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MRI atlas-based volumetric mapping of the cervical cord gray matter in cervical canal stenosis

Zachary A. Smith¹, Kenneth A. Weber II², Monica Paliwal¹, Benjamin S. Hopkins¹, Alexander J. Barry³, Donald Cantrell⁴, Aruna Ganju¹, Tyler R. Koski¹, Todd B. Parrish⁴, Yasin Dhaheer⁵

¹Department of Neurological Surgery, Northwestern University; Chicago, IL.

²Department of Anesthesiology, Perioperative and Pain Medicine, Stanford University School of Medicine; Palo Alto, CA.

³Shirley Ryan Ability Lab, Chicago, IL.

⁴Department of Radiology, Northwestern University; Chicago, IL.

⁵Department of Physical Medicine and Rehabilitation, University of Texas, Southwestern; Dallas, TX

Introduction:

Degenerative cervical spinal compression is a leading cause of non-traumatic spinal disability^{1,2}. Progressive degenerative changes in the cervical spine lead to subsequent cord compression and injury. On a neuronal level, there may be direct injury to the neuronal cell bodies, tissue ischemia, and biomechanical stress^{3,4}. Injury to the cord may occur in both white matter (WM) and gray matter (GM) and may extend both rostral and caudal to the site of injury. As the presentation of clinical symptoms may not occur until a patient has had many years of spinal compression, imaging modalities that accurately detect and characterize early injury may be critical to guiding the appropriate intervention⁵.

Recent innovations in spinal cord neuroimaging, including post-processing technologies and atlas-based measurements, have made it possible to quantify both gray matter (GM) and white matter (WM) volumes in spinal disease using probabilistic anatomical maps.^{6–8} These maps may be utilized to evaluate specific white matter pathways (ex: lateral corticospinal pathway) or distinct regions of the gray matter, including the ventral, and dorsal horns. Few radiographic grading systems exist to categorize spinal cord compression and ongoing spinal injury in CSM. Given this, the application of atlas-based mapping in spinal disease has the potential to inform our early understanding of how the anatomic architecture of the cord is impacted in this disease.

*Corresponding Author: Zachary A. Smith, M.D., Associate Professor Neurological Surgery, Northwestern University School of Medicine, 676 N. St. Clair Street, Chicago, IL 60611, zsmith1@nm.org.

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We have previously demonstrated that descending white matter tract volumes associate with clinical myelopathy in patients with cervical canal stenosis.⁹ Further, significant differences in Diffusion Tensor Imaging (DTI) in these same pathways have been shown in cervical stenosis patients as compared to the healthy spine (references). Less attention, however, has been paid to the gray matter architecture of the cervical cord. In this study, we have utilized 3T high-resolution axial MRI images, analyzed with an open source atlas-based processing application (SCT)^{6,7}, to evaluate cervical spinal cord gray matter volume in patients and controls. We analyzed volumetric changes in relation to established clinical metrics for sensorimotor function. We hypothesized that atlas-based probability mapping of the gray matter would demonstrate volume loss in all regions of the spinal gray matter when compared to controls and that gray matter volumetric loss will be significantly associated with decreased clinical outcomes of sensorimotor function and quality of life scores.

Methods:

Subjects:

Twenty-nine subjects consisting of fifteen adult patients and fourteen healthy controls were recruited to the study. Patients were included if they reported characteristic signs of symptomatic cervical canal stenosis, including upper extremity weakness, sensory loss, and lack of coordination, in combination with spinal imaging indicating cervical spine compression. Subjects with major neurodegenerative diseases such as Alzheimer's or multiple sclerosis, spinal tumors or trauma, active systemic rheumatological disease, diabetes, peripheral or vascular neuropathy, and a history of spinal surgery were excluded. In addition to the exclusion criteria for patients, controls were also screened for current spinal conditions, neck pain or other neurological deficits. All participants provided written informed consent as approved by the Northwestern University's Institutional Review Board. All identifying patient information was removed from patient images or clinical data. Patients and controls were made aware of any risks included in the study as well as that participation would not impact clinical care. They were made aware of that participation was optional. The authors have read the journal policies on clinical studies and concur that the following work is in compliance with these guidelines.

Clinical and Health Related Quality of life (HRQOL) Assessment:

Modified Japanese Orthopedic Association (mJOA) and Nurick scores were evaluated for all subjects. The mJOA score is a widely used scale to assess upper and lower extremity sensorimotor function and sphincter dysfunction, while the Nurick scale assesses ambulatory status. All subjects completed the neck and arm numerical rating scales (NRS), and neck disability index (NDI).

MRI Acquisition and analysis:

All imaging data were collected with a 3.0 Tesla Siemens Prisma MR scanner (Siemens, Erlangen, Germany) equipped with a 64-channel head/neck coil. Participants were placed supine on the scanner bed, and a localizer scan was obtained to identify the location of the intervertebral discs of the cervical spine (C2–3, C3–4, C4–5, C5–6, C6–7, and C7–T1). Six transverse slices with high gray to white matter contrast were acquired at each intervertebral

disc using a multi-echo T2*-weighted gradient-echo sequence (TR=300 ms, TE=18 ms, flip angle=30°, FOV=180×180, matrix size=384×384, In-plane resolution=0.47×0.47 mm², slice thickness=6 mm, and number of averages=2). Image processing and analysis were performed using the SCT (version 3.0)^{6,7}. For each slice, the spinal cord was first manually segmented from the images. Then the PAM50 template was registered to each slice using the subject's native space as the registration destination and the spinal cord mask to initialize the registration. The gray and white matter were then segmented from the spinal cord using a multi-atlas method, and the template registration was then fine-tuned to the gray matter. The gray matter volumes of the left ventral, right ventral, left dorsal and right dorsal horn were extracted.¹⁰ Previous validation has suggested high dice coefficients when compared to manual verification (>0.9) and a high degree of accuracy when segmenting and extracting volumes from such regions of the cord.⁶

Total horn volumes were calculated as sum of left and right ventral and left and right dorsal horns. Mean ventral and dorsal horn volumes across all cervical levels was calculated. A board-certified blinded radiologist identified level of maximum compression. Mean volumes in the compression region were defined as the average volumes of the 3 levels- above, at and below the level of maximum compression. Mean volumes across all levels and at compression region are reported in results and figures. To account for normal variability in horn volumes within individuals, normalized mean horn volumes were calculated by taking a ratio of volume at a cervical level and volume at C2-C3. C2-C3 level was chosen for normalization.

Statistical Analysis:

2-sample t-tests were performed to assess significant differences in mean gray matter (ventral and dorsal horn) volumes across the cervical spine and disability scoring (SPSS software version 24). Secondly, we conducted ANCOVA to evaluate differences in volumes between groups with C2-C3 volume as a covariate. Significance level was set at $p < 0.05$. Spearman's correlations were performed to assess associations between radiographic findings and clinical scores.

Results:

The patient cohort consisted of 6 females and 9 males while the control group consisted of 5 females and 9 males; mean ages 61.07 ± 8.7 years and 56.07 ± 5.3 years respectively ($p > 0.05$). Patients had significantly worse clinical and HRQOL scores. Patients had higher Nurick (1.87 ± 0.83 vs 0 ± 0 , $p < 0.001$) and lower mJOA scores (14.4 ± 1.7 vs 18.0 ± 0 , $p < 0.001$) as compared to controls. Patients with CSM also reported higher neck discomfort (4.33 ± 1.91 vs 0.29 ± 0.61 , $p < 0.001$), arm discomfort (4.60 ± 2.92 vs 0.29 ± 0.47 , $p < 0.001$), and NDI (16.53 ± 7.30 vs 1.64 ± 2.56 , $p < 0.001$) scores. Patient demographic data, clinical, and HRQOL scores are listed in Table 1. Figure 1 is a representative comparison of a patient with CSM (61 years old female, reported mJOA= 13, ventral volume = 20.2 voxels, dorsal volume = 11.0 voxels) and an age and sex matched control (61 years old female with mJOA =18, total ventral horn volume =32.2 voxels, dorsal volume =20.2 voxels) at the level of maximum compression observed in the patient (C5-C6). The probabilistic masks for left and right

ventral horn (blue), left and right dorsal horn (yellow) and the spinal cord (translucent red) are overlaid on the axial image.

Spinal gray matter, both ventral and dorsal horn volumes, were significantly different in patients as compared to controls. In patients, mean ventral volume (26.55 ± 2.99 vs 29.76 ± 4.19 , $p=0.024$) and ventral volume at compressed region (27.55 ± 4.38 vs 33.690 ± 6.50 , $p=0.008$) were significantly decreased in patients (Figure 2). Similarly, mean dorsal volume at compression region in patients was significantly lower than in controls; 17.0 ± 2.97 vs 20.56 ± 4.0 , $p=0.015$. Dorsal volume across all levels of cervical spine was also lower; 16.83 ± 2.58 vs 19.06 ± 3.35 , $p=0.054$ (Figure 3). Mostly consistent with the findings of the absolute horn volumes, normalized horn volumes were also different in patients than controls. Normalized mean ventral volume across all levels and in compression region were significantly lower in patients (1.05 ± 0.11 vs 1.18 ± 0.17 , $p=0.024$ and 1.103 ± 0.21 vs 1.35 ± 0.32 , $p=0.027$ respectively). Likewise, normalized mean dorsal volume in compression region was significantly lower in patients (0.90 ± 0.17 vs 1.04 ± 0.15 , $p=0.049$). The mean dorsal volume across all levels showed trend towards significance (0.90 ± 0.16 vs 1.04 ± 0.18 , $p=0.067$). Similarly, while comparing volumes between groups adjusting for C2-C3 volume, the ventral horn volume across all levels ($F(1, 23) = 4.765$, $p=0.040$) and at the compression region ($F(1, 22) = 12.450$, $p=0.002$) were significantly different. However, dorsal horn volumes ($F(1, 23) = 0.724$, $p=0.404$) did not show significance. This indicates that ventral horn volume loss may be more central in driving cervical canal stenosis than dorsal horn volumes.

Decreased gray matter volumes were also significantly associated with poor clinical and patient reported HRQOL scores. Lower mean ventral horn volumes predicted worse mJOA score ($p = 0.469$, $p = 0.016$). Upon bifurcation of patients by mJOA disability into discrete groups (moderate group: 12–14 and mild: 15–17); mJOA scores showed the statistically significant decline with decreasing ventral volumes ($p=0.050$). Nurick score were negatively related to increasing ventral horn volume loss ($\rho = -0.448$, $p = 0.022$) (Figure 4). Ventral horn volume negatively correlated with NDI ($\rho = -0.433$, $p = 0.027$) and neck disability (Neck NRS: $\rho = -0.394$, $p = 0.046$) and arm disability (Arm NRS: $\rho = -0.549$, $p = 0.004$) (Figure 5). Additionally, normalized dorsal volumes at compression region were associated with decreasing mJOA ($\rho = -0.391$, $p = 0.036$), Nurick ($\rho = -0.339$, $p = 0.090$) (Figure 6). Dorsal and ventral horn volumetric loss showed a strong, positive association with each other (mean across entire cervical spine: ($\rho = 0.964$, $p < 0.001$) and at compression ($\rho = 0.815$, $p < 0.001$)).

Discussion:

The current study demonstrates that gray matter volumes, including both the ventral and dorsal horns, are decreased in patients with symptomatic cervical canal stenosis. These gray matter changes are further correlated with clinical impairment as evidenced both by clinical myelopathy and disability scores. These deficits are uniquely influenced by the specific region gray matter volumetric change. To our knowledge, this is the first study to evaluate probabilistic gray matter volumes in association with clinical deficits in patients with degenerative cervical myelopathy.

Spinal Cord Gray Matter in Cervical Canal Stenosis

The impact of white matter injury has been a significant area of investigation. We have previously shown that advanced MRI techniques may aid in the identification of white matter tract injury in cervical canal stenosis.^{9,11,12} Utilizing magnetization transfer-MRI pulse sequences, a MRI technology that may isolate injury to myelin fibers, we found that cervical compression patients may have clinically significant white matter injury in the anterior column of the spinal cord¹¹. Subsequent tract-volume analysis utilizing the SCT demonstrated that medial white matter pathways, including the reticulospinal, corticospinal, and rubrospinal pathways had decreased tract-volume in cervical compression patients as compared to healthy controls⁹. Our findings are in congruence with other recent works. Liu et. al used myelin water imaging (MWI) and somatosensory evoked potentials (SSEPs) to demonstrate decreased myelin in the spinal cord of cervical stenosis patients that was associated with clinical conduction deficits¹³. Multiple investigators have utilized Diffusion Tensor Imaging (DTI) metrics, including focal anisotropy, to demonstrate clinically predictive diffusion patterns in cervical stenosis patients¹⁴.

While much attention has been previously focused upon descending pathways, there has been less focus on the spinal cord gray matter. In the current study, we demonstrated that gray matter volumes were decreased in patients with cervical canal stenosis compared to healthy controls. Grabher et.al, in a study utilizing voxel-based imaging processing, found that that gray matter atrophy of 7.2% occurred in the cord above the regions of most prominent stenosis¹⁵. In a separate report, the same authors demonstrated that gray matter DTI imaging metrics changed in parallel with white matter pathways in the cervical cord above areas of stenosis^{15,16}. This occurred in patients with mild and moderate symptoms of clinical myelopathy, implying that early radiographic changes may precede clinical symptoms. Similarly, patients with severe spinal cord injury have been shown demonstrate both ventral and dorsal horn atrophy above the level of their injury¹⁷.

Probability mapping and clinical disability

The recent development of imaging process technology has the potential to greatly expand our understanding of spinal cord disease. Conventional MRI, while useful for characterizing general structure and compression, lacks the ability to delineate white and gray matter microstructure as well as markers of function in the spine¹⁸. Further, while multiple brain neuroimaging software packages were developed for advanced processing of multi-parametric MRI similar technologies did not exist for spinal imaging. In the current report, we use a new atlas-based software package, the SCT, which is free and open-source. The SCT works with multiple image contrasts and provides probabilistic anatomical maps for known structures within the spinal cord. We previously used this technology to analyze specific white matter pathways in the cervical spine of cervical stenosis patients (ex: lateral corticospinal pathway)⁹. In the current work, we utilize the capabilities of the SCT for gray matter segmentation across multiple spinal levels.

The current findings demonstrate that anatomic compression and volume loss in the ventral horns predict clinically significant changes in established patient-reported outcome metrics. These include the mJOA score, Nurick score, NDI, and numeric rating scales. Similarly, the

dorsal horn probabilistic volumes also showed robust relationships between volume loss and clinical deficits on mJOA and Nurick scores. These findings suggest that ventral and dorsal horn gray matter neuronal impacts may play a significant role in neuromechanics of cervical canal stenosis and compressive myelopathy.

While clinical myelopathy scores, such as the mJOA score, are commonly used to evaluate patients with the diagnosis of cervical myelopathy, many investigators have directly assessed physical manifestations of disease. Harrop et.al retrospectively evaluated 54 cervical myelopathy patients in comparison to 49 normal controls and found that 85% of the cervical stenosis patients had signs of hyper-reflexia on physical exam¹⁷. In a study of 225 patients, including both cervical stenosis patients and asymptomatic volumes, Houten and Noce found the most consistent exam finding in this population was the presence of a Hoffman's sign¹⁹. In patients with CSM, 68% had this sign and in patients with mJOA scores at or below 10, a Hoffman's reflex was found in 81% of patients. Nemani et.al evaluated patients symptomatic cervical stenosis with cord signal change, a cardinal radiographic sign of significant level-specific cord compression and injury. They found that only 11 of 43 (26%) of patients had exam findings concordant with the level of spinal cord signal change²⁰. These findings suggest that more precise clinical measures need to be developed to accurately assess clinical injury in this patient population.

Limitations

While the majority of patients in this work had mild or moderate cervical spinal compression, the cord may still be notably distorted at the site of most significant disease. This commonly will create an indistinct margin between the spinal cord and either cerebrospinal fluid (CSF) or disk-osteophyte complexes at this level. While 3T imaging has improved the definition of this margin, manual segmentation of the spinal cord was required in subjects with significant compression as the automated spinal cord detection methods performed poorly at compressed levels. We acknowledge that manual segmentation introduces the potential for either human error or evaluator bias. While the analysis was blinded, the presence or absence of disease can be commonly ascertained. The need for manual segmentation may also pose a challenge for the current application of this technology. Until imaging technology can accurately and consistently delineate cord boundaries at sites of compression automatically, the process will require time-consuming manual input. Furthermore, although well validated with extremely high degrees of accuracy, given the use of sequential steps throughout the automated segmentation and volume extraction process, each with a marginal degree of error, it is possible that our measurements collected may not be completely reflective of the true volumes.⁶ While well validated by previous studies, the spinal cord toolbox remains a new tool and likewise results must be interpreted in the appropriate context. Further, an additional limitation of this work is that we did not employ EMG-NCV studies in our patient population. Future use of EMG-NCV could be used to substantiate volumetric results and the clinical symptom severity could be tied directly to volume loss. It is our plan to incorporate EMG-NCV in our future work.

This study evaluates gray matter volumes in cervical stenosis. We acknowledge that changes in degenerative cervical compression encompass both the white and gray matter of the cervical cord. While we have previously reported on white matter pathway volumes in cervical stenosis, one limitation of this work is that it considers gray matter impacts in isolation. We concede that the picture is more complex. Patients with ventral horn volume changes will demonstrate similar impacts on the surrounding descending spinal tracts, such as the lateral corticospinal pathways. A more accurate picture is one that considers a cumulative impact of both white and gray matter volume loss as well as cord distortion as underlying drivers of neural dysfunction.

Conclusions

The current study demonstrates the application of the SCT, an open-source spinal atlas-based software package, in the analyzing gray volume loss in cervical spondylotic myelopathy. While this technical advance has been recently applied to other spinal pathologies, as well as white matter volume analysis in cervical stenosis, the current work provides an initial report of gray matter analysis for this disease. When compared to asymptomatic population, patients with cervical stenosis had significant decreases in mean ventral, intermediate, and dorsal horn gray matter volumes. Both ventral and dorsal gray matter volume loss are clinically relevant and are associated with changes in multiple clinical outcomes, including mJOA, Nurick scale, NRS arm and neck, and NDI scores. Region specific volume loss has the potential to produce unique clinical presentations.

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Abbreviations-

CSM	Cervical Spondyloatic Myelopathy
MRI	Magnetic Resonance Imaging
mJOA	modified Japanese Orthopedic Association Score
NRS	Neck and Arm Numerical Rating Scale
NDI	Neck Disability Index
GM	Gray Matter
WM	White Matter
SCT	Spinal Cord Toolbox
HRQOL	Health Related Quality of Life
MWI	Myelin Water Imaging

DTI	Diffusion Tensor Imaging
SSEP	Somatosensory Evoked Potentials

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Figure 1:

Comparison of a 61-year-old female patient with cervical spondylotic myelopathy (A) and an age- and sex-matched control subject (B) at the level of maximum compression observed in the patient (C5-C6). The probabilistic masks for the left and right ventral horn (blue), left and right dorsal horn (yellow), and spinal cord (translucent red) are overlaid on the axial image.

Figure 2:

(A) Mean ventral volume across all levels. (B) Ventral volume at compressed region.

Figure 3:
(A) Mean dorsal volume across all levels. (B) Dorsal volume at compressed region.

Figure 4:

(A) Modified Japanese Orthopaedic Association scores showed a statistically significant decline with decreasing ventral volumes. (B) Nurick scores were negatively related to increasing ventral horn volume loss. mJOA, modified Japanese Orthopaedic Association.

Figure 5: Ventral horn volume was negatively correlated with arm numeric rating scale scores. NRS, numeric rating scale.

Figure 6: Normalized dorsal volumes in the compression region were associated with decreasing modified Japanese Orthopaedic Association (A) and Nurick Scale (B) scores. mJOA, modified Japanese Orthopaedic Association.

Table 1:

Demographic and atlas-mapped gray matter volumes of all the subjects is presented. Mean and SD of age, Nurick, mJOA, Neck NRS, Arm NRS, NDI scores Ventral and Dorsal Horn volumes across all levels and in the compression region have been reported. [SD = Standard Deviation, mJOA= modified Japanese Orthopedic Association, NRS= Numerical rating system, NDI= Neck Disability Index, VH= Ventral Horn, DH= Dorsal Horn, CR= Compression Region].

Subject	M/F	Age	Nurick	MJOA	NeckNRS	ArmNRS	NDI	Mean VH Volume	Mean DH Volume	VH Volume at CR	DH Volume at CR
CSM008	M	54	0	18	0	0	0	24.74	36.25	26.52	40.48
CSM009	M	56	0	18	0	0	0	17.24	29.33	17.96	34.4
CSM013	F	56	0	18	0	0	0	23.67	35.46	25.87	45.32
CSM015	F	56	0	18	0	1	0	16.93	27.68	19.15	33.27
CSM017	F	57	0	18	0	0	1	15.44	25.94	NA	NA
CSM023	M	68	0	18	0	0	0	20.19	32.17	20.32	34.92
CSM024	M	52	0	18	0	1	0	15.05	23.64	14.8	25.04
CSM025	M	52	0	18	0	0	2	23.83	36.57	26.13	38.77
CSM026	F	64	0	18	2	1	9	15.92	24.66	18.96	29.86
CSM027	M	55	0	18	0	0	1	16.21	27.57	16.84	32.3
CSM038	M	62	0	18	1	1	4	19.21	28.16	18.11	22.63
CSM039	F	61	0	18	0	0	0	19.26	29.98	21.5	33.65
CSM040	M	51	0	18	1	0	2	22.11	32.02	NA	NA
CSM041	M	50	0	18	0	0	4	17.03	27.24	NA	NA
Mean	9M (5F)	56.71	0.00	18.00	0.29	0.29	1.64	19.06	29.76	20.56	33.69
SD	-	5.27	0.00	0.00	0.61	0.47	2.56	3.35	4.19	4.00	6.50
CSM005	F	38	1	17	4	2	16	16.21	26.04	16.94	25.73
CSM007	M	66	2	16	7	10	30	19.08	29.08	19.73	33.16
CSM010	M	54	2	15	6	2	18	16.32	26.6	19.08	33
CSM011	F	64	1	15	3	0	10	14.78	24.64	13.83	25.65
CSM012	M	72	2	12	6	5	12	20.7	29.02	19.8	28.41
CSM016	M	55	2	12	5	7	25	19.45	30.41	18.13	25.32
CSM018	F	70	4	13	5	4	10	17.79	28.31	18.91	34.38

Subject	M/F	Age	Nurick	MJOA	NeckNRS	ArmNRS	NDI	Mean VH Volume	Mean DH Volume	VH Volume at CR	DH Volume at CR
CSM019	M	62	1	17	3	4	8	16.89	26.16	16.47	24.92
CSM021	F	51	1	16	1	1	14	15.12	23.89	15.9	27.84
CSM022	M	64	1	15	4	3	17	20	30.35	22.18	33.91
CSM030	M	69	2	12	1	4	4	11.97	20.37	11.08	20.19
CSM031	M	64	2	14	3	4	24	13.12	23.29	12.88	25.04
CSM032	M	60	3	14	7	9	24	17.51	28.36	16.03	21.97
CSM034	F	66	2	15	4	6	14	14.57	23.02	15.02	24.79
CSM036	F	61	2	13	6	8	22	19.01	28.75	19	29
Mean	9M (6F)	61.07	1.87	14.40	4.33	4.60	16.53	16.83	26.55	17.00	27.55
SD	-	8.70	0.83	1.72	1.91	2.92	7.30	2.58	2.99	2.97	4.39