular to the RF field where induced currents are the greatest. Two other catheter models were found to be magnetic and, being subject to displacement by the magnetic forces in the scanner, were judged to be unsuitable for use in patients in the MRI environment. The maximum temperature increases recorded at the maximum SAR levels provided by the scanners were 0.1°C to 1.4°C at 1.5 T and 0.5°C to 7°C at 3 T for all catheters at 3 T or 1.4°C or less at 3 T, if the 2 Arrow devices are excluded (Tables 1, 2).

Because regulatory agents have limited RF exposure for conventional clinical MRI examinations,[10,15] commercial MRI scanners must estimate the SAR for each subject being studied. Such estimates are performed automatically within the scanner's operating system and may, for example, be based on the subject's weight as recorded by the scanner operator. The scanner uses the estimate to limit any MRI scanning to the FDA guideline as applied to that subject.[9–11] However, the scanner SAR estimates do not account for the presence of metallic implants or catheters, and consequently in most cases, patients with these are ineligible for MRI. The reason the scanner's SAR estimates are no longer applicable is that the local SAR or energy deposited depends on the (RF) electrical properties of the tissue, whose conductivity is greatly increased by the presence of a conductor.[13] Because our

TABLE 1. Maximum and Average Increases in Catheter Temperature by Location in the 1.5-T Scanner

	Catheter Tip		Catheter Bend		Entry Point
Catheter Brand	Mean increase, °C	Max increase, °C	Mean increase, °C	Max increase, °C	Max increase, °C
Braun Contiplex Polyamide PNC	0.3	0.4	0.5	0.7	0.1
Smith/Portex Epifuse Nylon Epidural	0.8	1.4	0.8	1.0	0.1
Arrow Flex-Tip Plus Epidural	0.5	0.7	1.0	1.1	0.3
Arrow MultiPort Flex-Tip Plus Epidural	0.5	0.8	1.0	1.1	0.1

measurements were performed at the maximum SAR allowed by the scanner for this phantom (Tables 1, 2), and because the results were then normalized to the actual FDA body-average SAR exposure limit (Tables 3, 5) as determined by calorimetry (Table 4), catheters that do not heat significantly under these conditions should not heat in FDA-compliant MRI scanners operating in a configuration comparable to that tested (ie, same field strength, catheter geometry, body coil excitation).

The maximum body-average RF exposure that could actually be applied by the scanner in these studies corresponded to 1.5 to 2.7 W/kg and locally up to 4.5 W/kg peak SAR, as measured at the catheter locations but with the catheters removed (Table 4). These are both below the FDA guidelines for average and local SAR,[10,11] reflecting conservatism in the scanners' in-built SAR computations.[16,17] The maximum temperature increase seen at these levels was 1.4°C or less in both scanners (Table 1, 2) in all but the 2 Arrow catheters at 3 T. These temperature increases are below levels that which would be considered thermally injurious. The temperature increases are in general lower at 1.5 T, and it appears that all of the catheters tested would be safe for use at 1.5 T. The B. Braun and the Smith/Portex devices could be used at 3 T under the MRI conditions tested as well and may not need to be removed during MRI out of concern for RF heating. The anomalous behavior of the Arrow catheters at the S3 entry point suggests an interaction between the catheter's conducting structural member and the RF electromagnetic (EM) field at the phantom tissue-air interface. Such behavior is seen in numerical EM simulations and may be attributable to the combined effect of an impedance mismatch between the phantom and air at the entry point and the length of conductor in the phantom approaching the shorter, potentially resonant, RF one-fourth wavelength at 3 T, as compared with 1.5 T.[13] Note that heating at the entry point would be relatively accessible to thermal monitoring during MRI.

There are national differences in regulatory metrics used to evaluate the safety of ancillary devices during MRI. The current FDA guidelines for routine MRI focus on SAR levels, with a whole-body average limit of 4 W/kg over a 15-minute period and an 8-W/kg local SAR limit for 5 minute in any 1 g of tissue in the torso.[10] In Europe, the International Electro-technical Commission's guidelines for RF exposure include local temperature limits of 1°C to 2°C in any 10 g of tissue[15] and SAR limits that are comparable to those of the FDA.[9] Although SARs can be

TABLE 2. Maximum and Average Increases in Catheter Temperature by Location in the 3-T Scanner

	Catheter Tip		Catheter Bend		Entry Point	
Catheter Brand	Mean Increase, °C	Max increase, °C	Mean Increase, °C	Max Increase, °C	Mean Increase, °C	Max Increase, °C
Braun Contiplex Polyamide PNC	0.5	0.7	0.5	0.7	1.2	1.4
Smith/Portex Epifuse Nylon Epidural	0.5	0.6	0.5	0.6	1.4	1.6
Arrow Flex-Tip Plus Epidural	0.5	0.6	0.4	0.7	1.7	4.1*
Arrow MultiPort Flex-Tip Plus Epidural	0.5	1.2	0.8	1.2	2.5	6.8†

*Individual runs measured 1.82°C, 4.05°C, 1.04°C, and 0.0°C.

†Individual runs: 6.82°C, 1.37°C, 1.14°C, and 0.48°C.

TABLE 3. Projected Average and Maximum Temperature Increases by Location in 1.5-T Scanner With an Applied Average SAR of 4 W/kg for 15 min

	Catheter Tip		Catheter Bend		Entry Point
Catheter Brand	Mean Increase, °C	Max Increase, °C	Mean Increase, °C	Max Increase, °C	Max Increase, °C
Braun Contiplex Polyamide PNC	0.6	0.9	1.2	1.8	0.1
Smith/Portex Epifuse Nylon Epidural	1.6	1.4	1.7	1.0	0.1
Arrow Flex-Tip Plus Epidural	1.1	1.6	2.1	2.5	0.5
Arrow MultiPort Flex-Tip Plus Epidural	1.1	1.5	2.1	2.4	0.3

TABLE 4. Maximum Temperature Increase and Local SAR at Locations R1, R2, and R4 and the Volume Averaged SAR Recorded During Reference: MRI Experiments With the Catheters Removed

	1.5-T Scanner		3-T Scanner	
	Maximum Temperature Rise,°C	SAR, W/kg	Maximum Temperature Rise,°C	SAR, W/kg
Tip reference point (R1)	0.7	0.99–2.76	0.5	1.57–1.60
Bend reference point (R2)	0.6	1.38–1.85	0.6	1.43–2.08
Reference probe (R4)	0.6	1.62–1.82	1.3	2.77–4.50
Spatial average SAR, W/kg	1.49–1.99		1.94–2.72	

computed numerically from EM simulations, these still require empirical measures of the total power delivered to the body by the scanner in order to scale them to an actual MRI study.[16,17] For catheters and electrically conducting implants, local SAR depends on a variety of factors including implant length, insulation, shape, and the RF field transmitted by the MRI coil.[12,13,18,19] Validating the computations and/or measuring the local SAR is not straightforward, other than by measuring the direct consequence of SAR (ie, heating) as was done here and elsewhere.[18,19] We used the RF heating measurement technique of Atalar.[14]

For a perspective on the interplay between SAR guidelines and temperature, the heat equation for SAR (Eq. 1), would translate the 4-W/kg body-average FDA limit[10] to a volume-average temperature increase of 0.86°C in 15 minutes. The local 8-W/kg 1-g SAR guideline corresponds approximately to a 1.7°C increase in the $10 \times 10 \times 10$ mm^3 of tissue. Although the temperature increases, we observed it was less than 1.7°C for all catheters at 1.5 T and for the B. Braun and Smith/Portex catheters at 3 T at maximum scanner power (Tables 1, 2), if the volume average SAR was increased (beyond the levels permitted by these scanners) up to the 4-W/kg body average permitted by the FDA guideline, then higher local heating of up to 2.5°C would be anticipated for all devices at 1.5 T (Table 4) and up to 2.7°C at 3 T if the Arrow MultiPort catheter is excluded (Table 5). This neglects the counter-effects of perfusion and blood flow during the 15-minute exposure, which would reduce the local temperature rise and likelihood of thermal injury. However, even with a 3°C local temperature rise, the temperature would remain well less than 43°C, which is an accepted threshold where injury becomes a concern. For example, the standard "cumulative equivalent minutes at 43°C" metric, CEM_{43}, used for quantifying thermal dose, is only 0.06 minutes or 4 seconds integrated over the examination period, assuming the MRI sequence or thermal dose is applied uniformly in time.[15]

In evaluating local SAR in the context of the regulatory guidelines, the effect of volume averaging is also a consideration. It is our experience based on numerical EM calculations around electrically conducting catheter or wire leads that averaging the SAR over regulatory specified volumes of 1 or 10 g of tissue can significantly reduce the local SAR (or point temperature) estimates when there are high SAR gradients close to the device.[13] Compared with absolute thermal sensor measurements, which correspond to a tissue volume of order 1 to 10 mg (~$1 \times 1 \times 1$ mm^3), a 1- or 10-g volume average local temperature or SAR can be more than 10-fold lower.[13] In our opinion, because tissue heating is the sole safety concern associated with RF exposure when considering surgical devices that do not involve connections to other sensors or electronics, the conservative course is to consider only the maximum local temperature change, rather than volume averages for assessing RF safety during MRI.

Indeed, the absolute temperature increase or MRI-induced thermal dose that may be considered "safe" (ie, not cause tissue damage) for catheters is difficult to determine. The pathophysiologic sequelae of thermal injury may vary with tissue type, and neural tissues are potentially among those most at risk of thermal injury.[20] There is a lack of research on thresholds for thermal injury and a dearth of in vivo studies on the type and extent of damage at the lower range of hyperthermic exposure (eg, 39°C-43°C).[21] In a study examining heating and sensing leads implanted in the brain or spine of sheep and exposed to RF-induced heating to 37°C to 49°C for 30 minutes, histopathologic examinations performed 7 days after recovery found that the effects of deep brain and spinal RF heating of up to 43°C were indistinguishable from tissue maintained at 37°C, whereas exposures greater than 43°C produced localized temperature-dependent thermal injury.[10] This is consistent with use of the CEM_{43} standard as a threshold for gauging thermal dose.[19]

Limitations to the present work include differences in how well the phantom measurements approximate the conditions extant in the human body and possible variations between devices of the same manufacturer that lead to different heating behaviors. Although there is no universal epidural catheter placement configuration, we positioned the epidural catheter at right angles in the phantom to simulate the typical clinical configuration and maximize potential heating, but different epidural placements could produce different temperature readings. The size and high (RF)

TABLE 5. Projected Average and Maximum Temperature Increase by Location in 3-T Scanner With an Applied SAR of 4 W/kg × 15 min

	Catheter Tip		Catheter Bend		Entry Point	
Catheter Brand	Mean Increase, °C	Max Increase, °C	Mean Increase, °C	Max Increase, °C	Mean Increase, °C	Max Increase, °C
Braun Contiplex Polyamide PNC	0.8	1.3	0.8	0.9	1.8	2.1
Smith/Portex Epifuse Nylon Epidural	0.8	1.0	0.8	1.1	2.2	2.6
Arrow Flex-Tip Plus Epidural	0.8	1.1	0.7	1.5	2.4	2.7
Arrow MultiPort Flex-Tip Plus Epidural	1.2	2.3	1.6	1.6	5.9	14.1

electrical conductivity of the phantom compared with many tissues in the body, as well as the lack of any blood flow or perfusion that could mitigate local heating, suggest that the phantom may present a worst case scenario. Superficial adipose, bone, and lung tissue, for example, have much lower electrical conductivity and therefore reduced SAR. The phantom also does not accommodate the effects of tissue heterogeneity, although combinations of tissues with lower electrical conductivity also tend to exhibit lower SAR, depending on the tissue distribution. We did not investigate the effects of broken leads, which could conceivably produce larger temperature rises than seen here (≤14°C),[22] but at inspection before and after testing, all of our catheters were defect-free. Also, with the phantom in the scanner at room temperature, even the highest recorded local temperatures were less than 37°C and incapable of causing thermal damage to either catheter or phantom. Finally, we did not assess other aspects such as catheter movement or interference with the quality of the MRI scan that might detract from the decision to leave an epidural or peripheral nerve catheter in place during MRI.

We conclude that in the MRI scanners tested, all 4 tested catheters could be left in place during 1.5-T MRI scanning and that the B. Braun and Smith/Portex catheters are also unlikely to cause RF heating injuries at 3 T. Even if the actual SAR could be increased to the scanner's whole body-average regulatory limits, injury is unlikely with these devices, since heating less than 3°C. However, the differences in findings for 1.5- and 3-T scanning and between catheters from different manufacturers, underscore the need for scanner, device, and application-specific testing when considering device safety during MRI procedures.

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