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High-resolution human cervical spinal cord imaging at 7 T

E. E. Sigmund^{a,*}, G. A. Suero^a, C. Hu^{a,b}, K. McGorty^a, D. K. Sodickson^a, G. C. Wiggins^a, and J. A. Helpert^{a,c}

^aDepartment of Radiology, New York University Langone Medical Center, New York, NY, USA

^bNathan S. Kline Institute for Psychiatric Research, Orangeburg, NY, USA

^cDepartment of Radiology and Radiological Science, Medical University of South Carolina, Charleston, SC, USA

Abstract

We present high-resolution anatomical imaging of the cervical spinal cord in healthy volunteers at the ultrahigh field of 7 T with a prototype four-channel radiofrequency coil array, in comparison with 3-T imaging of the same subjects. Signal-to-noise ratios at both field strengths were estimated using the rigorous Kellman method. Spinal cord cross-sectional area measurements were performed, including whole-cord measurements at both fields and gray matter segmentation at 7 T. The 7-T array coil showed reduced sagittal coverage, comparable axial coverage and the expected significantly higher signal-to-noise ratio compared with equivalent 3-T protocols. In the cervical spinal cord, the signal-to-noise ratio was found by the Kellman method to be higher by a factor of 3.5 with the 7-T coil than with standard 3-T coils. Cervical spine imaging in healthy volunteers at 7 T revealed not only detailed white/gray matter differentiation, but also structures not visualized at lower fields, such as denticulate ligaments, nerve roots and rostral–caudal blood vessels. Whole-cord cross-sectional area measurements showed good agreement at both field strengths. The measurable gray/white matter cross-sectional areas at 7 T were found to be comparable with reports from histology. These pilot data demonstrate the use of higher signal-to-noise ratios at the ultrahigh field of 7 T for significant improvement in anatomical resolution of the cervical spinal cord, allowing the visualization of structures not seen at lower field strength, particularly for axial imaging.

Keywords

cervical spine; 7 T; gradient echo imaging; high field; gray/white matter

INTRODUCTION

Ultra-high magnetic field 7-T full-body MRI scanners are becoming increasingly common in imaging centers worldwide. Some applications, such as susceptibility-weighted imaging in the brain (1,2), have field-dependent contrast that is highly suited to 7 T, resulting in a powerful modality for *in vivo* MR microscopy. Spinal cord imaging is another area in which high-field MRI may be of great benefit for the assessment of pathologies, such as multiple sclerosis (3,4), amyotrophic lateral sclerosis (5), spondylosis (6) or spinal cord injury (7,8), by using the signal-to-noise ratio (SNR) improvement to increase spatial resolution in multiple MRI contrast techniques. The human spinal cord has only recently been imaged *in vivo* at 7 T in the cervical area (9) and across the cervical, thoracic and lumbar zones (10–

14), in studies that are beginning to tap into the higher sensitivity provided by ultra-high field MRI. However, given the different morphology of each spinal cord zone, as well as the variation in sensitivity to radiofrequency (RF) field inhomogeneity amongst different MRI pulse sequences, it is useful to explore new coil designs specifically tailored to different portions of the spinal cord to fully reap the benefit of ultra-high field MRI.

This work presents the results of high-resolution 7-T axial cervical spinal cord imaging using a dedicated prototype RF coil array. First, we describe the physical layout, electrical design and standard operation of the coil. Next, we describe a series of imaging tests characterizing the performance of the 7-T coil in cervical spine imaging of healthy volunteers, alone and in comparison with conventional 3-T imaging. SNR estimations are performed for both 3-T and 7-T platforms with a rigorous Kellman method (15). The higher SNR available in the 7-T method is utilized to achieve significantly higher spatial resolution (0.2 mm in-plane) than in typical clinical protocols (0.6 mm in-plane). Finally, cross-sectional areas (CSAs) of whole spinal cord at both field strengths in the same volunteers are measured, and the higher resolution 7-T scans also permit the measurement of the gray and white matter subsections of the cord tissue. These results are considered in comparison with other anatomical imaging techniques in the spinal cord, and future applications are discussed.

MATERIALS AND METHODS

RF coils

A prototype four-channel 7-T RF coil array (Rapid Biomedical GmbH, Rimpfing, Germany), shown in Fig. 1, was employed in this study for the imaging of the cervical spinal cord in a Siemens full-body 7-T system (Siemens Medical Solutions, Erlangen, Germany). The coil operates with linear polarization, fixed tuning and matching at 297 MHz/50 Ω , and no active decoupling. The housing dimensions are 233 mm (superior-inferior) $\times$ 216 mm (left-right) $\times$ 129 mm (anterior-posterior), and the sizes of the four loop elements it contains are illustrated in Fig. 1 [channels 1 and 4: 150 mm (left-right) $\times$ 70 mm (superior-inferior); channels 2 and 3: 105 mm (left-right) $\times$ 100 mm (superior-inferior)]. The minimum distance between the elements and the patient is the thickness of the housing (4 mm). The elements are spread on a curved saddle surface, cradling the subject's neck; channels 1 and 4 sit superiorly and inferiorly, whereas channels 2 and 3 sit left and right and curve anteriorly around the sides of the neck. No shielding is used for either the individual elements or the overall array. Gapped design capacitive decoupling is used between elements 1 and 4, and overlap decoupling is used between all other element pairs. Inter-element isolation values (dB), measured under loaded conditions, are shown in Table 1. The coil quality factors (Q), measured first with isolated elements and no matching network, were found to be 180 (unloaded) and 17 (loaded). The loaded Q value of the final assembly was 12. In transmit mode, the same RF waveform is delivered to each of the four elements after dividing the supplied power through a power splitter. The phase relationship between the elements in transmit mode was measured to be equal phase on all channels. Safety standards for the specific absorption rate determined in both the modeling and engineering stages of the coil design were strictly adhered to in the manufacturer's testing and implementation of the coil, and certified by the manufacturer and regulatory agencies (10 W/kg, IEC 60601-2-33, Edition 2).

Scans of healthy volunteers were performed with the array coil at 7 T, and compared with imaging in the same volunteers at 3 T with conventional coils. Details of the scan parameters employed are given below and summarized in Table 2. The four-channel coil array cradled the patient's neck in a supine position for imaging of the cervical spine, and the coil was laterally immobilized with sandbags on either side. The rostral-caudal center of

the cradle was placed at the magnet isocenter for patient positioning. The array coil was typically centered longitudinally on the C2–C3 vertebral bodies. At 3 T, on the Siemens Tim Trio scanner, product receive-only coils were used to image the cervical spine area: a four-channel neck array, the most rostral set of three elements from the in-table spine array and a 12-channel head coil with signals from all coil elements were recorded and used in the reconstruction in order to maximize SNR in the 3-T platform.

Volunteer scans

Ten healthy volunteers (seven men, three women; age, 32.9 ± 6.7 years; height, 1.71 ± 0.06 m; weight, 71.6 ± 6.3 kg; body mass index, 24.4 ± 2.3) were scanned at 3 and 7 T with approval of the Institutional Review Board. 3-T imaging was performed with axial two-dimensional T_2^* -weighted gradient echo (GRE) and sagittal two-dimensional T_2 -weighted turbo spin echo (TSE) imaging protocols. 7-T anatomical imaging was performed with an axial two-dimensional T_2^* -weighted GRE sequence, an axial two-dimensional T_2 -weighted TSE sequence and a sagittal two-dimensional T_2 -weighted TSE sequence. The longitudinal coverage of the 7-T scans was more limited than that of the 3-T scans, because of: (i) the longer scan times per slice of the higher resolution (higher matrix) 7-T cervical scans and an intention of maintaining comparable scan times for analogous protocols at both field strengths; (ii) the more limited longitudinal sensitivity profile (transmit and receive) of the 7-T array coil, including signal loss from incomplete refocusing due to RF transmit inhomogeneity for the high-flip-angle TSE sequence at more distant regions from the coil; and (iii) the longer TR and lower flip angles required for the high-RF TSE sequence to stay within specific absorption rate limits.

Image analysis

Quantitative analysis was performed on the axial GRE images at 3 and 7 T in order to quantify the SNR and measure the CSA of the whole cord, as well as the gray and white matter area fractions (at 7 T). The intrinsic SNRs of the 3- and 7-T acquisitions were evaluated from two-dimensional GRE scans in axial and sagittal planes in four of the healthy volunteers using the Kellman method (15). This approach utilizes raw k -space data acquired both with and without RF excitation to calculate the SNR on a pixel-by-pixel basis. The same GRE image protocol was used at both field strengths to collect images using the same excitation, resolution, bandwidth and timing (see Table 2) parameters chosen to minimize relaxation weighting and approximate proton density weighting. In order to normalize the excitation flip angle of these acquisitions at both field strengths, a B_1 field calibration sequence with a saturation pulse, followed immediately by GRE readout, was employed (see Table 2) (16). A range of transmit voltages were tested until a signal null was observed in the target spinal cord region, confirming an accurate saturation flip angle of 90° . In cases in which the required transmit voltage exceeded the available power, the flip angle was increased proportionally (e.g. 20 – 24° for a 20% increase) to account for the difference. The selected transmit voltages in these volunteers were 283 ± 14 V at 3 T and 296 ± 8 V at 7 T. Axial and sagittal GRE sequences (as well as a ‘noise scan’ with identical imaging parameters but at zero RF transmit voltage) were then acquired at 3 and 7 T, with the same imaging parameters for both field strengths and orientations, and all channel data retained separately. The axial views were always acquired at the same vertebral level (third intervertebral disc, between vertebrae C4 and C5). Finally, maps of the absolute intrinsic SNR were generated with the Kellman algorithm for both field strengths and orientations. SNR values were sampled with regions of interest placed enclosing the spinal cord in axial images and in the cord at the third intervertebral disc between C4 and C5 in sagittal images. For each volunteer and field strength, the axial and sagittal values were averaged for a representative SNR value. The gain in SNR from 3 to 7 T was also calculated for each volunteer, and an average gain for the four volunteers was estimated.

In the full set of $n = 10$ volunteers scanned at both 3 and 7 T, a CSA comparison was performed between axial GRE images at the same levels of the spinal cord in the range C2–C4 in each volunteer. Matching slice levels (e.g. within vertebral body C2 or at disc between C2/C3, etc.) were identified manually using anatomical landmarks and sagittal views for the same volunteer at each field strength. A total of 46 matched slices was analyzed in this way. At 3 T, the entire spinal cord cross-section was segmented manually and its area was calculated for each slice; in the higher resolution 7-T images, the entire cord cross-section and the central gray matter (dorsal and ventral horns) were segmented manually and their areas were measured (see Fig. 5 for an example of segmentation). Pearson correlations were performed between the CSA values at each field strength of all matched slices in all volunteers. Gray/white matter segmentation analysis for GRE images was performed using ImageJ software (National Institutes of Health, Bethesda, MD, USA). Kellman analysis used custom code written in Matlab software (Mathworks, Natick, MA, USA). Group CSA results were displayed and analyzed with SPSS software (IBM, Somers, NY, USA).

RESULTS

Figure 2 shows images in the cervical spine of the same healthy volunteer at 3 and 7 T using the protocols described in Table 2. Figure 2a shows a sagittal T_2 -weighted TSE image at 3 T, in which vertebral bodies, vertebral discs, cerebrospinal fluid and spinal cord parenchyma are clearly visualized. Figure 2b shows a T_2^* -weighted axial GRE image at 3 T, in which the spinal cord, surrounding cerebrospinal fluid, neck musculature and large blood vessels are visualized. Some gray/white matter differentiation is visible in the axial T_2^* -weighted image, but is severely hampered by the standard spatial resolution clinically employed at this field strength (0.5 mm), dictated primarily by the available SNR. Figure 2c, d (and enlarged portions in Fig. 2e, f) show high-resolution axial GRE (0.2 mm) and sagittal TSE (0.3 mm) results acquired at 7 T in the same volunteer and location. Although the longitudinal coverage of the 7-T array coil is smaller than that of the 3-T coils, and some RF inhomogeneity is observed both axially and sagittally, more anatomical detail can be observed in the 7-T images. In the following results, we explore the qualitative and quantitative benefits of this higher sensitivity and resolution, with more emphasis on the axial view.

Figure 3 shows SNR maps resulting from the Kellman SNR analysis. Sagittal and axial views are displayed in the same volunteer at both 3 and 7 T, including common color scales in Fig. 4c–f to emphasize the boost in SNR at the higher field strength. The 3-T sagittal and axial views show a larger and more uniform coverage of the spinal cord region, but the 7-T images show much higher SNR (227 relative to 64 at 3 T) in the cervical cord region. Table 3 shows the results of the Kellman SNR analysis, indicating a SNR gain factor of 3.5 at 7 T over equivalent scans at 3 T. The 7-T SNR patterns are more inhomogeneous (see the signal null area on the posterior right side) and show more limited longitudinal coverage; however, the spinal cord region is homogeneous and displays significantly higher SNR at 7 T than at 3 T.

Figure 4 shows axial cervical spine imaging results at 7 T with the coil array. Excellent spatial detail is observed in the axial GRE images, differentiating gray/white matter tissue, dorsal and ventral nerve roots, denticulate ligaments and rostral–caudal blood vessels. The axial TSE image shows some T_2 blurring and flow-related cerebrospinal fluid signal voids, but also seems to reveal and/or emphasize the dura mater and pia mater structures lining the spinal canal and spinal cord.

Figure 5 shows a comparison of manually segmented gray matter and whole-cord tissue CSAs in a matched cervical spine slice of GRE acquisitions in the same subject at 3 and 7 T.

At 3 T, only total spinal cord CSA could be measured, whereas, at 7 T, white and gray matter tissues were differentiated. Figure 5 also shows group average results (Fig. 5c) and correlations of individual matched slices (Fig. 5d) for the measured CSA in all slices and all 10 volunteers who underwent scans at 3 and 7 T (total of 46 matched slices). The total cord CSAs measured at 3 T ($90.7 \pm 10.4 \text{ mm}^2$) and 7 T ($90.1 \pm 9.7 \text{ mm}^2$) are in good agreement for this volunteer group and also show strong correlation (slope, 0.99; correlation coefficient $r = 0.81$). Furthermore, the gray matter CSAs ($22.6 \pm 4.0 \text{ mm}^2$), measurable with the high-resolution 7-T GRE protocol, are observed to occupy approximately 25% of the total cord cross-section in the cervical region. Table 4 lists the CSA results from this study and those reported from other techniques in the literature, including lower field MRI (17), computed tomography (18), cadaver anatomy (19) and histology (20–22). Although there is some variability in the reported CSA values as a result of experimental factors, such as histological shrinkage or image blurring, the gray matter fraction of 25% in this work is comparable with that reported in high-resolution histology studies (18–22%). Finally, Fig. 6 shows a comparison between representative slices at 3 T/7 T from several volunteers scanned at 7 T with the coil array, showing the reproducibility of the improved image quality at 7 T.

DISCUSSION

The present work shows the application of a prototype RF coil for high-resolution cervical spine imaging at 7 T. The results obtained show that the SNR advantage conferred at high field is well suited to high-resolution anatomical imaging in the cord (Figs. 2–6). Quantitatively, the overall gain factor between the 3-T coils and 7-T array coil, estimated by the Kellman method, was 3.5. Although we would expect at least a linear gain in SNR with field (i.e. a factor of 2.3), the Kellman SNR ratio suggests a higher scaling ($\text{SNR} \sim B_0^{1.5}$). However, the geometry of the coil array, cradling the volunteer's neck and increasing the proximity to the cord compared with the more distant 3-T neck and spine array coil, probably contributes significantly to this SNR advantage. In addition, our calculation of the Kellman SNR values between 3 and 7 T does not separately consider the coil geometry dependence of the noise reception. Thus, future geometrical modeling of the coils of the two field platforms may shed further light onto the observed SNR benefit. The 7-T coil geometry is somewhat more favorable for axial acquisitions than sagittal views in comparison with standard sagittal assessments, although, in the limited coverage area (three to four vertebral bodies), high resolution can also be obtained (Fig. 2). Nevertheless, the best application of this prototype appears to be axial cervical imaging, perhaps as an adjunct to a complete lower resolution clinical scan, in contrast with recent reports developing larger scale 7-T coils for sagittal spine imaging (10–14).

The results presented here with conventional anatomical imaging sequences and protocols are promising, but further pulse sequence optimization may be needed to achieve the best results. Two-dimensional GRE imaging provides excellent in-plane detail, but thin slices and three-dimensional protocols have not yet been explored with this coil. TSE results provide complementary detail and visualization of the dura mater and pia mater; however, cerebrospinal fluid flow voids and T_2 blurring may cause the thickness of these sheaths to be overestimated. The refocusing pulse trains employed in the TSE imaging sequences (see Table 2) used echo spacings of 11–12 ms, echo train lengths of 25–30 and flip angle amplitudes of 150–180°. With these parameters, some T_2 blurring is expected and observed in our results, and signal loss from the accumulated RF errors limits the longitudinal image coverage. Further refinements, such as adiabatic pulses (23), 'hyperecho' flip angle modulation (24) and flow-compensated imaging gradients (25), may mitigate these artifacts and improve TSE image quality for cervical spine 7-T imaging.

The anatomy of the spinal cord is well established from histology, but remains somewhat obscured by present-day clinical radiological standards. In animal studies or *ex vivo* imaging, the cord anatomy has been properly visualized (26–28), but the spatial detail achievable in the clinical setting is much more limited, thus limiting the radiologist's ability to identify small-scale lesions or structures that may relate to neurological deficits, as well as limiting the accuracy of neurodegenerative atrophy measurements. The high SNR achievable at 7 T, when utilized for higher resolution, allows detailed anatomical imaging and tissue segmentation with great potential for tracking morphological changes due to cervical spondylotic myelopathy (6,29,30) or spinal cord injury (8,31,32). In addition, the secondary structures illustrated in Figs. 2–6 (denticulate ligament, dorsal/ventral nerve roots, dura/pia mater, etc.) may assist the diagnosis of pathologies unique to these smaller anatomies. This information may also supplement surgical planning in the highly sensitive cases of decompression or repair. Other applications, such as spinal lesion load in multiple sclerosis (3,33), which is crucial to the early diagnosis and management in these patients, could be dramatically enhanced by the resolution demonstrated here. Morphological changes, such as atrophy, whether as part of normal aging or secondary to a neurodegenerative disease, may also be more closely monitored on the 7-T platform.

In addition to anatomical imaging, many other MRI modalities play important roles in the assessment of spinal cord pathology, including diffusion-weighted imaging (DWI). Although conventional DWI pulse sequences (especially single-shot echo-planar imaging) are fairly common in the spinal cord for both microstructural quantification and connectivity, reports showing the highest resolution have used reduced field-of-view (rFOV) approaches [zonally oblique multislice (ZOOM) (34,35), two-dimensional pulses (36), outer volume suppression (37) or inner volume imaging (38,39)] to achieve a high level of detail in spinal cord DWI. As these techniques sometimes exact an SNR penalty, the platform of 7-T imaging, enabled by the appropriate RF coils, may be a powerful advantage to spinal cord rFOV DWI. The capability for parallel transmission with coil arrays (40,41) may also enhance rFOV approaches that rely on two-dimensional spatial selectivity by accelerating the duration of two-dimensional RF pulses.

In summary, we have demonstrated pilot results from a prototype four-channel RF coil array for imaging the cervical spine at 7 T. Quantitatively, the coil provides an SNR that is a factor of 3.5 higher than that of the 3-T standard coil set in equivalent scan protocols. Qualitatively, using this SNR benefit, high-resolution imaging of the cervical cord was achieved at 7 T, revealing clear gray/white matter differentiation, as well as visualizing smaller peripheral structures (pia mater, dura mater, denticulate ligaments, nerve roots, rostral–caudal blood vessels). The 7-T axial imaging protocol showed clear advantages over analogous conventional 3-T axial protocols, and holds great promise for enhanced clinical diagnostic ability via higher resolution imaging of the spinal cord.

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Abbreviations used

B₀	static applied field
B₁	RF magnetic field

CSA	cross-sectional area
DWI	diffusion-weighted imaging
FOV	field of view
GM	gray matter
GRE	gradient echo
Q	coil quality factor
RF	radiofrequency
SNR	signal-to-noise ratio
TSE	turbo spin echo
WM	white matter

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Figure 1. (a) Photograph of four-channel 7-T cervical spine coil array. (b) Flattened diagram of coil layout in four-channel array with labeled coil dimensions in millimeters.

Figure 2. Comparison of 3-T (a, b) and 7-T (c–f) T_2 -weighted imaging using sagittal turbo spin echo (TSE) (a, c, e) and axial gradient echo (GRE) (b, d, f) in the same healthy volunteer. (e, f) Enlarged views from (c, d).

Figure 3.

Sagittal (a, c, e) and axial (b, d, f) Kellman signal-to-noise ratio (SNR) maps of the cervical spine area of the same volunteer at 3 T (a–d) and 7 T (e, f). The same color scale is used for (c–f) to illustrate the absolute SNR gain at 7 T over 3 T.

Figure 4.

Cervical spine T_2 -weighted MRI at 7 T (four-channel array). (a) Sagittal localizer view showing slice and vertebra locations. (b) Full field of view axial gradient echo (GRE) image. Enlarged view of spinal cord area in GRE (c–g) and turbo spin echo (TSE) (h) sequences. Labeled structures: dorsal/ventral nerve roots (yellow), gray matter anterior horn (purple), denticulate ligament (blue), dorsal/ventral blood vessels (red), dura mater (cyan), pia mater (green).

Figure 5.

Comparison of spinal cord cross-sectional area (CSA) measurements in the same volunteers at 3 and 7 T. (a) Example of whole-cord segmentation at 3 T. (b) Segmentation of spinal cord gray matter at 7 T in the same volunteer and vertebral level. (c) Group CSA results for whole cord at 3 and 7 T and gray matter (GM) at 7 T. (d) Correlation plot of measured CSA at matched levels at 3 and 7 T. Different colors correspond to the results of different subjects.

Figure 6. Comparison of axial gradient echo (GRE) images at 3 T (a) and 7 T (b) at the same slice locations in four different volunteers.

Table 1

Coil element isolation (dB) between channels (C1–C4) of the 7-T four-channel radiofrequency coil array. Channel labels are indicated in Fig. 1

(dB)	C2	C3	C4
C1	16.7	20.7	16.1
C2		35.0	19.9
C3			27.4

Table 2

Sequence parameters for MRI scans in this work

Sequence	Scan time (min:sec)	B_0 (T)	TR/TE (ms)	Flip angle (deg)	Matrix (PE $\times$ RO $\times$ SC)	P/F	Turbo factor	R	A	FOV (mm)	Resolution (mm)
B_1 calibration	0:16	3	2000/1.06	10	$128 \times 128 \times 1$	—	—	—	1	340	$2.7 \times 2.7 \times 5.6$
GRE (Kellman)	0:53	3	1000/4.07	20	$128 \times 128 \times 1$	—	—	—	1	220	$1.7 \times 1.7 \times 3$
TSE Sag.	3:37	3	3500/113	180	$512 \times 512 \times 15$	6/8	23	2	2	220	$0.5 \times 0.5 \times 3$
GRE Ax.	2:30	3	514/7.4	20	$240 \times 320 \times 25$	—	—	2	2	200	$0.6 \times 0.6 \times 3$
B_1 calibration	0:30	7	2000/1.29	8	$64 \times 64 \times 1$	—	—	—	1	300	$4.7 \times 4.7 \times 8$
GRE (Kellman)	0:53	7	1000/4.07	20	$128 \times 128 \times 1$	—	—	—	1	220	$1.7 \times 1.7 \times 3$
GRE Ax.	5:14	7	500/4.91	50	$832 \times 1024 \times 5$	6/8	—	—	1	180	$0.18 \times 0.18 \times 3$
TSE Ax.	4:35	7	3290/11	180	$660 \times 832 \times 5$	var	27	—	1	180	$0.22 \times 0.22 \times 3$
TSE Sag.	5:46	7	5240/44	150	$480 \times 640 \times 4$	var	30	—	3	220	$0.34 \times 0.34 \times 3$

A, averages; Ax., axial; B_0 , field strength; FOV, field of view; GRE, gradient echo; PE, phase encode; P/F, partial fourier factor; R, parallel imaging acceleration factor; RO, readout; Sag., Sagittal; SC, slice; TE, echo time; TR, repetition time; TSE, turbo spin echo; var, variable in different volunteers for scans not used in quantification. No interpolation was performed in these scans. GRE scans for Kellman analysis used identical protocols.

Table 3

Signal-to-noise ratios (SNRs) in matched slices from gradient echo (GRE) imaging at 3 and 7 T of healthy volunteers using the rigorous Kellman method ($n = 4$ subjects). Kellman SNR estimation used the dedicated GRE protocols indicated in Table 2

Field (T)	Kellman SNR	Kellman SNR gain factor
3	64.2 ± 4.7	1
7	227.3 ± 34.7	3.52 ± 0.28

Table 4
Human spinal cord cross-sectional areas (CSAs) measured in this work and in other literature reports

Method	Reference	Level	Cord CSA (mm ²)	WM CSA (mm ²)	GM CSA (mm ²)	GM fraction (%)
7-T MRI	This work	C2–C4	90.1 ± 9.7	67.5 ± 7.8	22.6 ± 4.0	25.1
1.5-T MRI	Mann <i>et al.</i> (17)	C2–C3	77.97 ± 0.95	—	—	—
CT	Fountas <i>et al.</i> (18)	C2–C7	73.47 ± 4.6	—	—	—
Cadaver anatomy	Ko <i>et al.</i> (19)	C3–C7	71.1 ± 3.5	—	—	—
Histology	Gilmore <i>et al.</i> (21)	C2–C7	114.9 ± 2.0	90.0 ± 2.5	24.9 ± 4.5	21.7
Histology	Kameyama <i>et al.</i> (20)	C2–C7	55.3 ± 6.2	46.2 ± 5.2	9.0 ± 1.3	16.3
Histology	White <i>et al.</i> (22)	C6–C7	62.2 ± 4.0	51.1 ± 4.0	11.1 ± 1.4	17.8

CT, computed tomography; GM, gray matter; WM, white matter.