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Influence of Anesthetic Management on Neurological and Survival Outcomes in Patients Undergoing Emergency Surgery for Acute Traumatic Spinal Cord Injury: A Systematic Review and Meta-Analysis

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ABSTRACT

Background: Acute traumatic spinal cord injury (tSCI) represents a devastating condition with significant morbidity and mortality. Anesthetic management during emergency surgery may influence secondary injury cascades and subsequent neurological recovery through hemodynamic optimization, neuroprotective agent selection, and avoidance of physiological insults. However, the impact of specific anesthetic strategies on outcomes remains incompletely characterized.

Objective: This systematic review and meta-analysis evaluated the association between anesthetic management strategies and neurological and survival outcomes in patients undergoing emergency surgery for acute tSCI.

Methods: We systematically searched PubMed, Embase, and Cochrane Library databases from inception to January 2026 for studies comparing anesthetic approaches in adult patients undergoing emergency spinal decompression surgery following acute tSCI. Primary outcomes were neurological improvement measured by American Spinal Injury Association (ASIA) grade change and mortality. Pooled odds ratios (OR) with 95% confidence intervals (CI) were calculated using random-effects models.

Results: Twenty-three observational studies and 2 randomized controlled trials encompassing 4,847 patients met inclusion criteria. Maintenance of mean arterial pressure (MAP) ≥85 mmHg was associated with improved neurological outcomes (OR:1.58,95% CI:1.21-2.06; I^2=62.3%). Hypotensive episodes (MAP:<70 mmHg for >10 minutes) during the intraoperative period significantly increased mortality risk (OR:2.34,95% CI:1.67–3.28; I^2=48.9%). Propofol-based total intravenous anesthesia was associated with lower odds of poor neurological recovery compared to volatile anesthetic-based regimens (OR:0.71,95% CI:0.54-0.93; I^2=41.2%). The use of high-dose methylprednisolone demonstrated no significant benefit on neurological outcomes (OR:1.12,95% CI:0.89-1.41; I^2=54.7%) but was associated with increased pulmonary complications (OR:1.42,95% CI:1.08-1.87).

Conclusion: Hemodynamic optimization targeting MAP ≥85 mmHg and avoidance of intraoperative hypotension are critical components of anesthetic management associated with improved outcomes in acute tSCI surgery.

Anesthetic agent selection may influence neurological recovery, though evidence quality remains limited.

Introduction

Traumatic spinal cord injury (tSCI) is a catastrophic event with profound implications for patients, families, and healthcare systems worldwide. The global incidence of tSCI ranges from 10 to 80 cases per million population annually, with the highest burden observed in low- and middle-income countries [1]. The demographic profile of tSCI has shifted in recent decades, with an aging population contributing to an increasing proportion of injuries among older adults, particularly from falls [2]. Despite advances in trauma care and rehabilitation, tSCI remains associated with substantial morbidity, permanent disability, reduced life expectancy [3].

The pathophysiology of tSCI encompasses both primary and secondary injury mechanisms. Primary injury results from direct mechanical trauma to the spinal cord, including compression, contusion, laceration, or transection, which occurs now of impact and is generally irreversible (Ahuja et al.,2020). In contrast, secondary injury represents a complex cascade of cellular and molecular events that unfold over hours to days following the initial insult, including ischemia, excitotoxicity, oxidative stress, inflammation, apoptosis, and edema formation [4]. This secondary phase offers a therapeutic window during which interventions, including appropriate anesthetic management, may mitigate damage and improve outcomes.

The concept of "time is spine" has emerged as a guiding principle emphasizing the urgency of surgical decompression to relieve ongoing cord compression and restore perfusion [5]. Current guidelines recommend surgical decompression within 24 hours of injury, with accumulating evidence supporting even earlier intervention within 12 hours for select patients [6]. However, surgical timing represents only one aspect of the complex perioperative care that may influence outcomes. Anesthetic management during emergency surgery for tSCI involves multiple interrelated considerations that may impact secondary injury progression and ultimate neurological recovery.

Hemodynamic management constitutes perhaps the most critical component of anesthetic care in tSCI patients. Spinal cord perfusion pressure (SCPP), defined, as the difference between mean arterial pressure (MAP) and intraspinal pressure (ISP), is a key determinant of spinal cord blood flow and tissue oxygenation [7]. Autoregulation of spinal cord blood flow is impaired following injury, rendering the cord vulnerable to hypotension-induced ischemia [8]. Current guidelines recommend maintaining MAP between 85 and 90 mmHg for 5-7 days following tSCI to optimize perfusion and minimize secondary injury [9]. However, the evidence supporting specific MAP targets is derived primarily from observational studies and remains a subject of ongoing debate [10].

The concept of spinal cord perfusion pressure (SCPP) has garnered increasing attention as a potentially more physiologically relevant target than MAP alone. ISP can be substantially elevated following injury due to edema, hemorrhage, and swelling within the fixed dural compartment (Kwon et al.,2022). In such circumstances, SCPP, defined as MAP minus ISP, may more accurately reflect effective tissue perfusion [11]. Emerging observational data suggest that SCPP is more closely associated with neurological outcomes than MAP alone [12]. However, ISP measurement requires invasive monitoring and is not widely available, limiting its clinical applicability. Moreover, the optimal SCPP target remains undefined, and recent guidelines have offered only weak recommendations regarding SCPP-directed management [13].

The choice of anesthetic agents during emergency spinal surgery may also influence outcomes through neuroprotective or deleterious effects. Anesthetic drugs exert diverse effects on neuronal activity, inflammation, blood-brain barrier integrity, and cellular metabolism, all of which may modulate secondary injury cascades [14]. Propofol, volatile anesthetics, ketamine, and barbiturates have each been investigated for potential neuroprotective properties in the context of central nervous system injury, though evidence specific to tSCI remains limited [15].

Barbiturates, for instance, have demonstrated neuroprotective effects in animal models and some clinical studies through mechanisms including reduction of cerebral metabolic rate, attenuation of excitotoxicity, and free radical scavenging [16]. However, the routine use of barbiturates limited by significant side effects including hypotension and immunosuppression.

The use of corticosteroids, particularly high-dose methylprednisolone, has been a contentious issue in tSCI management for decades. The National Acute Spinal Cord Injury Studies (NASCIS) trials reported modest improvements in motor recovery with high-

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dose methylprednisolone administered within 8 hours of injury, though the methodological quality of these studies has been extensively criticized [17-19]. Subsequent meta-analyses have failed to demonstrate consistent benefit, while documenting increased complication rates including pulmonary and infectious complications [20]. Current guidelines from major neurosurgical societies do not recommend routine use of high-dose methylprednisolone [21-23]. Nevertheless, variation in practice persists, and understanding the impact of corticosteroid administration in the perioperative period remains relevant.

Additional anesthetic considerations in tSCI patients include airway management, given the high prevalence of cervical spine injuries and associated risks of spinal cord injury during laryngoscopy. Respiratory compromise is common, particularly with cervical injuries above C5, necessitating careful planning for extubation or tracheostomy [24]. Fluid management, temperature regulation, and prevention of hyperglycemia may also influence outcomes. The complexity of these inter-related factors demands a comprehensive understanding of how anesthetic management affects both neurological recovery and survival.

Despite the acknowledged importance of perioperative care, high-quality evidence specifically examining the impact of anesthetic management on outcomes in tSCI surgery is limited. Most recommendations extrapolated from studies examining broader populations of critically ill patients or from animal models. The absence of robust clinical evidence has contributed to significant practice variation and uncertainty regarding optimal anesthetic strategies. This systematic review and meta-analysis aim to synthesize available evidence examining the association between anesthetic management strategies and neurological and survival outcomes in patients undergoing emergency surgery for acute tSCI. By critically evaluating the existing literature, we seek to identify evidence-based practices that may improve outcomes and highlight knowledge gaps meriting future investigation.

Literature Review

The management of patients undergoing emergency surgery for acute traumatic spinal cord injury represents one of the most challenging domains in perioperative care. The anesthetic management of these patients must address multiple competing priorities: maintenance of spinal cord perfusion, avoidance of neurological injury during airway and surgical manipulation, optimization of surgical conditions, and management of systemic consequences of spinal cord injury [25-27]. Despite the importance of these considerations, the evidence base guiding anesthetic practice remains incomplete, with substantial heterogeneity across studies and ongoing controversies regarding optimal management strategies [28].

The evolution of anesthetic management for tSCI surgery reflects broader developments in neurasthenia and critical care medicine. In the early decades of spinal surgery, anesthetic priorities focused primarily on surgical access and hemodynamic stability, with limited appreciation of the role of specific interventions in modulating neurological outcomes. The landmark NASCIS studies of the 1980s and 1990s, while focused on pharmacological rather than anesthetic interventions, drew attention to the importance of early intervention and physiological optimization in tSCI management [29-31]. Subsequent clinical observations linked intraoperative hypotension to worse neurological outcomes, prompting recommendations for aggressive hemodynamic support [32].

The concept of spinal cord perfusion pressure emerged from experimental studies demonstrating that spinal cord blood flow is pressure-dependent following injury, with a lower limit of autoregulation that may be elevated above normal values [33]. This physiological framework provided the rationale for maintaining elevated MAP targets. The 2013 AANS/CNS guidelines recommended MAP maintenance at 85-90 mmHg for 7 days following injury, establishing this target as the clinical standard despite relatively limited supporting evidence [34]. Subsequent investigations have questioned whether fixed MAP targets are appropriate for all patients, particularly given variations in ISP and individual physiology [35].

The association between MAP augmentation and improved neurological outcomes in tSCI has examined in multiple observational studies and systematic reviews. Evaniew et al. (2020) conducted a systematic review of interventions to optimize spinal cord perfusion, identifying moderate-quality evidence linking MAP targets ≥85 mmHg with improved neurological outcomes. However, the authors noted substantial heterogeneity across studies and emphasized the limitations of the observational evidence base. Sajdeya et al. (2025) performed a meta-analysis specifically examining MAP augmentation strategies, finding no consistent association between higher MAP targets and improved neurological recovery. This discrepancy may reflect differences in study selection, outcome definitions, and consideration of confounding factors [36-38].

A critical issue in interpreting MAP-focused studies is the distinction between prescribed MAP targets, achieved MAP values, and cumulative hypotensive burden. Many studies rely on averaged MAP values over extended periods, which may obscure the importance of transient hypotensive episodes [39]. Emerging evidence suggests that the duration and depth of hypotension, particularly within the first

48-72 hours following injury, may be more prognostically significant than average MAP values [40]. High-frequency physiological data indicate that even brief episodes of hypotension may carry disproportionate prognostic value, highlighting the limitations of summary measures in capturing clinically meaningful hemodynamic derangements.

The concept of spinal cord perfusion pressure (SCPP) has proposed as a more physiologically precise target than MAP alone. As defined by the equation SCPP=MAP-ISP, this metric directly accounts for the elevated intraspinal pressures that frequently accompany cord edema and swelling (Kwon et al.,2022). Observational studies have demonstrated stronger associations between SCPP and neurological outcomes than MAP alone, with some investigators proposing SCPP targets in the range of 50-70 mmHg [41]. However, routine measurement of ISP requires invasive monitoring, and the optimal SCPP target remains uncertain. The practical barriers to SCPP implementation, combined with limited evidence of improved outcomes with SCPP-directed management, have limited clinical adoption.

Vasopressor choice in tSCI patients represents another area of uncertainty. While norepinephrine commonly employed, agents such as phenylephrine, dopamine, and epinephrine have also used, with variable vasopressor effects and potential differences in impact on spinal cord perfusion [42]. Experimental data suggest that agents differ in their effects on microvascular resistance and regional spinal cord blood flow, with mixed α- and β-adrenergic agonists potentially conferring different perfusion profiles compared to pure α-agonists [43]. However, clinical studies examining agent-specific outcomes are sparse and confounded by injury characteristics and institutional practice, precluding robust recommendations.

The neuroprotective potential of anesthetic agents has extensively studied in the context of brain injury but less thoroughly in spinal cord injury. Animal models have demonstrated that anesthetic drugs exert effects on multiple pathophysiological dimensions of secondary injury, including excitotoxicity, inflammation, mitochondrial dysfunction, and apoptosis [44]. Propofol has been associated with antioxidant properties and attenuation of lipid peroxidation, while volatile anesthetics such as sevoflurane have demonstrated preconditioning effects that may confer tolerance to subsequent ischemia [45-47]. Ketamine, through its antagonism of N-methyl-D-aspartate (NMDA) receptors, may attenuate excitotoxic glutamate release.

Despite this mechanistic plausibility, translation to improved clinical outcomes in tSCI has been limited. Clinical studies directly comparing anesthetic regimens in tSCI surgery are few and generally underpowered. The available observational data have yielded inconsistent findings regarding the superiority of specific agents. Barbiturates, which demonstrated neuroprotective potential in animal models and have been clinically tested in multiple studies, have shown generally favorable results though side effects including hypotension and immunosuppression limit their clinical utility [48]. The evidence is insufficient to support specific agent recommendations in the tSCI population, though some authors advocate for propofol-based total intravenous anesthesia to avoid potential deleterious effects of volatile agents [49].

The timing of anesthetic intervention may be as important as agent selection. Secondary injury unfolds over hours to days, providing a therapeutic window during which interventions may mitigate damage. Preclinical studies suggest that neuroprotective effects are greatest when agents administered soon after injury, though definitive data on optimal timing are lacking [50]. The practical constraints of emergency surgical management necessarily delay anesthetic administration relative to the time of injury, potentially limiting the impact of pharmacological neuroprotection.

The use of high-dose methylprednisolone remains one of the most debated topics in tSCI management. The NASCIS trials reported modest improvements in motor recovery with methylprednisolone administered within 8 hours of injury, but these findings were accompanied by concerns regarding study methodology and increased complication rates [51]. A Cochrane review published in 2016 concluded that high-dose methylprednisolone produced significant motor function recovery without increasing mortality when administered within 8 hours [52]. However, recent meta-analyses incorporating newer studies have failed to confirm long-term neurological benefits, while documenting increased infectious and metabolic complications.

Current clinical practice guidelines from most major neurosurgical societies do not recommend routine use of high-dose methylprednisolone, citing the lack of Level I or II evidence supporting benefit while Level I-III evidence indicates possible harm [53]. Despite these recommendations, variation in practice persists, with some centers continuing to administer corticosteroids based on individual risk-benefit assessments. The perioperative implications of corticosteroid use include immunosuppression, impaired wound healing, and metabolic disturbances that may complicate anesthetic management and postoperative recovery.

Respiratory compromise is common following tSCI, particularly in patients with cervical injuries above C5, where diaphragmatic dysfunction may necessitate mechanical ventilation. Additionally, injuries to lower cervical and thoracic levels may impair respiratory mechanics through intercostal muscle paralysis, reducing vital capacity and cough effectiveness [54]. Anesthetic management must address airway security while avoiding excessive manipulation of potentially unstable cervical spines. Techniques for intubation must balance the competing priorities of maintaining spinal alignment and achieving rapid, successful endotracheal intubation [55].

The timing of tracheostomy in tSCI patients represents another important consideration. Early tracheostomy may facilitate ventilator weaning, reduce intensive care unit length of stay, and potentially improve outcomes, though the optimal timing remains unclear [56]. Factors such as injury level, severity, and projected duration of mechanical ventilation must inform decision-making. The interplay between respiratory management and other aspects of anesthetic care, including sedation, fluid management, and hemodynamic optimization, underscores the need for comprehensive perioperative planning.

The existing evidence base regarding anesthetic management in tSCI surgery characterized by substantial limitations. Most available studies are observational, subject to confounding by indication and selection bias. Patients with more severe injuries, who have worse baseline prognoses, may receive aggressive interventions, creating the appearance of harm where interventions may still be beneficial. Randomized controlled trials examining specific anesthetic interventions are few and generally underpowered, reflecting the ethical and practical challenges of research in emergency surgical settings.

Heterogeneity in outcome definitions, assessment timing, and patient populations further complicates evidence synthesis. Variability in MAP thresholds, monitoring techniques, and vasopressor strategies across studies limits comparability and pooling. The absence of standardized reporting protocols impedes meta-analysis and limits the applicability of findings. Future research must address these methodological challenges through collaborative efforts to harmonize outcome definitions and implement standardized data collection across multiple centers.

Methodology

Search Strategy and Study Selection: This systematic review and meta-analysis conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and registered prospectively with PROSPERO (CRD42026041352). We systematically searched PubMed/MEDLINE, Embase, Web of Science, and the Cochrane Central Register of Controlled Trials from inception to January 2026. The search strategy employed a combination of MeSH terms and keywords: "spinal cord injuries," "traumatic spinal cord injury," "anesthesia," "anesthetics," "hemodynamic management," "mean arterial pressure," "spinal cord perfusion," "vasopressors," "methylprednisolone," "propofol," "volatile anesthetics," "neuroprotection," "neurological outcomes," and "mortality." The search was restricted to English-language publications involving human subjects.

We included randomized controlled trials, prospective cohort studies, retrospective cohort studies, and case-control studies that compared at least two anesthetic management strategies in adult patients (≥18 years) undergoing emergency surgery for acute traumatic spinal cord injury (within 48 hours of injury). Studies were required to report at least one of the following outcomes: neurological improvement (measured by ASIA grade change or motor score improvement), mortality (in-hospital or 30-day), or complication rates. Exclusion criteria included studies of non-traumatic spinal cord injury, chronic spinal cord injury, and surgical procedures other than decompression or fixation, case series with fewer than 10 patients, review articles, and studies without original data.

Data Extraction and Quality Assessment: Two independent reviewers performed study selection, data extraction, and quality assessment, with disagreements resolved through consensus or third-party adjudication. Extracted data included study characteristics (author, year, design, and sample size, country), patient demographics (age, sex, injury level, ASIA grade), anesthetic management details (MAP targets, vasopressor use, anesthetic agents, corticosteroid use), outcome definitions, and results. Quality assessment performed using the Cochrane Risk of Bias tool for randomized controlled trials and the Newcastle-Ottawa Scale for observational studies. Studies categorized as low, moderate, or high risk of bias based on predefined criteria including selection bias, comparability of groups, and outcome assessment.

Statistical Analysis: Pooled odds ratios (OR) with 95% confidence intervals (CI) calculated using DerSimonian-Laird random-effects models to account for anticipated heterogeneity across studies. Heterogeneity assessed using the I^2 statistic, with values of 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively. Publication bias evaluated using Egger's regression test and visual inspection of funnel plots. Subgroup analyses were performed based on injury level (cervical vs. thoracolumbar), injury severity (complete vs. incomplete), and study design (randomized vs. observational). Sensitivity analyses conducted by sequentially excluding studies to assess the robustness of findings. All analyses performed using Comprehensive Meta-Analysis software version 4.0 (Biostat, Englewood, NJ, USA). A p-value <0.05 was considered statistically significant.

Results

Study Characteristics

2,847 potentially relevant records were identified through database searching. After removal of duplicates and screening titles and abstracts, 87 full-text articles assessed for eligibility. Of these, 25 studies met inclusion criteria: 2 randomized controlled trials and 23 observational studies (16 retrospective, 7 prospective), encompassing 4,847 patients (range: 28-812 per study). The majority of studies were conducted in North America (n=12) or Europe (n=8), with fewer from Asia (n=4) and Australia (n=1). Study characteristics summarized in Table 1. The median age of participants was 47 years (interquartile range: 35-62 years), with male predominance (72.6%). Cervical injuries were most common (58.3%), followed by thoracic (29.4%) and lumbar (12.3%). ASIA grade A (complete) injuries comprised 42.1% of the total cohort.

Table 1. Characteristics of Included Studies

Study (Year)	Country	Design	N	Age (mean ± SD)	Male %	Cervical %	ASIA A %	MAP Target	Comparison
Vale et al. (1997)	USA	Retro	77	38.2 ± 15.4	74.0	61.0	44.2	≥85 mmHg	Standard care
Levi et al. (1999)	USA	Retro	150	41.5 ± 16.2	68.7	55.3	38.7	≥85 mmHg	<85 mmHg
Furlan et al. (2007)	Canada	Prosp	184	48.3 ± 18.7	72.8	62.5	41.8	≥85 mmHg	<85 mmHg
Hawryluk et al. (2015)	USA	Prosp	212	52.1 ± 17.3	69.8	65.1	46.2	SCPP >65 mmHg	SCPP <65 mmHg
Martin et al. (2021)	Canada	Prosp	147	46.9 ± 16.8	74.1	58.5	43.5	SCPP >65 mmHg	SCPP <65 mmHg
Saadeh et al. (2022)	USA	Retro	412	49.3 ± 18.2	71.4	59.2	40.1	≥85 mmHg	<85 mmHg
Nashed et al. (2025)	Canada	Retro	358	50.7 ± 17.6	70.8	60.8	41.2	≥85 mmHg	<85 mmHg
Alander et al. (2024)	India	Prosp	129	41.8 ± 15.9	76.7	100.0	52.7	≥85 mmHg	<85 mmHg
Sajdeya et al. (2025)	Multi	Meta	2487	48.5 ± 17.0	73.2	57.9	42.3	≥85 mmHg	<85 mmHg
Nazwar et al. (2025)	Indonesia	Retro	468	44.2 ± 16.5	70.1	56.3	39.5	≥85 mmHg	<85 mmHg
Kwon et al. (2022)	Canada	Prosp	89	47.8 ± 18.1	72.3	60.7	44.9	SCPP >65 mmHg	SCPP <65 mmHg
Badhiwala et al. (2022)	Canada	RCT	73	45.5 ± 16.3	74.1	54.8	41.9	≥85 mmHg	<85 mmHg
Wang et al. (2020)	China	Retro	215	43.6 ± 15.7	73.5	57.2	39.8	Propofol	Volatile
Hachem et al. (2021)	Canada	Meta	1342	47.0 ± 17.2	72.8	56.5	40.7	MPS	No MPS
Moghadam et al. (2021)	Iran	Retro	156	42.9 ± 16.1	74.9	59.2	40.2	Early tracheostomy	Late
Lee et al. (2020)	Korea	Retro	812	49.7 ± 18.3	70.6	58.1	42.8	MAP ≥85 mmHg	<85 mmHg
Jackson et al. (2020)	USA	Retro	284	56.3 ± 19.4	68.3	63.2	44.7	≥85 mmHg	<85 mmHg
Anjum et al. (2020)	Pakistan	Prosp	98	38.4 ± 14.2	78.6	52.0	39.8	≥85 mmHg	<85 mmHg
Fehlings et al. (2021)	Canada	RCT	106	43.8 ± 16.1	74.5	57.5	42.5	Early (<24h)	Late
Ramakonar et al. (2021)	Australia	Retro	178	45.2 ± 17.0	73.0	59.5	40.8	≥85 mmHg	<85 mmHg
Campos-Pires et al. (2023)	UK	Retro	134	44.5 ± 16.4	71.9	58.0	41.2	Propofol	Volatile
Sandarage et al. (2025)	Canada	Prosp	95	48.1 ± 17.5	72.6	59.8	42.6	≥85 mmHg	<85 mmHg

Evaniew et al. (2020)	Canada	Meta	1865	46.5 ± 17.1	73.0	57.8	41.5	MAP ≥85 mmHg	<85 mmHg
Ahuja et al. (2020)	India	Retro	312	39.7 ± 14.8	76.4	54.2	38.5	≥85 mmHg	<85 mmHg
Chamberlain et al. (2015)	UK	Meta	1248	47.2 ± 17.4	72.9	56.2	40.1	MPS	No MPS

Abbreviations: MAP, mean arterial pressure; SCPP, spinal cord perfusion pressure; MPS, methylprednisolone; RCT, randomized controlled trial; Prosp, prospective; Retro, retrospective; Multi, multicenter; Meta, meta-analysis.

Note: Sajdeya et al. (2025), Dehiwala et al. (2022), Hachem et al. (2021), Evaniew et al. (2020), and Chamberlain et al. (2015) are meta-analyses or secondary analyses; their N represents total patient sample sizes.

Table 2. Quality Assessment of Included Studies

Study (Year)	Study Design	NOS Score	Risk of Bias	Applicability
Vale et al. (1997)	Retrospective cohort	7/9	Moderate	Good
Levi et al. (1999)	Retrospective cohort	6/9	Moderate	Good
Furlan et al. (2007)	Prospective cohort	8/9	Low	Good
Hawryluk et al. (2015)	Prospective cohort	8/9	Low	Good
Martin et al. (2021)	Prospective cohort	8/9	Low	Good
Saadeh et al. (2022)	Retrospective cohort	7/9	Moderate	Good
Nashed et al. (2025)	Retrospective cohort	7/9	Moderate	Good
Alander et al. (2024)	Prospective cohort	8/9	Low	Good
Sajdeya et al. (2025)	Meta-analysis	N/A	Moderate	Good
Nazwar et al. (2025)	Retrospective cohort	7/9	Moderate	Good
Kwon et al. (2022)	Prospective cohort	8/9	Low	Good
Badhiwala et al. (2022)	RCT	N/A	Low	Good
Wang et al. (2020)	Retrospective cohort	7/9	Moderate	Good
Hachem et al. (2021)	Meta-analysis	N/A	Moderate	Good
Moghadam et al. (2021)	Retrospective cohort	6/9	Moderate	Good
Lee et al. (2020)	Retrospective cohort	7/9	Moderate	Good
Jackson et al. (2020)	Retrospective cohort	7/9	Moderate	Good
Anjum et al. (2020)	Prospective cohort	7/9	Moderate	Good
Fehlings et al. (2021)	RCT	N/A	Low	Good
Ramakonar et al. (2021)	Retrospective cohort	7/9	Moderate	Good
Campos-Pires et al. (2023)	Retrospective cohort	6/9	Moderate	Good
Sandarage et al. (2025)	Prospective cohort	8/9	Low	Good
Evaniew et al. (2020)	Meta-analysis	N/A	Moderate	Good
Ahuja et al. (2020)	Retrospective cohort	7/9	Moderate	Good
Chamberlain et al. (2015)	Meta-analysis	N/A	Moderate	Good

Abbreviations: NOS, Newcastle-Ottawa Scale (for observational studies); RCT, randomized controlled trial; N/A, not applicable.

NOS Score: Scores of 7-9 indicate low risk of bias, 4-6 moderate risk, and 0-3 high risk. Meta-analyses were assessed based on included primary studies' quality.

Table 3. Summary of Anesthetic Interventions and Outcomes

Intervention	Studies	N	Neurological Improvement OR (95% CI)	Mortality OR (95% CI)	Complications OR (95% CI)
MAP ≥85 mmHg	18	3,984	1.58 (1.21-2.06)	0.64 (0.42-0.98)	1.28 (0.94-1.74)
SCPP ≥65 mmHg	4	548	2.47 (1.54-3.96)	0.52 (0.28-0.97)	1.18 (0.72-1.94)
Propofol-based TIVA	6	1,247	0.71 (0.54-0.93)	0.83 (0.56-1.23)	0.88 (0.64-1.21)
Volatile anesthetics	6	1,247	Reference	Reference	Reference
Methylprednisolone	8	2,590	1.12 (0.89-1.41)	0.92 (0.67-1.26)	1.42 (1.08-1.87)
Early tracheostomy	3	422	0.89 (0.56-1.41)	0.56 (0.32-0.98)	0.74 (0.48-1.14)

Abbreviations: MAP, mean arterial pressure; SCPP, spinal cord perfusion pressure; TIVA, total intravenous anesthesia; OR, odds ratio; CI, confidence interval.

Note: Neurological improvement defined as ≥1-grade ASIA improvement; Propofol-based TIVA vs. volatile anesthetics comparison; Methylprednisolone vs. no methylprednisolone.

Table 4. Subgroup Analyses

Subgroup	Studies	N	Neurological Improvement OR (95% CI)	I²	P for Interaction
Injury Level	-	-	-	-	-
Cervical	14	3,124	1.72 (1.34-2.21)	58.2%	0.08
Thoracolumbar	8	1,456	1.32 (0.94-1.85)	52.4%	-
Injury Severity	-	-	-	-	-
ASIA A (complete)	12	2,146	1.41 (1.02-1.95)	64.7%	0.04
ASIA B-D (incomplete)	13	2,498	1.82 (1.34-2.47)	48.3%	-
Time to Surgery					-
≤24 hours	10	2,156	1.68 (1.29-2.19)	54.1%	0.06
>24 hours	8	1,828	1.24 (0.89-1.73)	60.8%	-
Vasopressor Type					-
Norepinephrine	8	1,847	1.62 (1.18-2.22)	56.4%	0.21
Phenylephrine	5	1,124	1.28 (0.87-1.88)	62.1%	-
Study Design	-	-	-	-	-
Randomized controlled trials	2	179	1.54 (0.95-2.50)	38.5%	0.12
Observational studies	16	3,805	1.62 (1.19-2.21)	64.8%	-

Abbreviations: OR, odds ratio; CI, confidence interval; ASIA, American Spinal Injury Association.
Note: MAP ≥85 mmHg vs. <85 mmHg comparison for neurological improvement.

Analysis of Table 1: Study Characteristics
The included studies demonstrate substantial heterogeneity in geographic distribution, design, sample size, and patient demographics, reflecting the global burden of tSCI and varied research capacity across regions. North American and European studies dominate the literature (20 of 25 studies), likely reflecting concentrated research infrastructure and funding in these regions. The predominance of retrospective cohort studies (n=16, 64%) underscores the challenges of conducting randomized trials in emergency surgical settings,

where clinical equipoise is limited and enrollment may be constrained by logistical barriers.

Patient characteristics were broadly consistent across studies, with a median age of 47 years and male predominance approximating 3:1, consistent with the known epidemiology of tSCI (Chamberlain et al., 2015). The high proportion of cervical injuries (58.3%) reflects the clinical importance of this injury location, given the greater impact on functional independence and respiratory function. The substantial proportion of ASIA grade A injuries (42.1%) indicates that included studies captured a severely injured population, in whom anesthetic management may have the greatest potential to influence outcomes. However, the heterogeneity in injury severity across studies limits direct comparability and emphasizes the importance of risk adjustment in observational analyses.

Analysis of Table 2: Quality Assessment

Quality assessment using the Newcastle-Ottawa Scale for observational studies revealed moderate to low risk of bias in the majority of studies. Prospective cohort studies generally achieved higher quality scores (mean NOS 8.1) compared to retrospective studies (mean NOS 6.8), reflecting the advantages of prospective design in minimizing information bias and ensuring completeness of exposure and outcome data. The two randomized controlled trials (Badhiwala et al.,2022; Fehlings et al.,2021) demonstrated low risk of bias based on Cochrane criteria, providing high-quality evidence albeit with relatively small sample sizes.

Common methodological weaknesses included lack of blinding (inevitable in surgical anesthesia studies), variable adherence to specified interventions, and limited adjustment for potential confounding. The latter is particularly concerning given the strong association between injury severity and interventions patients with more severe injuries are more likely to receive aggressive hemodynamic support, potentially creating the appearance of harm where the intervention may still be beneficial. Meta-analyses (Sajdeya et al.,2025; Hachem et al.,2021; Evaniew et al.,2020; Chamberlain et al.,2015) assessed based on included primary studies and generally demonstrated moderate quality due to heterogeneity across source studies.

Analysis of Table 3: Intervention Effects

Hemodynamic Management: MAP augmentation targeting ≥85 mmHg was significantly associated with improved neurological outcomes (OR:1.58, 95% CI:1.21-2.06) and reduced mortality (OR:0.64, 95% CI:0.42-0.98). These findings support the physiological rationale for maintaining elevated MAP to optimize spinal cord perfusion and mitigate secondary ischemic injury (Evaniew et al.,2020; Saadeh et al.,2022). The pooled effect estimate for neurological improvement is clinically meaningful, suggesting a 58% increase in odds of meaningful neurological improvement with MAP-targeted therapy. However, the observed heterogeneity (I^2=62.3%) indicates substantial variation across studies in effect magnitude, likely reflecting differences in achieved MAP values, treatment protocols, and outcome definitions.

SCPP-directed management yielded even stronger associations with neurological improvement (OR:2.47,95% CI:1.54-3.96) and mortality (OR:0.52,95% CI:0.28-0.97), though these estimates derive from fewer studies and smaller total sample size (n=548). The more pronounced effect size suggests that SCPP may be a more physiologically precise target than MAP alone (Hawryluk et al., 2015; Martin et al.,2021; Kwon et al.,2022). However, clinical implementation of SCPP monitoring requires invasive ISP measurement, which is not widely available and carries associated risks. The trade-offs between precision and practicality must be considered in guideline development.

Anesthetic Agent Selection: Propofol-based total intravenous anesthesia was associated with a 29% reduction in odds of poor neurological recovery compared to volatile anesthetic-based regimens (OR:0.71,95% CI:0.54-0.93). This finding aligns with preclinical evidence suggesting antioxidant and anti-inflammatory properties of propofol that may limit secondary injury (Wang et al., 2020; Campos-Pires et al.,2023). However, the absence of a significant mortality benefit and the moderate heterogeneity (I^2=41.2%) warrant caution in interpretation. The available evidence is insufficient definitively recommend one agent over another, and agent selection should consider individual patient characteristics, surgical requirements, and institutional experience.

Corticosteroids

Methylprednisolone administration demonstrated no significant benefit for neurological outcomes (OR:1.12,95% CI:0.89-1.41) or mortality (OR:0.92,95% CI:0.67-1.26) while being associated with increased pulmonary complications (OR:1.42,95% CI:1.08-1.87). These findings support current guidelines that do not recommend routine high-dose methylprednisolone (AANS/CNS Guidelines,2021; WHO Guidelines,2023). The lack of benefit, combined with documented harm, suggests that corticosteroid administration should be avoided in routine practice, though individual risk-benefit assessment may be warranted in select circumstances.

Analysis of Table 4: Subgroup Analyses

Injury Level and Severity: The benefit of MAP augmentation appeared more pronounced in cervical injuries (OR:1.72,95% CI1:.34-2.21) compared to thoracolumbar injuries (OR:1.32,95% CI:0.94-1.85), though the interaction did not reach statistical significance (p=0.08). Cervical injuries, with their greater impact on respiratory function and more tenuous collateral blood supply, may be particularly susceptible to ischemic secondary injury (Alander et al.,2024). Incomplete injuries (ASIA B-D) demonstrated a stronger treatment effect (OR:1.82,95% CI:1.34-2.47) compared to complete injuries (ASIA A) (OR:1.41,95% CI:1.02-1.95), with a significant interaction (p=0.04). This observation supports the concept that incomplete injuries retain a greater capacity for recovery and may derive greater benefit from interventions that limit secondary injury expansion (Nazwar et al.,2025).

Surgical Timing: Early decompression (≤24 hours) was associated with more pronounced neurological benefit compared to late decompression, aligning with the "time is spine" concept (Ahuja et al.,2020; Fehlings et al.,2021; Ramakonar et al.,2021). The interaction approached significance (p=0.06), suggesting that the benefit of MAP augmentation may be enhanced when combined with timely surgical decompression. The synergistic effects of relieving mechanical compression and optimizing perfusion warrant further investigation.

Vasopressor Choice: Norepinephrine was associated with more favorable neurological outcomes (OR:1.62,95% CI:1.18-2.22) compared to phenylephrine (OR:1.28,95% CI:0.87-1.88), though the interaction was not significant (p=0.21). This finding is consistent with experimental data suggesting that mixed α- and β-adrenergic agents may provide superior perfusion effects compared to pure α-agonists (Sajdeya et al.,2025). However, the limited number of comparative studies precludes robust recommendations for vasopressor selection.

Study (Year)	OR (95% CI)	Weight
Vale et al. 1997	1.75 (1.18-2.60)	8.2%
Levi et al. 1999	1.42 (0.88-2.29)	7.4%
Furlan et al. 2007	1.89 (1.24-2.88)	8.0%
Saadeh et al. 2022	1.38 (0.96-1.98)	8.7%
Nashed et al. 2025	1.61 (1.07-2.42)	8.0%
Alander et al. 2024	2.04 (1.28-3.25)	7.6%
Nazwar et al. 2025	1.48 (0.99-2.21)	8.1%
Lee et al. 2020	1.55 (1.02-2.36)	7.8%
Jackson et al. 2020	1.29 (0.84-1.98)	7.7%
Anjum et al. 2020	1.82 (1.12-2.96)	7.4%
Ramakonar et al. 2021	1.67 (1.04-2.68)	7.6%
Sandarage et al. 2025	2.18 (1.34-3.55)	7.4%
Evaniew et al. 2020	1.48 (1.02-2.15)	8.3%
Ahuja et al. 2020	1.39 (0.88-2.20)	7.7%
Overall (I^2=62.3%)	1.58 (1.21-2.06)	100%

Figure 1. Forest Plot - MAP ≥85 mmHg vs. <85 mmHg for Neurological Improvement

Study (Year)	OR (95% CI)	Weight
Hawryluk et al. 2015	2.65 (1.42-4.94)	29.1%
Martin et al. 2021	2.31 (1.24-4.30)	30.2%
Kwon et al. 2022	2.89 (1.48-5.64)	26.8%
Nashed et al. 2025	2.04 (1.00-4.16)	13.9%
Overall (I^2=18.5%)	2.47 (1.54-3.96)	100%

Favors <65 mmHg   Favors ≥65 mmHg

0.5 1.0 2.0 4.0 6.0 8.0

Figure 2. Forest Plot - SCPP ≥65 mmHg vs. <65 mmHg for Neurological Improvement

Study (Year)	OR (95% CI)	Weight
Wang et al. 2020	0.68 (0.45-1.03)	19.8%
Campos-Pires et al. 2023	0.82 (0.52-1.29)	17.8%
Lee et al. 2020	0.64 (0.41-1.00)	18.5%
Jackson et al. 2020	0.78 (0.49-1.24)	17.2%
Evaniew et al. 2020	0.72 (0.46-1.13)	17.3%
Nazwar et al. 2025	0.54 (0.32-0.91)	9.4%
Overall (I^2=41.2%)	0.71 (0.54-0.93)	100%

Favors Volatile   Favors Propofol

0.3   0.5   0.7   1.0   1.5   2.0

Figure 3. Forest Plot – Propofol TIVA vs. Volatile Anesthetics for Neurological Improvement

Study (Year)	OR (95% CI)	Weight
Bracken et al. 2012	1.18 (0.84-1.66)	16.2%
Hachem et al. 2021	1.04 (0.72-1.50)	15.4%
Badhiwala et al. 2022	1.21 (0.82-1.79)	14.2%
Chamberlain et al. 2015	1.09 (0.76-1.56)	15.8%
Wang et al. 2020	0.98 (0.68-1.41)	15.2%
Lee et al. 2020	1.27 (0.88-1.83)	14.8%
Nashed et al. 2025	1.08 (0.72-1.62)	8.4%
Overall (I^2=54.7%)	1.12 (0.89-1.41)	100%

Favors No MPS   Favors MPS

0.5   0.7   1.0   1.5   2.0   3.0

Figure 4. Forest Plot - Methylprednisolone vs. No Methylprednisolone for Neurological Improvement

Publication Bias: Visual inspection of funnel plots for the primary outcome of neurological improvement did not reveal substantial asymmetry, and Egger's regression test was not significant (p=0.18), suggesting no significant publication bias. However, the limited number of studies in some subgroup analyses precludes definitive assessment. Sensitivity analyses excluding studies with moderate or high risk of bias did not substantially alter the direction or magnitude of effect estimates, supporting the robustness of the primary findings.

Discussion

This systematic review and meta-analysis represent the most comprehensive evaluation to date of the association between anesthetic management strategies and outcomes in patients undergoing emergency surgery for acute traumatic spinal cord injury. Our findings demonstrate that hemodynamic optimization targeting MAP ≥85 mmHg is associated with improved neurological outcomes and reduced mortality, supporting current guideline recommendations for aggressive hemodynamic support. Additionally, we identified potentially beneficial associations with propofol-based anesthesia and early tracheostomy, while confirming the lack of benefit and potential harm associated with methylprednisolone. These findings have important implications for clinical practice and provide a foundation for future research priorities.

Hemodynamic Management: From MAP to SCPP

The association between MAP augmentation and improved neurological outcomes observed in this meta-analysis is consistent with the prevailing physiological framework that spinal cord perfusion is pressure-dependent following injury (Evaniew et al.,2020; Martin et al.,2021). The spinal cord, like the brain, possesses autoregulatory mechanisms that maintain blood flow across a range of perfusion pressures. Following injury, however, autoregulation is impaired, and blood flow becomes directly dependent on perfusion pressure [57]. The observation that MAP targets ≥85 mmHg confer benefit aligns with the concept that elevated perfusion pressure may overcome the effects of increased vascular resistance and edema that characterize the injured spinal cord.

The finding that SCPP-directed management demonstrated even stronger associations with outcomes is noteworthy and suggests that MAP may be an incomplete surrogate for effective tissue perfusion. The relationship between MAP, ISP, and SCPP is complex and dynamic. Following injury, ISP can be substantially elevated due to edema, hemorrhage, and swelling within the fixed dural compartment, potentially reducing SCPP even when MAP is maintained in the target range [58]. The pressure-volume relationship within the spinal canal is non-linear, such that small reductions in edema volume may substantially reduce ISP and improve SCPP. This observation has therapeutic implications: interventions to reduce ISP, including surgical decompression, dermoplasty, and neuroprotective strategies, may enhance the benefits of MAP augmentation.

However, the practical barriers to SCPP monitoring are substantial. ISP measurement requires placement of an intrathecal catheter or pressure probe, which carries risks of infection, hemorrhage, and technical failure. The equipment and expertise required for such monitoring are not widely available, particularly in resource-limited settings where the global burden of tSCI is greatest. Moreover, the optimal SCPP target remains undefined, with proposed thresholds ranging from 50 to 70 mmHg [59]. Until these issues are resolved through further research, MAP targets are likely to remain the practical standard.

The observation that even brief episodes of hypotension may carry disproportionate prognostic value is clinically important (Sajdeya et al.,2025; Nashed et al.,2025). The reliance on averaged MAP values over extended periods may obscure the impact of transient but clinically significant hypotensive episodes. This finding underscores the need for continuous, high-fidelity monitoring and prompt intervention for any deviation from target. In practice, achieving and maintaining target MAP values is challenging, with studies indicating that patients spend approximately 25% of the first week below target thresholds [60]. The cumulative burden of hypotension, rather than average MAP, may be a more relevant metric for outcome prediction and quality improvement.

The choice of vasopressor agent represents another dimension of hemodynamic management with potential implications for outcomes. Our meta-analysis suggested that norepinephrine may be associated with superior outcomes compared to phenylephrine, though the evidence is limited and the difference did not reach statistical significance. Norepinephrine, through its mixed α- and β-adrenergic agonism, may provide superior perfusion of the injured cord through effects on microvascular resistance and cardiac output [61]. However, physiological differences must be weighed against other considerations including arrhythmogenic potential, ease of administration, and institutional familiarity. The absence of high-quality evidence precludes definitive recommendations, and agent selection should be individualized based on patient-specific factors.

Anesthetic Agent Selection: Neuroprotection or Clinical Equipoise? The association between propofol-based total intravenous anesthesia and improved neurological outcomes compared to volatile anesthetics represents a novel finding that warrants careful interpretation. Propofol has been demonstrated to possess antioxidant, anti-inflammatory, and neuroprotective properties in preclinical models, and the clinical literature suggests a benefit in other forms of central nervous system injury [62-67]. Volatile anesthetics, particularly sevoflurane, have also demonstrated potential neuroprotective effects through preconditioning and inhibition of apoptosis. The balance of these effects in the clinical setting of tSCI remains uncertain.

Several methodological considerations limit the strength of the conclusion regarding anesthetic agent selection. First, the observed association derives entirely from observational studies, which are subject to confounding by indication. Patients with more severe injuries or comorbidities have preferentially managed with one agent or the other, introducing systematic differences between groups. Second, the biological plausibility of the finding challenged by the complexity of anesthetic effects, which may be beneficial or harmful depending on dose, duration, and clinical context. Third, the heterogeneity across studies (I^2=41.2%) suggests that the association is not consistent, and unmeasured factors may account for the observed differences [68-70].

The clinical implication of this finding is not to recommend propofol universally but rather to highlight the potential for agent selection to influence outcomes and emphasize the need for further research. Until high-quality evidence is available, anesthetic agent selection should consider individual patient characteristics, the requirements of the surgical procedure, and institutional protocols. Propofol's benefits in reducing postoperative nausea and facilitating neurological assessment may be relevant considerations, but definitive neuroprotective claims cannot be justified.

Corticosteroids: An Evolving Consensus

The absence of neurological benefit and the association with increased pulmonary complications for methylprednisolone in this meta-analysis reinforces the current guideline recommendations against routine use [71-73]. The NASCIS trials, which provided the original impetus for corticosteroid use, have been the subject of sustained criticism regarding their methodology, statistical analysis, and clinical significance (Bracken,2012). Subsequent studies and meta-analyses have failed to replicate the early positive findings, while documenting consistently increased complication rates.

The observation of increased pulmonary complications is biologically plausible given the immunosuppressive effects of high-dose corticosteroids. In a population already at risk of respiratory compromise due to injury level, the addition of immunosuppression may predispose to ventilator-associated pneumonia and other pulmonary infections [74]. The absence of mortality benefit despite potentially increased complications suggests that the risk-benefit balance does not favor routine administration.

That said, the debate surrounding corticosteroid use not fully resolved. Some clinicians continue to administer methylprednisolone in select cases based on individual risk-benefit assessment, particularly when injury is severe and early administration is possible [75]. While our findings do not support such practice, the limitations of the evidence base allow for individual clinical judgment in exceptional circumstances.

Respiratory Management: The Role of Tracheostomy: The association between early tracheostomy and reduced mortality observed in this meta-analysis reflects the substantial impact of respiratory complications on outcomes in tSCI. Patients with cervical injuries, particularly those at or above C5, may require prolonged mechanical ventilation due to diaphragmatic dysfunction. Delayed tracheostomy may be associated with extended intensive care unit stays, increased sedation requirements, and higher rates of ventilator-associated complications.

The optimal timing of tracheostomy remains controversial. While early tracheostomy may facilitate ventilator weaning and reduce sedation burden, it also carries procedural risks and may not be appropriate for all patients. The decision must consider injury level, severity, trajectory of respiratory function, and the presence of other injuries or complications. Our findings suggest that, when clinically appropriate, early tracheostomy may confer survival benefit, though the limited number of studies and modest sample sizes preclude definitive conclusions.

Strengths and Limitations

This systematic review and meta-analysis has several strengths that enhance the credibility of its findings. The comprehensive search strategy, including multiple databases and manual reference checking, ensures that all relevant evidence considered. The inclusion of both randomized and observational studies allowed for evaluation of the evidence across different levels of quality. Subgroup analyses enabled exploration of heterogeneity and identification of patient characteristics that may modify treatment effects. Sensitivity analyses confirmed the robustness of the primary findings.

However, several important limitations acknowledged. The predominance of observational studies (92% of included studies) limits the ability to draw causal inferences. Confounding by indication is a particular concern, as patients with more severe injuries may receive aggressive interventions, potentially creating spurious associations. The heterogeneity across studies in inclusion criteria, outcome definitions, and treatment protocols limits direct comparability. The lack of standardized reporting of anesthetic interventions and outcomes constrains the synthesis of evidence. Publication bias may affect the literature, though our analyses did not reveal significant asymmetry. Finally, the clinical applicability of findings limited by the predominance of North American and European studies, with relatively few contributions from Asia, Africa, or South America where the global burden of tSCI is substantial [76].

Clinical Implications and Future Directions

Despite these limitations, our findings support several recommendations for clinical practice. First, aggressive hemodynamic support targeting MAP ≥85 mmHg considered standard of care in patients undergoing emergency surgery for acute tSCI. This requires continuous monitoring and prompt intervention for hypotensive episodes. The use of a dedicated vasopressor infusion, typically norepinephrine, may facilitate achievement and maintenance of target MAP [77]. Second, the choice of anesthetic agent, while less firmly supported by evidence, made with consideration of the potential for neuroprotective effects. Propofol-based total intravenous anesthesia may be preferred, though the evidence does not mandate its use over volatile anesthetics. Third, methylprednisolone not administered routinely, given the absence of benefit and increased complications. Fourth, early consideration of tracheostomy in patients with cervical injuries and anticipated prolonged mechanical ventilation may improve outcomes.

Future research priorities should include the conduct of high-quality randomized controlled trials to evaluate specific anesthetic interventions, including MAP targets, vasopressor choices, and anesthetic agent comparisons [78-80]. The development of standardized outcome definitions and reporting protocols would facilitate evidence synthesis and meta-analysis. Research on SCPP-directed management and the relationship between ISP, MAP, and neurological outcomes needed to refine hemodynamic targets. The potential for patient-specific, precision-based approaches explored, including the role of injury level, severity, and comorbidities in determining optimal management. The implementation of multimodal monitoring strategies may improve the precision of hemodynamic management and patient outcomes. Finally, the generalizability of findings to different healthcare settings, particularly in low- and middle-income countries where the burden of tSCI is greatest, addressed through multicenter studies across diverse settings [81].

Conclusion

This systematic review and meta-analysis demonstrate that anesthetic management significantly impacts outcomes in patients undergoing emergency surgery for acute traumatic spinal cord injury. Hemodynamic optimization targeting MAP ≥85 mmHg is associated with improved neurological recovery and reduced mortality, supporting current guideline recommendations. Propofol-based total intravenous anesthesia may offer advantages over volatile anesthetics, though evidence quality is limited. Methylprednisolone administration provides no neurological benefit and increases pulmonary complications, consistent with guidelines recommending against routine use. Early tracheostomy may improve survival in appropriately selected patients. The limitations of the current evidence base, particularly the predominance of observational studies and substantial heterogeneity across studies, highlight the need for further research. High-quality randomized controlled trials needed to confirm the benefits of specific interventions and refine management strategies. The development of standardized protocols and outcome assessments would facilitate evidence synthesis and translation to clinical practice. Until such evidence is available, clinicians should prioritize hemodynamic optimization and individualize care based on patient-specific factors. Anesthetic management considered a critical component of the comprehensive, multidisciplinary care required to optimize outcomes in this vulnerable patient population.

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Conflicts of interest

The authors declare that they have no competing interests.

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