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Traumatic central cord Syndrome: An integrated neurosurgical and neurocritical care perspective

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ABSTRACT

Traumatic Central Cord Syndrome (TCCS) presents complex challenges in the management of spinal cord injury. Characterized by disproportionate upper limb weakness, TCCS is the most common clinical spinal cord syndrome, typically affecting males in a bimodal age distribution. Mechanisms include hyperextension injuries in older adults with degenerative cervical spine disease and high-energy trauma in younger individuals. Diagnosis is based on neurological assessment, with the American Spinal Injury Association (ASIA) Impairment Scale used for severity classification. Management strategies, including surgical and medical approaches, may influence functional outcomes, although high-quality comparative evidence is limited. Surgical decompression and stabilization are often pursued to relieve mechanical compression, while nonoperative strategies may be considered in selected cases with less severe neurological deficits. The timing of surgical intervention remains a subject of ongoing debate and must be individualized. Neurocritical care considerations are increasingly recognized as potentially important in the early phase of TCCS. Experimental and clinical investigations into intraspinal pressure (ISP), mean arterial pressure (MAP), and spinal perfusion pressure (SPP) monitoring suggest these parameters may aid in minimizing secondary injury, though their routine clinical use is not yet established. Complications such as venous thromboembolism, infection, pressure injuries, and autonomic dysfunction are common and require comprehensive management. The role of corticosteroids remains controversial.

This narrative review synthesizes current knowledge on TCCS, with emphasis on diagnostic, surgical, and neurocritical care considerations. As the field advances, further evidence is needed to clarify optimal management pathways and improve outcomes in this challenging clinical entity.

1. Introduction

Traumatic Central Cord Syndrome (TCCS) represents the most common form of incomplete spinal cord injury (SCI) and poses a distinct set of diagnostic, therapeutic, and prognostic challenges within neurotrauma and neurocritical care practice (Brooks, 2017). Clinically defined by disproportionate motor impairment in the upper compared to the lower extremities, TCCS reflects complex spinal cord pathophysiology often associated with cervical canal stenosis and hyperextension mechanisms (Adegeest et al., 2024). Its bimodal distribution, affecting both older adults with spondylotic changes and younger individuals involved in high-energy trauma, further complicates clinical management and outcome prediction. In recent years, the approach to TCCS has evolved with improvements in neuroimaging, operative planning, and critical care strategies. However, consensus on optimal management remains elusive, particularly regarding surgical timing, patient selection for operative versus nonoperative treatment, and the role of advanced neurocritical monitoring. These clinical uncertainties are amplified in

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low- and middle-income countries (LMICs), where disparities in infrastructure, access to pre-hospital care, diagnostic imaging, and trained personnel frequently hinder adherence to established SCI guidelines (McKinley et al., 2007).

Prehospital immobilization, timely transfers, and access to definitive care are often compromised in resource-limited settings, delaying surgical decompression and diminishing opportunities for early neuroprotection. Diagnostic practices, including the use of ASIA grading and advanced imaging, vary significantly by region and are often dictated by cost and availability. Consequently, global variability in TCCS management underscores the need for context-sensitive clinical frameworks that account for disparities in access to care.

This narrative review aims to synthesize contemporary evidence on the neurosurgical and neurocritical care considerations in TCCS, highlighting evolving management strategies, existing knowledge gaps, and regional challenges affecting implementation. In doing so, we seek to support clinicians and policymakers in optimizing care for this complex and often under-recognized SCI phenotype.

2. Methodology

2.1. Rationale for the review

Traumatic Central Cord Syndrome (TCCS) is the most common form of incomplete spinal cord injury, classically affecting older adults with cervical spondylosis who sustain hyperextension injuries. Despite its high incidence, the optimal timing of surgical intervention, role of conservative vs. aggressive neurocritical care, and tailored rehabilitation strategies remain poorly defined and inconsistently applied. Existing literature is largely limited to observational studies with heterogeneous inclusion criteria, and neurocritical care considerations are seldom integrated into neurosurgical decision-making frameworks. This review aims to synthesize current evidence, identify knowledge gaps, and propose an interdisciplinary management algorithm for TCCS. The following key questions were identified for the review topic.

1. What are the current neurosurgical indications and optimal timing for surgical decompression in TCCS?
2. What are the neurocritical care priorities in acute TCCS, particularly regarding spinal cord perfusion, hemodynamic management, and multimodal monitoring?
3. How does the integration of neurocritical care into surgical planning impact outcomes in TCCS?

2.2. Search strategy development

2.2.1. Eligibility criteria

A comprehensive and systematic literature search was performed to identify relevant publications addressing the clinical, surgical, and neurocritical care aspects of traumatic central cord syndrome (TCCS). The review targeted articles published between January 2000 and March 2025, with the intent to capture both foundational studies and recent advances in the understanding and management of TCCS. Only articles written in English were considered eligible for inclusion. The review included a wide range of publication types such as original research articles, narrative and systematic reviews, evidence-based clinical guidelines, randomized and non-randomized clinical trials, prospective and retrospective cohort studies, case-control studies, and expert consensus statements. Eligible study designs encompassed both interventional and observational methodologies, including meta-analyses and systematic reviews, to ensure a comprehensive and multidimensional perspective.

The population of interest was restricted to adult human subjects with a clinical diagnosis of traumatic central cord syndrome, regardless of etiology within the trauma spectrum. Studies focusing on non-traumatic causes of central cord-like presentations, such as demyelinating disorders, ischemic myelopathies, or congenital spinal anomalies, were excluded. Additionally, pediatric populations, preclinical animal studies, conference abstracts lacking full-text availability, and editorials or commentaries without original data were excluded from the analysis to maintain methodological rigor and clinical relevance. The search was conducted across three major biomedical databases: PubMed (MEDLINE), Embase, and Scopus. The detailed Boolean search strategies employed for each platform, including Medical Subject Headings (MeSH) and Emtree terms, are provided in the "Supplementary Materials" section accompanying this manuscript.

2.2.2. Incidence and prevalence of traumatic central cord syndrome (TCCS)

Traumatic Central Cord Syndrome (TCCS) represents a distinct subset of spinal cord injuries (SCIs) characterized by specific clinical manifestations, predominantly affecting the upper extremities (Adegeest et al., 2024). The precise incidence and prevalence of TCCS are subjects of considerable interest within the field of neurosurgery, neurology, critical care, orthopaedics, and spinal cord injury research.

In a retrospective analysis conducted by McKinley and colleagues, encompassing 839 patients with spinal cord injuries treated at a tertiary care level one trauma center, Central Cord Syndrome (CCS) emerged as the predominant clinical spinal cord syndrome (Demetriades et al., 2022). Notably, CCS exhibits a distinct demographic pattern, with a higher incidence in males and a bimodal age distribution. The younger population tends to experience CCS due to falls or motor vehicle collisions, while older individuals often suffer from CCS because of hyperextension injuries, often in the presence of pre-existing spinal conditions, like osteoarthritis or cervical spondylosis (Peterson et al., 2019).

The prevalence of CCS ranges from 15 % to 25 %. However, it is worth noting that CCS can occasionally elude diagnosis, particularly when patients present with mild initial symptoms. The annual incidence of central cord syndrome in the United States is estimated to be approximately 11,000 cases, emphasizing its impact within the spectrum of spinal cord injuries (Divi et al., 2019).

2.2.3. Pathophysiology and mechanisms of injury in TCCS

Central cord syndrome (CCS) is the most common form of incomplete cervical spinal cord injury (SCI) and is traditionally defined by disproportionately greater motor impairment in the upper extremities compared to the lower extremities. This clinical pattern was historically attributed to a somatotopically organized corticospinal tract (CST), in which axons innervating the upper limbs were believed to be located medially within the lateral columns of the spinal cord and therefore more susceptible to centrally located lesions. Originally proposed by Schneider et al., in 1954, this hypothesis gained wide acceptance and has been perpetuated in classic neuroanatomical atlases and surgical teaching paradigms for decades (Shakil et al., 2023). According to this traditional view, hyperextension injuries (particularly in patients with pre-existing cervical spondylosis or congenital stenosis) produce transient anteroposterior compression of the spinal cord without fracture or instability. The presumed central location of upper limb fibers within the lateral CST thus served as a mechanistic explanation for the characteristic motor deficits seen in CCS (Shakil et al., 2023). However, recent advances in primate neuroanatomy, high-resolution tract-tracing, and diffusion tensor imaging have increasingly challenged this classical somatotopic model (Shakil et al., 2023; Morecraft et al., 2013). Studies in non-human primates and postmortem human specimens have demonstrated that CST fibers within the cervical spinal cord are not arranged in discrete concentric lamellae. Instead, they are heterogeneously distributed throughout the dorsolateral white matter, particularly within the lateral funiculus and intermediate zone. These axons exhibit substantial segmental arborization, interneuronal synapsing, and bilateral projections, especially within the cervical enlargement (C4–T1) where upper limb motor neurons reside (Shakil et al., 2023;

Morecraft et al., 2013, 2021).

Emerging evidence suggests that CCS represents a diffuse axonal and synaptic network injury, rather than a circumscribed lesion of medial CST fibers. The density and complexity of corticospinal projections, combined with overlapping input from corticoreticular and propriospinal pathways, may render the cervical enlargement uniquely vulnerable to traumatic disruption. Importantly, the cervical gray matter contains extensive intersegmental motor pools responsible for fine motor control, particularly of the hands and digits. This region is also richly innervated by descending fibers from the motor cortex, many of which collateralize before synapsing with lower motor neurons or local circuit interneurons within laminae VII–IX of the ventral horn (Shakil et al., 2023; Morecraft et al., 2021; Lemon, 2008). Thus, upper extremity dysfunction in CCS may reflect the selective vulnerability of these high-density synaptic and axonal domains in the cervical enlargement. Traumatic injury to this region (particularly under conditions of chronic compression, ischemia, or mechanical shear stress) results in disruption of a distributed and functionally integrated network. As such, this revised model reconceptualizes CCS as a network-level dysfunction of the cervical spinal cord, incorporating damage to both white matter tracts and gray matter interneuronal circuits, rather than a topographically localized lesion (Morecraft et al., 2013, 2021; Lemon, 2008). Fig. 1 depicts TCCS pathophysiology concept evolution through history.

In summary, this paradigm shift in pathophysiology carries important implications for clinical management. The recognition of CCS as a diffuse injury supports early surgical decompression in selected patients, with the goal of relieving dynamic compression and minimizing secondary axonal loss. Finally, it highlights the need for advanced imaging biomarkers and functional assessments capable of capturing the nuanced and distributed nature of motor system injury in CCS.

2.2.4. *Clinical and imaging diagnosis of TCCS*

Central Cord Syndrome causes out-of-proportion disturbances in the upper limb when compared to the lower limbs. Along with this motor asymmetry, individuals may exhibit varying degrees of sensory deficits below the level of the spinal cord lesion, and potentially experience urinary or gastrointestinal dysfunction. Pouw and colleagues have suggested a diagnostic criterion for Central Cord Syndrome based on the International Standards for Neurological Classification of SCI (ISNCSCI), specifically emphasizing a 10-point difference between upper and lower limb motor scores, thereby offering a more objective framework for diagnosis (Pouw et al., 2010).

According to the revised 2019 American Spinal Injury Association (ASIA) Impairment Scale (AIS) criteria, traumatic central cord syndrome (TCCS) is characterized as an incomplete cervical spinal cord injury with predominant motor deficits in the upper extremities relative to the lower extremities (Carr et al., 2024). Despite this established framework, the clinical definition of TCCS remains a subject of ongoing debate, owing to its variable phenotypic expression (van Middendorp et al., 2010). While the prototypical presentation involves bilateral upper limb weakness, a subset of patients may exhibit neuropathic pain and/or dysesthetic paresthesias isolated to the hands, in the absence of objective motor impairment. Conversely, in more severe injuries, longitudinal propagation of intramedullary edema or hemorrhage (hematomyelia) can result in profound quadriparesis, with preservation of only minimal distal lower limb motor function.

TCCS may also manifest with marked asymmetry in motor deficits, with unilateral arm weakness significantly exceeding contralateral involvement, a pattern that may be quantifiable using the aforementioned Pouw criteria (van Middendorp et al., 2010). Sensory disturbances are equally heterogeneous; patients may present with patchy hypoesthesia, allodynia, or neuropathic pain, commonly described as "burning hand syndrome", a hallmark symptom of central dysesthesia (Carr et al., 2024). Autonomic dysfunction, particularly neurogenic bladder, is frequently observed. Urodynamic assessments have demonstrated a range of abnormalities, including detrusor overactivity with synergistic sphincter coordination, detrusor-sphincter dyssynergia, and detrusor areflexia (Carr et al., 2024; van Middendorp et al., 2010). Despite these disturbances, long-term urological outcomes in TCCS are generally favorable, with many patients achieving spontaneous resolution of bladder dysfunction during recovery (Carr et al., 2024).

In cases where patients are medically stable, awake, and symptomatic, a radiographic assessment of the spinal cord and axial skeleton is warranted. Computed tomography (CT) serves as the initial imaging modality of choice due to its expediency in providing bony structures images. It is crucial to obtain neck flexion and extension images in patients with suspected cervical spinal cord injuries (Aarabi et al., 2008). However, in a substantial proportion of patients with traumatic central cord syndrome (TCCS), particularly those with underlying degenerative cervical spondylosis and associated canal stenosis, there may be no radiographic evidence of acute osseous injury on initial computed tomography (CT) imaging (Aarabi et al., 2008; Ryken et al., 2013). In these cases (typically involving low-energy hyperextension mechanisms without vertebral fracture), CT scans may reveal chronic structural abnormalities, including posteriorly projecting osteophytes, intervertebral disc herniation, ossification of the posterior longitudinal ligament (OPLL), and congenital or acquired cervical spinal canal stenosis (Ryken et al., 2013). These degenerative changes predispose the spinal cord to dynamic compression during hyperextension, even in the absence of direct structural disruption.

In clinical settings where CT or MRI is not readily accessible, the 2013 Congress of Neurological Surgeons (CNS) guidelines for cervical spinal cord injury recommend the use of plain radiographs, including anteroposterior, lateral, and open-mouth odontoid views, as an initial screening tool for gross instability or bony pathology (Carr et al., 2024; Ryken et al., 2013). However, due to its superior contrast resolution and multiplanar capability, magnetic resonance imaging (MRI) remains the gold standard for evaluating spinal cord integrity and intradural pathology in TCCS. MRI enables direct visualization of intramedullary signal changes (Fig. 2A–C), including cord edema, hematomyelia, and contusion, as well as ligamentous injury, epidural hematoma, disc extrusion, and hypertrophy of the ligamentum flavum (Zhang et al., 2022). Several imaging biomarkers have been investigated for their prognostic value in TCCS. These include the length of cervical spinal stenosis, anteroposterior canal diameter, and the Brain and Spinal Injury Center (BASIC) score (Vaccaro et al., 2013a), a semiquantitative ordinal scale that grades intramedullary changes on T2-weighted axial MRI.

Although the BASIC score has been validated as a practical tool for prognostication in acute cervical SCI (with higher grades correlating with more severe tissue damage and poorer neurological outcomes in patients with central cord injuries) (Vaccaro et al., 2013a), there are still controversies in the clinical neuroimaging diagnosis of TCCS. A simplified clinical definition has been proposed for CCS/TCCS, encompassing any acute sensorimotor deficit attributable to cervical spinal cord trauma in the absence of radiographically evident vertebral fracture or dislocation (Zhu et al., 2019). Transient symptoms, such as paresthesias or numbness in the hands or digits that resolve within 24 h, are more appropriately categorized as spinal cord concussion. However, persistent sensory disturbances involving the hands or fingers beyond the 24-h threshold, even in the absence of motor impairment, may represent the mildest expression of CCS and should prompt timely referral for neurosurgical or spine specialist evaluation (Zhu et al., 2019). At the severe end of the spectrum, TCCS may manifest as a complete spinal cord injury (SCI) at the cervical level (ASIA grade A), despite a lack of osseous disruption on imaging (Zhu et al., 2019), which will be discussed in further sections.

Differential diagnostic considerations include spinal cord injury without radiographic abnormality (SCIWORA), which is more typical in adolescents or young adults experiencing high-energy trauma, particularly when MRI reveals ligamentous or soft tissue injury (Sharma et al., 2009; Vaccaro et al., 2013b). Additionally, some experts have proposed that TCCS may be conceptualized as a subset within the broader

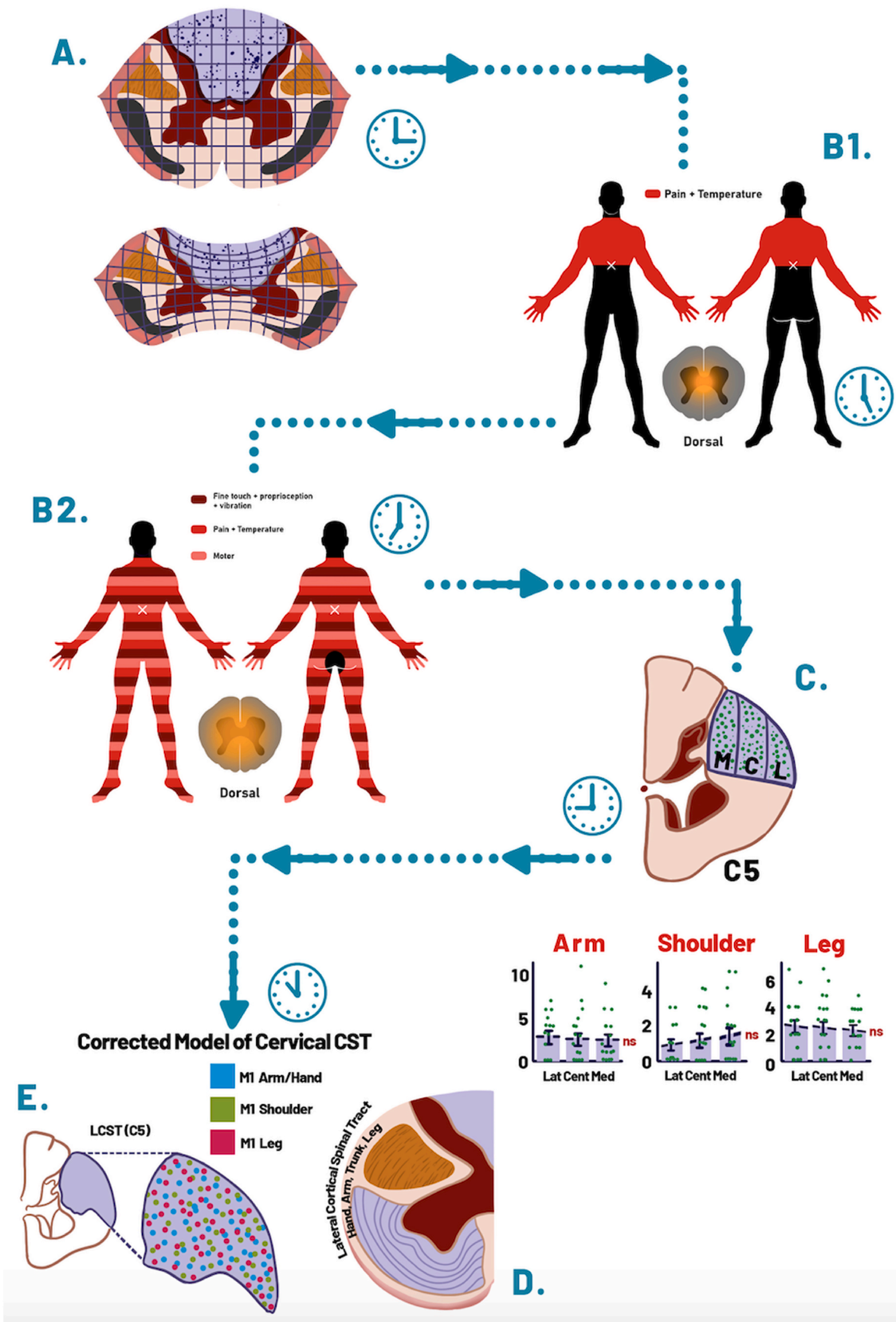

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Fig. 1. TCCS pathophysiology concept evolution. The "clocks" sketches were added to illustrate symbolically different time points in history. **(A)** Based on initial Sir William Thorburn theories, Schneider (Zhu et al., 2019) propose a model of the cervical spinal cord in cross-section, including major ascending and descending pathways and x- and y-axis grids, illustrating the change in shape, from a normal anatomical one to a compressed one, from midline anterior osteophytes and posterior ligamentum flavum, demonstrating preferential distortion of the central spinal cord with relative sparing of the lateral funiculi. **(B)** Theoretical clinical correlation of TCCS based on Schneider's model (Zhu et al., 2019); **(B1)** with an "epicenter" injury, and **(B2)** with a more "radially extensive" injury. **(C)** Recent data has demonstrated the lack of a uniform somatotopical organization, with no major differences in axon density in medial to lateral sections from upper and lower extremities throughout the cross-sectional area of the CST (Shakil et al., 2023). Figures **(D)** and **(E)** depict the results of an interesting work in non-human primates, showing absence of somatotopy in the cervical enlargement of spinal cord, with a random dispersion of CST axons, explaining why patients may present with a wide spectrum of clinical deficits. See text for further explanation (Shakil et al., 2023; Morecraft et al., 2013, 2021). **C:** center; **C5:** cervical spinal cord at C5 level; **CST:** corticospinal tract; **L:** lateral; **LCST:** lateral corticospinal tract; **M:** medial, **ns:** not specified. Some of the figures are original material from the authors, and others adapted and changed in format from cited references, considering authors' work copyright. https://creativecommons.org/licenses/by-nc-nd/4.0/.

category of spinal cord injury without radiological evidence of trauma (SCI-WORET) (Zhu et al., 2019; Vaccaro et al., 2013b). However, the SCI-WORET framework captures a more heterogeneous group of atraumatic or minimally traumatic spinal cord syndromes. Simplifying the operational definition of CCS based on pathophysiological criteria might allow for greater diagnostic specificity and facilitate epidemiological comparisons across institutions and populations (Vaccaro et al., 2013b). In the near future, further urgent work is needed to properly classify TCCS both clinically and radiologically.

2.2.5. Severity of TCCS assessed by ASIA Impairment Scale

The assessment of the severity of Traumatic Central Cord Syndrome (TCCS) is a critical aspect of clinical evaluation and treatment planning. One of the most widely utilized tools for this purpose is the American Spinal Injury Association (ASIA) Impairment Scale (Zhang et al., 2022).

The ASIA Impairment Scale consists of five grades, ranging from A to E, each representing a distinct level of neurologic impairment.

- Grade A (complete): This grade indicates the most severe impairment, where there is no sensory or motor function below the level of injury. Patients classified as Grade A have no voluntary anal sphincter contraction.
- Grade B (sensory incomplete): In this category, there is sensory, but no motor function preserved below the neurological level, including the sacral segments S4-S5. Like Grade A, patients in Grade B lack voluntary anal sphincter contraction.
- Grade C (motor incomplete): Grade C signifies motor function that is preserved below the neurological level of injury, with more than half of the key muscles below the level of injury having a muscle grade less than 3 (indicating muscle strength <50 % of normal). However, voluntary anal sphincter contraction is present.
- Grade D (motor incomplete): Patients categorized as Grade D exhibit motor function preservation below the neurological level, with at least half of the key muscles below the level of injury having a muscle grade greater than or equal to 3 (indicating muscle strength >50 % of normal).
- Grade E (Normal): Grade E represents the absence of any motor or sensory deficits, indicating a fully intact spinal cord and nerve function.

The main difference in ASIA (American Spinal Injury Association) scores between Central Cord Syndrome (CCS) and other spinal cord syndromes lies in the pattern of neurological deficits. In CCS, patients often exhibit more pronounced weakness in their upper extremities, particularly the arms and hands, while the lower limbs, including the legs, may have some preserved function, a characteristic known as "sacral sparing.' Sensory deficits in CCS also predominantly affect the upper limbs. In contrast, other spinal cord syndromes may result in varying patterns of weakness and sensory loss depending on the location and extent of the injury, without the specific upper limb dominance seen in CCS. Additionally, CCS can present with distinctive bladder and bowel dysfunction, further distinguishing it from other syndromes. These discrepancies in ASIA scores are essential for clinicians to accurately diagnose and manage spinal cord injuries (Zhang et al., 2022).

2.3. The impact of surgical vs. medical management of traumatic central cord syndrome (TCCS) on ASIA scale improvement and functional outcomes

TCCS represents a challenging clinical entity with a spectrum of management strategies, including both surgical and medical approaches (Vaccaro et al., 2013a). Understanding the impact of these interventions on outcomes, particularly in terms of ASIA scale improvement and functional recovery at six months, is vital for optimizing patient care. Neurosurgical management can be divided into decompression surgery and instrumentation and stabilization/fusion, and medical management comprises immobilization, pharmacological interventions and rehabilitation.

2.3.1. Surgical management of traumatic central cord syndrome (TCCS)

The decision to pursue surgery in TCCS hinges on ***injury severity, spinal stability, and neurological status,*** with the **AOSpine classification** providing critical guidance. **Type B injuries (ligamentous disruption with potential instability)** and **Type C injuries (fracture-dislocations with overt instability)** typically require **instrumented fusion** in addition to decompression, whereas **Type A injuries (compression without instability)** may be managed with decompression alone or conservatively in select cases (Vaccaro et al., 2013a).

2.3.2. Surgical approaches: anterior vs. posterior decompression

The choice of approach depends on the **location and morphology of compression**.

- ***Anterior decompression*** **(e.g., ACDF, corpectomy)** is preferred for **ventral pathology** (e.g., disc herniation, vertebral fractures) and offers direct neural element decompression with high fusion rates.
- ***Posterior decompression*** **(e.g., laminectomy, laminoplasty)** is suited for **dorsal compression** (e.g., ligamentum flavum hypertrophy, ossified posterior longitudinal ligament) or multilevel stenosis. Hybrid approaches may be needed for circumferential compression.

2.3.3. Extension duroplasty: an emerging adjunct

In cases of **severe TCCS with spinal cord swelling, extension duroplasty** (expansile duraplasty) has shown promise in small studies to facilitate cord expansion and mitigate intradural pressure. Early evidence suggests potential benefits in **ASIA grade A/B injuries with refractory edema**, though further validation is needed (Zhu et al., 2019).

2.3.4. Timing and outcomes

While **early surgery (< 24 h)** may improve motor recovery in **ASIA C/D injuries**, delayed intervention is considered for medically unstable patients. Postoperative rehabilitation remains pivotal for functional gains, particularly in upper extremity function (Vaccaro et al., 2013b; Fehlings et al., 2017).

Table 1 synthesizes data from these key studies.

- Primary AOSpine Classification References for injury types (A/B/C) and stability criteria (Vaccaro et al., 2013b, 2016).

Fig. 2. (From left to right and bottom): (A) Sagittal T2 weighted image of a 65 year old gentleman who suffered a neck hyperextension injury, and presented with central cord syndrome. He exhibited new severe upper limb weakness (0/5 in wrists and hands; 1/5 elbow extensors, 3/5 elbow flexors) and mild lower limb weakness (4/5 throughout). MRI showed disc bulging at C4/5 and C5/6, with canal stenosis and cord contusion. He underwent anterior cervical discectomy at C4/5 and C5/6 within 24 h, and within a week had improved to 2/5 in wrists and hands; 3/5 in elbow extensors; 4/5 elbow flexors; and 5/5 throughout the lower limbs. **(B)** Sagittal T2 weighted image in a 45 year old lady who fell down a ladder sustaining central cord syndrome. **(C)** Sagittal T2 weighted image in a 64 year old man who fell down the stairs sustaining central cord syndrome. All images original material belong to authors (AD).

- Surgical literature for approach-specific outcomes/complications (Johnson et al., 2020; Lee et al., 2021; Kepler et al., 2017).
- Clinical guidelines for timing/indication (Fehlings et al., 2017).

2.3.5. *Medical management*

This conservative approach is often considered for patients with less severe injuries or those who are not surgical candidates.

1. Immobilization: The use of cervical collars or braces aims to restrict neck movement, reducing the risk of exacerbating spinal cord injury.
2. Pharmacological Interventions: Medications such as methylprednisolone may be administered to mitigate secondary spinal cord injury

Table 1
AOSpine-based management of TCCS**: Classification, Management, and Outcomes** (Vaccaro et al., 2013b, 2016; Johnson et al., 2020; Lee et al., 2021; Kepler et al., 2017; Fehlings et al., 2017).

Type	Injury	Surgical Approach	Complications	1-Year ASIA Δ
A	Compression fracture	ACDF/ corpectomy	Dysphagia (15 %), graft failure (5 %)	+1.2 grades (Johnson et al., 2020)
B	Ligamentous injury	Posterior fusion + decompression	PJK (12 %), wound infection (8 %)	+1.5 grades (Lee et al., 2021)
C	Fracture-dislocation	360° fusion	Hardware failure (10 %), DVT (7 %)	+1.0 grade

by reducing inflammation and oxidative stress. Recently, Riluzole, a sodium channel blocker of the benzothiazole class that has been licensed for the purpose of reducing neurodegeneration in amyotrophic lateral sclerosis (ALS), has also being studied for its potential to provide neuroprotection in traumatic SCI by mitigating excess Na+ and Ca++ influx-mediated excitotoxicity (Vaccaro et al., 2013b).

3. Rehabilitation: Physical and occupational therapy focuses on maximizing functional recovery, enhancing mobility, and optimizing activities of daily living.

According to anecdotic data, medical management may lead to modest ASIA scale improvement in some cases (Zhang et al., 2022), especially for patients with less severe TCCS, while functional outcomes with this treatment approach can vary widely, with some patients achieving some recovery through intensive rehabilitation, however, at expense of persisting neuropathic pain and spasticity (Zhang et al., 2022).

It must be acknowledged that the choice between surgical and medical management of TCCS should be tailored to individual patient features and the specific nature of the injury. Surgical intervention, when indicated, may offer more rapid and significant ASIA scale improvement and functional recovery, especially in cases of severe spinal cord compression (Vaccaro et al., 2013a). However, medical management remains a valuable option for select patients, emphasizing the importance of comprehensive rehabilitation efforts in achieving optimal outcomes.

2.3.6. Timing of neurosurgical management in TCCS patients

The optimal timing of neurosurgical management in patients with TCCS is a critical consideration in the pursuit of improving outcomes and maximizing neurological recovery. This aspect of TCCS management has been a subject of on-going research and clinical debate.

Early surgical intervention in TCCS patients is primarily driven by the need for addressing spinal cord compression (SCC) promptly. In many cases, SCC occurs due to vertebral fractures or soft tissue injury, leading to neurological deficits. Early surgery aims to decompress, mitigate secondary injury mechanisms, and facilitate neural tissue recovery. The definition of "early' can vary, but often implies intervention within the first 24–72 h after injury, with some studies advocating for surgery within the first 24 h if feasible (Avila and Hurlbert, 2021). In fact, early surgical decompression is associated with significant improvement in motor recovery in upper limbs at 1-year (Zhu et al., 2019), which may have a profound impact in terms of functional recovery and return-to-work rates for patients with TCCS. In addition, by addressing SCC early, the risk of complications such as pressure sores, respiratory compromise, and urinary tract infections may be reduced (Zhang et al., 2022; Weerakkody et al.).

Late surgical intervention is typically considered when patients present with stable neurological deficits or when immediate surgery is contraindicated due to medical or logistical reasons (..). It may also be a choice for patients with milder TCCS presentations. "Late' surgery often refers to intervention beyond the initial 72 h after injury, but the exact timing can vary based on individual patient factors and clinical judgment (Parthiban et al., 2020; Yue et al., 2017). Delaying surgery allows for a more accurate assessment of the patient's neurological status and stability, aiding in surgical planning. Patients who may not be suitable candidates for early surgery due to medical comorbidities or polytrauma can benefit from comprehensive medical management before undergoing a procedure (Barz et al., 2022).

The timing of neurosurgical management in TCCS patients is a complex decision that must consider several factors, including the patient's context and comorbidities, presence of other injuries, and degree of neurological deficits (Consortium for Spinal Cord Medicine, 2008; Kirshblum et al., 2011; Fehlings et al., 2024). While early surgery aims to promptly address SCC in terms of functional improvements (Badhiwala et al., 2022; Chow et al., 2023). Late surgery can be carefully considered for selected patients who require stabilization or in cases where immediate intervention is not feasible (Wilson et al., 2017). Individualized assessment and multidisciplinary collaboration are essential in making informed decisions (Badhiwala et al., 2021).

According to research (Ter et al., 2024), there have been numerous surgical interventions throughout history aimed at modifying the progression of spinal cord injuries (SCI), yielding inconsistent outcomes. Although evidence has indicated a possible connection between time of surgery and the improvement of neurological function, the specific effect of doing surgery immediately on particular patients is still uncertain (Aarabi et al., 2021). It is increasingly clear that neurological recovery is influenced not just by surgical intervention, but also by factors related to the patient and their unique surgical therapy.

After accounting for many independent factors and confirming spinal cord decompression on post-operative MRI, our study found that the timing of surgery did not have a significant impact on the final ASIA motor score at the 6-month follow-up (Aarabi et al., 2021; Rask et al., 2024). Due to shifting demographic patterns and evolving indicators of injury severity, it is probable that there will be a rise in the number of individuals diagnosed with spinal stenosis and acute traumatic cervical cord syndrome (ATCCS) (Aarabi et al., 2021; Walters et al., 2013). This study provides evidence in favor of spinal cord decompression, however it does not provide a certain timeframe for the decompression procedure. Given the intricate imaging challenges of the cervical spine in older individuals with ATCCS and additional health conditions, it is advisable to thoroughly assess and plan the surgical intervention before the operation. This should involve not only relieving pressure on the spinal cord but also addressing any complex structural abnormalities of the spine promptly and effectively (Rask et al., 2024; Walters et al., 2013).

2.3.7. Neurocritical care for TCCS

Neurocritical care has become an essential component of modern spinal cord injury (SCI) management, especially in patients with traumatic central cord syndrome (TCCS), the most common incomplete cervical SCI phenotype. Optimal outcomes in TCCS depend not only on timely surgical decompression but also on meticulous physiological support to minimize secondary injury. In recent years, clinical guidelines—particularly those published in 2013 b y leading neurosurgical and spine societies (Walters et al., 2013), have emphasized the importance of hemodynamic optimization, early VTE prophylaxis, and complication surveillance as core tenets of acute SCI care. These recommendations advocate for maintaining mean arterial pressure (MAP) above 85–90 mmHg during the first week post-injury to promote spinal cord perfusion, although real-world adherence to this threshold remains inconsistent. While several observational studies report an increase in MAP targeting practices post-guideline implementation, only a fraction of patients achieve sustained goal-directed pressures, often due to comorbidities, vasopressor limitations, or monitoring gaps (Rask et al., 2024).

Parallel shifts in clinical practice include a decline in high-dose methylprednisolone use, in alignment with updated evidence-based recommendations discouraging its routine administration due to its limited efficacy and association with adverse effects. Despite this pharmacologic transition, neuroprotective benefit has not been clearly demonstrated through retrospective outcome analyses, and neurological improvement remains modest in many patients, even when protocolized neurocritical care is applied (Rask et al., 2024; Walters et al., 2013).

Importantly, guideline adoption has led to meaningful improvements in secondary outcome domains. Earlier surgical timing is now more frequently pursued, enabling more timely initiation of venous thromboembolism (VTE) prophylaxis (Christie et al., 2011). Although prophylaxis often still falls outside the optimal 72-h window—particularly in cases with delayed operative intervention—rates of thromboembolic events have declined, underscoring the importance of aggressive risk mitigation. Furthermore, attention to early respiratory and skin care has contributed to reductions in pulmonary infections and pressure ulcers, though other complications such as urinary tract infections (UTIs) remain prevalent, reflecting the multifactorial vulnerability of this population (Rask et al., 2024).

As the understanding of traumatic central cord syndrome continues to evolve, so too does the role of precision neurocritical care in guiding acute management. The limitations of current interventions underscore

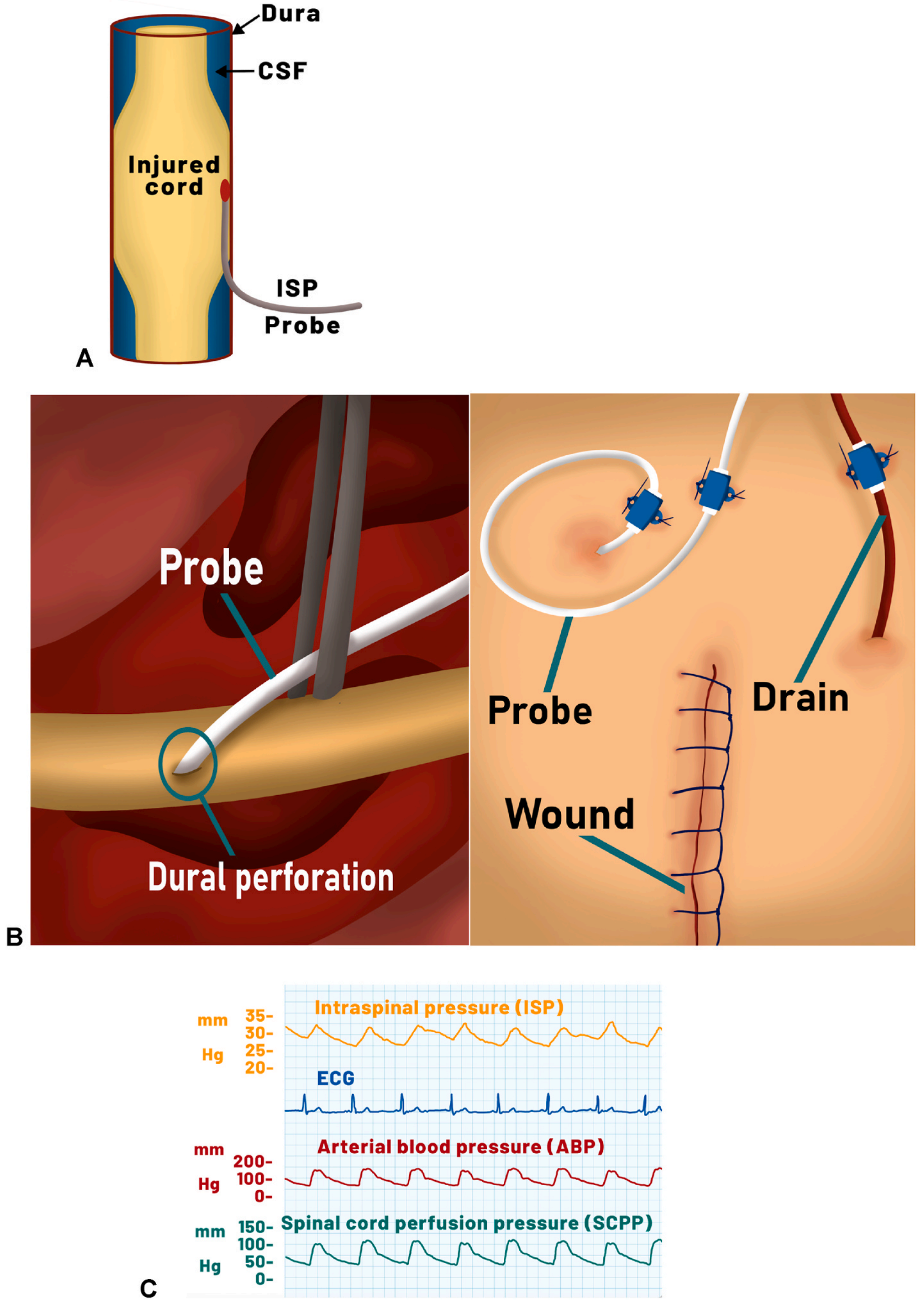

Fig. 3. Important steps in intraspinal pressure (ISP) monitoring technique and physiological variables assessment. **(A)** Probe proper location is in the subdural space (Phang and Papadopoulos, 2015; Varsos et al., 2015). **(B)** A tunneler pulls the ISP probe through the skin into the wound. Then, dura is perforated with a 90° bent needle one spinal level below the injury, and the probe is inserted through the dural perforation. The surgical incision is closed and the probe secured to skin using sutures (Phang and Papadopoulos, 2015). **(C)** Recorded data can be visualized in a monitor using specific plugins, or directly using a software interface (Varsos et al., 2015; Visagan et al., 2022; Werndle et al., 2014). **CSF:** cerebrospinal fluid; **ECG:** electrocardiogram; **ISP:** intraspinal pressure. **[**Figures were adapted and changed in format from cited references, considering authors' work copyright. https://creativecommons.org/licenses/by-nc-nd/4.0/.].

the need to explore novel strategies for physiologic monitoring and complication prevention in this uniquely vulnerable population. In the following sections, we explore the emerging role of advanced neuromonitoring techniques, including intraspinal pressure, spinal perfusion pressure, and spinal cord tissue oxygenation, as well as the medical complications most frequently encountered in the early phase following injury. These considerations are critical to developing a comprehensive, individualized approach to care that extends beyond decompressive surgery and addresses the complex interplay of systemic and spinal cord-specific pathophysiology in TCCS.

2.3.8. Neuromonitoring in TCCS

Neuromonitoring is increasingly recognized as a cornerstone in the early management of traumatic central cord syndrome (TCCS) and broader traumatic spinal cord injury (TSCI), providing real-time physiological insight that can inform both surgical and neurocritical care decisions. Parameters such as intraspinal pressure (ISP), mean arterial pressure (MAP), and spinal perfusion pressure (SPP) (Fig. 3) are central to understanding the hemodynamic and compartmental physiology of the injured spinal cord (Phang and Papadopoulos, 2015). Optimizing these parameters is essential not only for maintaining adequate perfusion and oxygenation but also for reducing the burden of secondary injury cascades that can exacerbate neuronal and glial damage (Phang and Papadopoulos, 2015; Varsos et al., 2015). Importantly, all ISP-related data in this review refer specifically to invasive subdural intraspinal pressure monitoring, which involves the surgical placement of a pressure transducer into the subdural space, adjacent to the site of injury. This technique, often performed intraoperatively following decompressive laminectomy, offers direct, anatomically localized measurements of spinal compartment pressure, in contrast to indirect methods such as lumbar CSF pressure monitoring (Phang and Papadopoulos, 2015; Varsos et al., 2015). The latter may fail to accurately reflect segmental pressure gradients due to pressure compartmentalization, post-traumatic arachnoiditis, or rostral-caudal disparities in CSF dynamics. Subdural ISP monitoring is therefore considered theoretically superior in fidelity and regional specificity, providing a more accurate representation of the mechanical and perfusional environment surrounding the injured spinal cord (Phang and Papadopoulos, 2015).

ISP reflects the net pressure exerted within the confined intraspinal compartment and is influenced by several dynamic and interrelated variables, including cerebrospinal fluid pressure, microvascular blood volume, interstitial edema, vasogenic permeability changes, and the presence of space-occupying lesions such as intramedullary hematomas or necrotic tissue (Phang and Papadopoulos, 2015; Varsos et al., 2015). Elevated ISP can impair capillary perfusion, promote tissue hypoxia, and initiate a cascade of secondary injuries involving glutamate excitotoxicity, mitochondrial dysfunction, oxidative stress, and apoptotic signaling pathways (Varsos et al., 2015). Clinically, these pathophysiological processes are associated with lesion expansion and poorer functional outcomes, emphasizing the importance of both early detection and therapeutic modulation of ISP.

Mean arterial pressure (MAP) remains a modifiable systemic parameter and has been the cornerstone of hemodynamic therapy in acute TSCI. Consensus guidelines support maintaining MAP above 85–90 mmHg for at least the first 5–7 days post-injury, although emerging evidence suggests that individualized targets based on real-time spinal cord monitoring may be more effective (Varsos et al., 2015). Maintaining adequate MAP is particularly critical in TCCS, which often affects elderly patients with comorbid vascular risk factors and underlying spinal canal stenosis, potentially compounding microvascular insufficiency and impairing autoregulatory responses (Phang and Papadopoulos, 2015; Varsos et al., 2015). The integration of spinal perfusion pressure (SPP) (defined as the difference between MAP and ISP) offers a more refined and regionalized assessment of spinal cord perfusion. Analogous to cerebral perfusion pressure in traumatic brain injury, SPP represents the effective pressure gradient across the spinal capillary bed. While mathematical calculation is straightforward, the determinants of SPP are highly complex and vary based on anatomical level, injury morphology, systemic physiology, and ongoing surgical manipulation. Observational and preclinical studies suggest that SPP values above 50–70 mmHg are associated with better neurological outcomes and reduced lesion propagation. These findings have driven interest in SPP-guided therapy, though prospective, protocolized clinical trials remain limited (Varsos et al., 2015).

Complementing this hemodynamic monitoring paradigm, spinal cord tissue oxygenation ($psctO_2$) has emerged as a novel parameter for assessing the metabolic health of injured spinal tissue (Visagan et al., 2022). Direct measurement using intraparenchymal oxygen sensors placed adjacent to the lesion site allows for continuous, real-time monitoring of tissue oxygen tension. A 2022 prospective study (Visagan et al., 2022) demonstrated the feasibility, safety, and clinical utility of $psctO_2$ monitoring in patients with acute, severe cervical TSCI. The study found that $psctO_2$ levels correlate with metabolic distress indicators, such as elevated lactate/pyruvate ratios, and could identify regional hypoxia despite MAP and SPP values falling within conventionally acceptable thresholds (Visagan et al., 2022). This finding underscores the value of $psctO_2$ as a complementary, functionally integrative parameter, capable of identifying tissue-level ischemia not evident through pressure-based metrics alone.

Incorporating $psctO_2$ monitoring alongside ISP and SPP enables a multiparametric, physiologically guided approach to spinal cord injury management (Werndle et al., 2014). This approach allows clinicians to make dynamic, patient-specific adjustments to vasopressor therapy, surgical decompression strategies, and fluid management, with the goal of optimizing both perfusion and oxygen delivery at the site of injury. In the context of TCCS, where parenchymal injury may be subtle on imaging yet functionally devastating, such fine-grained monitoring may be especially useful for detecting covert deterioration and guiding early interventions (Tykocki et al., 2017). As neuromonitoring technologies evolve, the combined use of subdural ISP, SPP, and $psctO_2$ offers the potential to shift spinal trauma management from protocolized MAP targets toward real-time, feedback-driven therapeutic strategies tailored to the metabolic and hemodynamic demands of each patient (Visagan et al., 2022; Werndle et al., 2014; Tykocki et al., 2017). This individualized approach is particularly compelling for TCCS, which presents with diverse injury patterns and degrees of cord compromise, often in patients with complex anatomical and vascular substrates. While broader adoption awaits further validation in large, multicenter studies, early evidence supports the integration of this multi-parameter monitoring framework into advanced neurocritical care pathways for severe TSCI.

Finally, it is important to note that individual patient characteristics, including age, comorbidities, and the extent of spinal cord injury, can influence the choice of neuromonitoring targets. Moreover, clinical judgment and the patient's overall clinical status play a significant role in determining the appropriate targets. Monitoring ISP, MAP, and SPP should be viewed as part of a comprehensive strategy to optimize spinal cord perfusion while minimizing the risk of complications associated with aggressive blood pressure management; clinical trials such as DISCUS (Saadoun et al., 2023) and WISP (Dhaliwal et al., 2022) may provide clearer data in this scenario in the near future. An individualized approach, guided by the evolving clinical status of the patient, is paramount in achieving these objectives.

2.3.9. Incidence and prevalence of medical complications in TCCS

TCCS is not only associated with neurological deficits but also with a range of medical complications that can significantly impact patient outcomes. Understanding the incidence and prevalence of these complications is crucial for comprehensive patient care.

- Venous Thromboembolism (VTE): Venous thromboembolism, encompassing pulmonary embolism (PE) and deep venous

thrombosis (DVT), is a prevalent concern in TCCS patients. Immobility, spinal cord injury-related hypercoagulability, and venous stasis contribute to its development. The incidence of VTE in TCCS varies, but studies have reported rates as high as 25 % in the acute phase post-injury, emphasizing the need for vigilant thromboprophylaxis (..).
- Infections: Infectious processes in general, particularly pneumonia and urinary tract infection (UTI), are common complications in TCCS patients due to impaired respiratory function, urinary retention, and urinary catheter use. Pneumonia occurs in up to 30 % of TCCS patients, while UTIs are reported in 20–50 % of cases during the acute phase, necessitating aggressive prevention and treatment strategies (Burns, 2007).
- Pressure Ulcers: Pressure ulcers result from prolonged immobility and sensory deficits in TCCS patients. These ulcers can be debilitating and delay rehabilitation. The incidence of pressure ulcers varies, but can be as high as 25 % in individuals with severe TCCS. Preventative measures are paramount to reduce their occurrence (Weaver et al., 2006; Iyun et al., 2012; Idowu et al., 2011).
- Bowel Dysfunction: Bowel dysfunction is a significant concern in TCCS patients, leading to constipation, incontinence, and other gastrointestinal issues due to disrupted neural control. The prevalence of bowel dysfunction is relatively high, affecting up to 70 % of TCCS patients during the acute phase, highlighting the importance of comprehensive bowel management strategies (Shiferaw et al., 2020; Furusawa et al., 2012)

Managing and mitigating these medical complications is essential in TCCS care. Strategies include early mobilization, anticoagulation therapy for VTE prevention, respiratory support, strict catheter care and urinary hygiene, pressure ulcer prevention protocols, and bowel management regimens (Adegeest et al., 2024; Johns et al., 2021).

2.3.10. Role of steroids in the setting of TCCS

It is essential to acknowledge the on-going debate and varying opinions surrounding the use of steroids in traumatic spinal cord injury (TSCI), including TCCS. Some studies and guidelines may support their use, while others may raise concerns or provide conflicting evidence (Bracken, 2012; Sterner and Sterner, 2023). The potential role of steroids is thought to be the mitigation of secondary spinal cord injury by reducing inflammation and oxidative stress (Bracken, 2012).

The standard regimen, as outlined in the National Acute Spinal Cord Injury Study (NASCIS) protocol, involved a high initial dose followed by a maintenance dose (Bracken, 2012). Methylprednisolone is the most used steroid and is administered intravenously. The initial high-dose regimen consists of a bolus of 30 mg/kg of methylprednisolone followed by a continuous infusion of 5.4 mg/kg/hour for 23 h. The total duration of steroid therapy is typically 24 or 48 h. Administering steroids within the first 8 h after injury is recommended for optimal effectiveness (Dhaliwal et al., 2022). This regime, however, remains highly controversial, and the risks and benefits of using steroids should be carefully considered on an individual basis.

The adherence to guidelines for the management of secondary damage of traumatic spinal cord injury (TSCI) worldwide is not consistent. Most physicians treating TSCI in low- and middle-income countries (LMICs) sometimes use high-dose steroids, but not regularly. While most LMICs have reported the availability of intensive care units (ICUs), significant proportions still manage TSCI in regular hospital wards. Low-resource areas have the lowest rate of ICU admissions for TSCI. Many respondents do not perform surgery on TSCIs within the recommended 24 or 48-h timeframes, and delays in some areas are substantial. Excessive transfer times are commonly cited as the main reason for surgical delays. Rehabilitation options vary significantly based on income and geographic areas, with dedicated spinal units being less accessible in low-resource settings. Once the local situation is explained, it is necessary to develop plans to address the obstacles that arise while implementing the current standards for Traumatic Spinal Injury (TSI) and Traumatic Spinal Cord Injury (TSCI) in Low- and Middle-Income Countries (LMICs). This is done to enhance patient outcomes and alleviate economic pressures (Marchesini et al., 2022).

Table 2 summarises the key points from each of the several aspects discussed in the management of TCCS.

3. Conclusions

Traumatic central cord syndrome (TCCS) continues to pose significant diagnostic and management challenges due to its heterogeneous presentation and evolving pathophysiological understanding. Traditionally viewed as a central lesion affecting medially located upper limb corticospinal fibers, recent evidence supports a more diffuse model involving complex, segmentally organized CST architecture and interneuronal networks within the cervical enlargement. This paradigm shift underscores the importance of individualized surgical and neurocritical care strategies aimed at mitigating secondary injury and optimizing recovery.

While advances in neuroimaging, intraoperative techniques, and hemodynamic management have improved clinical decision-making, significant knowledge gaps remain. These include uncertainty regarding the optimal timing and selection of surgical candidates, the prognostic value of metrics such as the BASIC score or canal diameter, and the precise thresholds for spinal cord perfusion optimization. Current literature is constrained by retrospective designs and variable outcome measures, limiting generalizability. Future efforts should focus

Table 2
Key summary points in traumatic central cord syndrome.

Topic	Key points
Pathophysiology and Mechanisms of Injury in TCCS	Recent anatomical studies challenge the classical somatotopic CST model; TCCS is better understood as a diffuse network-level injury localized to the cervical enlargement.
Clinical and Imaging Diagnosis of TCCS	MRI remains the gold standard for evaluating intramedullary pathology, revealing cord edema, hematomyelia, ligamentous injury, and predictors like canal diameter and BASIC score.
Severity of TCCS Assessed by ASIA Impairment Scale	The ASIA Impairment Scale is widely used for clinical severity grading in TCCS, but presentation heterogeneity—including asymmetric and sensory-predominant forms—complicates classification.
Neurosurgical Management	Surgical decompression is indicated in select patients with evidence of mechanical compression; outcomes depend on injury severity, timing, and comorbid pathology. There is no consensus on optimal surgical timing. Early surgery may offer benefits in preventing secondary injury, but clinical stability and radiological findings guide decisions.
Neurocritical Care for TCCS	Neurocritical care management emphasizes spinal cord perfusion, respiratory monitoring, and the prevention of secondary complications such as autonomic dysfunction and infections.
Neuromonitoring in TCCS	Experimental use of intraspinal pressure (ISP), spinal cord perfusion pressure (SCPP), MAP targets and spinal cord tissue oxygenation ($psctO_2$), shows potential, but standardized clinical protocols are lacking.
Incidence and Prevalence of Medical Complications in TCCS	Patients with TCCS are at high risk for complications including venous thromboembolism, pressure ulcers, urinary tract infections, and bowel/bladder dysfunction, necessitating multidisciplinary management.
Role of Steroids in the Setting of TCCS	The role of steroids in TCCS remains controversial. While previously used to mitigate secondary injury, current evidence does not support their routine administration.

on high-quality, prospective multicenter studies incorporating advanced imaging and perfusion-based metrics to refine treatment algorithms. A better understanding of the structural and physiological correlates of TCCS is essential for tailoring interventions and predicting functional outcomes. Continued integration of neurosurgical precision with neurocritical care principles holds promise for improving long-term prognosis in this uniquely vulnerable patient population.

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Conflict of interests

Authors declare no conflict of interests.

Appendix A. Supplementary data

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