Accepted Manuscript online: 2022-03-30 Article published online: 2023-07-26

A Review of Strategies Associated with Surgical Decompression in Traumatic Spinal Cord Injury

Ying-Kang Zhu[1] Fa-Tai Lu[1] Guo-Dong Zhang[1] Zun-Peng Liu[1]

[1] Department of Orthopedics, The Fourth Affiliated Hospital, China Medical University, Shenyang, China

J Neurol Surg A Cent Eur Neurosurg 2023;84:570–577.

Address for correspondence Zun-Peng Liu, PhD, Department of Orthopedics, The Fourth Affiliated Hospital, China Medical University, Shenyang, China (e-mail: zpliu@cmu.edu.cn).

Abstract

Traumatic spinal cord injury (TSCI) is frequent. Timely diagnosis and treatment have reduced the mortality, but the long-term recovery of neurologic functions remains ominous. After TSCI, tissue bleeding, edema, and adhesions lead to an increase in the intraspinal pressure, further causing the pathophysiologic processes of ischemia and hypoxia and eventually accelerating the cascade of secondary spinal cord injury. Timely surgery with appropriate decompression strategies can reduce that secondary injury. However, disagreement about the safety and effectiveness of decompression surgery and the timing of surgery still exists. The level and severity of spinal cord injury do have an impact on the timing of surgery; therefore, TSCI subpopulations may benefit from early surgery. Early surgery perhaps has little effect on recovery from complete TSCI but might be of benefit in patients with incomplete injury. Early decompression should be considered in patients with incomplete cervical TSCI. Patient age should not be used as an exclusion criterion for early surgery. The best time point for early surgery is although influenced by the shortest duration to thoroughly examine the patient's condition and stabilize the patient's state. After the patient's condition is fully evaluated, we can perform the surgical modality of emergency myelotomy and decompression. Therefore, a number of conditions should be considered, such as standardized decompression methods, indications and operation timing to ensure the effectiveness and safety of early surgical intervention, and promotion of the functional recovery of residual nerve tissue.

Keywords
- ► TSCI
- ► surgical decompression
- ► surgical timing
- ► functional recovery

Introduction

Traumatic spinal cord injury (TSCI) is a catastrophic event mostly affecting a large proportion of young people who are in the peak period of productivity in their lives. It can cause sensory and motor dysfunction, which in turn affects the patient's ability of independent living.[1] This urges clinical and basic science researchers to formulate effective strategies for the treatment of patients with TSCI. Although timely diagnosis and treatment reduce the mortality in TSCI, the long-term recovery of neurologic functions and improvement in patients' quality of life are still not optimistic.[2] We summarize the pathophysiologic mechanisms of primary and secondary spinal cord damage in TSCI and analyze the current status of early surgical treatment. The relationship between early surgical strategies and open questions is outlined in ►**Fig. 1**.

Epidemiology of TSCI

The etiology and incidence of TSCI may vary regionally, with road traffic accidents and falls being the leading causes worldwide.[3] In the developing countries, transition to motorized transportation, poor infrastructure, regulatory

received
December 29, 2021
accepted after revision
March 30, 2022
accepted manuscript online
March 30, 2022
article published online
July 26, 2023

Georg Thieme Verlag KG,
Rüdigerstraße 14,
70469 Stuttgart, Germany

DOI https://doi.org/10.1055/a-1811-8201.
ISSN 2193-6315.

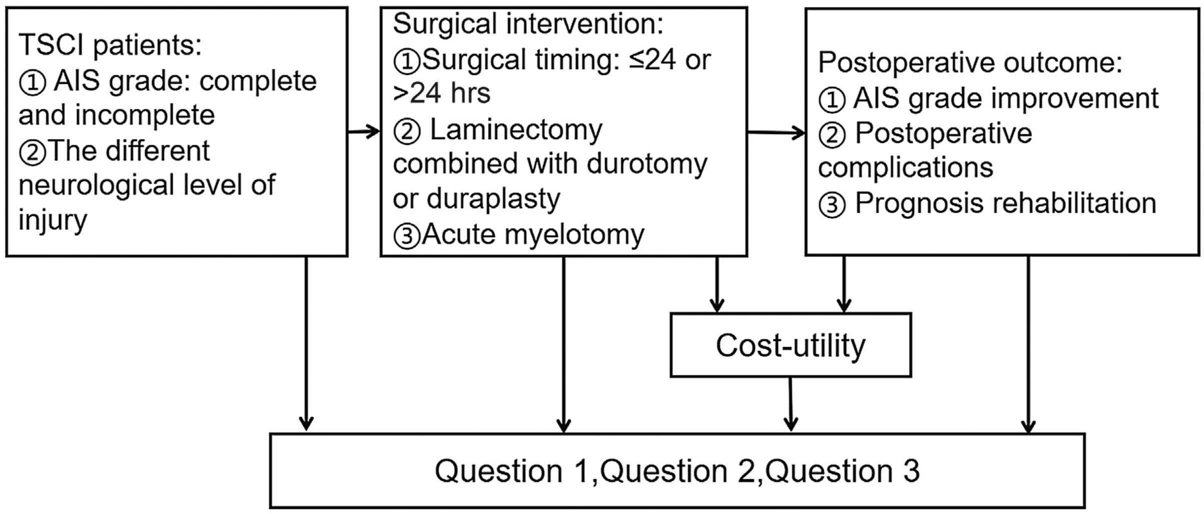

Fig. 1 Analytic framework.

challenges, and poor safety culture leads to TSCI, with the majority of cases being transportation related; in developed countries, the number of cases of TSCI resulting from falls is increasing with the increase in the aging population.[4] Males are at a higher risk than females. This may be due to a greater propensity for men to engage in dangerous behavior, which makes them vulnerable to injury.[3,5] From 1993 to 2012, the average age of patients with acute TSCI increased from 40.5 to 50.5 years. Meanwhile, the incidence of TSCI in young men (16–44 years) in developed countries is steadily decreasing. However, the incidence of TSCI in elderly (65–74 years old) male population is rapidly increasing and may continue to rise with life expectancy prolongation.[2] A meta-analysis of the literature on TSCI from 2000 to 2016 found that 48.8% of TSCI patients required interventional surgery.[3] Therefore, taking this into consideration, it is very important to solve the problems related to surgical intervention.

Pathophysiology of TSCI

The process of SCI includes primary and secondary injury mechanisms. Understanding the injury mechanism is essential to find out the effective treatment strategies. Pressure caused by events such as bending, stretching, axial load and rotation, fracture of the spine, and soft-tissue toughness causes primary trauma to the spinal cord, which constitutes the initial stage of TSCI.[1] The initial mechanical insult immediately destroys the normal neural cells,[6] leading to irreversible function loss and initiating the cascade of secondary spinal cord damage.[7] A small proportion of patients have a neurogenic shock, characterized by reduction of vascular tone and peripheral resistance, bradycardia, peripheral vasodilation, and hypotension with other clinical symptoms due to sympathetic nerve inhibition.[8] The extent of primary and subsequent secondary spinal damage is directly proportional to the amount of energy delivered to the spinal cord by mechanical force.[9] High-impact trauma lead to spinal fracture and dislocation, often with complete spinal cord damage, which could be treated surgically, promoting the regeneration of nerve fibers in the partial TSCI caused by low-energy trauma, the anatomical integrity of the spinal cord is often preserved and the neurologic deficit is not complete, but the effective clinical neuroprotective treatment strategy is still under exploration.[10]

The secondary spinal cord damage, initiated by the initial spinal cord damage, involves a series of interrelated biochemical events, including alterations in microvascular perfusion, free radical generation, lipid peroxidation, and necrotic and apoptotic cell death with the dysregulation of ionic homeostasis, which further aggravates the local "spinal fascial compartment syndrome" following the spinal cord edema, eventually leading to the pathophysiologic process nerve cell apoptosis (►**Fig. 2**).[1,11] It is necessary to formulate treatment strategies for stimulating axon regeneration, preventing neurodegeneration, differentiation, and proliferation of new neurons and glial cells to repopulate at the injured site while functionally integrating into surviving neural tissues.[7] Secondary injury is both preventable and reversible.[6] Ischemia is the key trigger factor of secondary injury cascade as it initiates the derangements in cationic homeostasis and oxidative cell injury. At the same time, continuous compression of the spinal cord caused by bone, intervertebral disk, or epidural blood clot may also exacerbate local ischemia.[12] Therefore, reducing the pressure on the spinal cord should be considered conducive for the recovery of blood supply in the damaged area, thus inhibiting the occurrence of secondary ischemia. Additionally, research conducted on the nerve evoked potential test in the animal model of spinal cord compression showed that long-term spinal cord compression aggravates the pathologic changes in the spinal cord and further deteriorates the neurological function, which proves that the continuous mechanical compression is a crucial factor in the process of secondary injury.[13] With this background, the adjustment of intraspinal pressure (ISP) after TSCI has been paid more attention to

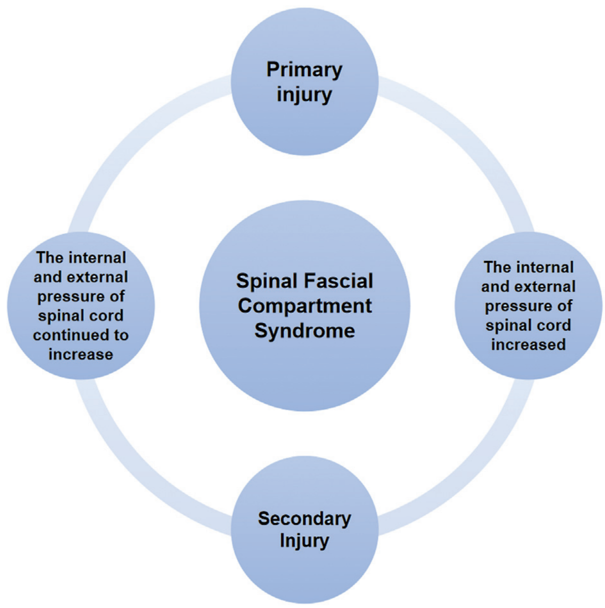

Fig. 2 The objective to investigate the mechanism of the vicious cycle of spinal cord compression after traumatic spinal cord injury (TSCI). Following the initial mechanical injury, extensive edema and hematoma in the spinal cord occur and the the pressure in the spinal cord increases: primary spinal cord injury. Restricted by bony vertebral canal and dural sac, the spinal cord external pressure increases, leading to cerebrospinal fluid blocking, venous congestion, local ischemia, hypoxia, electrolyte disorders: secondary spinal cord damage. Local stenosis, adhesion, ischemia, and hypoxia further aggravate the spinal cord edema and necrosis, with a further increase of the spinal cord pressure, forming a vicious circle.

maintain the blood perfusion and oxygenation of the impacted and adjacent spinal cord tissue to minimize the secondary injury. Khaing et al established an animal model of TSCI, further confirming that increase in ISP limited the functional recovery after TSCI.[10] However, due to the differences in physiology, anatomy, and nature of the injury, there were differences in ISP values after SCI among different species; therefore, it is difficult to translate the findings to TSCI in humans. Werndle et al inserted a pressure probe under the dura to measure the ISP while performing spinal stabilization or decompression in 18 TSCI patients. They showed the feasibility and safety of measuring ISP after TSCI, by further demonstrating that the ISP values in TSCI patients are significantly increased.[14] Reference to ISP values in the early phase after TSCI may help in providing optimal medical and surgical treatment. Clinical data show that after TSCI placement of a pressure probe intradurally within the first 72 hours of surgery is appropriate and that ISP monitoring for a week is safe.[15] In addition, the ISP can help in the evaluation of the effect of surgical decompression.[16] Therefore, it is critical to carry out decompressive surgery in TSCI patients to reduce the ISP.

Contradictory Statements of TSCI

A clinical strategy to restore spinal stability and decompress the spinal cord is to prevent further deterioration of neurologic function in patients with TSCI. However, the timing of surgery is still controversial.[17] Most opinions advocate that early decompression with or without stabilization preserves spinal cord tissue at risk by reducing the amount of secondary injury,[18] and significantly reduces the length of hospital stay.[17] Researchers believe that there is a theoretical basis for early surgical intervention in TSCI. Badhiwala et al proposed that "time is spine" and emphasized that there is a critical time window after TSCI. If the mechanical compression of the spinal cord is relieved within that time window, the pathophysiologic processes leading to secondary injury can be alleviated, which may improve outcome.[2] This also suggests that severity of the primary injury seems to play an important role in the timing of surgery after TSCI.[19] Early decompression strategies are more cost-effective than delayed decompression, and result in better quality of life of the patients.[20]

On the contrary, the often instable clinical status of patients shortly after the trauma might accelerate the progress of injury leading to more serious injury if surgery is performed (too) early.[21] Jones et al quantified the spinal cord, dura, and subarachnoid space dimensions preinjury and postdecompression in TSCI animals and found that early decompression may lead to spinal cord swelling and deformation, resulting obstruction of the subarachnoid spaces with varied outcome depending on the severity of the initial injury. This study further suggests that these observations partly explain the poor results after early decompression in some patients, and that attention should be paid to gross morphologic changes in the spinal cord for timing surgery.[22] Similarly, some clinical studies could not conclude that early surgical intervention was better than late surgery. On the contrary, they found that early surgery leads to a higher incidence of neurologic deterioration and mortality.[21] Therefore, there is no strong evidence to support the advantage of early spinal decompression after TSCI, but nonetheless should at least be discussed individually.[23,24] The clinical condition of TSCI patients range from mild neurologic impairment to significant disability, which might explain the different findings in the studies. The same holds true for the level of the injury. We evaluated the available literature (►**Table 1**) to explore if the early surgery outcomes after TSCI may have different effects depending on the injured level, severity, and timing of surgery.

For treatment of the elderly with SCI, there is currently a lack of convincing evidence to support surgical or conservative treatment and more studies to define the treatment strategy are required.[25] Due to the comorbidities of the elderly as well as the preexisting degenerative changes of the spine, the current focus of research is on patients younger than 65 years,[26] which may lead to ageism and affect the physician's judgments.[27] However, a retrospective cohort study has noted that early surgery within 24 hours of injury in TSCI patients older than 65 years results in more favorable neurologic improvement.[25] Therefore, we consider age should not be considered as exclusion criterion for early decompression.

Table 1 Summary of neurologic outcomes after early (<24 hours) and late (>24 hours) surgery

Author, study design	No. of patients	Surgical timing (24 h)	AIS improvement	Neurologic outcomes Early group (<24 h) Late group (>24 h)
Cervical TSCI				
Umerani[37] Prospective cohort study	$N = 98$ AIS grade A: 36 AIS grades B,C,D: 62	34 < 24 h, 64 > 24 h	At 6 mo ≥1 AIS grade ≥2 AIS grades	Early group: 52.94%; late group: 39.06% (OR: 3.12; 95% CI: 1.21–8.02; $p < 0.01$) Early group: 23.3%; late group: 8.7% (OR: 3.05; 95% CI: 0.89–10.51; $p < 0.01$)
Aarabi[35] Retrospective analysis of prospectively collected data	$N = 72$ AIS grade A: 27 AIS grades B,C,D: 45	57 < 24 h,15 > 24 h	At 6 mo ≥1 AIS grade	Early group:63.2% (OR: 0.455; 95% CI: 0.118–1.752; $p = 0.25$) Late group: 80% (OR: 0.832; 95% CI: 0.141–4.88; $p = 0.83$)
Sewell[29] Retrospective analysis	$N = 95$ AIS grade A: 28 AIS grades B,C,D: 67	40 < 24 h, 55 > 24 h	At 6 mo ≥1AIS grade ≥2 AIS grades	Early vs. late group showed that incomplete TSCI (A vs. B,C,D; OR: 14.9; 95% CI: 3.1–72.4; $p < 0.01$) were significantly associated with improvement by 1 grade Early group: 32.5%; late group: 15% ($p = 0.78$) Early group: 34.5%; late group: 7.5% ($p = 0.24$)
Fehlings[36] Prospective cohort study	$N = 313$ AIS grade A: 101 AIS grades B,C,D: 212	182 < 24 h, 131 > 24 h	At 6 mo ≥1AIS grade ≥2 AIS grades	Early group: 56.5%; late group: 49.5% (OR: 1.37; 95% CI: 0.80–2.57; $p = 0.31$) Early group: 19.8%; late group: 8.8% (OR: 2.83; 95% CI: 1.10–7.28; $p = 0.03$)
Thoracolumbar TSCI				
Rahimi-Movaghar et al[38] Prospective cohort study	$N = 35$ AIS grade A: 16 AIS grades B,C,D: 19	16 < 24 h, 19 > 24 h	At 12 mo ≥1AIS grade ≥2 AIS grades	Early group: 31.2%; late group: 44% (OR: 0.85; 95% CI: 0.33–2.16) Early group: 18.1%; late group: 5.2% (OR: 3.56; 95% CI: 0.41–30.99)
Du[39] prospective cohort study	$N = 721$ AIS grade A: 0 AIS grades B,C,D: 721	335 < 24 h, 386 ≥ 24 h	At 12 mo ≥1AIS grade ≥2 AIS grades	Early group: 51.4%; late group: 41.6% (OR: 1.487; $p = 0.009$) Early group: 11.5%; late group: 5.0% (OR: 2.471; $p = 0.002$)
Wilson[58] Prospective cohort study	$N = 86$ AIS grade A: 55 AIS grades B,C,D: 31	25 < 24 h, 53 ≥ 24 h	At mean 8 mo	Total motor score improvement Early vs. late showed early group was associated with an additional 7 points in motor recovery (PE: 7.74; 95% CI: 0.58–14.88; $p = 0.03$)

Abbreviations: AIS, American Spinal Injury Association Impairment Score; CI, confidence interval; OR, odds ratio; PE, parameter estimate; TSCI, traumatic spinal cord injury.

Influence of Complete and Incomplete TSCI on Outcome

Some studies have pointed out that the timing of surgery may have a different effect on the outcomes in patients with complete and incomplete SCIs; however, there is no consensus on the association between early decompression in TSCI patients and the AIS (American Spinal Injury Association Impairment Score) subgroups.[28] In a retrospective analysis, incomplete (AIS grades B, C, and D) TSCI patients undergoing early decompression surgery had significantly more often an improvement by one grade (odds ratio = 14.9; 95% confidence interval [95%CI]: 3.1–72.4; $p < 0.01$), whereas there was no significant effect of early surgery on neurologic function recovery in complete (AIS A) TSCI patients.[29 30] Another study showed that surgery is beneficial for recovery of neurologic function in AIS A patients, and that especially early (<24 hours) decompression promotes neurologic recovery in these patients.[31] However, this study did not include TSCI patients with complete loss of sensorimotor function. In addition, for the evaluation of nonneurologic functional recovery, some prospective studies have also confirmed that early surgery can reduce the length of hospital stay of TSCI patients. However, the degree of trauma, injury mechanism, and other conditions, heavily biased these results.[32,33]

In summary, early surgery has little effect on the recovery of AIS A patients but some effect in patients with incomplete spinal cord injury.

Influence of the injured Level on Outcome

The level of neurologic injury in TSCI patients has a significant effect on recovery after early decompression.[28] Therefore, many studies investigated the treatment results in patients with cervical or thoracolumbar TSCI alone or in combination.

Studies Examining Cervical TSCI Patients

Many studies have included patients with cervical TSCI and have obtained consistent results.[29,35–37] Early surgical decompression (<24 hours) can improve recovery of neurologic function and the quality of life of these patients, with better improvement of patients with an incomplete TSCI.[29] Aarabi et al showed that recovery of neurologic function in severe cervical TSCI after surgery was significantly better, but the level of evidence was low (OR = 0.832; 95% CI: 0.141–4.88; $p = 0.83$).[35] The researchers reporetd that the long-term neurologic outcome was determined by the intramedullary lesion length, rather than the timing of surgery, which further shows the importance of paying attention to the severity of the primary injury for outcome prognosis. Regarding complications, it was reported that 2.2% of the patients in the early surgery group had neurologic deterioration, while it was only in 0.8% of the patients in the late decompression group.[35] The wound infection and mortality rate was also much higher in the early surgery group, whereas the incidence of pulmonary embolism was higher in the late surgery group. Cardiopulmonary complications were most common in both groups.[36]

Studies Examining Thoracolumbar TSCI Patients

In a small randomized controlled study, early decompression (<24 hours) had no significant clinical advantage for recovery of the neurologic function in patients with thoracolumbar TSCI. The motor score increased slightly in patients with incomplete TSCI, but the sensory score of all patients showed no significant improvement.[38] However, another randomized controlled study has reported that early surgery had no significant effect on the improvement rate of AIS in patients with incomplete thoracolumbar TSCI.[31] In both studies, the sample size was small, possibly confounding the results. A large prospective study evaluated the efficacy of surgical intervention in 711 patients with incomplete T1–L1 TSCI .[39] The study showed that early surgery (<24 hours) had better AIS improvement. As this study was not randomized and double-blinded, bias could not be avoided. Some retrospective studies, in which the operation was performed within 8 hours, have shown that the quality of life of patients was improved, with the recovery of neurologic function, but the level of evidence was low.[32,40] Concerning complications, the incidence of surgical site infection and sepsis was higher in the early surgery group, but there was no difference in deep vein thrombosis, surgical success rate, or mortality between the early and late surgery groups.[38]

Therefore, it is essential to consider the effect of the level of the injury on the results of early and late surgery. There is stronger evidence to support early decompression of cervical TSCI, especially in patients with incomplete TSCI. Overall, the timing of the operation has a significant impact on the recovery of the neurologic deficits in patients with thoracolumbar TSCI. Future research should study the effect of surgery in specific subgroups: probably, patients with incomplete thoracolumbar TSCI should undergo more urgent surgery than patients with complete TSCI.[41] The above mentioned clinical studies have methodological flaws, reducing the evidence level. Although the findings in the subgroups are interesting, they may have been caused by selection bias. However, performing a randomized study in patients, in which previous studies already have suggested a benefit, is ethically problematic. It also has to be considered that severity of injury is a strong prognostic factor, which means that a high number of patients would be necessary for avoiding an imbalance between the groups.

Best Time Point for Early Surgery

Although most researchers support early surgery, the optimal time point for early surgery remains controversial. Generally, early surgery is defined as being performed within the first 24 to 72 hours following the injury. A survey conducted on 971 spinal surgeons showed that 80% of the surgeons agreed for decompression within 24 hours.[42] Therefore, many scholars suggest early operation within 24 hours,[28,37,43] but contrary views also exist. Kim et al proposed that 48 hours after injury should be regarded as the upper time limit for the early surgery.[44] Other researcher believe that surgery should be performed within 8 hours after injury.[45] Studies have shown that patients who underwent surgery within 8 hours after TSCI had better neurologic outcomes than patients who underwent surgery more than 8 hours after injury, without an increase in complications.[46,48] Mattiassich et al showed that ultra-early (<5 hours) surgery does not provide better improvement in neurologic function than early ($\geq$5–24 hours) surgery.[49]

Decompression of the spinal cord can be delayed due to the transportation, rescue, resuscitation, surgery preparation, and other factors.[42] Statistically, only 23.5 to 51.4% of TSCI patients can be operated on within the first 24 hours after injury; these numbers are even lower in the developing countries.[38] It is also an important step to identify TSCI patients immediately and transport them directly to a specialized treatment center.[50] The arguments for early decompression are reasonable. However, they have to weight against the risk of bleeding and hypotension, which might affect the surgical results negatively, making the definition of the best time point for surgery difficult.[51] Patients must be stabilized before they can safely undergo spinal cord decompression surgery; further delay after assessing and stabilizing the patient's condition should be avoided.

Various Decompression Techniques in TSCI

Decompression is an important means of TSCI treatment. Various techniques had been proposed.[52]

Laminectomy Combined with Durotomy or Duraplasty

Laminectomy cannot completely and effectively reduce ISP. The swollen spinal cord expands into the subarachnoid space, thereby blocking the cerebrospinal fluid, contributing to a continuous intradural pressure increase.[16] Furthermore, swelling of the subcutaneous tissue after laminectomy can be directly transmitted to the injured spinal cord, aggravating symptoms.[14] Compared with laminectomy alone, laminectomy combined with duraplasty or durotomy releases ISP more effectively, allowing recovery of the injured spinal cord. The risk of damaging initially healthy spinal cord tissue by secondary pathophysiologic mechanisms could be reduced.[53] Saadoun et al confirmed evidence that the dura not the bony spinal canal is the main cause of spinal cord compression after TSCI and stated that the simple bony decompression has a poor effect on outcome.[54] Laminectomy combined with durotomy provides more room for the swollen spinal cord, which can more effectively reduce ISP and increase spinal cord perfusion. Therefore, durotomy or duraplasty might be required in addition to laminectomy to reduce the elevated ISP.

Myelotomy

Although laminectomy combined with durotomy or duraplasty proved to be effective, this operation cannot eliminate the hematoma and necrotic tissue in the spinal cord. Therefore, midline myelotomy in the region of the injured spinal cord, followed by removal of the necrotic tissue with the surrounding extravasated blood is proposed by some.[55] It has been shown in animal models, that myelotomy reduces the amount of spinal cord imjury SCI and promote recovery of neurologic function.[52,56,57] Myelotomy has the potential risk of further complicating TSCI; therefore, it has not widely used clinically. However, myelotomy should be kept in mind as a surgical option. Standardization of the surgical technique, better definition of indications, and timing of the operation are required.

Conclusions

Early decompression should be considered in patients with incomplete cervical TSCI. The definition of the role of early surgery in patients with a thoracolumbar TSLC and a complete loss of sensory and motor function is still needed. Rejecting early surgery in patients on the basis of chronological age alone is not justified. At present, the logistic aspects before hospital admission seem to pose an obstacle to early surgical intervention in a large proportion of these patients. It may be necessary to imrove the early care strategies to ensure that TSCI patients can obtain surgical decompression in time. After a comprehensive assessment of the patient's condition, the eligible patient should be operated on as soon as possible (<24 hours). Collaboration between orthopaedic spinal surgeons and neurosurgeons for evaluating the best decompression method and, if necessary, carrying out myelotomy can completely relieve the compression of the spinal cord. This intervention can further prevent the occurrence of secondary injury and improve the neurologic outcome, thereby reducing the economic burden.

Author Contributions
Y.Z. and Z.L. contributed to the study design, study performance, and preparation of the manuscript. Z.L. and Y.Z. contributed to literature analysis and interpretation, and preparation and revision of the manuscript. F.L. and G.Z. contributed to the study performance. All the authors read and approved the final manuscript.

Funding
This study was supported by the General program of Postdoctoral Science Foundation of China (2019M66166) and Liaoning Provincial Doctoral Start-up Foundation (20180540065) for the writing, polishing, and publication of the manuscript.

Conflict of interest
None declared.

Availability of Data and Material
All data generated or analyzed during this study are included in this article.

References

1 Kwon BK, Tetzlaff W, Grauer JN, Beiner J, Vaccaro AR. Pathophysiology and pharmacologic treatment of acute spinal cord injury. Spine J 2004;4(04):451–464

2 Badhiwala JH, Ahuja CS, Fehlings MG. Time is spine: a review of translational advances in spinal cord injury. J Neurosurg Spine 2018;30(01):1–18
3 Kumar R, Lim J, Mekary RA, et al. Traumatic spinal injury: global epidemiology and worldwide volume. World Neurosurg 2018; 113:e345–e363
4 Lee BB, Cripps RA, Fitzharris M, Wing PC. The global map for traumatic spinal cord injury epidemiology: update 2011, global incidence rate. Spinal Cord 2014;52(02):110–116
5 Singh A, Tetreault L, Kalsi-Ryan S, Nouri A, Fehlings MG. Global prevalence and incidence of traumatic spinal cord injury. Clin Epidemiol 2014;6:309–331
6 Fehlings MG, Perrin RG. The timing of surgical intervention in the treatment of spinal cord injury: a systematic review of recent clinical evidence. Spine 2006;31(11, Suppl):S28–S35, discussion S36
7 Oyinbo CA. Secondary injury mechanisms in traumatic spinal cord injury: a nugget of this multiply cascade. Acta Neurobiol Exp (Warsz) 2011;71(02):281–299
8 Summers RL, Baker SD, Sterling SA, Porter JM, Jones AE. Characterization of the spectrum of hemodynamic profiles in trauma patients with acute neurogenic shock. J Crit Care 2013;28(04): 531.e1–531.e5
9 Blight AR, Decrescito V. Morphometric analysis of experimental spinal cord injury in the cat: the relation of injury intensity to survival of myelinated axons. Neuroscience 1986;19(01): 321–341
10 Khaing ZZ, Cates LN, Fischedick AE, McClintic AM, Mourad PD, Hofstetter CP. Temporal and spatial evolution of raised intraspinal pressure after traumatic spinal cord injury. J Neurotrauma 2017; 34(03):645–651
11 Repair, protection and regeneration of spinal cord injury. Neural Regen Res 2015;10(12):1953–1975
12 Fehlings MG. The impact of continued cord compression following traumatic spinal cord injury. J Neurosurg Spine 2009;11(05): 568–569, discussion 569
13 Carlson GD, Gorden CD, Oliff HS, Pillai JJ, LaManna JC. Sustained spinal cord compression: part I—time-dependent effect on long-term pathophysiology. J Bone Joint Surg Am 2003;85(01):86–94
14 Werndle MC, Saadoun S, Phang I, et al. Monitoring of spinal cord perfusion pressure in acute spinal cord injury: initial findings of the injured spinal cord pressure evaluation study*. Crit Care Med 2014;42(03):646–655
15 Phang I, Zoumprouli A, Saadoun S, Papadopoulos MC. Safety profile and probe placement accuracy of intraspinal pressure monitoring for traumatic spinal cord injury: injured spinal cord pressure evaluation study. J Neurosurg Spine 2016;25(03):398–405
16 Tykocki T, Poniatowski Ł, Czyż M, Koziara M, Wynne-Jones G. Intraspinal pressure monitoring and extensive duroplasty in the acute phase of traumatic spinal cord injury: a systematic review. World Neurosurg 2017;105:145–152
17 Dvorak MF, Noonan VK, Fallah N, et al; RHSCIR Network. The influence of time from injury to surgery on motor recovery and length of hospital stay in acute traumatic spinal cord injury: an observational Canadian cohort study. J Neurotrauma 2015;32 (09):645–654
18 Piazza M, Schuster J. Timing of surgery after spinal cord injury. Neurosurg Clin N Am 2017;28(01):31–39
19 Ter Wengel PV, Feller RE, Stadhouder A, et al. Timing of surgery in traumatic spinal cord injury: a national, multidisciplinary survey. Eur Spine J 2018;27(08):1831–1838
20 Furlan JC, Craven BC, Massicotte EM, Fehlings MG. Early versus delayed surgical decompression of spinal cord after traumatic cervical spinal cord injury: a cost-utility analysis. World Neurosurg 2016;88:166–174
21 Liu Y, Shi CG, Wang XW, et al. Timing of surgical decompression for traumatic cervical spinal cord injury. Int Orthop 2015;39(12): 2457–2463
22 Jones CF, Cripton PA, Kwon BK. Gross morphological changes of the spinal cord immediately after surgical decompression in a large animal model of traumatic spinal cord injury. Spine 2012;37 (15):E890–E899
23 van Middendorp JJ, Hosman AJ, Doi SA. The effects of the timing of spinal surgery after traumatic spinal cord injury: a systematic review and meta-analysis. J Neurotrauma 2013;30(21): 1781–1794
24 Marshall LF, Knowlton S, Garfin SR, et al. Deterioration following spinal cord injury. A multicenter study. J Neurosurg 1987;66(03): 400–404
25 Inoue T, Suzuki S, Endo T, Uenohara H, Tominaga T. Efficacy of early surgery for neurological improvement in spinal cord injury without radiographic evidence of trauma in the elderly. World Neurosurg 2017;105:790–795
26 Ahn H, Bailey CS, Rivers CS, et al; Rick Hansen Spinal Cord Injury Registry Network. Effect of older age on treatment decisions and outcomes among patients with traumatic spinal cord injury. CMAJ 2015;187(12):873–880
27 McKinley W, Cifu D, Seel R, et al. Age-related outcomes in persons with spinal cord injury: a summary paper. NeuroRehabilitation 2003;18(01):83–90
28 Wilson JR, Tetreault LA, Kwon BK, et al. Timing of decompression in patients with acute spinal cord injury: a systematic review. Global Spine J 2017;7(3, Suppl):95S–115S
29 Sewell MD, Vachhani K, Alrawi A, Williams R. Results of early and late surgical decompression and stabilization for acute traumatic cervical spinal cord injury in patients with concomitant chest injuries. World Neurosurg 2018;118:e161–e165
30 Rahimi-Movaghar V. Efficacy of surgical decompression in the setting of complete thoracic spinal cord injury. J Spinal Cord Med 2005;28(05):415–420
31 Bourassa-Moreau É, Mac-Thiong JM, Li A, et al. Do patients with complete spinal cord injury benefit from early surgical decompression? Analysis of neurological improvement in a prospective cohort study. J Neurotrauma 2016;33(03):301–306
32 Wutte C, Klein B, Becker J, et al. Earlier decompression (< 8 hours) results in better neurological and functional outcome after traumatic thoracolumbar spinal cord injury. J Neurotrauma 2019;36 (12):2020–2027
33 Du JP, Fan Y, Zhang JN, Liu JJ, Meng YB, Hao DJ. Early versus delayed decompression for traumatic cervical spinal cord injury: application of the AOSpine subaxial cervical spinal injury classification system to guide surgical timing. Eur Spine J 2019;28(08): 1855–1863
34 Wilson JR, Witiw CD, Badhiwala J, Kwon BK, Fehlings MG, Harrop JS. Early surgery for traumatic spinal cord injury: where are we now? Global Spine J 2020;10(1, Suppl):84S–91S
35 Aarabi B, Akhtar-Danesh N, Chryssikos T, et al. Efficacy of ultra-early (< 12 h), early (12-24 h), and late (>24-138.5 h) surgery with magnetic resonance imaging-confirmed decompression in American Spinal Injury Association Impairment Scale grades A, B, and C cervical spinal cord injury. J Neurotrauma 2020;37(03): 448–457
36 Fehlings MG, Vaccaro A, Wilson JR, et al. Early versus delayed decompression for traumatic cervical spinal cord injury: results of the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS). PLoS One 2012;7(02):e32037
37 Umerani MS, Abbas A, Sharif S. Clinical outcome in patients with early versus delayed decompression in cervical spine trauma. Asian Spine J 2014;8(04):427–434
38 Rahimi-Movaghar V, Niakan A, Haghnegahdar A, Shahlaee A, Saadat S, Barzideh E. Early versus late surgical decompression for traumatic thoracic/thoracolumbar (T1-L1) spinal cord injured patients. Primary results of a randomized controlled trial at one year follow-up. Neurosciences (Riyadh) 2014;19(03):183–191
39 Du JP, Fan Y, Liu JJ, et al. Decompression for traumatic thoracic/thoracolumbar incomplete spinal cord injury:

application of AO spine injury classification system to identify the timing of operation. World Neurosurg 2018;116:e867–e873
40 Wutte C, Becker J, Klein B, et al. Early decompression (<8 hours) improves functional bladder outcome and mobility after traumatic thoracic spinal cord injury. World Neurosurg 2020;134:e847–e854
41 Ter Wengel PV, Martin E, De Witt Hamer PC, et al. Impact of early (<24 h) surgical decompression on neurological recovery in thoracic spinal cord injury: a meta-analysis. J Neurotrauma 2019;36(18):2609–2617
42 Fehlings MG, Rabin D, Sears W, Cadotte DW, Aarabi B. Current practice in the timing of surgical intervention in spinal cord injury. Spine 2010;35(21, Suppl):S166–S173
43 Wilson JR, Singh A, Craven C, et al. Early versus late surgery for traumatic spinal cord injury: the results of a prospective Canadian cohort study. Spinal Cord 2012;50(11):840–843
44 Kim M, Hong SK, Jeon SR, Roh SW, Lee S. Early (≤48 hours) versus late (>48 hours) surgery in spinal cord injury: treatment outcomes and risk factors for spinal cord injury. World Neurosurg 2018;118:e513–e525
45 Grassner L, Wutte C, Klein B, et al. Early decompression (< 8 h) after traumatic cervical spinal cord injury improves functional outcome as assessed by spinal cord independence measure after one year. J Neurotrauma 2016;33(18):1658–1666
46 Ma Y, Zhu Y, Zhang B, Wu Y, Liu X, Zhu Q. the impact of urgent (<8 hours) decompression on neurologic recovery in traumatic spinal cord injury: a meta-analysis. World Neurosurg 2020;140: e185–e194
47 Jug M, Kejžar N, Vesel M, et al. Neurological recovery after traumatic cervical spinal cord injury is superior if surgical decompression and instrumented fusion are performed within 8 hours versus 8 to 24 hours after injury: a single center experience. J Neurotrauma 2015;32(18):1385–1392
48 Haldrup M, Schwartz OS, Kasch H, Rasmussen MM. Early decompressive surgery in patients with traumatic spinal cord injury improves neurological outcome. Acta Neurochir (Wien) 2019;161 (10):2223–2228
49 Mattiassich G, Gollwitzer M, Gaderer F, et al. Functional outcomes in individuals undergoing very early (< 5 h) and early (5-24 h) surgical decompression in traumatic cervical spinal cord injury: analysis of neurological improvement from the Austrian Spinal Cord Injury Study. J Neurotrauma 2017;34(24):3362–3371
50 Ghajarzadeh M, Saberi H. Transportation mode and timing of spinal cord decompression and stabilization in patients with traumatic spinal cord injury in Iran. Spinal Cord 2019;57(02): 150–155
51 Gaudin XP, Wochna JC, Wolff TW, et al. Incidence of intraoperative hypotension in acute traumatic spinal cord injury and associated factors. J Neurosurg Spine 2020;32(01):127–132
52 Yang DG, Li JJ, Gu R, et al. Optimal time window of myelotomy in rats with acute traumatic spinal cord injury: a preliminary study. Spinal Cord 2013;51(09):673–678
53 Phang I, Werndle MC, Saadoun S, et al. Expansion duroplasty improves intraspinal pressure, spinal cord perfusion pressure, and vascular pressure reactivity index in patients with traumatic spinal cord injury: injured spinal cord pressure evaluation study. J Neurotrauma 2015;32(12):865–874
54 Saadoun S, Werndle MC, Lopez de Heredia L, Papadopoulos MC. The dura causes spinal cord compression after spinal cord injury. Br J Neurosurg 2016;30(05):582–584
55 Meyer C, Bendella H, Rink S, et al. The effect of myelotomy following low thoracic spinal cord compression injury in rats. Exp Neurol 2018;306:10–21
56 Khaing ZZ, Cates LN, Dewees DM, et al. Effect of durotomy versus myelotomy on tissue sparing and functional outcome after spinal cord injury. J Neurotrauma 2021;38(06):746–755
57 Hu AM, Li JJ, Sun W, et al. Myelotomy reduces spinal cord edema and inhibits aquaporin-4 and aquaporin-9 expression in rats with spinal cord injury. Spinal Cord 2015;53(02):98–102
58 Wilson JR, Jaja BNR, Kwon BK, et al. Natural History, Predictors of Outcome, and Effects of Treatment in Thoracic Spinal Cord Injury: A Multi-Center Cohort Study from the North American Clinical Trials Network. J Neurotrauma 2018;35(21):2554–2560

