In Vivo Magnetic Resonance Imaging of the Human Cervical Spinal Cord at 3 Tesla

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**Purpose:** To demonstrate the feasibility of obtaining high-quality magnetic resonance (MR) images of the human cervical spinal cord in vivo at a magnetic field strength of 3 T and to optimize the signal contrast between gray matter, white matter, and cerebrospinal fluid (CSF) on 2D gradient recalled echo (GRE) images of the cervical spinal cord.

**Materials and Methods:** Using a custom-built, anatomically molded radio frequency (RF) surface coil, the repetition time and flip angle of a 2D GRE sequence were systematically varied in five volunteers to assess tissue contrast in the cervical spinal cord.

**Results:** The 2D GRE parameters for an optimal balance between gray-white matter and CSF-white matter contrast at 3 T were determined to be a time-to-repetition (TR) of 2000 msec and a flip angle of 45°, with the constant short time-to-echo (TE) of 12 msec used in this study. Excellent tissue contrast and visualization of the internal anatomy of the spinal cord was demonstrated reproducibly in eight subjects using these optimal parameters.

**Conclusion:** This study demonstrates that imaging the cervical spinal cord and delineating internal spinal cord structures such as gray and white matter is feasible at 3 T.

**Key Words:** MRI; 3 Tesla; cervical spinal cord; gradient echo; gray matter; white matter.


HIGH-RESOLUTION MAGNETIC RESONANCE imaging (MRI) is the imaging technique of choice for evaluating the location and extent of tissue damage associated with disorders of the spinal cord (1–7). Fast spin echo (FSE) and gradient recalled echo (GRE) are two sequences that are commonly used because they provide relatively good lesion contrast and anatomical resolution of spinal cord structures (8). Despite this, in vivo imaging of the spinal cord by MRI still remains challenging due to artifacts caused by motion, magnetic susceptibility, and pulsatile flow (9,10).

Deficits in motor and sensory function from damage to the spinal cord are mainly due to the disruption of long ascending and descending tracts within the white matter rather than from localized damage to central gray matter. Thus, an accurate picture of the extent and location of white matter damage is needed in order to relate anatomical findings to clinical presentation. To quantify white matter loss, it is imperative to clearly delineate healthy white matter from damaged tissue, adjacent gray matter, and surrounding cerebrospinal fluid (CSF). The ability to differentiate gray matter from white matter in vivo within the human spinal cord is feasible, although somewhat limited, with current MRI techniques (10–14). In transverse MR images of the spinal cord it is sometimes possible to discern the “H” or butterfly-shaped central gray matter within the surrounding white matter and CSF. However, in many in vivo human imaging studies of the spinal cord, the focus has primarily been on maximizing CSF-cord contrast rather than on delineating the internal gray-white structure. For example, in humans in vivo, Ahmad et al (15) have shown that when the cervical spinal cord is deformed through injury or disease, the distortions in the gray-white anatomy can be used as a reference to help determine the extent of damage. Similarly, in vivo longitudinal MRI studies in rats have shown a consistent loss in contrast between gray and white matter two days after traumatic injury, the loss of contrast mainly due to edema accumulated in the white matter (16).

Most in vivo MRI studies of the human spinal cord have been conducted at or below a magnetic field strength of 1.5 T. The current development and proliferation of clinical 3 T MRI systems provides the impetus to investigate spinal cord imaging at 3 T. Imaging of the brain at high field has been performed for many years, whereas whole-body imaging at higher field strengths has been explored only recently. This has been primarily due to the lack of availability of high-field radio frequency (RF) coils necessary to study regions other
than the head. Increasing field strength enhances the signal-to-noise ratio (SNR), which can be used to achieve greater resolution and more anatomically detailed images of the spinal cord. In addition, changes in relaxation time and potential image contrast are expected at higher fields. An increase in field strength can also augment potential image artifacts due to magnetic susceptibility. Although a functional MRI study of the spinal cord at 3 T has been presented by Stroman et al (17), the focus of their study was on imaging functional activation using low-resolution images, rather than high-resolution anatomical imaging of the human cervical spinal cord.

The purpose of this study was to demonstrate the feasibility of obtaining high-quality images of the human cervical spinal cord at 3 T in vivo. A suitable RF coil for imaging the cervical spinal cord at 3 T was designed and constructed. Using a 2D GRE pulse sequence the optimal parameters for delineating gray matter, white matter, and CSF were investigated at 3 T. Reproducibility of these optimal parameters was tested across eight subjects with no known history of neurological injury or disease.

**MATERIALS AND METHODS**

An RF surface coil was designed and constructed in-house for imaging the cervical spinal cord at 3 T (Fig. 1). The coil was shaped to fit along the curvature of the posterior surface of the head and neck and was used to both transmit and receive. Distributed capacitance, along with external tune and match circuitry, was also incorporated into the design. The dimensions of the single loop coil were 10 cm wide and 18 cm long, RF coil dimensions were neither varied nor optimized in this preliminary study. Images were acquired on a Surrey Medical Imaging Systems (Marconi Medical Systems, Cleveland, OH) console using the following hardware: 3 T, 80-cm bore Magnex magnet (Yarnton, UK), 8 kW AMT RF amplifier (Anaheim, CA), PCI gradient amplifier (MTS System, Horsham, PA), and Magnex body gradient set. The RF coil was tuned to 127.7 MHz and matched to 50 Ω for each subject. For each volunteer, the transmitter amplitude of the excitation RF pulse was adjusted on a sagittal GRE scout image until the visible dark 180° band over the cord. The ability to align the 180° band uniformly on the spinal cord was affected by the fact that the spinal cord varies in depth relative to the back of the neck. Measurements were obtained from the second to fourth cervical vertebra (C2–C4) because the 180° band usually followed the cervical spine quite uniformly in this region. Since it is well known that the B1 RF field and hence the flip angle vary linearly with current, the 90°, 45°, and 30° flip angles used in the 2D GRE sequence were defined by using 50%, 25%, and 16.5% of the current required to achieve a 180° RF pulse over the cord, respectively. Signal intensity measurements after adjustment of the RF amplitude confirmed the position of the 90° band over the spinal cord.

Seventeen 5-mm-thick transverse slices with a 1-mm separation between each slice (256 × 256, field of view (FOV) = 160 mm, bandwidth = 50 kHz, 1 average) were obtained using a 2D, RF spoiled GRE pulse sequence. The in-plane resolution was 0.625 × 0.625 mm. The phase encode direction was anterior-posterior. Gating, flow compensation, and saturation bands were not used in this preliminary study. To determine optimal parameters for image contrast and SNR of 2D GRE of the spinal cord at 3 T, repetition time (TR) and flip angle were varied systematically. Fifteen sets of images with TR values of 2000, 1000, 800, 650, and 500 msec for each flip angle of 90°, 45°, and 30° were acquired per volunteer (N = 5). The time-to-echo (TE) was kept short at 12 msec to maximize the SNR and to minimize susceptibility and motion-related artifacts.

MRVision image analysis software (MRVision, Winchester, MA) was used to measure the signal intensity (SI) of gray matter, white matter, and CSF, as well as the SD of background noise in eight consecutive transverse images per volunteer between the second and fourth cervical vertebra (C2–C4). Individual regions of interest (ROIs) were defined with respect to the set of images with the highest tissue contrast. The same ROIs were transposed onto corresponding transverse sections from the various TR-flip angle combinations and, if necessary, were adjusted to account for any motion between scans. The SNR (= I/SD_{noise}) was calculated for gray matter, white matter, and CSF. The contrast to noise ratio (CNR) was calculated to assess image contrast between gray and white matter (CNR = (I_{GM} - I_{WM})/SD_{noise}), as well as between CSF and white matter (CNR = (I_{CSF} - I_{WM})/SD_{noise}). Values of CNR and SNR for the various TR and flip angle combinations were averaged over the eight slices (C2–C4) per subject, and then further averaged across the five subjects. The optimal image parameters were obtained by choosing TR values and flip angles that yielded a balance between gray-white matter and CSF-white matter contrast, as well as reasonable SNR. Eight normal volunteers were imaged in the transverse plane using the optimized pulse sequence parameters (TR = 2000 msec, TE = 12 msec, FOV = 160 mm, 5 mm thick, flip angle = 45°, 1 average) to confirm the reproducibility of the initial results on a cross section of neck and body types.

**RESULTS**

Excellent coverage of the cervical spinal cord was obtained using the anatomically molded, custom-made 3 T surface coil as demonstrated in the sagittal image of Figure 2. With this surface coil configuration, the signal
dropped off abruptly at the edges of the coil near the cerebellum and at the seventh cervical vertebra. Note that the strongest signal occurred between C2 and C4, where all subsequent measurements were taken.

Figure 3 shows a typical set of eight transverse GRE images from C2–C4 that were analyzed to obtain the optimal TR and flip angle combination for gray matter vs. white matter and CSF vs. white matter contrast at 3 T. The CNRs of gray vs. white matter and CSF vs. white matter for the eight analyzed slices (C2–C4) were averaged together for each subject (N = 5) for a particular TR and flip angle. The corresponding individual averages were then averaged together to produce the grouped data in Figure 4. The maximal gray-white matter contrast ranged from 4–12 over the five subjects and the maximal CSF-white matter contrast ranged from 6–15. Note that the gray vs. white matter contrast was poor at short TR values but increased with TR for all flip angles, especially for the two larger flip angles (45° and 90°) (Fig. 4a). In comparison, at long TR values, the maximal contrast between CSF and white matter occurred at the two smaller flip angles (30° and 45°) (Fig. 4b).

Based on the results from Figure 4, the parameters that gave both optimal gray-white matter and CSF-white matter contrast on the transverse 2D GRE images were a TR of 2000 msec and a flip angle of 45°, with the TE of 12 msec used in this study. An example of a transverse image acquired using these parameters is shown in Figure 5. The SNR at the shorter, 45° flip angle (TR = 2000 msec), namely, 60 ± 33 and 52 ± 30 for gray and white matter, respectively, was reduced by 23% relative to the maximum SNR obtained with the 90° flip angle.

Images at the C2–C3 level, using the optimum parameters described above, were obtained on eight different volunteers (Fig. 6). The excellent gray-white differentiation, as evident by the readily visible “H” within the spinal cord, proved to be reproducible on all of the subjects despite observable differences in neck musculature and spinal cord anatomy. In every case, the border between the white matter of the spinal cord and the surrounding CSF was well delineated.

**DISCUSSION**

This study shows that anatomical imaging of the cervical spinal cord at a magnetic field strength of 3 T is feasible and that it can provide visualization of internal structures such as gray and white matter in the cord. The only other published paper on imaging of the cervi-
vical spinal cord at 3 T was an echo planar imaging study whose focus was on detecting functional activation rather than anatomical detail of the cord (17). The CNR and the SNR were measured as a function of both flip angle and time-to-repetition for axial images obtained with a 2D RF spoiled GRE sequence in order to determine suitable imaging parameters at 3 T. Overall, the CNR for gray matter vs. white matter was greater for larger flip angles, whereas the reverse was true for CSF vs. white matter, where the desired appearance is CSF brighter than white matter (Fig. 4). In both cases, the CNR improved with increasing TR over the range of 500–2000 msec. Although the 90° flip angle yielded the greatest CNR for gray-white matter (CNR = 7.8 ± 1.2), it yielded a poor CNR of CSF-white matter. Likewise, the 30° flip angle yielded the largest CSF-white matter contrast (CNR = 14 ± 3), but a poor gray-white matter contrast. The 45° flip angle with a long TR of 2000 msec was therefore considered optimal of the parameter sets tested because it provided good contrast among all three regions, such that both CSF and gray matter were more intense than white matter (Fig. 5).

A published study at 1.5 T by Held et al (18) using shorter TR values (582–770 msec), smaller flip angles (20°–30°), and longer TE values (22–27 msec) demonstrated good gray-white matter and CSF-white matter contrast ratios of ~2.6 and 16, respectively, with 2D FLASH (i.e., GRE) single echo and ~4.1 and 22, respectively, with 2D FLASH multiecho with magnetization transfer. Our study at 3 T yielded higher CNR for gray-white matter (6.8 ± 1.5) and less CNR for CSF-white matter (10 ± 2) with 2D GRE using our optimal parameters (Fig. 4). The gray-white matter contrast is presumably due to differences in proton density between these tissues given the long TR and short TE (12 msec) used in the 2D GRE sequence (19). The echo time was kept short at 12 msec to maximize SNR and since it is known that long TE values exacerbate susceptibility and motion-related artifacts (9,12,14). These detrimental ef-

![Figure 4. a: Greater contrast between gray and white matter is observed as the TR is increased. The maximum gray vs. white matter contrast occurred for a TR of 2000 msec and a flip angle of 90°. The 45° flip angle with a TR of 2000 msec has a similar gray vs. white matter contrast yet yields markedly improved CSF vs. white matter contrast, as shown in (b), and represents the optimum balance for overall spinal cord appearance. A TE of 12 msec was used in all cases. The mean ± standard error of the mean is presented for each data point from five subjects.](image)

![Figure 5. A transverse 2D GRE image from vertebral level C2 obtained with the pulse sequence parameters that yielded the optimal compromise between gray-white matter and CSF-white matter contrast. The central gray matter is well visualized within the cord and the cord is well delineated from the surrounding CSF (TR = 2000 msec, flip angle = 45°, TE = 12 msec, 1 average.](image)
Effects would be expected to be worse at a higher magnetic field strength such as 3 T. The reproducibility of the aforementioned parameters for visualizing the central gray matter was confirmed on eight healthy volunteers (Fig. 6). The CNR for CSF-white matter was less using our optimal parameters at 3 T than in the study using 2D FLASH single echo by Held et al (18) at 1.5 T because 1) our parameters yielded the balance between good gray-white matter contrast, as well as CSF-white matter contrast; 2) the saturation of the CSF signal for a given TR at 3 T was greater, since the longitudinal relaxation times of water within the cord are expected to increase with higher field, and 3) our echo time (12 msec) was much shorter than theirs (22 msec).

The focus of this study was on imaging in the axial plane since it provides the best orientation for distinguishing gray matter vs. white matter in the spinal cord. In fact, most studies reporting axial images of the cervical spinal cord with gray-white matter contrast use gradient echo techniques (10–13,18). Some of the better quality images of gray-white matter in the cervical spinal cord published have not been in vivo, but rather have been on cadavers (11). Our results in vivo confirm that gradient echo is a suitable technique for delineation of internal spinal cord structures in axial images at the higher magnetic field strength of 3 T. The increased signal at 3 T permits higher resolution images (0.625 × 0.625 mm in-plane resolution) of the spinal cord with adequate SNR (~50–60) using only one average.

Maximization of the “myelographic” effect (i.e., CSF brighter than the spinal cord) to better delineate the cord surface appears to be the goal of most image optimization studies (8,9,12). Few studies emphasize the delineation of internal structures of the spinal cord on MRI (10,11,18), let alone optimization of these parameters. In our study, the relevant parameters that influence tissue contrast were varied, and a set of parameters that yielded an optimal balance between the myelographic effect (CSF-white matter contrast) and gray-white matter contrast were determined at 3 T. We found that long TR values such as 2 seconds, in combination with a short echo time of 12 msec in an RF spoiled 2D GRE, provided superior gray-white matter contrast over shorter TR values. The price to pay for larger TR values is longer scan times. Nonetheless, temporal efficiency was not the goal of this study. If necessary, anatomical conspicuity can be sacrificed to some extent in exchange for reduced scan time, i.e., smaller TR (Fig. 4). Although very short TR values and small flip angles (10°) have been reported in the literature to be useful in creating the myelographic effect, they have the disadvantage of yielding a poor SNR within the spinal cord itself, which is not ideal when one is interested in not only the outline of the cord but also its internal structure. Furthermore, saturation of the signal will be greater for a given TR at 3 T since longitudinal relaxation times (T₁) of water within the cord are expected to increase with higher fields.

Figure 6. 2D GRE images with the optimal compromise between CSF-white matter and gray-white matter contrast for eight subjects between C2 and C3 (TR = 2000 msec, flip angle = 45°, TE = 12 msec, 1 average). The central gray matter is visible in all cases.
In addition to gradient echo, the value of spin echo will need to be evaluated at 3 T because spin echo techniques are valuable for the detection of various spinal cord lesions, such as degenerative disease, tumors, inflammatory myelopathies, and trauma (2, 5–7). Our current 3 T setup was not well suited for this spin echo comparison because of the use of a surface coil for RF transmission and the lack of cardiac gating capabilities. Other MRI contrast mechanisms such as diffusion anisotropy (20–22) and magnetization transfer (18, 23, 24) may also permit more specific investigation of white matter damage, detection of lesions not visible on conventional MR images, or even better gray-white matter delineation in the spinal cord.

There are several limitations in our study. First, the primary limitation of our study was the use of a surface coil for both RF transmission and signal reception at 3 T, whereas standard clinical 1.5 T scanners use whole-body RF coils for RF transmission and an actively decoupled surface coil for signal reception. This latter configuration has the advantage of transmitting a more controlled homogeneous RF field (i.e., same flip angle) across the sample while maintaining improved sensitivity from the close proximity surface coil. Whole-body RF coils at 3 T are in their infancy at present and are certainly not widespread. Although surface coil excitation is necessarily nonuniform, the flip angle contours in the spinal cord itself around C2–C4 appeared uniform; thus this region was chosen for the measurements presented in this study. One advantage of our transmit-receive-only RF coil for imaging the cervical spinal cord was that the anterior portion of the neck was not excited, thereby minimizing image degradation from motion. The coverage of the cervical spinal cord and the sensitivity of the imaging sequences could have been improved by the use of a circularly polarized, phased array surface coil, rather than a single loop, as used in this study. Second, as mentioned earlier, we evaluated only the 2D GRE sequence in detail. Third, further improvements in reproducible image quality that could result from cardiac gating, saturation bands, and flow compensation were not evaluated. Fourth, images were optimized to look at the spinal cord itself, and hence the use of 3 T for the assessment of the musculoskeletal system around the spinal cord was not addressed. Fifth, a direct comparison of 3 T to the current standard clinical field strength of 1.5 T would be useful; however, this was not the goal of our study at this stage. Direct field strength comparison would have been further confounded by the use of different spectrometer configurations.

Differentiation of healthy and damaged gray and white matter, as well as CSF, is essential for quantifying white matter loss in spinal cord injury or disease. Currently, clinical neurological examination remains the primary method for the assessment of the location and extent of spinal cord damage. High-resolution MRI has the potential to significantly improve this assessment because it may allow for the evaluation of fiber tracts whose status is not detected by neurological exams, in addition to providing a more accurate picture of the etiology, location, and extent of damage in specific areas of the spinal cord. Potentially, the latter information will be useful in understanding which fiber tracts are required for the production of certain motor behaviors (25) and which white matter tracts are needed for specific therapeutic interventions to be effective. Our future studies will examine the utility of MRI at 3 T in the evaluation of pathology of the spinal cord.

In conclusion, consistent high-quality 2D GRE images of the cervical spinal cord can be obtained at 3 T. The visualization of internal anatomic features such as the gray matter demonstrates that 3 T imaging of the cervical spinal cord is a promising technique. Further refinement of these techniques, taking advantage of the increased SNR and resolution, may make 3 T imaging the future method of choice for the evaluation of spinal cord disorders.

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REFERENCES