applied sciences

MDPI

Review

Diffusion Tensor Imaging in Degenerative Cervical Myelopathy: Clinical Translation Opportunities for Cause of Pain Detection and Potentially Early Diagnoses

Suhani Sharma [1,2], Alisha Sial [1,3,4], Georgia E. Bright [5,6], Ryan O'Hare Doig [6,7,*] and Ashish D. Diwan [1,3,4]

1 Spine Labs, St George and Sutherland Clinical School, University of New South Wales, Sydney, NSW 2217, Australia; suhanisharma24@rcsi.com (S.S.); a.sial@unsw.edu.au (A.S.); a.diwan@unsw.edu.au (A.D.D.)
2 School of Medicine, Royal College of Surgeons in Ireland, 123 St Stephens Green, D02 YN77 Dublin, Ireland
3 Spine Service, Department of Orthopedic Surgery, St George and Sutherland Clinical School, University of New South Wales, Sydney, NSW 2217, Australia
4 Spinal Unit, Discipline of Orthopaedic Surgery, Royal Adelaide Hospital, Adelaide, SA 5000, Australia
5 School of Biomedicine, Faculty of Health and Medical Sciences, University of Adelaide, Adelaide, SA 5005, Australia; georgia.bright@adelaide.edu.au
6 Neil Sachse Centre for Spinal Cord Research, Lifelong Health Theme, South Australian Health and Medical Research Institute, Adelaide, SA 5000, Australia
7 Adelaide Medical School, Faculty of Health and Medical Sciences, University of Adelaide, Adelaide, SA 5000, Australia
* Correspondence: ryan.doig@adelaide.edu.au

Abstract

Degenerative cervical myelopathy (DCM) is a common cause of spinal cord dysfunction in adults and is frequently accompanied by pain, a symptom that remains under-recognised despite its profound impact on quality of life. Conventional magnetic resonance imaging (MRI) is indispensable for identifying structural spinal cord compression; however, it is unable to detect early microstructural alterations, particularly those that may contribute to pain pathophysiology. This narrative review critically appraises the limitations of standard MRI in the diagnostic assessment of DCM and examines the expanding role of advanced imaging modalities—most notably diffusion tensor imaging (DTI)—in evaluating spinal cord integrity. DTI-derived parameters, including fractional anisotropy (FA), mean diffusivity (MD), axial diffusivity (AD), and radial diffusivity (RD), demonstrate sensitivity to axonal and myelin injury. For example, reductions in FA and AD have been linked to axonal disruption in sensory pathways, while elevations in RD suggest demyelination, a hallmark of neuropathic pain. Despite this potential, the widespread implementation of DTI is constrained by technical heterogeneity, limited accessibility, and the absence of standardised protocols. Future research priorities include the incorporation of pain-specific imaging endpoints, longitudinal validation across diverse cohorts, and integration with artificial intelligence frameworks to enable automated analysis and predictive modelling. Collectively, these advances hold promise for enabling earlier diagnosis, refined symptom stratification, and more personalised therapeutic strategies in DCM.

Keywords: degenerative cervical myelopathy; diffusion tensor imaging; pain biomarkers; spinal cord microstructure

check for updates

Academic Editors: Alexandros A. Lavdas, Valeria Sacca and Fabiana Novellino

Received: 3 September 2025
Revised: 16 October 2025
Accepted: 29 October 2025
Published: 30 October 2025

Citation: Sharma, S.; Sial, A.; Bright, G.E.; O'Hare Doig, R.; Diwan, A.D. Diffusion Tensor Imaging in Degenerative Cervical Myelopathy: Clinical Translation Opportunities for Cause of Pain Detection and Potentially Early Diagnoses. *Appl. Sci.* **2025**, *15*, 11607. https://doi.org/10.3390/app152111607

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Degenerative cervical myelopathy (DCM) refers to a spectrum of progressive, age-related degenerative changes affecting the cervical spine, including cervical spondylosis, disc degeneration, and ossification of ligaments such as the posterior longitudinal ligament [1]. These changes can result in chronic spinal cord compression and neurological dysfunction, contributing to stepwise functional decline and significant deterioration in quality of life [2]. Pain is a prominent, disabling, and frequently under-recognised feature of DCM, yet conventional imaging often fails to explain its origin [3]. This disconnection between symptom burden and radiological findings represents a key diagnostic gap that limits timely recognition and targeted treatment.

An international working group of clinicians and scientists initiated a structured consensus process to standardise outcome reporting and prioritise research in DCM, culminating in the RECODE-DCM initiative. This review engages with key RECODE-DCM priorities, encompassing diagnostic criteria, assessment and monitoring, and the development of novel imaging approaches, with a particular focus on DCM pathobiology—specifically the mechanisms of pain and their potential characterisation through diffusion tensor imaging (DTI). As defined in the RECODE-DCM core outcome set, pain encompasses attributes such as location, intensity, perception, and control, reflecting its multidimensional impact on patients [4]. It may manifest as axial neck pain, radicular upper limb pain, or diffuse discomfort associated with posture and movement [5]. It can arise from a range of anatomical sources, including the intervertebral discs, facet joints, ligaments, or directly from the spinal cord itself through tract disruption [5]. However, distinguishing the precise pain generator—whether structural, neural, or both—remains diagnostically challenging. Furthermore, it is unclear whether pain arises predominantly from segmental instability, mechanical compression, or a combination thereof, and whether involvement of a single vertebral level or multiple levels is of greater clinical significance, in terms of symptom severity and prognosis.

Globally, DCM is the most common cause of non-traumatic spinal cord dysfunction in adults [2,6]. Yet, its heterogeneous clinical presentation—including sensory deficits, motor impairment, and pain—often leads to misdiagnosis and delayed intervention [7]. Given that up to 60% of symptomatic patients deteriorate without surgery, and that earlier surgical treatment is associated with more favourable outcomes, prompt recognition remains a clinical priority [8–12]. However, mean diagnostic delays ranging from 2 to 6 years continue to be reported [13,14], underscoring the need for improved diagnostic strategies. Given the ageing demographic, the burden of diseases associated with DCM is anticipated to increase substantially over time, highlighting the critical need for improved awareness and timely diagnosis.

Conventional magnetic resonance imaging (MRI) remains the cornerstone for diagnosing DCM, as it reliably demonstrates spinal canal stenosis, cord compression, and intramedullary signal changes, such as T2-weighted hyperintensity and T1-weighted cord atrophy [15]. Unlike plain radiographs, which depict only osseous structures [16], MRI enables direct visualisation of the spinal cord and surrounding soft tissues. Despite its widespread clinical utility, standard MRI sequences have recognised limitations: subtle microstructural damage may go undetected, and radiological findings do not always correlate with clinical severity or functional impairment [17,18]. A standard MRI is not effective in determining the source of pain in DCM and also falls short in picking up DCM earlier. These recognised limitations of conventional MRI, which is largely restricted to structural sequences such as T1- and T2-weighted imaging, have prompted growing interest in advanced imaging techniques (e.g., DTI, DKI) that provide quantitative assessments of spinal cord microstructure and function beyond what can be visualised on standard imaging.

Among advanced MRI techniques, diffusion kurtosis imaging (DKI) captures non-Gaussian water diffusion, offering additional microstructural detail beyond DTI; however, its use in DCM remains limited to preliminary studies [19]. In contrast, DTI is a quantitative MRI technique that maps the directional diffusion of water molecules, providing objective information on white matter integrity. Validated in other neurological disorders, such as multiple sclerosis, where it sensitively detects demyelination and axonal injury, DTI has clear translational potential for assessing both macrostructural cord compression and microstructural tract degeneration in DCM [20–23]. These microstructural metrics may detect early cord changes that precede irreversible injury, enabling identification of pain-generating lesions—particularly when conventional imaging appears normal. Hence, this review aims to provide a concise overview of the current role of MRI in the diagnosis of DCM, and to appraise the emerging potential and inherent limitations of spinal cord DTI, with a specific emphasis on its capacity to detect and localise pain-related pathology.

2. Methods

A narrative review approach was used to synthesise evidence on the diagnostic and pain-related applications of DTI in DCM. Literature was identified through searches of PubMed, EMBASE and Cochrane up to August 2025 using combinations of keywords and MeSH terms including “degenerative cervical myelopathy”, “cervical spondylotic myelopathy”, “diffusion tensor imaging”, “DTI”, “pain”, “microstructure”, and “magnetic resonance imaging”. Reference lists of relevant studies and reviews were also screened to capture additional articles. Original research, systematic reviews, and meta-analyses involving DTI in DCM or related cervical cord pathology were included. Non-MRI studies and non-English publications were excluded. Consistent with the narrative design, no formal evidence grading was applied.

3. Conventional MRI as the Diagnostic Standard for DCM

Conventional MRI remains the preferred first-line investigation of DCM, as it offers direct evidence of spinal cord compression, informs treatment selection, and guides prognostic outcomes. It offers high-resolution visualisation of the spinal cord, intervertebral discs, ligaments, and surrounding soft tissues that are often inaccessible through other imaging techniques [24]. Standard T1- and T2-weighted sequences enable evaluation of key degenerative changes—including disc herniation, facet arthropathy, ligamentum flavum hypertrophy, and ossification of the posterior longitudinal ligament (OPLL) [25–27]. T2-weighted hyperintensity within the cord typically reflects increased water content due to oedema, demyelination, or gliosis and is considered a marker of myelopathic injury [16], while T1-weighted hypointensity and spinal cord atrophy are associated with more chronic and potentially irreversible damage, such as axonal loss and cavitation [24]. Notably, the co-existence of T2 hyperintensity with T1 hypointensity has been associated with more severe clinical deterioration and poorer surgical outcomes than T2 hyperintensity alone [15,28–31]. However, most studies have assessed this combined pattern as a prognostic marker rather than evaluating its diagnostic sensitivity and specificity [32,33].

Despite its central role in diagnostic imaging, conventional MRI has well-established limitations. Crucially, spinal cord compression and signal abnormalities do not consistently correlate with clinical severity or functional impairment [17]. Compression alone is highly sensitive (>98%) but lacks specificity; up to 50% of asymptomatic individuals may demonstrate some degree of cord deformation [34–36]. Conversely, intramedullary T2 hyperintensity is highly specific (~98%) for DCM but is absent in approximately 15–50% of affected individuals, limiting its sensitivity [17,28,37–46]. As such, neither imaging marker, in isolation, is sufficient for diagnosing clinical myelopathy.

Beyond diagnostic confirmation, conventional MRI has also been investigated for its potential to assess disease severity and predict post-operative outcomes. Various indices—including anterior–posterior spinal cord diameter, cross-sectional area (CSA), maximum canal compromise (MCC), and maximum spinal cord compression (MSCC)—have been developed to quantify structural compromise [39,47–49]. Among these, CSA has shown the most consistent correlation with clinical impairment and recovery (using Japanese Orthopedic Association JOA scores and recovery ratio, respectively) [48], though results vary depending on sagittal alignment (e.g., lordosis vs. kyphosis) [49]. Other indices, including MCC and MSCC, have demonstrated more limited prognostic utility, with inconsistent associations with neurological outcomes [39].

Signal-based measures have similarly produced equivocal results. T2 hyperintensity, whilst a recognised biomarker in DCM, its correlation with baseline neurological status and post-operative recovery remains weak [50]. Moreover, there are no clinical correlates of spinal cord signal changes to pain scores, the closest work correlating MRI changes in the spinal column structural elements and spinal cord signal changes was conducted by Sial et al. who demonstrated that intramedullary T2 hyperintensity is independently associated with age, facet joint degeneration, maximum cord compression, and disc herniation width [16]. T1 hypointensity, although less frequently reported, has shown stronger associations with irreversible spinal cord damage, including cavitation and cell loss [51]. Nevertheless, its rarity (reported in only 19–30% of patients) limits its applicability as a routine prognostic marker [51].

An additional consideration is the static nature of conventional MRI. Most scans are acquired in the supine position and may fail to detect dynamic compression that manifests only with flexion or extension [52]. While flexion-extension MRI may reveal clinically relevant pathology in select cases, such imaging is technically challenging due to patient discomfort and motion artefacts during prolonged positioning [52].

Perhaps most fundamentally, conventional MRI is intrinsically limited in its ability to distinguish among overlapping pathological processes—such as demyelination, inflammation, oedema, gliosis, and axonal degeneration—due to the non-specific nature of T1- and T2-weighted signal changes [24]. These limitations significantly curtail the utility of conventional MRI in prognostication and patient stratification.

In view of these constraints, there is a growing imperative for advanced imaging modalities capable of characterising spinal cord microstructure with greater resolution and specificity. Such techniques may facilitate earlier diagnosis, more accurate correlation with clinical presentation—including pain—and improved monitoring of disease progression and treatment response.

4. Diffusion Tensor Imaging in the Spinal Cord

Diffusion-weighted MRI enhances the inherent sensitivity of conventional MRI to the diffusion of water molecules in biological tissues to obtain information about microstructural organisation of the spinal cord, including axons, myelin, and cytoskeletal components that act as barriers to diffusion [53]. The displacement of water molecules is influenced by the cellular and subcellular environment, as structures such as cell membranes, myelin, and cytoskeletal proteins act as physical barriers. In white matter, the longitudinal arrangement of these barriers leads to preferential diffusion along, rather than across, axonal fibres [54]. Axonal membranes contribute most significantly to diffusion anisotropy, followed by the myelin sheath and cytoskeletal elements, including neurofilaments and microtubules [55]. This anisotropic diffusion can be quantified through reconstruction methods of diffusion-weighted images, such as DTI.

DTI is a quantitative MRI technique and is the most widely implemented reconstruction method in diffusion-weighted MRI in neuroimaging, particularly within the brain and central nervous system, due to its availability, relatively short acquisition times, and high reliability [56]. DTI models anisotropic water diffusion in white matter using a diffusion tensor, represented mathematically as an ellipsoid. The three orthogonal axes of the ellipsoid correspond to eigenvectors (v_1, v_2, v_3), with their lengths described by the respective eigenvalues (λ_1, λ_2, λ_3) [57]. From these, several scalar metrics are derived: axial diffusivity (AD; λ_1), representing diffusion parallel to axons; radial diffusivity (RD; mean of λ_2 and λ_3), representing diffusion perpendicular to axons; and mean diffusivity (MD; average of all three eigenvalues), reflecting the overall magnitude of diffusion [57]. The apparent diffusion coefficient (ADC) similarly quantifies overall water diffusion but is calculated without reference to directional information, making it mathematically distinct yet conceptually related to MD. Fractional anisotropy (FA) quantifies the degree of directional diffusion on a scale from 0 (isotropic) to 1 (fully anisotropic) [58].

In the spinal cord, the principal diffusion direction is aligned with white matter tracts due to the predominance of parallel fibre bundles, in contrast to the more complex crossing fibre architecture in the brain [59]. High FA values in a healthy spinal cord reflect the uniform alignment of axons, whereas injury disrupts this organisation [60]. Indeed, reduced FA is a consistent finding at the injury epicentre, while other diffusivity changes vary between studies [58]. Preclinical models have shown that reductions in AD correlate with axonal degeneration, while increases in RD indicate demyelination, with histological confirmation supporting these associations [20–23]. In addition to characterising focal lesions, DTI can detect microstructural changes remote from the injury epicentre, offering a broader assessment of cord integrity [58].

DTI metrics can be assessed quantitatively, with FA and MD most frequently reported, or qualitatively through tractography, which reconstructs three-dimensional white matter fibres using algorithmic post-processing [58]. Importantly, reductions in FA and increases in MD have been shown to correlate with clinical impairment and disease severity, as measured by functional scales such as the modified Japanese Orthopaedic Association (mJOA) score and Nurick grade, supporting the role of DTI in both research and clinical evaluation [58].

First described by Basser and colleagues in 1994 [59], DTI is among the most widely implemented in vivo, non-invasive quantitative MRI techniques for assessing spinal cord white-matter microstructure. Compared with other quantitative MRI modalities—such as magnetisation transfer quantitative T1/T2 mapping, or T2* imaging—DTI offers high sensitivity to axonal and myelin integrity, though each technique provides complementary insights into spinal cord pathology. Notably, DTI can detect early microstructural changes that may precede visible alterations on conventional MRI, making it a valuable tool for the timely assessment of spinal cord injury and degeneration.

5. Diagnostic and Prognostic Utility of DTI in DCM

A substantial body of evidence supports the diagnostic utility of DTI in DCM, particularly through FA and, to a lesser extent, ADC measurements. Across multiple studies, FA has shown strong correlations with established clinical assessment tools such as the modified Japanese Orthopedic Association (mJOA) score, with higher FA at the level of compression predicting better functional recovery following surgical decompression [61–66]. In a prospective longitudinal study, Wang et al. [67] demonstrated that ratio-based DTI metrics—calculated by dividing the absolute DTI value at the most compressed cervical level by that at C1-C2—provided superior diagnostic value compared to absolute metrics, which may be confounded by factors such as age and spinal level.

In terms of diagnostic accuracy, FA consistently outperforms conventional T2-weighted hyperintensity for detecting DCM, with reported sensitivities ranging from 65% to 97% and specificities from 27.6% to 100% (Table 1) [61,68–76]. DTI parameters measured at the site of stenosis have also been shown to better differentiate between asymptomatic and symptomatic DCM patients than somatosensory- or motor-evoked potentials, which assess conduction in sensory and motor pathways, respectively [51,76]. Meta-analytic evidence confirms that DCM patients exhibit lower FA and higher ADC values than healthy controls across a range of imaging protocols and anatomical levels, with both maximal compression (MC) and multi-level averaged measurements demonstrating comparable diagnostic performance [60].

Table 1. Diagnostic accuracy of diffusion tensor imaging (DTI) parameters in degenerative cervical myelopathy (DCM). Abbreviations: DCM: degenerative cervical myelopathy; DTI: diffusion tensor imaging; FA: fractional anisotropy; ADC: apparent diffusion coefficient; MD: mean diffusivity; AD: axial diffusivity; RD: radial diffusivity; MC: maximal compression level; CSM: cervical spondylotic myelopathy. Dashed lines (—) indicates not reported.

Author (Year)	Sample Size (DCM/Controls)	MRI Field Strength	Levels Assessment Strategy	Parameters	Sensitivity (%)	Specificity (%)
Demir (2003) [68]	12/19	1.5T	MC	FA, ADC	FA: 72 ADC: —	FA: 50 ADC: —
Mamata (2005) [69]	40 (mixed age-related and CSM)	1.5T	MC	FA, ADC	FA: ~80 ADC: —	FA: ~60 ADC: —
Facon (2005) [71]	11/15	—	MC	FA, ADC	FA: 73.3 ADC: 13.4	FA: 100 ADC: 80
Keřkovský (2012) [76]	13/52	—	MC	FA, ADC	FA: 65 ADC: 70	FA: 71.9 ADC: 75
Uda (2013) [70]	30/26	3.0T	MC	MD, FA	MD: 100 FA: —	MD: 75 FA: 76
Ellingson (2014) [61]	9/48	3.0T	MC	FA, RD	FA: 72 RD: —	FA: 75 RD: 89.4
Lee (2015) [72]	50/14	3.0T	MC	FA, MD, AD, RD	FA: 100 MD: 100	FA: 27.6 MD: 44.8
Wu (2020) [75]	29/29	—	Mean of several levels	FA, ADC	FA: 75.9 ADC: 96.6	FA: 89.7 ADC: 72.4
Mostafa (2023) [73]	30/60	—	Mean of several levels	FA, ADC	FA: 97 ADC: 88.1	FA: 92.7 ADC: 98
Ragaee (2024) [74]	30 (DCM cohort only)	—	—	FA, ADC, AD, RD	FA: 83.9 ADC: 76.8 AD/RD: —	—

FA has repeatedly been shown to correlate with neurological impairment, as measured by mJOA and Nurick scores [44,61,63,65,66,77], with the strongest associations observed in the lateral columns [78]. Beyond cross-sectional severity, longitudinal studies have further demonstrated that FA can detect disease progression [79]; for example, Martin et al. [80] observed FA reductions at, above, and below the stenotic segment over a one-year period in patients with mild, non-operatively managed DCM. Importantly, similar alterations in FA, MD, AD, and RD have been detected in regions rostral and caudal to the compression site, including the upper cervical cord and lumbosacral enlargement [66,77,78,80–84]. Whilst these changes are typically most pronounced at the stenosis, their presence in remote segments supports the concept of anterograde and retrograde axonal degeneration affecting dorsal sensory pathways, lateral corticospinal tracts, and possibly other cord structures [85,86].

While FA is a sensitive marker of microstructural disruption and disease severity, its prognostic value remains less consistent. Several studies, including those by Wen et al., [66] have reported higher preoperative FA to be associated with better postoperative recovery ratios; however, meta-analytic findings indicate that FA is more reliable for assessing preoperative disease severity than for predicting outcomes after decompression [60]. In contrast, ADC appears to correlate more robustly with postoperative functional improvement, despite showing weaker or absent correlations with preoperative symptom severity [87]. This distinction may have important implications for clinical decision-making, particularly in mild DCM, where surgical indications remain debated. If validated in future research, ADC could serve as a prognostic biomarker to guide surgical selection, while FA may remain the preferred parameter for staging disease severity and monitoring progression.

6. Unexplored Relationships Between DTI Metrics and Pain

Pain, particularly neck pain, is a sensitive (76–94%) and specific (11–73%) symptom of DCM [7]. Yet relatively few studies have examined the association between DTI parameters and pain, despite pain being a common, debilitating, and diagnostically ambiguous symptom in DCM. It is worth noting that in DCM, axial neck pain and radicular arm pain represent two distinct yet often overlapping pain phenotypes with different neuroanatomical substrates. Axial pain is typically segmental, originating from disc degeneration, facet arthropathy, or ligamentous strain, and may involve the dorsal horn or medial dorsal column pathways [1,88]. In contrast, radicular pain reflects root or tract-level pathology, most likely mediated by spinothalamic tract disruption or anterior horn compression [89].

Nevertheless, in other neurological and pain-related disorders, DTI has been successfully applied to detect microstructural alterations linked to pain presence, severity, and chronicity. In trigeminal neuralgia, combined DTI and diffusion kurtosis imaging of the cisternal trigeminal nerve revealed reduced FA, mean kurtosis (MK; reflecting overall tissue complexity), and radial kurtosis (Kr; reflecting myelin integrity), with increased apparent diffusion coefficient (ADC) on the symptomatic side [90]. The FA difference ratio achieved excellent diagnostic accuracy (AUC $\approx$ 0.97; 100% sensitivity; 95% specificity), underscoring the ability of diffusion metrics to capture pain-related tissue change [90].

In the brainstem, automated tractography of nine pain-modulatory pathways identified inverse correlations between FA and pain severity—most prominently in the dorsal and medial longitudinal fasciculi—with complementary alterations in axial and radial diffusivities [91]. Longitudinal studies in urologic chronic pelvic pain syndrome from the MAPP Network have demonstrated reproducible microstructural abnormalities correlating with pain severity over several years, highlighting the potential of DTI as a stable imaging biomarker in chronic pain [92].

Spinal cord DTI has also shown relevance. In post-herpetic neuralgia, patients with persistent pain displayed significant FA reductions and ADC elevations at affected levels, consistent with chronic neuropathic injury [93]. Studies of cervical cord compression and myelopathy have similarly reported FA loss and tractographic abnormalities at the stenosis site, correlating with symptom duration [75]. Across chronic pain research, quantitative DTI methods—including region-of-interest analysis of predefined anatomical areas, tract-based spatial statistics enabling voxel-wise group comparisons, and tractography reconstructing three-dimensional fibre pathways—consistently implicate FA, ADC/MD, RD, and AD as sensitive markers of pain-related microstructural change [75]. However, these findings remain disease-specific and cannot be directly extrapolated to DCM, where the anatomical substrates and pain mechanisms differ.

Although pain-specific DTI research in DCM is sparse, early work is promising. Yoo et al. [94] stratified patients into classical myelopathic and pain-dominant subgroups.

While T2-weighted MRI findings were comparable, DTI revealed significantly higher ADC values across anterior, lateral, and posterior cord regions in the pain-dominant group, with only mild, non-significant FA reductions—indicating that DTI can detect pain-associated injury invisible to conventional imaging [94]. Yet, because pain was not subtyped into axial versus radicular categories, the specific microstructural correlates underlying these findings remain uncertain. Vallotton et al. [95] reported that elevated MD, RD, and AD in the upper cervical cord correlated with reduced pain thresholds in C6/C8 dermatomes ($r \approx -0.56$ to -0.65), even in the absence of T2 hyperintensities, suggesting DTI can detect sensory pathway disruption beyond the compression site [95]. This provides preliminary evidence that DTI can capture sensory pathway disruption relevant to radicular pain. However, the study did not concurrently assess axial pain, leaving unclear whether these changes are phenotype-specific or represent generalised cord involvement. Case reports by Nukala et al. [96] further demonstrate that patients with chronic neck pain and subtle myelopathy can exhibit FA reductions and ADC increases on tensor maps, which are not visible on conventional MRI. While provocative, these isolated cases highlight the need for larger, systematically stratified cohorts before conclusions about phenotype-specific DTI signatures can be drawn.

Tract-specific approaches provide mechanistic insight. Qiu et al. [97] investigated the spinothalamic tract in patients with chronic neck and shoulder pain, a symptom complex relevant to DCM. Segmental analysis revealed significantly reduced FA and increased MD in the cervical spinothalamic tract, most marked at C5 and C1–C2. FA was inversely correlated, and MD was positively correlated, with pain intensity and duration [97]. These changes were also associated with anxiety and depression scores, suggesting that persistent nociceptive input may drive demyelination, axonal injury, and maladaptive neuroplasticity, contributing to central sensitisation [97]. However, the study design did not explicitly differentiate between axial and radicular subgroups, limiting the interpretability of these tract-specific findings.

Despite such findings, pain measurement in DCM DTI studies is inconsistent. Commonly used instruments with embedded pain criteria—such as the modified Prolo-score, European Myelopathy Score (EMS), Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire (JOACMEQ, QOL domain), EQ-5D, SF-12, SF-36, and WHOQOL-Bref—typically capture pain as a single subdomain within broader functional assessments. Pain-specific measures, including the visual analogue scale (VAS), Neck Disability Index (NDI), arm pain scores, neck pain scores, and QuickDASH, are seldom applied, and their relationship with DTI parameters has rarely been analysed. Moreover, most composite severity scores prioritise funicular myelopathic symptoms (e.g., gait disturbance, hand dysfunction) and show limited correlation with pain, paraesthesia, reflex changes, or muscle tone abnormalities—meaning improvements in these scores may not reflect meaningful changes in pain or quality of life [98].

Collectively, current evidence indicates that DTI—particularly FA and MD—can detect pain-related microstructural alterations in DCM at and beyond the site of compression, with emerging data implicating the spinothalamic tract, and in selected studies, the dorsal columns, as key pathways [78,84]. However, these observations remain inconsistent, reflecting methodological heterogeneity and the limited incorporation of pain-specific outcome measures. Furthermore, a recurring limitation across studies is the failure to clearly define and stratify pain phenotypes. Axial neck pain, often linked to segmental degeneration, and radicular upper limb pain, more reflective of tract or root-level injury, remain conflated in most analyses [5]. This ambiguity obscures whether reported diffusion abnormalities correspond to axial, radicular, or mixed pain, restricting clinical translation. To improve comparability, future DCM–DTI studies should include a minimum core pain assessment set, such as the VAS (neck

and arm), NDI, DN4, and QuickDASH, combined with pre-registration of participants into pain-predominant, motor-predominant, or mixed phenotypes. Future research must also pair them with tract-focused analyses to delineate the neuroanatomical substrates of different pain types in DCM. Such an approach will be critical for moving from descriptive associations to clinically actionable, mechanistic insights.

7. Methodological and Interpretative Barriers in DCM

While the emerging evidence linking DTI metrics to clinical outcomes in DCM is promising, several methodological and interpretative barriers limit its current applicability. Many existing studies are constrained by small sample sizes, suboptimal study designs, potential selection bias, and insufficient blinding when evaluating novel imaging approaches [18]. Moreover, current evidence is largely derived from studies in typical DCM cohorts, with limited representation of patients with comorbid conditions or atypical presentations [99]. Furthermore, variability in MRI hardware further complicates interpretation; studies conducted at 1.5T are inherently limited by a lower signal-to-noise ratio and reduced spatial resolution compared to 3T systems, impairing the sensitivity of DTI to detect subtle microstructural changes [96,99]. Although spatial resolution can be adjusted through acquisition parameters.

From a technical standpoint, spinal cord DTI demands high spatial resolution and is particularly susceptible to motion artefacts, partial volume effects, and inter-study variability in acquisition protocols [100]. These factors contribute to measurement inconsistency, complicating both intra- and inter-centre comparisons [24]. Many studies employ only a single axial slice at the level of maximal compression, which risks missing diffuse or remote microstructural changes that may contribute to pain, especially when pain arises from tract involvement beyond the focal stenotic segment [101]. Furthermore, DTI indices provide an indirect representation of tissue pathology and may be influenced by confounding variables such as ageing, inflammation, or comorbid neurological conditions, which are seldom systematically controlled for in existing work [23]. Establishing normative datasets and standardising acquisition and processing pipelines are therefore essential prerequisites for clinical translation.

As outlined in the preceding section, most DCM studies employing DTI have relied on global severity or quality-of-life instruments, which include pain as one component of a composite score but do not measure it as an independent construct. Similarly, validated pain-specific tools (e.g., VAS, NDI) have rarely been incorporated into imaging studies. Even in studies that do measure pain, cohorts are seldom stratified by pain severity or phenotype, limiting the ability to identify microstructural signatures unique to pain-dominant presentations. Without the use of targeted and stratified pain metrics, it becomes challenging to disentangle whether diffusion changes are driven by pain domains that may evolve independently in DCM, including motor impairment, or broader disability. Consequently, the absence of such measures limits the ability to establish clinically meaningful associations between microstructural alterations and the pain experience in DCM.

Beyond the technical challenges lies a conceptual gap in how pain is studied within DCM. Most neuroimaging research on neuropathic pain—particularly following spinal cord injury—has focused on brain-level changes, mapping alterations in pain-processing networks and identifying cortical and subcortical correlates of pain perception [102]. While informative, these approaches do not directly interrogate spinal cord pathology. Conversely, spinal cord DTI studies in DCM have tended to focus on compression-related injury without integrating broader cognitive, affective, and psychosocial factors known to shape the pain experience [103]. This disconnects risks underestimating the complexity of pain in DCM.

Moreover, the potential of specific DTI indices to elucidate neuropathic pain mechanisms remains largely theoretical in DCM. Motor deficits in DCM largely reflect corticospinal tract and dorsal column pathology, whereas pain—particularly neuropathic pain—may arise from injury to spinothalamic pathways, altered central processing, and secondary neuroplastic changes [57]. Yet most DTI studies to date have not attempted to separate these dimensions in their analyses. The challenge is compounded by the fact that FA, the most reported DTI metric, is non-directional and does not localise tract-specific degeneration [104]. This is a significant limitation, as dorsal column versus spinothalamic tract involvement has markedly different implications for pain generation and persistence [105]. While tractography and tract-based spatial statistics permit localisation, these methods are less frequently applied in the spinal cord. Moreover, the presence of crossing fibres—even less common in the cord than the brain—further complicates interpretation, as apparent increases in FA may reflect loss of perpendicular fibres rather than true improvements in tract integrity, risking false-positive conclusions (e.g., post-surgery) [106,107].

In related neurological conditions, reductions in FA have been linked to disruption of sensory pathways and central sensitisation; increases in MD reflect extracellular water accumulation from oedema or chronic inflammation, both implicated in aberrant pain signalling; reductions in AD correspond to axonal injury in pathways such as the dorsal columns and spinothalamic tracts; and elevations in RD suggest demyelination, a hallmark of neuropathic pain associated with sensory disinhibition [108]. These pathophysiological signatures have yet to be systematically investigated in DCM, leaving a critical knowledge gap regarding how microstructural injury maps onto pain-specific clinical outcomes.

A concise synthesis of key DTI metrics, their pathophysiological significance, pain-related clinical correlates, and current methodological limitations is provided in Table 2. Incorporating such multidimensional frameworks will be essential for capturing the full complexity of pain in this patient population.

Table 2. Summary of key DTI metrics, pain-related clinical correlates, evidence source/level and study limitations in DCM. Abbreviations: FA: fractional anisotropy; MD: mean diffusivity; AD: axial diffusivity; RD: radial diffusivity; VAS: Visual Analogue Scale; NDI: Neck Disability Index; DN4: Douleur Neuropathique 4; SF-36: Short Form-36. Arrow (↑) indicates increased.

DTI Metric	Pathophysiological Interpretation	Key Clinical Correlate	Pain Outcome Used	Evidence Source/Level	Main Limitation
Fractional Anisotropy (FA)	Integrity and degree of coherence of white matter tracts	Reduced FA in dorsal columns linked to sensory pathway disruption and central sensitisation	VAS, NDI, SF-36 pain subscale	Mixed evidence—DCM-specific [61,66] and cross-condition extrapolation from neuropathic pain [92]	Non-directional; limited tract specificity due to crossing fibres; like other diffusion metrics, FA is sensitive but not specific to the underlying pathology (e.g., demyelination vs. axonal loss).
Mean Diffusivity (MD)	Overall water mobility; ↑ MD suggests oedema or chronic inflammation	Higher MD associated with poorer function and neuropathic pain features	VAS, DN4	DCM-specific	Susceptible to ageing and comorbidity effects
Axial Diffusivity (AD)	Axonal integrity	Lower AD associated with dorsal column/spinothalamic tract injury	VAS, NDI	DCM-specific and experimental confirmation in animal models	Rarely stratified by pain phenotype
Radial Diffusivity (RD)	Myelin integrity; ↑ RD indicates demyelination	Elevated RD implicated in neuropathic pain mechanisms	VAS, DN4	Cross-condition extrapolation (post-herpetic neuralgia, chronic pain models)	Limited pain-specific DCM research

8. Future Directions: DTI as a Pain—Specific Imaging Biomarker in DCM

While DTI has demonstrated value in quantifying spinal cord microstructural changes in DCM, its application to pain-specific pathology remains limited. Pain in DCM is often diagnostically ambiguous, poorly captured by conventional severity scales, and inadequately

stratified in imaging studies. Future research must therefore move beyond broad myelopathy indices to designs that explicitly integrate pain as a primary outcome, enabling more precise characterisation of its neuroanatomical correlates. These studies should combine tract-specific DTI with validated pain instruments and longitudinal designs, enabling a more precise understanding of the neurobiological underpinnings of pain in DCM and its broader quality-of-life implications.

One promising avenue lies in prospective longitudinal studies that combine DTI with validated pain assessment tools, such as VAS, the Neuropathic Pain Symptom Inventory, or disease-specific QoL measures. Stratifying participants into motor-predominant, pain-predominant, and mixed phenotypes would help disentangle the distinct contributions of microstructural changes to sensory versus motor impairment. Similarly, cross-sectional comparisons between pain-stratified cohorts could clarify whether degeneration in specific tracts, such as the dorsal columns or spinothalamic pathways, maps to distinct pain mechanisms. This tract-specific approach may improve localisation but does not resolve the intrinsic limitations of FA as a non-directional scalar metric that summarises anisotropy across all three eigenvalues. Its interpretation is model-dependent and context-sensitive, requiring consideration of underlying tissue geometry and acquisition parameters. Advanced diffusion models such as DKI may help mitigate these limitations by characterising non-Gaussian water diffusion, thereby enhancing the accuracy of spinal cord microstructural assessment [19]. While tract-specific methods can enhance anatomical specificity, the interpretation of FA, AD, or RD alone remains problematic, as these indices measure diffusion in only one direction and are therefore prone to false positives or negatives. Incorporating multidirectional measures such as MD or ADC provides critical complementary information; for example, unchanged FA may mask diffuse injury if proportional changes occur across all axes, whereas corresponding reductions in MD or ADC would reveal underlying pathology.

In parallel, retrospective analyses of existing datasets offer an efficient method to explore latent DTI-pain associations. Re-examining studies that include DTI and multi-domain clinical scales, such as the mJOA, JOACMEQ, or EQ-5D, could reveal patterns that have been unexplored when pain data are aggregated into composite severity scores.

Emerging computational approaches further expand these possibilities. Artificial intelligence (AI) has the potential to automate tract segmentation, standardise acquisition variability, and detect voxel-level signal heterogeneity associated with central sensitisation [109,110]. In addition, AI models may directly and more accurately estimate diffusion parameters by compensating for noise, motion artefacts, and acquisition inconsistencies, thereby improving the precision of DTI quantification. This could facilitate the identification of imaging-defined pain phenotypes and enable predictive modelling of pain evolution or treatment response, as represented in Figure 1. However, several barriers currently constrain clinical implementation, including heterogeneity in acquisition protocols, the absence of large, annotated datasets, and the risk of algorithmic overfitting, all of which limit reproducibility across centres [111]. Given that DTI abnormalities can extend beyond the site of compression, multi-slice or volumetric acquisitions are recommended to better capture diffuse microstructural changes relevant to pain and disease severity. Nonetheless, AI-driven approaches remain promising avenues for future research and may ultimately enable robust, clinically translatable imaging biomarkers. Complementary to this, the Decay Variance (DeVa) technique offers a low-burden method for quantifying microstructural heterogeneity from standard MRI sequences [112]. By capturing subtle tissue changes linked to aberrant sensory processing, DeVa may serve as a valuable adjunct to DTI in localising pain generators; however, further validation in the cervical spine is needed.

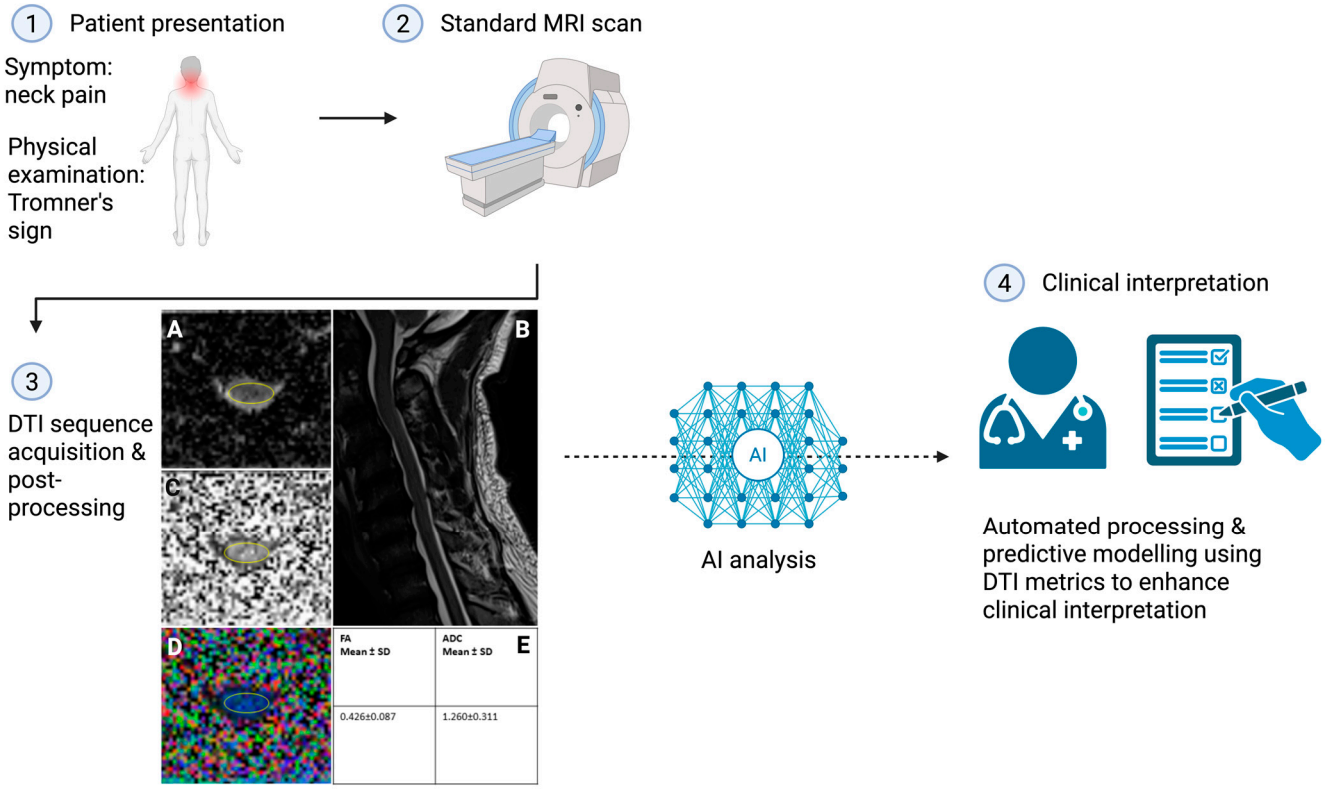


Figure 1. Schematic of clinical-to-imaging workflow in DCM with integration of AI-enhanced post-processing of DTI metrics. AI algorithms may support automated analysis, pattern detection, and prognostic modelling to aid clinical decision-making. (**A**) Diffusion weighted image at C5–C6 level (3 mm slice thickness; 3.0 T system; b = 1000 s/mm^2; matrix 128 × 130) with ROI in place (yellow circle). (**B**) T2 sagittal image shows posterior disc bulge at C5–C6 level in a 53-year-old male with chronic neck pain and a mJOA 15. (**C**) FA image at this level with ROI in place over the region of maximal compression while avoiding partial-volume artefacts. (Yellow circle). (**D**) FA colour map image at the same level. (**E**) FA and ADC values calculated at this level show decreased FA value and increased ADC value at the level of the stenotic segment. Abbreviations: MRI: magnetic resonance imaging; DTI: Diffusion tensor imaging; FA: Fractional anisotropy; SD: Standard deviation; ADC: Apparent diffusion coefficient; AI: artificial intelligence; DCM: Degenerative cervical myelopathy; ROI: Region of interest; mJOA: Modified Japanese Orthopaedic Association. Created in Biorender. Sharma, S. (2025).

The convergence of these strategies—pain-focused study designs, tract-specific imaging, AI-driven analytics, and multi-parametric biomarkers—offers a pathway toward developing DTI as a clinically viable, pain-specific imaging tool in DCM. Realising this potential will require the establishment of standardised acquisition and analysis protocols, multicentre collaborative datasets, and the systematic inclusion of pain endpoints in both prospective and retrospective research. Such an approach may ultimately enable earlier identification of pain-dominant phenotypes, more accurate prognostic stratification, and tailored interventions to optimise patient outcomes.

9. Conclusions

Pain in DCM is under-explored in imaging studies, limiting understanding of its mechanisms and impact. DTI can reveal microstructural changes beyond conventional MRI and holds potential as a pain-specific biomarker; however, inconsistent methodology, the lack of pain-stratified cohorts, and reliance on non-specific scales hinder clinical translation. Standardised protocols, validated pain measures, and advanced analytics, such as AI-driven

modelling and voxel-wise metrics, may enable exploration of patient-centred outcomes and facilitate earlier, more targeted interventions.

Author Contributions: Writing—original draft preparation, visualization, investigation, formal analysis, and methodology, S.S.; writing—review and editing, A.S. and G.E.B.; conceptualization, supervision, project administration, validation, resources, and funding acquisition, R.O.D. and A.D.D. All authors have read and agreed to the published version of the manuscript.

Funding: Spine Labs, Sydney is supported by unrestricted research grants from Baxter inc. and Globus/Nuvasive inc. Spine Labs Adelaide is supported by research donations from Spine Service Pty Ltd. & Evolution Surgical. Internal funding via unrestricted foundational grant from the faculty of Health & Medical Sciences University of Adelaide. A.S. and G.E.B are supported by a Research Training Scholarship from the Australian Government.

Conflicts of Interest: The authors declare no conflicts of interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AD	Axial diffusivity
ADC	Apparent diffusion coefficient
AI	Artificial intelligence
AUC	Area under the curve
CSA	Cross-sectional area
CSM	Cervical spondylotic myelopathy
DCM	Degenerative cervical myelopathy
DeVa	Decay variance
DN4	Douleur Neuropathique 4
DTI	Diffusion tensor imaging
EMS	European Myelopathy Score
EQ-5D	EuroQol 5-Dimension Questionnaire
FA	Fractional anisotropy
JOA	Japanese Orthopaedic Association
JOACMEQ	Japanese Orthopaedic Association Cervical Myelopathy Evaluation Questionnaire
Kr	Radial kurtosis
MCC	Maximum canal compromise
MD	Mean diffusivity
MK	Mean kurtosis
MRI	Magnetic resonance imaging
MSCC	Maximum spinal cord compression
mJOA	Modified Japanese Orthopaedic Association
NDI	Neck Disability Index
OPLL	Ossification of the posterior longitudinal ligament
QOL	Quality of life
RD	Radial diffusivity
ROI	Region of interest
SD	Standard deviation
SF-12	Short form-12
SF-36	Short form-36
VAS	Visual Analogue Scale

References

1. Nouri, A.; Tetreault, L.; Singh, A.; Karadimas, S.K.; Fehlings, M.G. Degenerative Cervical Myelopathy: Epidemiology, Genetics, and Pathogenesis. *Spine* **2015**, *40*, E675–E693. [CrossRef]
2. Akter, F.; Yu, X.; Qin, X.; Yao, S.; Nikrouz, P.; Syed, Y.A.; Kotter, M. The pathophysiology of degenerative cervical myelopathy and the physiology of recovery following decompression. *Front. Neurosci.* **2020**, *14*, 138.
3. Sharma, S.; Sial, A.; Sima, S.; Aggarwal, A.; Yull, D.; Diwan, A. Making the diagnosis of degenerative cervical myelopathy in clinical practice: Essential evidence-based examination tools for healthcare practitioners. *J. Clin. Neurosci.* **2025**, *137*, 111297. [CrossRef] [PubMed]
4. Davies, B.M.; Yang, X.; Khan, D.Z.; Mowforth, O.D.; Touzet, A.Y.; Nouri, A.; Harrop, J.S.; Aarabi, B.; Rahimi-Movaghar, V.; Kurpad, S.N.; et al. A minimum data set-Core outcome set, core data elements, and core measurement set-For degenerative cervical myelopathy research (AO Spine RECODE DCM): A consensus study. *PLoS Med.* **2024**, *21*, e1004447. [CrossRef]
5. Sial, A.W.; Sima, S.; Narulla, R.; Najib, N.; Davies, M.; Diwan, A.D. Is neck pain a marker for something serious? Like myelopathy. *Spinal Cord* **2024**, *62*, 718–720. [CrossRef]
6. Badhiwala, J.H.; Ahuja, C.S.; Akbar, M.A.; Witiw, C.D.; Nassiri, F.; Furlan, J.C.; Curt, A.; Wilson, J.R.; Fehlings, M.G. Degenerative cervical myelopathy—Update and future directions. *Nat. Rev. Neurol.* **2020**, *16*, 108–124. [CrossRef] [PubMed]
7. Sharma, S.; Sial, A.; Sima, S.; Diwan, A. Clinical signs and symptoms for degenerative cervical myelopathy: A scoping review of case-control studies to facilitate early diagnosis among healthcare professionals with stakeholder engagement. *Spinal Cord* **2025**, *63*, 171–180. [CrossRef]
8. Davies, B.M.; Mowforth, O.D.; Smith, E.K.; Kotter, M.R. Degenerative cervical myelopathy. *BMJ* **2018**, *360*, k186. [CrossRef] [PubMed]
9. Fehlings, M.G.; Tetreault, L.A.; Kurpad, S.; Brodke, D.S.; Wilson, J.R.; Smith, J.S.; Arnold, P.M.; Brodt, E.D.; Dettori, J.R. Change in functional impairment, disability, and quality of life following operative treatment for degenerative cervical myelopathy: A systematic review and meta-analysis. *Glob. Spine J.* **2017**, *7*, 53S–69S. [CrossRef]
10. Karadimas, S.K.; Erwin, W.M.; Ely, C.G.; Dettori, J.R.; Fehlings, M.G. Pathophysiology and natural history of cervical spondylotic myelopathy. *Spine* **2013**, *38*, S21–S36. [CrossRef]
11. Rodrigues-Pinto, R.; Montenegro, T.S.; Davies, B.M.; Kato, S.; Kawaguchi, Y.; Ito, M.; Zileli, M.; Kwon, B.K.; Fehlings, M.G.; Koljonen, P.A. Optimizing the application of surgery for degenerative cervical myelopathy [AO Spine RECODE-DCM Research Priority Number 10]. *Glob. Spine J.* **2022**, *12*, 147S–158S. [CrossRef]
12. Tetreault, L.; Côté, P.; Kopjar, B.; Arnold, P.; Fehlings, M. AOSpine North America and International Clinical Trial Research Network. A clinical prediction model to assess surgical outcome in patients with cervical spondylotic myelopathy: Internal and external validations using the prospective multicenter AOSpine North American and international datasets of 743 patients. *Spine J.* **2015**, *15*, 388–397.
13. Behrbalk, E.; Salame, K.; Regev, G.J.; Keynan, O.; Boszczyk, B.; Lidar, Z. Delayed diagnosis of cervical spondylotic myelopathy by primary care physicians. *Neurosurg. Focus* **2013**, *35*, E1. [CrossRef]
14. Sadasivan, K.K.; Reddy, R.P.; Albright, J. The natural history of cervical spondylotic myelopathy. *Yale J. Biol. Med.* **1993**, *66*, 235.
15. Nouri, A.; Martin, A.R.; Kato, S.; Reihani-Kermani, H.; Riehm, L.E.; Fehlings, M.G. The Relationship Between MRI Signal Intensity Changes, Clinical Presentation, and Surgical Outcome in Degenerative Cervical Myelopathy: Analysis of a Global Cohort. *Spine* **2017**, *42*, 1851–1858. [CrossRef]
16. Sial, A.W.; Sima, S.; Chen, X.; Saulys, C.; Kuan, J.; Davies, M.; Diwan, A.D. Spinal column radiological factors associated with increased spinal cord intramedullary signal intensity—A study evaluating aging spinal cord's relation to spinal disc degeneration. *J. Clin. Neurosci.* **2024**, *126*, 86–94. [CrossRef] [PubMed]
17. Harrop, J.S.; Naroji, S.; Maltenfort, M.; Anderson, D.G.; Albert, T.; Ratliff, J.K.; Ponnappan, R.K.; Rihn, J.A.; Smith, H.E.; Hilibrand, A.; et al. Cervical myelopathy: A clinical and radiographic evaluation and correlation to cervical spondylotic myelopathy. *Spine* **2010**, *35*, 620–624. [CrossRef]
18. He, B.; Sheldrick, K.; Das, A.; Diwan, A. Clinical and Research MRI Techniques for Assessing Spinal Cord Integrity in Degenerative Cervical Myelopathy-A Scoping Review. *Biomedicines* **2022**, *10*, 2621. [CrossRef] [PubMed]
19. Liu, Z.; Bian, B.; Wang, G.; Tian, C.; Lv, Z.; Shao, Z.; Li, D. Evaluation of microstructural changes in spinal cord of patients with degenerative cervical myelopathy by diffusion kurtosis imaging and investigate the correlation with JOA score. *BMC Neurol.* **2020**, *20*, 185. [CrossRef]
20. Budde, M.D.; Kim, J.H.; Liang, H.F.; Schmidt, R.E.; Russell, J.H.; Cross, A.H.; Song, S.K. Toward accurate diagnosis of white matter pathology using diffusion tensor imaging. *Magn. Reson. Med.* **2007**, *57*, 688–695. [CrossRef] [PubMed]
21. Kim, J.H.; Loy, D.N.; Liang, H.F.; Trinkaus, K.; Schmidt, R.E.; Song, S.K. Noninvasive diffusion tensor imaging of evolving white matter pathology in a mouse model of acute spinal cord injury. *Magn. Reson. Med.* **2007**, *58*, 253–260. [CrossRef] [PubMed]
22. Kozlowski, P.; Raj, D.; Liu, J.; Lam, C.; Yung, A.C.; Tetzlaff, W. Characterizing white matter damage in rat spinal cord with quantitative MRI and histology. *J. Neurotrauma* **2008**, *25*, 653–676. [CrossRef]

23. Xie, M.; Wang, Q.; Wu, T.H.; Song, S.K.; Sun, S.W. Delayed axonal degeneration in slow Wallerian degeneration mutant mice detected using diffusion tensor imaging. *Neuroscience* **2011**, *197*, 339–347. [CrossRef] [PubMed]
24. Nouri, A.; Martin, A.R.; Mikulis, D.; Fehlings, M.G. Magnetic resonance imaging assessment of degenerative cervical myelopathy: A review of structural changes and measurement techniques. *Neurosurg. Focus* **2016**, *40*, E5. [CrossRef]
25. Nagata, K.; Kiyonaga, K.; Ohashi, T.; Sagara, M.; Miyazaki, S.; Inoue, A. Clinical value of magnetic resonance imaging for cervical myelopathy. *Spine* **1990**, *15*, 1088–1096. [CrossRef]
26. Sun, Q.; Hu, H.; Zhang, Y.; Li, Y.; Chen, L.; Chen, H.; Yuan, W. Do intramedullary spinal cord changes in signal intensity on MRI affect surgical opportunity and approach for cervical myelopathy due to ossification of the posterior longitudinal ligament? *Eur. Spine J.* **2011**, *20*, 1466–1473. [CrossRef] [PubMed]
27. Yang, Y.M.; Yoo, W.K.; Yoo, J.H.; Kwak, Y.H.; Oh, J.K.; Song, J.S.; Kim, S.W. The functional relevance of diffusion tensor imaging in comparison to conventional MRI in patients with cervical compressive myelopathy. *Skelet. Radiol.* **2017**, *46*, 1477–1486. [CrossRef]
28. Mastronardi, L.; Elsawaf, A.; Roperto, R.; Bozzao, A.; Caroli, M.; Ferrante, M.; Ferrante, L. Prognostic relevance of the post-operative evolution of intramedullary spinal cord changes in signal intensity on magnetic resonance imaging after anterior decompression for cervical spondylotic myelopathy. *J. Neurosurg. Spine* **2007**, *7*, 615–622. [CrossRef]
29. Nouri, A.; Tetreault, L.; Côté, P.; Zamorano, J.J.; Dalzell, K.; Fehlings, M.G. Does Magnetic Resonance Imaging Improve the Predictive Performance of a Validated Clinical Prediction Rule Developed to Evaluate Surgical Outcome in Patients with Degenerative Cervical Myelopathy? *Spine* **2015**, *40*, 1092–1100. [CrossRef]
30. Yagi, M.; Ninomiya, K.; Kihara, M.; Horiuchi, Y. Long-term surgical outcome and risk factors in patients with cervical myelopathy and a change in signal intensity of intramedullary spinal cord on Magnetic Resonance imaging. *J. Neurosurg. Spine* **2010**, *12*, 59–65. [CrossRef]
31. Yukawa, Y.; Kato, F.; Yoshihara, H.; Yanase, M.; Ito, K. MR T2 image classification in cervical compression myelopathy: Predictor of surgical outcomes. *Spine* **2007**, *32*, 1675–1678. [CrossRef] [PubMed]
32. Chatley, A.; Kumar, R.; Jain, V.K.; Behari, S.; Sahu, R.N. Effect of spinal cord signal intensity changes on clinical outcome after surgery for cervical spondylotic myelopathy: Clinical article. *J. Neurosurg. Spine* **2009**, *11*, 562–567. [CrossRef]
33. Zhang, C.; Das, S.K.; Yang, D.J.; Yang, H.F. Application of magnetic resonance imaging in cervical spondylotic myelopathy. *World J. Radiol.* **2014**, *6*, 826–832. [CrossRef]
34. Kato, F.; Yukawa, Y.; Suda, K.; Yamagata, M.; Ueta, T. Normal morphology, age-related changes and abnormal findings of the cervical spine. Part II: Magnetic resonance imaging of over 1200 asymptomatic subjects. *Eur. Spine J.* **2012**, *21*, 1499–1507. [CrossRef]
35. Martin, A.R.; De Leener, B.; Cohen-Adad, J.; Cadotte, D.W.; Nouri, A.; Wilson, J.R.; Tetreault, L.; Crawley, A.P.; Mikulis, D.J.; Ginsberg, H.; et al. Can microstructural MRI detect subclinical tissue injury in subjects with asymptomatic cervical spinal cord compression? A prospective cohort study. *BMJ Open* **2018**, *8*, e019809. [CrossRef]
36. Smith, S.S.; Stewart, M.E.; Davies, B.M.; Kotter, M.R.N. The Prevalence of Asymptomatic and Symptomatic Spinal Cord Compression on Magnetic Resonance Imaging: A Systematic Review and Meta-analysis. *Glob. Spine J.* **2021**, *11*, 597–607. [CrossRef]
37. Chen, C.J.; Lyu, R.K.; Lee, S.T.; Wong, Y.C.; Wang, L.J. Intramedullary high signal intensity on T2-weighted MR images in cervical spondylotic myelopathy: Prediction of prognosis with type of intensity. *Radiology* **2001**, *221*, 789–794. [CrossRef]
38. Nakashima, H.; Yukawa, Y.; Ito, K.; Machino, M.; Kanbara, S.; Morita, D.; Takahashi, H.; Imagama, S.; Ito, Z.; Ishiguro, N.; et al. Prediction of lower limb functional recovery after laminoplasty for cervical myelopathy: Focusing on the 10-s step test. *Eur. Spine J.* **2012**, *21*, 1389–1395. [CrossRef]
39. Nouri, A.; Tetreault, L.; Zamorano, J.J.; Dalzell, K.; Davis, A.M.; Mikulis, D.; Yee, A.; Fehlings, M.G. Role of magnetic resonance imaging in predicting surgical outcome in patients with cervical spondylotic myelopathy. *Spine* **2015**, *40*, 171–178. [CrossRef] [PubMed]
40. Shin, J.J.; Jin, B.H.; Kim, K.S.; Cho, Y.E.; Cho, W.H. Intramedullary high signal intensity and neurological status as prognostic factors in cervical spondylotic myelopathy. *Acta Neurochir.* **2010**, *152*, 1687–1694. [CrossRef] [PubMed]
41. Singh, A.; Crockard, H.A.; Platts, A.; Stevens, J. Clinical and radiological correlates of severity and surgery-related outcome in cervical spondylosis. *J. Neurosurg.* **2001**, *94*, 189–198. [CrossRef]
42. Suri, A.; Chabbra, R.P.; Mehta, V.S.; Gaikwad, S.; Pandey, R.M. Effect of intramedullary signal changes on the surgical outcome of patients with cervical spondylotic myelopathy. *Spine J.* **2003**, *3*, 33–45. [CrossRef]
43. Uchida, K.; Nakajima, H.; Sato, R.; Kokubo, Y.; Yayama, T.; Kobayashi, S.; Baba, H. Multivariate analysis of the neurological outcome of surgery for cervical compressive myelopathy. *J. Orthop. Sci.* **2005**, *10*, 564–573. [CrossRef]
44. Vedantam, A.; Jonathan, A.; Rajshekhar, V. Association of magnetic resonance imaging signal changes and outcome prediction after surgery for cervical spondylotic myelopathy. *J. Neurosurg. Spine* **2011**, *15*, 660–666. [CrossRef]
45. Wada, E.; Yonenobu, K.; Suzuki, S.; Kanazawa, A.; Ochi, T. Can intramedullary signal change on magnetic resonance imaging predict surgical outcome in cervical spondylotic myelopathy? *Spine* **1999**, *24*, 455–461. [CrossRef] [PubMed]

46. Salem, H.M.; Salem, K.M.; Burget, F.; Bommireddy, R.; Klezl, Z. Cervical spondylotic myelopathy: The prediction of outcome following surgical intervention in 93 patients using T1- and T2-weighted MRI scans. *Eur. Spine J.* **2015**, *24*, 2930–2935. [CrossRef]
47. Martin, A.R.; De Leener, B.; Cohen-Adad, J.; Cadotte, D.W.; Kalsi-Ryan, S.; Lange, S.F.; Tetreault, L.; Nouri, A.; Crawley, A.; Mikulis, D.J.; et al. A Novel MRI Biomarker of Spinal Cord White Matter Injury: T2*-Weighted White Matter to Gray Matter Signal Intensity Ratio. *AJNR Am. J. Neuroradiol.* **2017**, *38*, 1266–1273. [CrossRef]
48. Okada, Y.; Ikata, T.; Yamada, H.; Sakamoto, R.; Katoh, S. Magnetic resonance imaging study on the results of surgery for cervical compression myelopathy. *Spine* **1993**, *18*, 2024–2029. [CrossRef] [PubMed]
49. Smith, J.S.; Lafage, V.; Ryan, D.J.; Shaffrey, C.I.; Schwab, F.J.; Patel, A.A.; Brodke, D.S.; Arnold, P.M.; Riew, K.D.; Traynelis, V.C.; et al. Association of myelopathy scores with cervical sagittal balance and normalized spinal cord volume: Analysis of 56 preoperative cases from the AOSpine North America Myelopathy study. *Spine* **2013**, *38*, S161–S170. [CrossRef] [PubMed]
50. Tetreault, L.A.; Dettori, J.R.; Wilson, J.R.; Singh, A.; Nouri, A.; Fehlings, M.G.; Brodt, E.D.; Jacobs, W.B. Systematic review of magnetic resonance imaging characteristics that affect treatment decision making and predict clinical outcome in patients with cervical spondylotic myelopathy. *Spine* **2013**, *38*, S89–S110. [CrossRef]
51. Martin, A.R.; Tetreault, L.; Nouri, A.; Curt, A.; Freund, P.; Rahimi-Movaghar, V.; Wilson, J.R.; Fehlings, M.G.; Kwon, B.K.; Harrop, J.S.; et al. Imaging and Electrophysiology for Degenerative Cervical Myelopathy [AO Spine RECODE-DCM Research Priority Number 9]. *Glob. Spine J.* **2022**, *12*, 130S–146S. [CrossRef]
52. Zhang, L.; Zeitoun, D.; Rangel, A.; Lazennec, J.Y.; Catonné, Y.; Pascal-Moussellard, H. Preoperative evaluation of the cervical spondylotic myelopathy with flexion-extension magnetic resonance imaging: About a prospective study of fifty patients. *Spine* **2011**, *36*, E1134–E1139. [CrossRef] [PubMed]
53. Song, T.; Chen, W.J.; Yang, B.; Zhao, H.P.; Huang, J.W.; Cai, M.J.; Dong, T.F.; Li, T.S. Diffusion tensor imaging in the cervical spinal cord. *Eur. Spine J.* **2011**, *20*, 422–428. [CrossRef] [PubMed]
54. Pierpaoli, C.; Jezzard, P.; Basser, P.J.; Barnett, A.; Di Chiro, G. Diffusion tensor MR imaging of the human brain. *Radiology* **1996**, *201*, 637–648. [CrossRef] [PubMed]
55. Beaulieu, C.; Allen, P.S. Determinants of anisotropic water diffusion in nerves. *Magn. Reson. Med.* **1994**, *31*, 394–400. [CrossRef]
56. Martin, A.R.; Aleksanderek, I.; Cohen-Adad, J.; Tarmohamed, Z.; Tetreault, L.; Smith, N.; Cadotte, D.W.; Crawley, A.; Ginsberg, H.; Mikulis, D.J.; et al. Translating state-of-the-art spinal cord MRI techniques to clinical use: A systematic review of clinical studies utilizing DTI, MT, MWF, MRS, and fMRI. *Neuroimage Clin.* **2016**, *10*, 192–238. [CrossRef]
57. Fehlings, M.G. *Degenerative Cervical Myelopathy: From Basic Science to Clinical Practice*; Elsevier: Amsterdam, The Netherlands, 2023.
58. Nanda, G.; Jain, P.; Suman, A.; Mahajan, H. Role of diffusion tensor imaging and tractography in spinal cord injury. *J. Clin. Orthop. Trauma* **2022**, *33*, 101997. [CrossRef]
59. Basser, P.J.; Mattiello, J.; LeBihan, D. Estimation of the effective self-diffusion tensor from the NMR spin echo. *J. Magn. Reson. B* **1994**, *103*, 247–254. [CrossRef]
60. Mohammadi, M.; Roohollahi, F.; Farahbakhsh, F.; Mohammadi, A.; Mortazavi Mamaghani, E.; Kankam, S.B.; Moarrefdezfouli, A.; Ghamari Khameneh, A.; Mahmoudi, M.M.; Baghdasaryan, D.; et al. Diffusion Tensor Imaging in Diagnosing and Evaluating Degenerative Cervical Myelopathy: A Systematic Review and Meta-Analysis. *Glob. Spine J.* **2025**, *15*, 267–283. [CrossRef]
61. Ellingson, B.M.; Salamon, N.; Grinstead, J.W.; Holly, L.T. Diffusion tensor imaging predicts functional impairment in mild-to-moderate cervical spondylotic myelopathy. *Spine J.* **2014**, *14*, 2589–2597. [CrossRef]
62. Gao, S.J.; Yuan, X.; Jiang, X.Y.; Liu, X.X.; Liu, X.P.; Wang, Y.F.; Cao, J.B.; Bai, L.N.; Xu, K. Correlation study of 3T-MR-DTI measurements and clinical symptoms of cervical spondylotic myelopathy. *Eur. J. Radiol.* **2013**, *82*, 1940–1945. [CrossRef]
63. Jones, J.G.; Cen, S.Y.; Lebel, R.M.; Hsieh, P.C.; Law, M. Diffusion tensor imaging correlates with the clinical assessment of disease severity in cervical spondylotic myelopathy and predicts outcome following surgery. *AJNR Am. J. Neuroradiol.* **2013**, *34*, 471–478. [CrossRef]
64. Maki, S.; Koda, M.; Ota, M.; Oikawa, Y.; Kamiya, K.; Inada, T.; Furuya, T.; Takahashi, K.; Masuda, Y.; Matsumoto, K. Reduced field-of-view diffusion tensor imaging of the spinal cord shows motor dysfunction of the lower extremities in patients with cervical compression myelopathy. *Spine* **2018**, *43*, 89–96. [CrossRef] [PubMed]
65. Martin, A.; Aleksanderek, I.; Cohen-Adad, J.; Cadotte, D.; Kalsi-Ryan, S.; Nugaeva, N. Next-generation MRI of the human spinal cord: A prospective longitudinal study in cervical spondylotic myelopathy (CSM) to develop quantitative imaging biomarkers. In Proceedings of the Congress of Neurological Surgeons Annual Meeting, New Orleans, LA, USA, 26–30 September 2015.
66. Wen, C.Y.; Cui, J.L.; Liu, H.S.; Mak, K.C.; Cheung, W.Y.; Luk, K.D.; Hu, Y. Is diffusion anisotropy a biomarker for disease severity and surgical prognosis of cervical spondylotic myelopathy? *Radiology* **2014**, *270*, 197–204. [CrossRef] [PubMed]
67. Wang, K.; Chen, Z.; Zhang, F.; Song, Q.; Hou, C.; Tang, Y.; Wang, J.; Chen, S.; Bian, Y.; Hao, Q.; et al. Evaluation of DTI Parameter Ratios and Diffusion Tensor Tractography Grading in the Diagnosis and Prognosis Prediction of Cervical Spondylotic Myelopathy. *Spine* **2017**, *42*, E202–E210. [CrossRef]

68. Demir, A.; Ries, M.; Moonen, C.T.; Vital, J.M.; Dehais, J.; Arne, P.; Caillé, J.M.; Dousset, V. Diffusion-weighted MR imaging with apparent diffusion coefficient and apparent diffusion tensor maps in cervical spondylotic myelopathy. *Radiology* **2003**, *229*, 37–43. [CrossRef]
69. Mamata, H.; Jolesz, F.A.; Maier, S.E. Apparent diffusion coefficient and fractional anisotropy in spinal cord: Age and cervical spondylosis-related changes. *J. Magn. Reson. Imaging* **2005**, *22*, 38–43. [CrossRef] [PubMed]
70. Uda, T.; Takami, T.; Tsuyuguchi, N.; Sakamoto, S.; Yamagata, T.; Ikeda, H.; Nagata, T.; Ohata, K. Assessment of cervical spondylotic myelopathy using diffusion tensor magnetic resonance imaging parameter at 3.0 tesla. *Spine* **2013**, *38*, 407–414. [CrossRef]
71. Facon, D.; Ozanne, A.; Fillard, P.; Lepeintre, J.F.; Tournoux-Facon, C.; Ducreux, D. MR diffusion tensor imaging and fiber tracking in spinal cord compression. *AJNR Am. J. Neuroradiol.* **2005**, *26*, 1587–1594.
72. Lee, S.; Lee, Y.H.; Chung, T.S.; Jeong, E.K.; Kim, S.; Yoo, Y.H.; Kim, I.S.; Yoon, C.S.; Suh, J.S.; Park, J.H. Accuracy of Diffusion Tensor Imaging for Diagnosing Cervical Spondylotic Myelopathy in Patients Showing Spinal Cord Compression. *Korean J. Radiol.* **2015**, *16*, 1303–1312. [CrossRef]
73. Mostafa, N.S.A.-A.; Hasanin, O.A.M.; Al Yamani Moqbel, E.A.H.; Nagy, H.A. Diagnostic value of magnetic resonance diffusion tensor imaging in evaluation of cervical spondylotic myelopathy. *Egypt. J. Radiol. Nucl. Med.* **2023**, *54*, 175. [CrossRef]
74. Ragaee, S.M.; Gawad, E.A.A.; Gamal, S.; Nageeb, M.M.; Ibrahim, A.S. Leverage of applying diffusion tensor imaging (DTI) indices in assessment of cervical spondylotic myelopathy. *Egypt. J. Radiol. Nucl. Med.* **2024**, *55*, 73. [CrossRef]
75. Wu, W.; Yang, Z.; Zhang, T.; Ru, N.; Zhang, F.; Wu, B.; Liang, J. Microstructural Changes in Compressed Cervical Spinal Cord Are Consistent with Clinical Symptoms and Symptom Duration. *Spine* **2020**, *45*, E999–E1005. [CrossRef]
76. Kerkovský, M.; Bednarík, J.; Dušek, L.; Sprláková-Puková, A.; Urbánek, I.; Mechl, M.; Válek, V.; Kadanka, Z. Magnetic resonance diffusion tensor imaging in patients with cervical spondylotic spinal cord compression: Correlations between clinical and electrophysiological findings. *Spine* **2012**, *37*, 48–56. [CrossRef]
77. Grabher, P.; Mohammadi, S.; Trachsler, A.; Friedl, S.; David, G.; Sutter, R.; Weiskopf, N.; Thompson, A.J.; Curt, A.; Freund, P. Voxel-based analysis of grey and white matter degeneration in cervical spondylotic myelopathy. *Sci. Rep.* **2016**, *6*, 24636. [CrossRef]
78. Valošek, J.; Labounek, R.; Horák, T.; Horáková, M.; Bednařík, P.; Keřkovský, M.; Kočica, J.; Rohan, T.; Lenglet, C.; Cohen-Adad, J.; et al. Diffusion magnetic resonance imaging reveals tract-specific microstructural correlates of electrophysiological impairments in non-myelopathic and myelopathic spinal cord compression. *Eur. J. Neurol.* **2021**, *28*, 3784–3797. [CrossRef]
79. Ellingson, B.M.; Salamon, N.; Woodworth, D.C.; Yokota, H.; Holly, L.T. Reproducibility, temporal stability, and functional correlation of diffusion MR measurements within the spinal cord in patients with asymptomatic cervical stenosis or cervical myelopathy. *J. Neurosurg. Spine* **2018**, *28*, 472–480. [CrossRef]
80. Martin, A.R.; De Leener, B.; Cohen-Adad, J.; Kalsi-Ryan, S.; Cadotte, D.W.; Wilson, J.R.; Tetreault, L.; Nouri, A.; Crawley, A.; Mikulis, D.J.; et al. Monitoring for myelopathic progression with multiparametric quantitative MRI. *PLoS ONE* **2018**, *13*, e0195733. [CrossRef]
81. Chen, X.; Kong, C.; Feng, S.; Guan, H.; Yu, Z.; Cui, L.; Wang, Y. Magnetic resonance diffusion tensor imaging of cervical spinal cord and lumbosacral enlargement in patients with cervical spondylotic myelopathy. *J. Magn. Reson. Imaging* **2016**, *43*, 1484–1491. [CrossRef] [PubMed]
82. Budzik, J.F.; Balbi, V.; Le Thuc, V.; Duhamel, A.; Assaker, R.; Cotten, A. Diffusion tensor imaging and fibre tracking in cervical spondylotic myelopathy. *Eur. Radiol.* **2011**, *21*, 426–433. [CrossRef]
83. Rajasekaran, S.; Yerramshetty, J.S.; Chittode, V.S.; Kanna, R.M.; Balamurali, G.; Shetty, A.P. The assessment of neuronal status in normal and cervical spondylotic myelopathy using diffusion tensor imaging. *Spine* **2014**, *39*, 1183–1189. [CrossRef]
84. Cui, J.L.; Li, X.; Chan, T.Y.; Mak, K.C.; Luk, K.D.; Hu, Y. Quantitative assessment of column-specific degeneration in cervical spondylotic myelopathy based on diffusion tensor tractography. *Eur. Spine J.* **2015**, *24*, 41–47. [CrossRef]
85. David, G.; Vallotton, K.; Hupp, M.; Curt, A.; Freund, P.; Seif, M. Extent of Cord Pathology in the Lumbosacral Enlargement in Non-Traumatic versus Traumatic Spinal Cord Injury. *J. Neurotrauma* **2022**, *39*, 639–650. [CrossRef] [PubMed]
86. Seif, M.; David, G.; Huber, E.; Vallotton, K.; Curt, A.; Freund, P. Cervical Cord Neurodegeneration in Traumatic and Non-Traumatic Spinal Cord Injury. *J. Neurotrauma* **2020**, *37*, 860–867. [CrossRef] [PubMed]
87. Mohammadi, M.; Roohollahi, F.; Mahmoudi, M.M.; Mohammadi, A.; Mohamadi, M.; Kankam, S.B.; Ghamari Khameneh, A.; Baghdasaryan, D.; Farahbakhsh, F.; Martin, A.R.; et al. Correlation Between Pre-Operative Diffusion Tensor Imaging Indices and Post-Operative Outcome in Degenerative Cervical Myelopathy: A Systematic Review and Meta-Analysis. *Glob. Spine J.* **2024**, *14*, 1800–1817. [CrossRef] [PubMed]
88. Baron, R.; Binder, A.; Wasner, G. Neuropathic pain: Diagnosis, pathophysiological mechanisms, and treatment. *Lancet Neurol.* **2010**, *9*, 807–819. [CrossRef]
89. Qiu, Z.; Liu, T.; Zeng, C.; Yang, M.; Xu, X. Local abnormal white matter microstructure in the spinothalamic tract in people with chronic neck and shoulder pain. *Front. Neurosci.* **2025**, *18*, 1485045. [CrossRef]

90. Qi, X.; He, Y.; Wang, Q.; Ren, S.; Yao, H.; Cao, W.; Guan, L. Diffusion tensor and kurtosis imaging reveal microstructural changes in the trigeminal nerves of patients with trigeminal neuralgia. *Eur. Radiol.* **2023**, *33*, 8046–8054. [CrossRef]
91. Zhang, Y.; Vakhtin, A.A.; Jennings, J.S.; Massaband, P.; Wintermark, M.; Craig, P.L.; Ashford, J.W.; Clark, J.D.; Furst, A.J. Diffusion tensor tractography of brainstem fibers and its application in pain. *PLoS ONE* **2020**, *15*, e0213952. [CrossRef]
92. Wang, C.; Kutch, J.J.; Labus, J.S.; Yang, C.C.; Harris, R.E.; Mayer, E.A.; Ellingson, B.M. Reproducible Microstructural Changes in the Brain Associated with the Presence and Severity of Urologic Chronic Pelvic Pain Syndrome (UCPPS): A 3-Year Longitudinal Diffusion Tensor Imaging Study From the MAPP Network. *J. Pain* **2023**, *24*, 627–642. [CrossRef]
93. Yacubian Fernandes, A.; Fernandes da Silva, F.E.; Hamamoto Filho, P.T.; Talamoni Fonoff, E. MR diffusion tensor imaging applied to the spinal cord of patients with neuropathic pain secondary to herpes zoster infection. *J. Clin. Neurosci.* **2024**, *130*, 110912. [CrossRef]
94. Yoo, W.K.; Kim, T.H.; Hai, D.M.; Sundaram, S.; Yang, Y.M.; Park, M.S.; Kim, Y.C.; Kwak, Y.H.; Ohn, S.H.; Kim, S.W. Correlation of magnetic resonance diffusion tensor imaging and clinical findings of cervical myelopathy. *Spine J.* **2013**, *13*, 867–876. [CrossRef]
95. Vallotton, K.; David, G.; Hupp, M.; Pfender, N.; Cohen-Adad, J.; Fehlings, M.G.; Samson, R.S.; Wheeler-Kingshott, C.; Curt, A.; Freund, P.; et al. Tracking White and Gray Matter Degeneration along the Spinal Cord Axis in Degenerative Cervical Myelopathy. *J. Neurotrauma* **2021**, *38*, 2978–2987. [CrossRef]
96. Nukala, M.; Abraham, J.; Khandige, G.; Shetty, B.K.; Rao, A.P.A. Efficacy of diffusion tensor imaging in identification of degenerative cervical spondylotic myelopathy. *Eur. J. Radiol. Open* **2019**, *6*, 16–23. [CrossRef] [PubMed]
97. Qiu, Z.; Liu, T.; Zeng, C.; Yang, M.; Yang, H.; Xu, X. Exploratory study on the ascending pain pathway in patients with chronic neck and shoulder pain based on combined brain and spinal cord diffusion tensor imaging. *Front. Neurosci.* **2025**, *19*, 1460881. [CrossRef] [PubMed]
98. Vitzthum, H.E.; Dalitz, K. Analysis of five specific scores for cervical spondylogenic myelopathy. *Eur. Spine J.* **2007**, *16*, 2096–2103. [CrossRef] [PubMed]
99. d'Avanzo, S.; Ciavarro, M.; Pavone, L.; Pasqua, G.; Ricciardi, F.; Bartolo, M.; Solari, D.; Somma, T.; de Divitiis, O.; Cappabianca, P.; et al. The Functional Relevance of Diffusion Tensor Imaging in Patients with Degenerative Cervical Myelopathy. *J. Clin. Med.* **2020**, *9*, 1828. [CrossRef] [PubMed]
100. Stroman, P.W.; Wheeler-Kingshott, C.; Bacon, M.; Schwab, J.M.; Bosma, R.; Brooks, J.; Cadotte, D.; Carlstedt, T.; Ciccarelli, O.; Cohen-Adad, J. The current state-of-the-art of spinal cord imaging: Methods. *Neuroimage* **2014**, *84*, 1070–1081. [CrossRef]
101. Huang, S.; Shao, H.; Liu, Q.; Liu, W.V.; Zhang, Q.; Deng, L.; Liu, C.; Omar, D.M.; Tang, X. Quantitative Assessment of Spinal Cord Injury in Cervical Spondylotic Myelopathy: A Comparison Study of MAGiC and MUSE-DTI. *Eur. J. Radiol.* **2025**, *190*, 112214. [CrossRef]
102. Alomar, S.; Bakhaidar, M. Neuroimaging of neuropathic pain: Review of current status and future directions. *Neurosurg. Rev.* **2018**, *41*, 771–777. [CrossRef]
103. Zhao, R.; Su, Q.; Chen, Z.; Sun, H.; Liang, M.; Xue, Y. Neural Correlates of Cognitive Dysfunctions in Cervical Spondylotic Myelopathy Patients: A Resting-State fMRI Study. *Front. Neurol.* **2020**, *11*, 596795. [CrossRef] [PubMed]
104. Figley, C.R.; Uddin, M.N.; Wong, K.; Kornelsen, J.; Puig, J.; Figley, T.D. Potential Pitfalls of Using Fractional Anisotropy, Axial Diffusivity, and Radial Diffusivity as Biomarkers of Cerebral White Matter Microstructure. *Front. Neurosci.* **2021**, *15*, 799576. [CrossRef]
105. Willis, W.D.; Westlund, K.N. Neuroanatomy of the pain system and of the pathways that modulate pain. *J. Clin. Neurophysiol.* **1997**, *14*, 2–31. [CrossRef]
106. Jones, D.K.; Knösche, T.R.; Turner, R. White matter integrity, fiber count, and other fallacies: The do's and don'ts of diffusion MRI. *Neuroimage* **2013**, *73*, 239–254. [CrossRef]
107. Wheeler-Kingshott, C.A.; Cercignani, M. About "axial" and "radial" diffusivities. *Magn. Reson. Med.* **2009**, *61*, 1255–1260. [CrossRef]
108. Drake-Pérez, M.; Boto, J.; Fitsiori, A.; Lovblad, K.; Vargas, M.I. Clinical applications of diffusion weighted imaging in neuroradiology. *Insights Imaging* **2018**, *9*, 535–547. [CrossRef] [PubMed]
109. Faiyaz, A.; Doyley, M.M.; Schifitto, G.; Uddin, M.N. Artificial intelligence for diffusion MRI-based tissue microstructure estimation in the human brain: An overview. *Front. Neurol.* **2023**, *14*, 1168833. [CrossRef]
110. Yang, S.; Li, J.; Fei, N.; Li, G.; Hu, Y. A Deep-Learning-Based Diffusion Tensor Imaging Pathological Auto-Analysis Method for Cervical Spondylotic Myelopathy. *Bioengineering* **2025**, *12*, 806. [CrossRef] [PubMed]
111. Tran, A.T.; Zeevi, T.; Payabvash, S. Strategies to Improve the Robustness and Generalizability of Deep Learning Segmentation and Classification in Neuroimaging. *BioMedInformatics* **2025**, *5*, 20. [CrossRef]
112. Sima, S.; Sial, A.; Sharma, S.; Ananthakrishnan, D.; Kuan, J.; Diwan, A. DeVa (Decay Variance): A Novel Score Calculated via Postprocessing the Changes in Signal Intensity of an Intervertebral Disc in a T2* Multi-Echo Magnetic Resonance Image Can Quantify Painful and Degenerate Lumbar Vertebral Discs. *JOR Spine* **2025**, *8*, e70056. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.