SPINE An International Journal for the study of the spine Publish Ahead of Print

DOI : 10.1097/BRS.0000000000001334

Magnetic resonance imaging of the Codman Microsensor Transducer used for intraspinal pressure monitoring

Findings from the Injured Spinal Cord Pressure Evaluation study

Isaac Phang[1], M.R.C.S., Marius Mada[2], Ph.D., Angelos G. Kolias[3], M.Sc., M.R.C.S., Virginia F.J. Newcombe[2], F.C.E.M., Ph.D., Rikin A. Trivedi[3], F.R.C.S (SN), Adrian Carpenter[2], Ph.D., Rob C. Hawkes[2], Ph.D., Marios C. Papadopoulos[1], M.D., F.R.C.S.(SN).

[1]Academic Neurosurgery Unit, St George's University of London, London, UK

[2]Wolfson Brain Imaging Centre and [3]Division of Neurosurgery, Department of Clinical Neurosciences, Addenbrookes' Hospital, Cambridge, U.K.

Correspondence to: Prof. MC Papadopoulos, Rm 0.316 Jenner, St George's University of London London SW17 0RE. T 02087252986 F 02087255139. Email: mpapadop@sgul.ac.uk

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.

The Fletcher Fund, the Neurosciences Research Foundation, London Deanery, and Wings for Life funds were received in support of this work.

Relevant financial activities outside the submitted work: grants, employment.

Introduction

The ISCoPE (Injured Spinal Cord Pressure Evaluation) 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.[1] 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.[2] 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.[3]

During the ISCoPE study, we found Magnetic Resonance Imaging (MRI) of TSCI patients invaluable. We use MRI pre- and post-operatively 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 T[4] and 3 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 localisation and RF fields. The effect of the RF field on the CMT was larger than that caused by the magnetic fields.[5] 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 to the non-eloquent right frontal cortex used for ICP monitoring. Second, due to 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 due to 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.

Methods

CMT/MRI setup. The CMT system (Depuy Synthes, UK) consists of a pressure probe tip, CMT wire, connector and a cable connected to the pressure monitor, which is placed outside the 5 x 10^{-4} T line of the MR imaging unit (Fig. 1A) for isolation from the magnetic and RF fields during imaging. For imaging in gel, a 3 T Siemens Magnetom Verio (Siemens Healthcare, UK) system was used. For imaging the TSCI patient, a 1.5 T Philips Intera (Philips Healthcare, UK) system was used, which has four-fold less RF energy deposited per kg bodyweight compared to the 3 T magnet.

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 Fluroptic thermometer (Luxtron, Santa Clara, CA) using four Fiberoptic Thermocouples (FT_1 – FT_4) secured at the tip of the pressure transducer (FT_1), 1 cm (FT_2) and 2 cm (FT_3) away from the tip, and outside the phantom to measure ambient temperature (FT_4). 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_1 – FT_4 were measured during a 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 due to the high RF deposition and switching rates, potentially causing larger energy deposition in tissue per kg weight compared to 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 x 224 mm, 0.7 x 0.7 x 4 mm resolution, 256 x 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) *vs.* into (configuration y) the magnet bore (Fig 1C), coiling *vs.* non-coiling of the transducer wire and connecting *vs.* not connecting the transducer to the pressure monitor. To examine the effect of these conditions, we imaged using four different protocols (Fig. 1B):

Protocol i. The transducer wire was not coiled, was passed away from the magnet bore (configuration x, Fig. 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, Fig. 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 non-inductive 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.

Post-operative 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 3T in the gel, but only at 1.5T 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[2]. 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. Post-operative 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°C ± 0.0 (mean ± s.e.m) on day 1 and 20.1°C ± 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 (Fig. 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. Fig. 2 shows the time course of the temperature changes at the tip of the transducer (FT_1). Testing in protocol i produced a maximal temperature rise of 0.8°C at d = 30 cm (Fig. 2A). Testing in protocol ii produced maximal temperature rises of 2.4°C at d = 0 cm and 5.2°C at d = 30 cm (Fig. 2B). Maximal heating was observed with protocol ii at d = 30 cm. To test whether coiling reduces the heating due to the resonance caused by the RF fields, the imaging sequence was repeated as per protocol iii. Coiling of the transducer abolished the heating effect (Fig. 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). Fig. 2D shows no detectable rise in CMT probe temperature when the ISP monitoring box was connected.

Patient. A sixty-five 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 Methods and was tunnelled under the skin for 3 cm.

Post-operative imaging in TSCI patient. MRI was done on post-operative day six. Imaging parameters are as follows: sagittal imaging FOV 275 mm, slice thickness 4mm; TE 120 ms / TR 3500 ms and TE 10 ms / TR 400 ms; axial imaging: FOV 225mm, slice thickness 4mm, TE 80 ms, TR 3078 ms. The CMT transducer was set up as follows (Fig. 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.

Fig. 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 *vs.* before the MR imaging. Fig. 3C and 3D show the ISP and SCPP 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.[6] 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.[7] During MRI, the CMT is subject to magnetic and RF fields.[4] 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 have been shown in a 3 T magnetic field.[5] The connector is only weakly ferromagnetic, i.e. the force exerted by the magnetic field was less than the gravitational force, and does not, therefore, move in the magnetic field.[5] 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.[4] 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_1. Heating of pressure transducers used for ICP monitoring due to 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 straight along the patient's neck,[8] 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.[5] 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[5]. Firstly, coiling of the CMT forms an induction coil that impedes the flow of the induced current.

Secondly, 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.[9] 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 *vs.* 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.

Figure Legends

Fig 1. Codman microsensor transducer in gel phantom. A. Schematic showing *(top)* components of transducer setup and *(bottom)* positioning of fiberoptic temperature transducers (FT_1 – FT_4). **B.** (i – iv) Different protocols used for imaging and temperature measurement (for details see 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.

Fig 2. Temperature at transducer tip *vs.* 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.

Fig 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.

References

1. Guidelines for the management of severe traumatic brain injury. *J Neurotrauma* 2007;24 Suppl 1:S1-106.

2. Werndle MC, Saadoun S, Phang I, et al. Monitoring of spinal cord perfusion pressure in acute spinal cord injury: initial findings of the injured spinal cord pressure evaluation study*. *Crit Care Med* 2014;42:646-55.

3. Phang I, Werndle MC, Saadoun S, et al. Expansion Duroplasty Improves Intraspinal Pressure, Spinal Cord Perfusion Pressure and Vascular Pressure Reactivity Index in Patients with Traumatic Spinal Cord Injury. *J Neurotrauma* 2014:In press.

4. Williams EJ, Bunch CS, Carpenter TA, et al. Magnetic resonance imaging compatibility testing of intracranial pressure probes. Technical note. *J Neurosurg* 1999;91:706-9.

5. Newcombe VF, Hawkes RC, Harding SG, et al. Potential heating caused by intraparenchymal intracranial pressure transducers in a 3-tesla magnetic resonance imaging system using a body radiofrequency resonator: assessment of the Codman MicroSensor Transducer. *J Neurosurg* 2008;109:159-64.

6. Protection TICoN-IR. Medical magnetic resonance (MR) procedures: protection of patients. *Health Physics* 2004;87:197-216.

7. Koskinen LO, Olivecrona M. Clinical experience with the intraparenchymal intracranial pressure monitoring Codman MicroSensor system. *Neurosurgery* 2005;56:693-8; discussion -8.

8. Tanaka R, Yumoto T, Shiba N, et al. Overheated and melted intracranial pressure transducer as cause of thermal brain injury during magnetic resonance imaging: case report. *J Neurosurg* 2012;117:1100-9.

9. Stroman PW, Wheeler-Kingshott C, Bacon M, et al. The current state-of-the-art of spinal cord imaging: methods. *Neuroimage* 2014;84:1070-81.

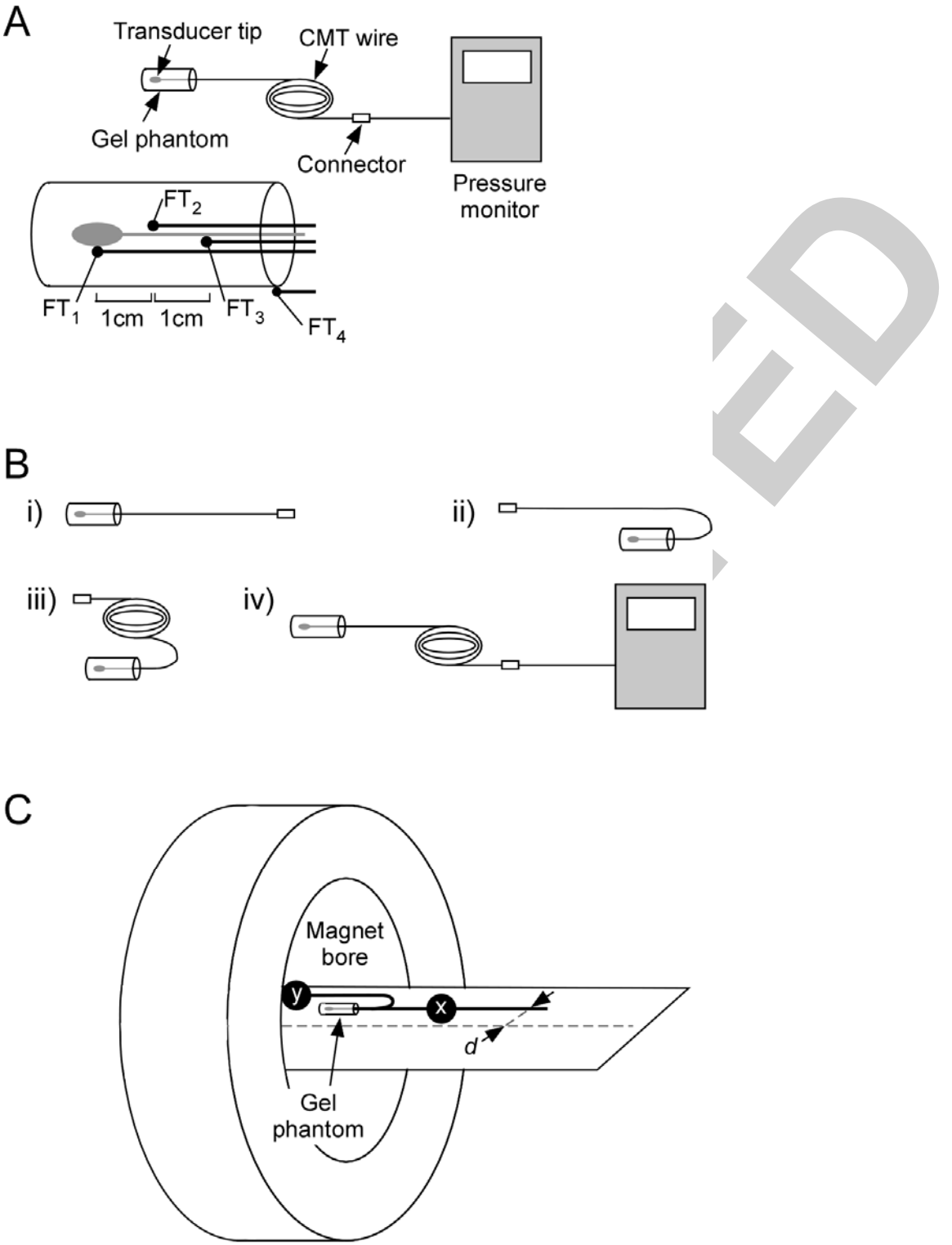

Figure 1

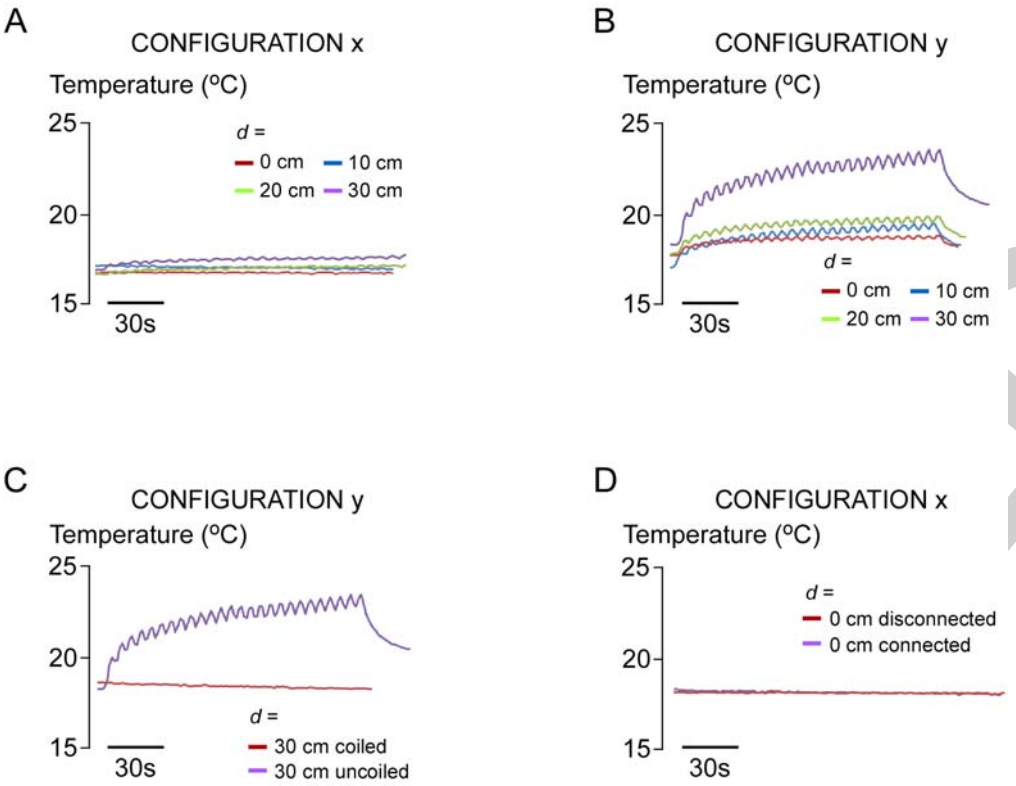

Figure 2

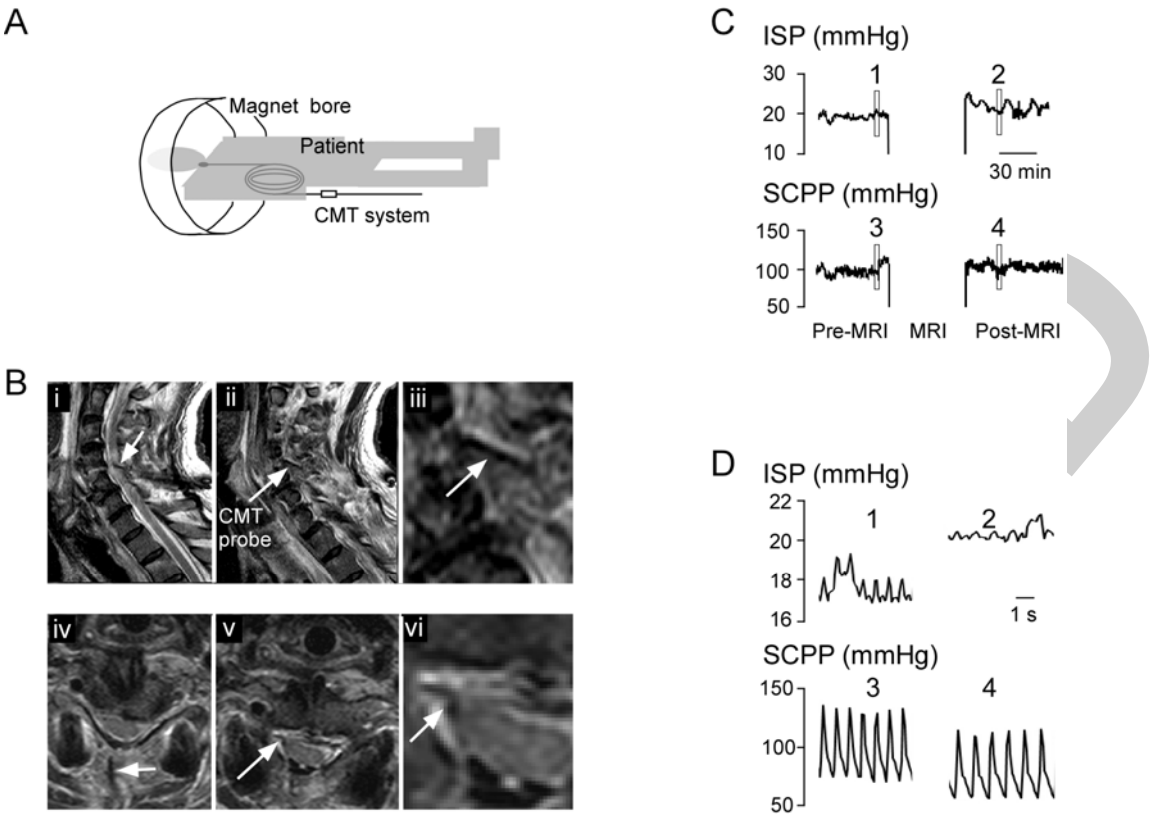

Figure 3

Table 1. Maximum temperature change of FT_1 – FT_4.

Protocol	**Distance, *d* cm**	**Max temperature change °C**			
		FT_1	**FT_2**	**FT_3**	**FT_4**
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, distance of probe tip from center of magnet bore; FT_{1-4}, fiberoptic transducer;

Protocols i – iv described in Methods and Fig. 1B.