



# Establishing the inter-rater reliability of spinal cord damage manual measurement using magnetic resonance imaging

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## Abstract

**Study design** Retrospective study.

**Objectives** To establish the inter-rater reliability in the quantitative evaluation of spinal cord damage following cervical incomplete spinal cord injury (SCI) utilizing magnetic resonance imaging (MRI). MRI was used to perform manual measurements of the cranial and caudal boundaries of edema, edema length, midsagittal tissue bridge ratio, axial damage ratio, and edema volume in 10 participants with cervical incomplete SCI.

**Setting** Academic university setting.

**Methods** Structural MRIs of 10 participants with SCI were collected from Northwestern University's Neuromuscular Imaging and Research Lab. All manual measures were performed using OsiriX (Pixmeo Sarl, Geneva, Switzerland). Intraclass correlation coefficients (ICC) were used to determine inter-rater reliability across seven raters of varying experience.

**Results** High-to-excellent inter-rater reliability was found for all measures. ICC values for cranial/caudal levels of involvement, edema length, midsagittal tissue bridge ratio, axial damage ratio, and edema volume were 0.99, 0.98, 0.90, 0.84, and 0.93, respectively.

**Conclusions** Manual MRI measures of spinal cord damage are reliable between raters. Researchers and clinicians may confidently utilize manual MRI measures to quantify cord damage. Future research to predict functional recovery following SCI and better inform clinical management is warranted.

## Introduction

Following a spinal cord injury (SCI), individuals are faced with uncertainty regarding recovery of motor and sensory function; incomplete SCIs are particularly unpredictable due to the wide variability in mechanism, severity, and type of injury [1]. The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) defines an incomplete SCI as a lesion of the cord with intact sensory function with a possible sparing of motor function below the level of injury [2]. Following SCI, the prioritization for the recovery of functional abilities, such as walking, upper extremity use, sphincter control for bowel and bladder care, and sexuality are highly patient dependent [3]. Thus, prognostic methods for functional recovery, on a patient-by-patient basis, following spinal cord injuries are invaluable for determining targeted rehabilitative approaches toward achieving individual patient priorities.

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**Table 1** Demographic information of study participants

Participant number	Sex	Age (years)	Height (cm)	Weight (kg)	Time since injury (years)	Mechanism of injury
1	M	44	177.7	68.04	5	Motorcycle injury
2	M	57	178	79.38	8	Cycling injury
3	F	52	157	83.91	0.33	MVC
4	M	31	178	72.57	4	Diving injury
5	M	27	191	86.18	4	Skiing injury
6	M	32	173	81.65	5	MVC
7	M	45	175	58.97	3.5	ATV injury
8	M	36	185	73.48	1.5	Motorcycle injury
9	M	50	178	72.57	5	Fall from height
10	M	64	175	108.86	4	Fall

MVC motor vehicle collision

ISNCSCI is a widely accepted standard for classifying individuals with SCI [2]. However, it requires the use of subjective clinical measures, such as manual muscle and sensory testing, a cognitively intact patient, and often the ISNCSCI examination does not fully or accurately evaluate the extent of a SCI. Rather, the ISNCSCI examination captures gross residual function secondary to the injury [4]. This classification system is subject to variability due to the complex nature of neurological injury [4, 5]. As a result, the supplementation of other objective measures are warranted to accompany, if not enhance, the present classification system.

Presently, T<sub>2</sub>-weighted magnetic resonance imaging (MRI) is the recommended imaging modality for viewing the specific pathological features of the injured spinal cord [6]. Edema is commonly observed on T<sub>2</sub>-weighted MRI as an irregularly shaped characterization of hyperintensity to indicate areas of the damaged cord [5]. While a variety of measures for quantifying the extent of edema have been reported [5, 7–16] and associated with functional recovery [5, 7, 8], more evidence is needed to establish the psychometric properties of these measurements.

The segmental levels of both cranial and caudal involvement (CCI) are reference measures used to locate the upper and lower anatomical bounds of edema [11, 17]. Edema length (EL) has been commonly measured and reported as the extent of edema along the cranial–caudal axis [7, 9–11, 13–15, 18]. Midsagittal tissue bridge (MTB) measures have emerged as a promising approach for functional prognosis [12, 19]. The axial damage ratio (ADR) is a novel measure used to capture the two-dimensional extent of edema within the cord [5]. Edema volume is calculated using consecutive axial slices through the damage. This study sought to establish the inter-rater reliability of five T<sub>2</sub>-weighted MRI-based manual measures across seven raters with varying levels of experience (novice to experienced): (1) CCI, (2) EL, (3) MTB, (4) ADR, and (5) edema volume.

## Methods

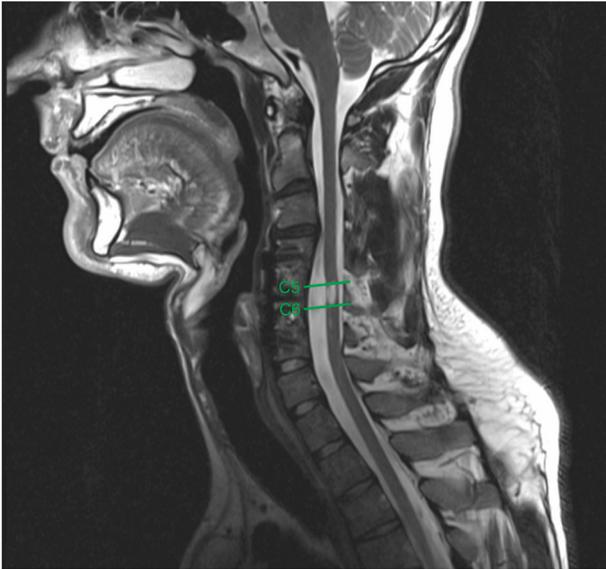
### Participant characteristics

This project was a retrospective analysis of MRI data from published studies [5, 8, 19]. It was approved by Northwestern University and Regis University Institutional Review Boards. Data were collected from Northwestern University's Neuromuscular Imaging and Research Lab. MR images of 10 participants with SCI were selected based on availability from previous work [19] (nine males and one female, mean age: 44, median age: 44, standard deviation: 12, range: 27–64). In terms of severity of injury, two participants were classified using the American Spinal Cord Injury Association Impairment Scale (AIS) as AIS C C5–C8, while eight participants were classified as AIS D. Participants were included if they had sensorimotor incomplete cervical SCI with images collected after cervical fusion. See Table 1 for additional participant demographic information.

All institutional and governmental regulations concerning the ethical use of human volunteers were certifiably followed during the course of this research according to the Declaration of Helsinki, including obtaining informed consent.

### Image acquisition

Images were provided from previous research in which trained personnel transferred participants to a supine position on the scanner bed [5]. MRI was performed with a 3.0 T Siemens (Munich, Germany). Prisma scanner equipped with a 64-channel head/neck coil. Localizer scans were completed, and patient safety and comfort were monitored throughout. A T<sub>2</sub>-weighted single slab 3D turbo spin echo sequence with a slab selective, variable excitation pulse (SPACE, TR = 1500 ms, TE<sub>eff</sub> = 115 ms, echo train length = 78, flip angle = 90°/140°, effective resolution = 0.8 × 0.8 × 0.8 mm<sup>3</sup> interpolated



**Fig. 1** A T<sub>2</sub>-weighted sagittal image demonstrating the cranial-most vertebral level (C5) and caudal-most vertebral level (C6) of edema involvement

resolution =  $0.8 \times 0.4 \times 0.4 \text{ mm}^3$ ) was used to create a high-resolution 3D image of the cervical and upper thoracic spine [5].

### Image processing

MRI data were analyzed using a medical image viewer software program, OsiriX (Pixmeo Sarl, Geneva, Switzerland). The segmental levels of both cranial and caudal involvement (CCI) were determined by identifying the cranial-most and caudal-most vertebral body where edema was present (see Fig. 1).

Edema length (EL) was measured using the sagittal slice with the maximal extent of edema, as the distance between the most cranial and caudal portions while keeping the measuring line parallel to the spinal cord (see Fig. 2a).

To quantify MTB, the midsagittal slice was used. Tissue bridges were calculated as the minimum distance from cerebrospinal fluid to the edema, on both the anterior and posterior sides of edema. The MTB ratio was quantified as the sum of anterior and posterior tissue bridges divided by the spinal cord diameter (see Fig. 2b).

For each patient, edema and surrounding spinal cord cross-sectional area (CSA) were measured for each axial slice where the edema was visibly present (see Fig. 2c). Edema volumes were calculated as the measured CSA multiplied by slice thickness:  $\text{volume} = \sum \text{CSA}_{\text{each slice}} \times \text{slice thickness}$  (see Fig. 3). For axial damage ratio (ADR) measure, the axial slice with the largest CSA of edema was identified. ADR was calculated as the maximum CSA of edema divided by its corresponding spinal cord CSA:  $\text{ADR} = \text{CSA}_{\text{max edema}} / \text{CSA}_{\text{spinal cord}}$  (see Fig. 2c).

All five manual measurements were completed by seven independent raters with a wide range of experience, ranging from 5 h to more than 4 years of experience.

### Statistical analysis

IBM SPSS version 21 (Armonk, NY, USA) was used to perform statistical analyses of the data. Intraclass correlation coefficients (ICC) were computed for CCI, EL, MTB, ADR, and edema volume measurements, to establish inter-rater reliability. A two-way mixed effects model, absolute agreement type, average measures approach was used for each ICC calculated. A  $p$ -value of  $< 0.05$  was used to define statistical significance for all measures.

### Results

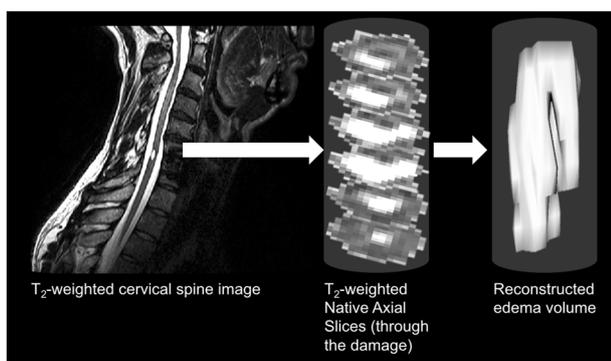
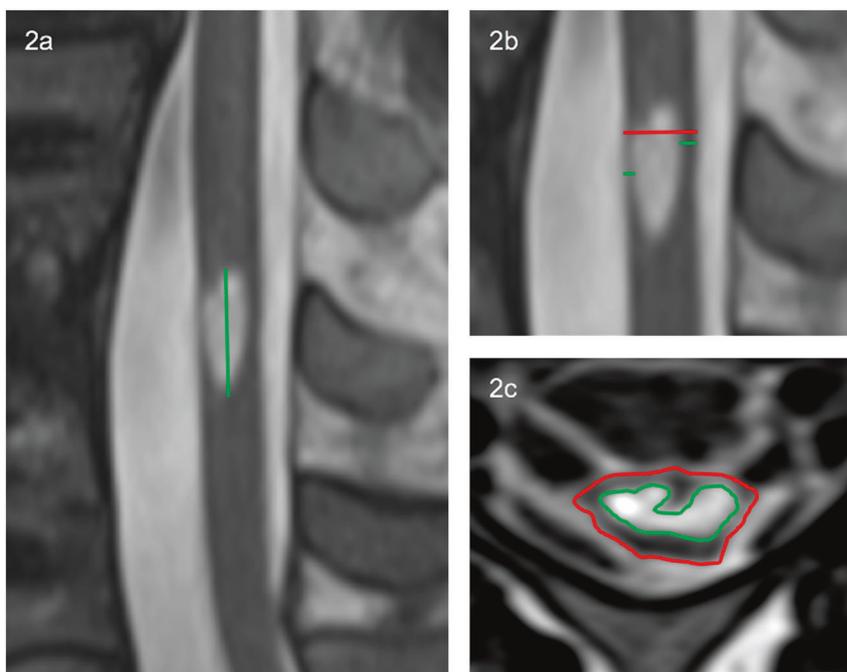
ICC values for one-dimensional measurements (CCI, EL), two-dimensional measurements (MTB, ADR), and the three-dimensional measurement (edema volume) demonstrated high-to-excellent inter-rater reliability (0.99, 0.98, 0.90, 0.84, and 0.93, respectively) at a significance value of  $p < 0.05$  (see Fig. 4).

### Discussion

All five manual measurements demonstrated a high-to-excellent level of inter-rater reliability ( $\text{ICC} > 0.75$ ). Our results demonstrate that edema characteristics can be reliably measured, even among novice raters. In regards to the MTB measure, high levels of inter-rater reliability were found in previous literature [12, 19]. Among two experienced raters, the inter-rater reliability of the axial damage ratio was previously reported as  $\text{ICC} = 0.82$  [5], consistent with our results. These manual measurements of spinal cord edema have been reported as important for relating to physical function [5, 11, 12]. In particular, MTB have shown to correlate with current and future walking ability following SCI [12, 19]. Based on our results, it may be possible for clinicians, regardless of imaging experience level, to reliably measure cord edema and use this as an adjunct tool to inform prognosis and thus, clinical management.

A previously reported clinical prediction rule used ISNCSCI testing and other clinical prognostic indicators for individuals with SCI [20]. While ISNCSCI is widely used and accepted, it is an indirect assessment of an individual's SCI using general tests of sensory and motor function. The testing used is also subject to spatial and temporal variability, due to the complex nature of SCI, concomitant traumatic brain injury, cognition altering medications, and spinal shock [4, 21]. The measurements used and reported in this study may inform and

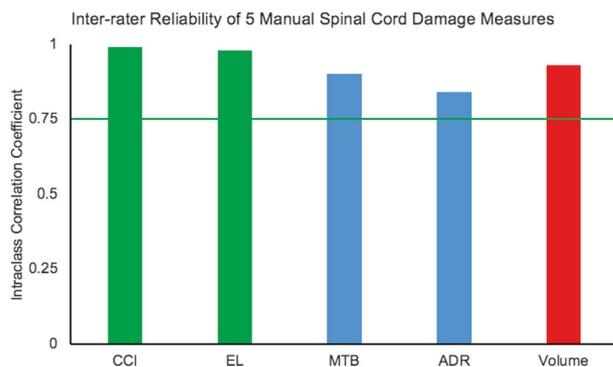
**Fig. 2** **a** An example of the edema length manual measurement. **b** The midsagittal tissue bridge ratio was calculated as the sum of the anterior and posterior tissue bridges (green) divided by the diameter of the cord (red). **c** The axial damage ratio was quantified as the maximal edema cross-sectional area (green) divided by the surrounding spinal cord cross-sectional area (red)



**Fig. 3** Edema volume was calculated using consecutive axial edema cross-sectional areas multiplied by the axial slice thickness

enhance prognosis and direct clinical management of patients with SCI. In particular, more precise measurements, using available imaging tests typical of standard practice, may help clinicians to better focus on valuable rehabilitation while considering available time and resources on a patient-by-patient basis. Several studies have demonstrated relationships between edema measurements and clinical outcomes [5, 12]. Our study demonstrated that several other measures of edema could be used in tandem with commonly used tests (e.g. ISNCSCI) and can be quantified reliably by novice raters. In particular, edema volume may be an even more useful measurement as it gives a more complete three-dimensional measure for the extent of spinal cord damage.

Limitations of our study exist and include a small and restrictive sample size of patients with incomplete SCI, which is not generalizable to all those who have sustained a SCI. Our sample only consisted of 10 participants, nine of whom were



**Fig. 4** A chart demonstrating the reliability values for all five measures: cranial/caudal levels of involvement (CCI), edema length (EL), midsagittal tissue bridge (MTB) ratios, axial damage ratios (ADR), and edema volume. The green bars represent one-dimensional measures, the blue bars represent two-dimensional measures, and the red bar represents the three-dimensional measure. The green line represents the cut-off of high inter-rater reliability at 0.75

men. Future studies should include a larger pool of participants with demographics reflective of and more generalizable to the population of those injured. For optimal clinical translation of these findings, future work should include a broad pool of imaging data from varying scanner strengths (i.e., 1.5 Tesla, 3.0 Tesla), different MR scanners, and data from multi-site trials. Another limitation with our manual measurement approaches is the variability in spinal cord anatomy across research participants. While the axial damage ratio attempts to account for spinal cord diameter variability, standardized spinal cord template-based approaches may be beneficial to compare anatomy and damage across participants [8, 22] (i.e., extent of edema encroaching into dorsal or ventral spinal columns).

Further research will be necessary to establish the clinical utility of these various edema measurements, especially those less recognized, such as the axial damage ratio and edema volume. Current literature, however, shows that edema measurements using T<sub>2</sub>-weighted MRI may be a useful prognostic tool to inform management of individuals with spinal cord injuries.

## Conclusion

With minimal training, clinicians demonstrate higher levels of reliability toward measuring edema using T<sub>2</sub>-weighted MRI following sensorimotor incomplete SCI. Establishing the validity of these measurements will be important to inform clinical practice and improve the prediction of functional (motor and sensory) recovery following SCI.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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