

# Magnetic Resonance Imaging of the Codman Microsensor Transducer Used for Intraspinal Pressure Monitoring

*Findings From the Injured Spinal Cord Pressure Evaluation Study*

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**Study Design.** Laboratory and human study.

**Objective.** To test the Codman Microsensor Transducer (CMT) in a cervical gel phantom. To test the CMT inserted to monitor intraspinal pressure in a patient with spinal cord injury.

**Summary of Background Data.** We recently introduced the technique of intraspinal pressure monitoring using the CMT to guide management of traumatic spinal cord injury [Werndle et al. *Crit Care Med* 2014;42:646]. This is analogous to intracranial pressure monitoring to guide management of patients with traumatic brain injury. It is unclear whether magnetic resonance imaging (MRI) of patients with spinal cord injury is safe with the intraspinal pressure CMT *in situ*.

**Methods.** We measured the heating produced by the CMT placed in a gel phantom in various configurations. A 3-T MRI system was used with the body transmit coil and the spine array receive coil. A CMT was then inserted subdurally at the injury site in a patient who had traumatic spinal cord injury and MRI was performed at 1.5 T.

**Results.** In the gel phantom, heating of up to 5°C occurred with the transducer wire placed straight through the magnet bore. The heating was abolished when the CMT wire was coiled

and passed away from the bore. We then tested the CMT in a patient with an American Spinal Injuries Association grade C cervical cord injury. The CMT wire was placed in the configuration that abolished heating in the gel phantom. Good-quality T1 and T2 images of the cord were obtained without neurological deterioration. The transducer remained functional after the MRI.

**Conclusion.** Our data suggest that the CMT is MR conditional when used in the spinal configuration in humans. Data from a large patient group are required to confirm these findings.

**Key words:** heating, human, ISP, magnetic, MRI, paralysis, radiofrequency, safety, spinal cord injury, spinal cord perfusion pressure, transducer.

**Level of Evidence:** N/A

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The Injured Spinal Cord Pressure Evaluation (ISCoPE) study was set up in 2009, aiming to develop intraspinal pressure (ISP) monitoring to guide the management of patients with severe traumatic spinal cord injury (TSCI). This is analogous to intracranial pressure (ICP) monitoring, which is widely used to manage patients with traumatic brain injury.<sup>1</sup> We simultaneously monitor ISP and arterial blood pressure to compute the spinal cord perfusion pressure (SCPP = mean arterial pressure MAP – ISP) and the spinal pressure reactivity index at the injury site. Our experiments show that after TSCI, the spinal cord swells at the level of injury causing raised ISP, reduced SCPP, and impaired pressure reactivity. By intervening to increase SCPP, motor outcome improves, assessed using motor-evoked responses and a limb motor outcome score. For details, see the paper by Werndle *et al.*<sup>2</sup> We also showed that surgical decompression (laminectomy + expansion duroplasty) after TSCI is beneficial by reducing ISP, increasing SCPP, and improving spinal pressure reactivity more effectively than laminectomy.<sup>3</sup>

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The device(s)/drug(s) that is/are the subject of this manuscript is/are not FDA-approved for this indication and is/are not commercially available in the United States.

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During the ISCoPE study, we found magnetic resonance imaging (MRI) of TSCI patients invaluable. We use MRI pre- and postoperatively to evaluate the extent of spinal cord edema (which determines the number of levels to decompress), to look for haematoma (that may require evacuation), and to assess the effectiveness of decompression (presence of cerebrospinal fluid around the swollen cord). Since ISP monitoring is achieved by using the Codman microsensor transducer (CMT), we tested the MRI safety of the CMT in a spinal configuration.

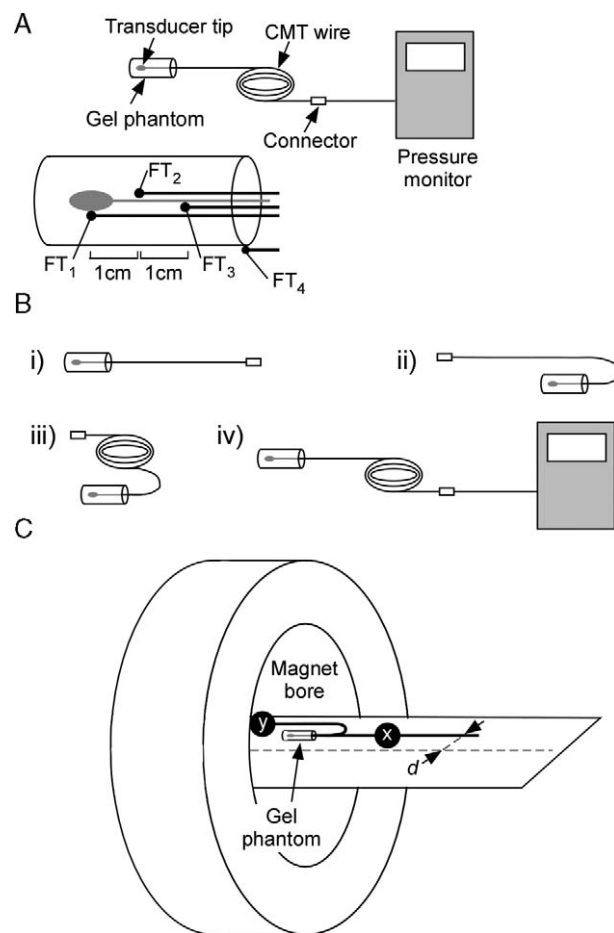
The CMT has been evaluated at  $0.5\text{ T}^4$  and  $3\text{ T}^5$  in a cranial setup measuring ICP, but has never been assessed in a magnet at a spinal configuration. For ICP measurement, the CMT was assessed in the magnetic and radiofrequency (RF) fields of the MRI system: the static magnetic field, switching magnetic fields for localization, and RF fields. The effect of the RF field on the CMT was larger than that caused by the magnetic fields.<sup>5</sup> Resonance in the CMT wire due to RF fields was demonstrated, with the energy dissipated from the induced current causing a significant heating effect. This was reduced with coiling of the CMT wire. In a high-field magnet, the CMT was deemed MR-conditional as defined by the American Society for Testing Materials International. The term MR-compatible was replaced by the terms MR-conditional and MR-safe. MR-safe poses no hazard in all MR environments. MR-conditional poses no hazards as long as it is used in a specified MR environment with specified conditions of use.

There are several differences in spinal imaging when using an ISP probe compared with cranial imaging when using an ICP probe. First, any potential damage caused by placing the CMT measuring ISP in MRI would cause neurological deterioration, compared with the noneloquent right frontal cortex used for ICP monitoring. Second, because of the depth of the spinal cord from the skin surface, there is a longer uncoiled CMT wire exposed to the RF field compared with the ICP configuration. Third, ISP monitoring does not require the steel cranial access bolt, and thus artefacts because of it are avoided. Here, we studied the heating effect on the CMT caused by a transmitter body coil combined with a receiver only coil for spinal imaging to determine the ideal configuration that abolishes heating. We reproduced the imaging in a human TSCI subject.

## MATERIALS AND METHODS

### CMT/MRI Setup

The CMT system (Depuy Synthes, Leeds, UK) consists of a pressure probe tip, CMT wire, connector, and a cable connected to the pressure monitor, which is placed outside the  $5 \times 10^{-4}\text{ T}$  line of the MR imaging unit (Figure 1A) for isolation from the magnetic and RF fields during imaging. For imaging in gel, a 3-T Siemens Magnetom Verio (Siemens Healthcare, Frimley, UK) system was used. For imaging the TSCI patient, a 1.5-T Philips Intera (Philips Healthcare, Guildford, UK) system was used, which has fourfold less RF energy deposited per kilogram bodyweight compared with the 3-T magnet.



**Figure 1.** Codman microsensor transducer in gel phantom. **A**, Schematic showing (top) components of transducer setup and (bottom) positioning of fiberoptic temperature transducers (FT<sub>1</sub>–FT<sub>4</sub>). **B** (i–iv), Different protocols used for imaging and temperature measurement (for details see Materials and Methods). **C**, Gel phantom in magnet bore at distance *d* from the center of the bore, parallel to the floor. Configuration *x* = transducer wire passing away from magnet bore, configuration *y* = transducer wire passing through magnet the bore. CMT indicates Codman microsensor transducer.

### CMT Setup in Gel Phantom

A spinal cord phantom made using a 15-mL Falcon centrifuge tube filled with agar gel. Temperature was measured with a Luxtron 3100 Fluoroptic thermometer (Luxtron, Santa Clara, CA) using four Fiberoptic Thermocouples (FT<sub>1</sub>–FT<sub>4</sub>) secured at the tip of the pressure transducer (FT<sub>1</sub>), 1 cm (FT<sub>2</sub>), and 2 cm (FT<sub>3</sub>) away from the tip, and outside the phantom to measure ambient temperature (FT<sub>4</sub>). The CMT wire, with the thermocouples secured to it, was inserted longitudinally midway into the gel phantom.

### CMT Testing in Gel Phantom

After allowing the fiberoptic thermocouples to equilibrate at ambient temperature, temperatures from FT<sub>1</sub> to FT<sub>4</sub> were measured during an FLAIR imaging sequence at 2-s intervals. Temperature measurements started 10 s before the start of imaging and stopped 10 s after the end of imaging. The FLAIR sequence was chosen because of the high RF

deposition and switching rates, potentially causing larger energy deposition in tissue per kilogram weight compared with T1 or T2-weighted sequences. The body transmit/receive coil was used, which is routinely used for spine imaging. The imaging parameters were FOV 179 × 224 mm, 0.7 × 0.7 × 4 mm resolution, 256 × 320 matrix size, TR = 7 s, TE = 96 ms, turbo factor 16. The imaging sequence was repeated on a second day.

### Protocols

Induced heating may be affected by  $d$  (distance of the CMT tip from the center of the magnet bore along a radius parallel to the floor), the transducer wire passing away from (configuration  $x$ ) versus into (configuration  $y$ ) the magnet bore (Figure 1C), coiling versus noncoiling of the transducer wire and connecting versus not connecting the transducer to the pressure monitor. To examine the effect of these conditions, we imaged using four different protocols (Figure 1B):

- Protocol i. The transducer wire was not coiled, was passed away from the magnet bore (configuration  $x$ , Figure 1C), and was not connected to the pressure monitor.  $d = 0, 10, 20, 30$  cm.
- Protocol ii. The transducer wire was not coiled, was passed through the magnet bore (configuration  $y$ , Figure 1C), and was not connected to the ISP monitoring box.  $d = 0, 10, 20, 30$  cm.
- Protocol iii. The transducer wire was coiled, used in the configuration that produced the largest temperature change ( $d = 30$  cm, configuration  $y$ ), and was not connected to the ISP monitoring box. The wire was coiled in 5-cm diameter loops such that each alternating loop was in an opposite direction to form a noninductive loop.
- Protocol iv. The transducer wire was coiled, used in the configuration that produced no temperature ( $d = 0$  cm, configuration  $x$ ) rise, and was connected to the ISP monitoring box.

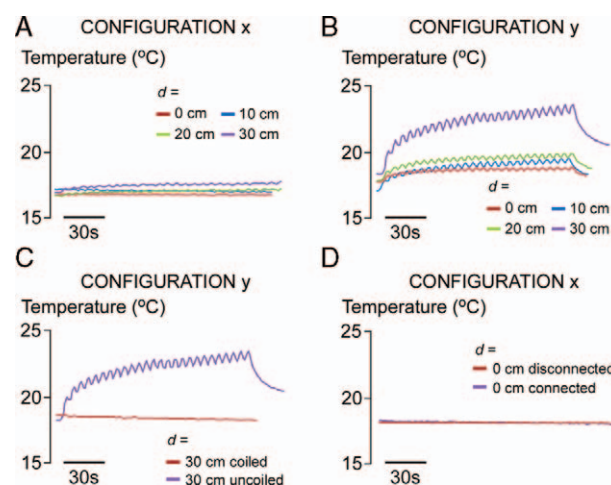
### Postoperative TSCI Patient Imaging

Approvals for the patient imaging study were obtained from the St. George's Joint Research Office and the National Research Ethics Service London – Camberwell St Giles Committee (No. 10/H0807/23) as part of the ISCoPE. We tested the CMT at 3 T in the gel, but only at 1.5 T in the patient to further reduce the risk of CMT heating. The transducer was implanted in the subdural space during surgery at the level of injury in a TSCI patient, as previously described.<sup>2</sup> In brief, after laminectomy and fixation, the dura is punctured distal to the level of injury with a 21-gauge needle bent 90°. The CMT was inserted through the dural puncture so that the transducer tip lies at the level of maximal cord swelling between the injured cord and the dura. Postoperative MR images were taken using a transmit/receive body coil in a 1.5-T magnet according to CMT manufacturer's guidelines. The CMT was coiled in 5-cm-diameter loops, away from the magnet bore (configuration  $x$ ), as close to the midline as possible but not touching the patient or the magnet bore.

## RESULTS

### CMT Testing in Gel

Ambient temperature was  $20.2^{\circ}\text{C} \pm 0.0$  (mean  $\pm$  s.e.m) on day 1 and  $20.1^{\circ}\text{C} \pm 0.0$  on day 2 ( $P = 0.27$ ). Temperature readings from the phantom were identical on both days. The temperature of the CMT probe tip fluctuated in a pulsatile fashion at a frequency of 0.1 Hz (Figure 2). The temperature elevations correspond to the RF pulses and the temperature falls to the periods between the RF pulses. There was insufficient time for the probe tip to cool to room temperature between RF pulses. In all configurations heating was localized to the tip of the transducer (Table 1). CMT probe heating occurred rapidly after the start of imaging and, once imaging was stopped, the thermocouple cooled down rapidly. Figure 2 shows the time course of the temperature changes at the tip of the transducer (FT<sub>1</sub>). Testing in protocol i produced a maximal temperature rise of  $0.8^{\circ}\text{C}$  at  $d = 30$  cm (Figure 2A). Testing in protocol ii produced maximal temperature rises of  $2.4^{\circ}\text{C}$  at  $d = 0$  cm and  $5.2^{\circ}\text{C}$  at  $d = 30$  cm (Figure 2B). Maximal heating was observed with protocol ii at  $d = 30$  cm. To test whether coiling reduces the heating because of the resonance caused by the RF fields, the imaging sequence was repeated as per protocol iii. Coiling of the transducer abolished the heating effect (Figure 2C). We then tested whether connecting the CMT system to ISP monitoring box would cause heating with the CMT transducer wire at the setup at which the lowest temperature change was detected ( $d = 0$  cm, configuration  $x$ , transducer wire coiled). Figure 2D shows no detectable rise in CMT probe temperature when the ISP monitoring box was connected.



**Figure 2.** Temperature at transducer tip versus time. Temperature at different  $d$  with wire uncoiled and not connected to the ISP monitoring box in (A) configuration  $x$  and (B) configuration  $y$ . C, Temperature in configuration  $y$  at  $d = 30$  cm with wire uncoiled (red) or coiled (purple) and not connected to the ISP monitoring box. D, Temperature in configuration  $x$  at  $d = 0$  cm with transducer wire coiled and disconnected (red) or connected (purple) to the ISP monitoring box. ISP indicates intraspinal pressure.



**TABLE 1. Maximum Temperature Change of FT<sub>1</sub>–FT<sub>4</sub>**

Protocol	Distance, <i>d</i> (cm)	Max Temperature Change (°C)			
		FT <sub>1</sub>	FT <sub>2</sub>	FT <sub>3</sub>	FT <sub>4</sub>
i	0	0.1	0.0	0.0	0.0
	10	0.0	0.0	0.0	0.0
	20	0.5	0.1	0.1	0.1
	30	0.8	0.1	0.1	0.2
ii	0	2.4	0.3	0.2	0.2
	10	1.0	0.0	0.1	0.2
	20	2.0	0.2	0.3	0.2
	30	5.2	0.7	0.5	0.5
iii	30 coiled	0.0	0.0	0.0	0.0
iv	0 coiled disconnected	0.1	0.1	0.0	0.0
	0 coiled connected	0.1	0.0	0.0	0.1

*d* indicates distance of probe tip from center of magnet bore; FT<sub>1</sub>–4, fiberoptic transducer. Protocols i–iv described in Materials and Methods and Figure 1B.

## Patient

A 65-year-old man sustained a cervical TSCI in a road traffic accident. On examination, he was classified as American Spinal Cord Injury Association (ASIA) C. CT and MR imaging revealed no spinal fracture, but disruption of the C4/5 intervertebral disc with associated ligamentous disruption and spinal cord edema. He underwent fixation anteriorly (C4/5 discectomy, interbody carbon cage, anterior plate with C4 and C5 screws) and posteriorly (C4 and C5 lateral mass screws and rods) with C4 and C5 laminectomies. The CMT probe was inserted subdurally at C4/5 as described in the Materials and Methods and was tunneled under the skin for 3 cm.

## Postoperative Imaging in TSCI Patient

MRI was done on postoperative day 6. Imaging parameters are as follows: sagittal imaging FOV 275 mm, slice thickness 4 mm; TE 120 ms/TR 3500 ms and TE 10 ms/TR 400 ms; axial imaging: FOV 225 mm, slice thickness 4 mm, TE 80 ms, TR 3078 ms. The CMT transducer was set up as follows (Figure 3A): the transducer wire was coiled into 5-cm-diameter loops at the skin exit site 3 cm from midline and was kept off the skin with gauze. The ISP monitoring box was disconnected. The transducer wire was passed away from the magnet bore (configuration *x*), next to but not touching the patient.

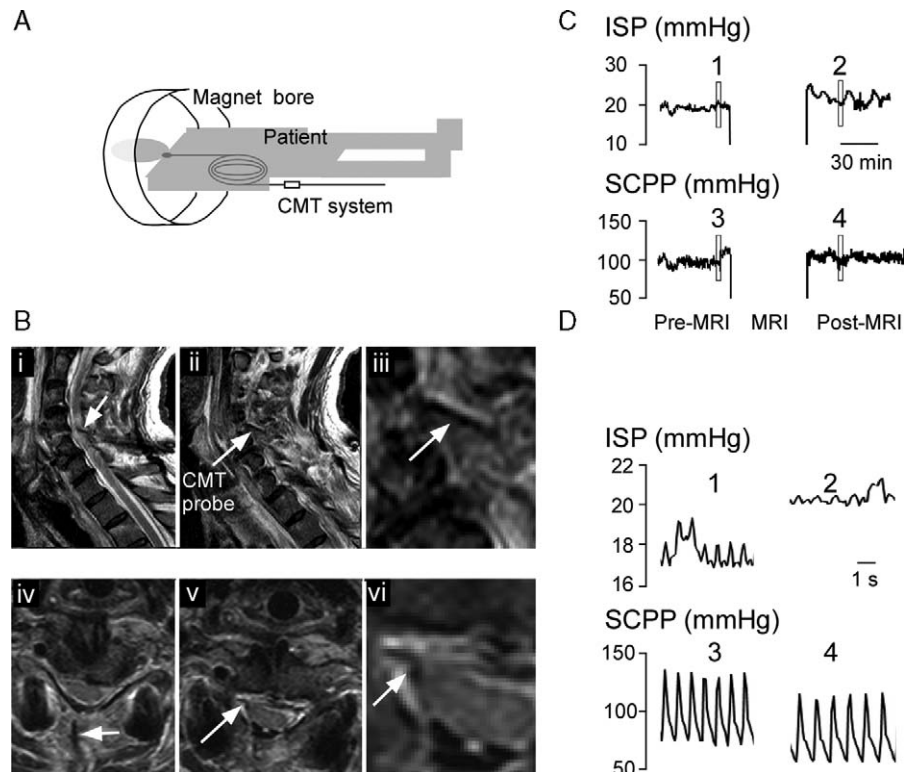
Figure 3B shows representative MR images obtained. The spinal cord could be seen clearly despite the presence of the intradural CMT wire and anteroposterior bony fixation. The transducer wire is visible as it passes through the subcutaneous tissues and the tip enters the subdural space. Importantly, there was no change in the neurological condition of the patient after *versus* before the MR imaging. Figure 3C and D shows the ISP and SPP signals before and after MR imaging. MR imaging did not affect the functioning of the CMT transducer.

## DISCUSSION

Our main finding is that it is possible to perform MRI of the cervical spinal cord with a CMT *in situ* to measure ISP. For safety, the CMT wire should be coiled and passed away from the magnet bore. The International Commission on Non-Ionizing Radiation Protection recommends limiting tissue temperature rise to 0.5°C for clinical use.<sup>6</sup> Our setup allows good-quality MR scans to be produced without heating the CMT, without affecting the CMT function, and without neurological deterioration.

The CMT is a silicon strain-gauge system covered in titanium with a tip diameter of 0.7 mm. It is connected by copper wires ensheathed in nylon to a connector.<sup>7</sup> During MRI, the CMT is subject to magnetic and RF fields.<sup>4</sup> The static magnetic field can exert torque or translational forces on ferrous objects causing them to align with the field. No torque or translational motion of the CMT has been shown in a 3-T magnetic field.<sup>5</sup> The connector is only weakly ferromagnetic, that is, the force exerted by the magnetic field was less than the gravitational force, and does not, therefore, move in the magnetic field.<sup>5</sup> Securing the connector to the imaging platform further prevents any movement of the connector.

The RF field used for proton excitation is the main source of heating during MRI.<sup>4</sup> As the RF power increases with the square of the magnetic field, the heating effect caused by the RF field becomes important when safety-testing devices in MRI. RF waves are reflected at the end of the wire, forming standing RF waves. The standing RF waves induce electrical currents in the wire, with maximum current density at the tip. Heat generated by the current is thus dissipated maximally at the CMT tip, as measured by the probe FT<sub>1</sub>. Heating of pressure transducers used for ICP monitoring because of resonance during MRI has been described; the heating effect had been severe enough to cause coagulative necrosis in brain and melt the insulation and copper wires within the CMT when the transducer wire was taped



**Figure 3.** MRI of TSCI patient with Codman microsensor transducer. **A**, Schematic showing CMT setup with transducer wire coiled and passed out of the magnet bore. **B**, T2 MR images. i, ii, iii Sagittal cuts; iv, v, vi axial cuts; iii magnified view from ii; vi magnified view from v; arrow = transducer tip. **C**, ISP and SCPP signals obtained before and after MR imaging. **D**, Magnified views of 1, 2, 3 and 4 from (C). CMT indicates Codman microsensor transducer; ISP, intraspinal pressure; MRI, magnetic resonance imaging; SCPP, spinal cord perfusion pressure.

straight along the patient's neck,<sup>8</sup> though heating was abolished by coiling the CMT.

Our findings of temperature rise of the CMT tip with the transducer wire straight through the magnet bore in a cervical spine phantom agree with the findings in a brain phantom.<sup>5</sup> Abolishing the temperature rise with transducer coiling in a configuration where there had previously been the largest temperature rise suggests that the induced current caused by resonance had been minimized. This phenomenon has previously been attributed to two reasons<sup>5</sup>. First, coiling of the CMT forms an induction coil that impedes the flow of the induced current. Second, coiling of the CMT reduces the effective length of the wire, thus shifting its resonant frequency outside that of the RF field.

We showed that it is possible to perform MRI of the cervical spine with a CMT in the ISP monitoring position with good-quality images. MRI of the spine poses several problems, briefly, the inhomogeneity of the magnetic field, small cross sectional area of the spinal cord, physiological movement of the spinal cord and cerebrospinal fluid, and lastly the presence of metallic constructs for fixation.<sup>9</sup> In our patient, the presence of titanium constructs for cervical fixation did not degrade spinal cord imaging appreciably. MRI quality of the thoracic spinal cord with the CMT *in situ* may be more challenging because of the longer and thicker metallic constructs used for thoracic *versus* cervical instrumentation. Our data, obtained from one TSCI patient, suggest that MR scanning with the CMT *in situ* for ISP monitoring may be safe. However, MR scanning of several TSCI patients needs to be performed to confidently conclude the safety of the CMT in the RF field.

ISP monitoring introduces a clinically useful physiological variable into the management of acute TSCI. The ability to perform MRI with the CMT *in situ* may further our understanding of TSCI pathophysiology in the acute setting.

## CONCLUSION

The Codman Microsensor transducer is MR-conditional in the cervical spine configuration in our 3-T system. We performed MRI of a patient with traumatic spinal cord injury in a 1.5-T system and obtained good-quality images of the cord without neurological deterioration.

## Key Points

- ❑ We recently described a technique to monitor intraspinal pressure to guide management of patients with traumatic spinal cord injury.
- ❑ Since it is necessary to perform MRI in these patients, we studied the safety of the pressure probe during MRI.
- ❑ Coiling the pressure probe wire and passing it away from a 3-T magnet abolished heating of the probe tip in a cervical gel phantom.
- ❑ Coiling the pressure probe wire and passing it away from a 1.5-T magnet allowed us to obtain good-quality images of the cord in a patient with the pressure probe *in situ*.
- ❑ After completing the imaging, there was no neurological deterioration and the pressure probe remained functional.

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