European Spine Journal (2020) 29:2505–2512
https://doi.org/10.1007/s00586-020-06420-9

ORIGINAL ARTICLE

Morphological features of thoracolumbar burst fractures associated with neurological outcome in thoracolumbar traumatic spinal cord injury

Julien Goulet[1,2] · Andréane Richard-Denis[1,2] · Yvan Petit[1,3] · Lucien Diotalevi[1] · Jean-Marc Mac-Thiong[2]

Received: 5 November 2019 / Revised: 15 March 2020 / Accepted: 11 April 2020 / Published online: 19 May 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract

Purpose To identify specific morphological characteristics in thoracolumbar burst fractures associated with neurological outcome after severe traumatic spinal cord injury (TSCI).

Methods We retrospectively analyzed the clinical and radiological (CT scan morphological characteristics) data of 25 consecutive patients admitted for TSCI secondary to a burst fracture at levels from T11 to L2 between 2010 and 2017 in single level-1 trauma center. We included severe TSCI, defined as American Spinal Injury Association Impairment Scale (AIS) grade A, B or C.

Results Among the 25 patients with severe TSCI, 14 were AIS A, 5 were AIS B, and 6 were AIS C upon initial preoperative neurological evaluation. The AIS grade and the burden of associated injuries (Injury Severity Score, ISS) were the only clinical factors significantly associated with poor neurological recovery. The trauma level of energy was not associated with neurological outcome. Several fractures parameters were independently related to neurological recovery: the postero-inferior corner translation, presence of retropulsed fragment comminution and complete lamina fracture. The magnitude of sagittal kyphosis angle, vertebral kyphosis index and vertebral body comminution were not associated with the neurological outcome.

Conclusions Morphological features of the bony structures involving the spinal canal in thoracolumbar burst fractures with severe TSCI are associated with the chronic neurological outcome and could provide more insight than the AIS clinical grading. The fracture pattern may better reflect the actual level of energy transferred to the spinal cord than distinguishing between low- and high-energy trauma.

Keywords Burst fracture · Thoracolumbar trauma · Neurological outcome · Spinal cord injury

Introduction

A better understanding of predictors of neurological recovery in traumatic spinal cord injury (TSCI) enables clinicians to deliver accurate information to patients and families, justify treatment decisions to administrators, optimize resources utilization and create specific rehabilitation programs according to the expected outcome [1].

The baseline neurological status is recognized as the single most important clinical predictor of neurological recovery [2, 3].

After clinical evaluation, surgeons will often scrutinize computed tomography scan (CT scan) reconstruction images to assess for pattern of injury and plan surgical management, as the great majority of patients with spinal injuries will undergo CT scan imaging.

The pattern of injury in the setting of TSCI is an important factor to consider when looking at long-term neurological outcomes. It has been demonstrated that such outcomes are less favorable in flexion distraction injuries in the cervical spine TSCI. However, studies on thoracolumbar TSCI examining potential prognostic factors have never specifically focused on a single type of injury [4]. Because neurological outcomes in thoracolumbar TSCI secondary to burst fractures are known to be different than distraction or shear

✉ Jean-Marc Mac-Thiong
jean-marc.mac-thiong@umontreal.ca

1 Hôpital du Sacré-Coeur de Montréal, Montréal, QC, Canada

2 Faculty of Medicine, Université de Montréal, Montréal, QC, Canada

3 Department of Mechanical Engineering, École de Technologie Supérieure (ETS), Montréal, Qc, Canada

injuries [5, 6], we deemed useful to independently revisit evaluation of these severe injuries.

Morphological characteristics related to the pattern of thoracolumbar injuries have been widely used for establishing classification schemes because these parameters can usually be obtained from readily available imaging studies. With respect to burst fractures in the thoracolumbar area, many morphological characteristics have been proposed to determine the relationship between the fracture and the intrinsic remaining stability. The loss of vertebral body height and corresponding local or segmental kyphosis [7] are widely used by clinicians and radiologists to describe these injuries. Although studies often analyzed these fracture parameters to provide insight on the occurrence of posterior ligamentous complex [8] or concomitant neurological injury at presentation [9], these measurements were never considered to predict the potential for neurological recovery [2, 6].

Therefore, it remains unclear from the literature if the morphological pattern of burst fracture is associated with neurological recovery. In addition, there is no consensus on which parameter clinicians should use to describe the fracture pattern among all the descriptors that have been proposed in the past.

Our objective is to identify specific morphological descriptors in thoracolumbar burst fractures associated with neurological outcome after severe TSCI. We hypothesize that specific features are related to the extent of irreversible injury to the spinal cord and thus the likelihood of neurological recovery in this patient population.

Material and methods—patients

We conducted a retrospective analysis of a prospective cohort of SCI patients from a level 1 trauma centre specialized in SCI care. We screened patients that were consecutively admitted from April 2010 to April 2017 with the following inclusion criteria: (1) patients age over 18 years old; (2) CT scan performed preoperatively; (3) TSCI associated with unstable thoracolumbar burst fracture from T11 to L2, classified as A3 or A4 according to the AO spine morphologic classification of thoracolumbar injury [7]; (4) severe neurological deficit defined as an American Spinal Injury Association Impairment Scale (AIS) grade A, B or C at the neurological evaluation performed preoperatively according to the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI); (5) surgical intervention that included decompression and spinal stabilization performed within 3 days (72 h) of the traumatic event; (6) minimum follow-up of 12 months postoperatively with neurological assessment according to ISNCSCI standards. Patients were excluded if they were operated in another centre, had adjacent vertebral injuries precluding adequate measurement of normal canal diameter above and below the level of injury and had TSCI from a penetrating injury. AIS D patients were excluded for a ceiling effect purpose, as their neurological outcome is being more predictable overall [10].

Methods—data collection

Neurological recovery was set as the main dependent variable and was defined as an improvement of at least one AIS grade from admission to follow-up at least 6 months after surgical intervention. The energy of the traumatic event was considered as low (trivial trauma, fall from standing height) or high (motor vehicle or motorcycle accident, pedestrian hit by vehicle, fall from more than 3 m, high-velocity contact sport injuries).

According to the Advanced Trauma Life Support protocols, all patients were safely transferred from the trauma stretcher and positioned supine on a semi-rigid spinal board for the preoperative CT scan duration only. Several parameters characterizing the fracture were measured on the axial, coronal and sagittal reconstructions (Fig. 1). The following seven parameters characterizing the burst fracture were measured by a single observer.

- Mean canal compromise (MCC) [11], calculated according to the formula as shown in section D of Fig. 1.
- The presence of comminution of the retropulsed vertebral body fragment reported as a dichotomous variable, defined by the presence of more than one intracanal bony fragment.
- Magnitude of posterior–inferior corner translation [9], measured as the distance in millimeters rounded to the closest integer between the postero-inferior corner of the injured vertebral body and the posterior vertebral line extending from the lower adjacent uninjured level.
- Presence of complete lamina fracture, defined as complete disruption of the lamina in both axial and coronal reconstructions.
- The vertebral body kyphosis index [9], calculated as a ratio between anterior and posterior vertebral body height at the injured level.
- The segmental kyphosis angle between the upper endplate of the vertebra above and the lower endplate of the vertebra below the injured level.
- The vertebral body comminution according to McCormack et al. [12], described as little (< 30%), more (30 to 60%) or gross (> 60%) comminution.

Methods—statistical analysis

Descriptive statistics were used to outline patient's characteristics. Categorical data are presented with percentages and proportions and compared using Chi-square tests.

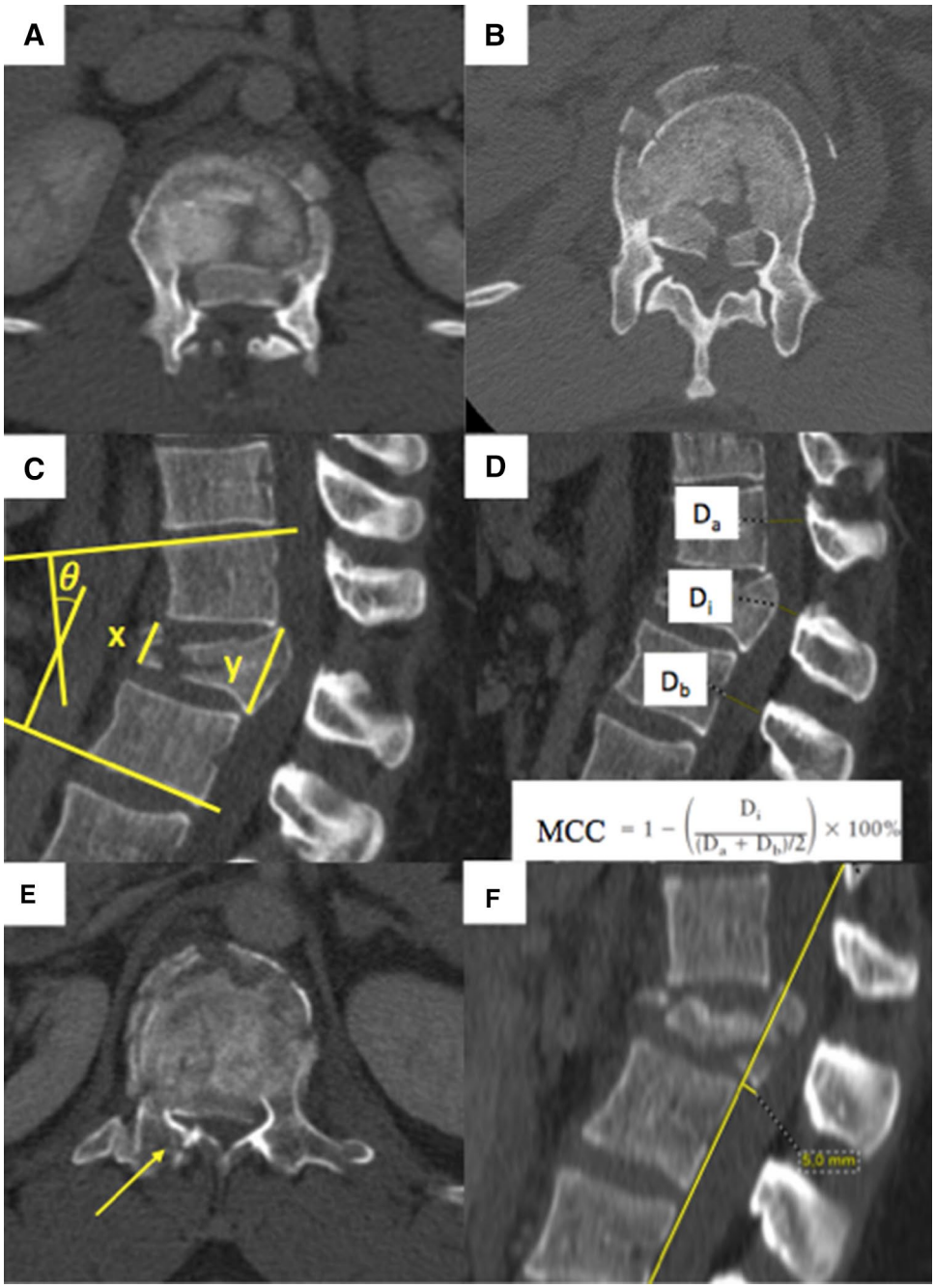

Fig. 1 Morphological parameters assessed in the study **a**. An axial reconstruction demonstrating a non-comminuted retropulsed fragment **b**. An axial reconstruction demonstrating a comminuted retropulsed fragment **c**. A sagittal reconstruction showing the segmental kyphosis angle (θ) and the anterior (x) and posterior (y) vertebral body height measurements **d**. A sagittal reconstruction showing the different mid-sagittal canal diameters used to calculate the MCC with the corresponding formulae **e**. An axial reconstruction with the arrow pointing to a complete lamina fracture **f**. A sagittal reconstruction with representation of the method used to measure the postero-inferior vertebral body corner translation

Continuous variables are presented with mean and standard deviation and compared using Mann–Whitney *U* tests. Univariate binary logistic regression analyses were applied to assess for the association between candidate predictors (descriptors of burst fracture pattern and clinical variables) and neurological recovery. Results are presented as odd ratios with 95% confidence interval and associated *p* value. A receiver operating characteristic (ROC) curve was constructed to assess for the area under the curve as a measure of the postero-inferior corner translation discriminative ability. All the statistical analyses were performed using SPSS Statistic version 24.0 (IBM Corp, NY). Statistical significance was considered when p value reached < 0.05.

Results

A total of 31 eligible patients with a severe TSCI due to a thoracolumbar burst fracture were identified from our database. Of those, 4 were excluded because of insufficient follow-up data; 2 patients were excluded because of a concomitant burst fracture at L3. Therefore, 25 patients were

included in the statistical analyses, among which 14 were AIS A, 5 were AIS B and 6 were AIS C upon initial preoperative neurological evaluation.

Table 1 describes sociodemographic and clinical characteristics of the final cohort. Patients with and without neurological recovery were similar in terms of age, gender, surgical delay, trauma subtypes and vertebral level injury. Only 1 patient (AIS C) was operated after 24 h (25.6 h). The mean Injury Severity Score (ISS) was higher in patients without neurological recovery ($p = 0.02$).

Table 2 outlines the conversion of AIS grade according to the initial neurological examination for patients with and without neurological recovery. At the yearly follow-up, 6 of the 14 AIS A patients and 3 of the 5 AIS B patients demonstrated recovery. All 6 AIS C patients recovered and 1 was considered neurologically intact at 12 months.

Results from the univariate logistic regressions are shown in Table 3 and 4. Among the clinical variables, the initial AIS grade and ISS were both related to neurological recovery ($p = 0.04$). The initial AIS grade resulted in the highest odds ratio (OR = 4.64) among clinical parameters. All features involving the morphology of the spinal canal were significantly related to neurological recovery, except for the MCC.

ROC curve analysis calculated a discriminating cut-off value of 3,50 mm for significant postero-inferior corner translation with the optimal combination of 93,3% specificity and 77,8% sensitivity. The AUC was calculated at 0,900 which is in the range of [0,8–0,9], "good" accuracy. We established the rounded off threshold value at 4 mm for further analysis given the measurement precision on CT scan sagittal reconstructions. Postero-inferior corner translation of ≥ 4 mm displayed the greatest odds ratio (OR = 49.00) for absence of neurological recovery followed by retropulsed fragment comminution (OR = 16.00), complete lamina fracture (OR = 13.50), initial AIS grade (OR = 4.64) and ISS (OR = 1.21).

Table 1 Patient population baseline characteristics

	No recovery	Recovery	*p*
N	10	15	
Age (SD)	50.00 (20.47)	43.13 (16.20)	0.41
Initial AIS grade			0.03*
A	8	6	
B	2	3	
C	0	6	
Gender (% male)	70.0	80.0	0.57
ISS (SD)	27.44 (7.27)	20.93 (5.20)	0.02*
Surgical delay, hours (SD)	15.63 (4.55)	17.86 (4.99)	0.22
Energy (% high energy)	50.6	66.6	0.62
Mechanism of trauma			0.96
Sport accident	2	3	
Blunt trauma	1	2	
Penetrating trauma	0	0	
Fall	5	6	
Vehicle accident	2	4	
Level of vertebral injury			0.56
T11	0	1	
T12	3	6	
L1	7	7	
L2	0	1	

*p is significant if < 0.05

Discussion

This study is the first to specifically assess the impact of morphological features in thoracolumbar burst fracture on the chronic neurological recovery in SCI patients. An interesting aspect associated with these parameters is related to the fact that they are readily available for most patients since CT scan is routinely obtained for most patients after severe spine injuries. Results of this study point out morphological characteristics of burst fractures that should be considered when assessing acute thoracolumbar SCI. We evaluated a cohort of patients with injuries that can cause a significant

Table 3 Univariate binary logistic regressions with clinical variables and AIS grade absence of conversion as dependant variable

	OR	C.I. (95%)	*p* value
Age	1.02	[0.98 – 1.07]	0.345
Initial AIS grade	4.64	[1.07 – 20.03]	0.040*
ISS	1.21	[1.01 – 1.46]	0.039*
Surgical delay	0.90	[0.76 – 1.08]	0.261
Energy	0.67	[0.13 – 3.35]	0.622

*p is significant if < 0.05

Table 2 Neurological status at admission and follow-up

	Follow-up AIS grade	A	B	C	D	E	Total
Initial AIS	A	8	4	0	2	0	14
	B	0	2	1	2	0	5
	C	0	0	0	5	1	6

Table 4 Univariate binary logistic regressions with morphological features and AIS grade absence of conversion as dependent variable

	OR	C.I. (95%)	*p* value
Retropulsed fragment comminution	16.00	[2.17–118.27]	0.007*
Postero-inferior corner translation ≥ 4 mm	49.00	[3.765–637.794]	0.003*
Complete lamina fracture	13.50	[1.340–135.983]	0.027*
Mean canal compromise (%)	0.99	[0.95–1.04]	0.798
Vertebral body kyphosis index	194.00	[0.11–3.5E10^5]	0.163
Segmental kyphosis angle	0.85	[0.72–1.01]	0.058
Vertebral body comminution	0.25	[0.03–2.24]	0.215

*p is significant if < 0.05

long-term distress to both patient and family, and of which outcomes are important to study. We presented the largest cohort of patients with such injuries and adequate long-term follow-up.

We identified 3 morphological characteristics significantly associated with a poor likelihood of neurological recovery. A postero-inferior corner translation ≥ 4 mm, complete lamina fracture and comminution of the retropulsed fragment all are radiological signs that are easy to define and available on the initial CT scan reconstructions. Although postero-inferior corner translation has been shown previously to correlate with the initial ASIA motor score deficit by Radcliff et al. [9], this study is the first to assess its relationship with neurological outcome in the chronic period. Moreover, we have identified the relevance of a specific objective threshold value for the postero-inferior corner translation. Its relevance could also lie in the fact that it displayed an odds ratio 10 times higher than the initial AIS grade for absence of neurological recovery and can be assessed for any patient, contrasting with the clinical evaluation at presentation which can be difficult to perform for sedated/unresponsive patients or those with multiple associated injuries.

When assessing the potential for neurological recovery, our results show that evaluating parameters involving the spinal canal is more helpful than the loss of vertebral body height, kyphosis or vertebral body comminution which does not directly consider spinal canal disruption. Our results suggest that these traditional morphological features describing thoracolumbar burst fractures [13] are not significantly related to neurological recovery in thoracolumbar TSCI.

The MCC and the postero-inferior corner translation are parameters that portray the final position of the damaged vertebral body fragments. It is generally understood that supine CT scan measures of fragment position underestimate the severity of compression sustained during the trauma [14, 15]. In line with most previous studies [16] the position of the retropulsed fragments evaluated by the MCC was not predictive of neurological recovery in our study. The MCC almost invariably implicate measurement of the displacement of the postero-superior wall, or so-called delta fragment. The retropulsion of this fragment during the traumatic event is more likely to compress the spinal canal content against the soft tissue structures of the interlaminar space. However, the magnitude of the postero-inferior wall translation was related to the absence of neurological recovery. Even though it bears the same interpretation limitations as the MCC, it provides more insight on which level of the posterior spinal canal the neural elements may have been compressed against. The retropulsion of the postero-inferior wall during the traumatic event is more likely to compress the spinal content against the bony lamina, therefore potentially amplifying the amount of energy directly transferred to the neural elements. This hypothesis has been supported by a recently published numerical model study [17].

Complete lamina fracture and comminution of the retropulsed fragment are static descriptors that could indicate high-energy transfer in structures adjacent to the neural elements. With respect to lamina fractures, several studies suggested that its presence was linked to the occurrence of neurological injury at presentation after burst fractures [18] and to the overall severity of trauma. We present the first results assessing its relationship with worst neurological outcome. The complete lamina fracture is produced either by a greater local energy level, completing a greenstick fracture [19], or by compressive forces directed more posteriorly during the trauma [20]. Both hypotheses involve a greater amount of energy being dissipated in the posterior elements of the spinal column in close proximity of the spinal cord. We interpret the comminution of the retropulsed fragment in a similar manner. Notably, this radiological sign has not previously been described nor studied as a morphological characteristic of burst fractures.

It is understood from biomechanical studies [14, 21] that the amount of energy that is transferred to the neural elements by the bony fragments of the burst fracture during the trauma dictates the tissue destruction hence the neurological deficit. Still, assessing the external level of energy by separating low from high-energy mechanisms is difficult and neglects the wide variability in the level of energy, trauma mechanisms and biomechanical conditions involved during the traumatic event. Therefore, the ISS is utilized

as an indicator of the amount of energy distributed inside the body of the polytraumatized patient (internal energy). However, the ISS is not specific to the evaluation of the spine and spinal cord, considering that other body regions are equally considered. In addition, the previous studies on TSCI outcomes that include ISS remain inconsistent [22]. Nevertheless, these reports included cervical and thoracic TSCI with variable pattern of spinal injury and were not specific to thoracolumbar trauma. In our cohort, higher ISS was related to absence of neurological recovery, but with weaker OR than the other variables. Consequently, local morphological features of the fracture are likely to better indicate the local energy sustained by the spinal cord during the trauma and hence the potential for irreversible spinal cord damage.

Limitations

The main limitation of our retrospective study is the small number of patients included, which precluded the possibility for multivariable analysis. Despite a small cohort, patients included in this study displayed a similar AIS conversion rate as shown in other larger-scale SCI studies [23]. Again, AIS A showed poorer rate of conversion and AIS C showed the best conversion rate. Other authors provided insight on thoracolumbar burst fractures with similar stratification between severe (AIS A, B or C) and low or no deficit (AIS D or E) [15]. Also, other studies that evaluate radiological patterns of thoracolumbar burst fracture include smaller number of TSCI patients [8, 9] that would fit the inclusion criteria of this study. In addition, since we present the first study looking at morphological features in relation to neurological recovery over an adequate follow-up period, we intend to identify key elements to evaluate in further large-scale studies.

Evaluating MRI parameters would be of great interest to estimate the trauma sustained by the neural elements [11, 24]. It would be valuable to look for a relationship between MRI signal changes or maximal spinal cord compression (MSCC) and parameters found in this study. Skeers et al. [5] found no relation between MSCC and AIS grade improvement based on univariate analyses. Their analysis included a small number of patients showing AIS conversion (n = 12, 27% of the cohort) and variable patterns of spinal injury. We acknowledge that accessibility for MRI studies to be performed in trauma situations varies from centre to centre and that lack of correlation with MRI parameters could be considered as a limitation in this study. However, the role of urgent MRI in the radiographic evaluation of spinal cord injury is still debated [25]. Since rapid surgical decompression is our institution's utmost priority, MRI is often not used prior to surgical management in order to minimize the risks of delay [26] with the assumption that the results would have little influence on surgical approach [27]. The delay from trauma to surgical intervention in our cohort is shorter than the standard of care in a Canadian population [12].

Conclusion

Classic parameters like vertebral body kyphosis, comminution and loss of height do not provide insight on the potential for neurological recovery in severe TSCI patients that undergo surgery. Our data show that other morphological features of thoracolumbar burst fractures are related to the neurological outcome in patients sustaining acute AIS A, B or C TSCI. Specifically, we focus on the importance of the amount of posterior translation of the postero-inferior vertebral body wall (> 4 mm), comminution of the retropulsed fragment and the presence of a complete lamina fracture as better indicators of poor prognostic for neurological recovery as opposed to clinical predictors of chronic neurological outcome. Further analysis of the implication of these morphological features in more powered studies for multivariable analysis could provide insight on their predictive potential and ultimately be used in future classification schemes.

This study was supported by the Fonds de recherche du Québec—Santé (FRQS), Department of the Army—United States Army Medical Research Acquisition Activity, Medtronic research chair in spinal trauma at Université de Montréal, and Rick Hansen Spinal Cord Injury Registry.

Funding This study was supported by the Fonds de recherche du Québec—Santé (FRQS), Department of the Army—United States Army Medical Research Acquisition Activity, Medtronic research chair in spinal trauma at Université de Montréal, and Rick Hansen Spinal Cord Injury Registry.

Compliance with ethical standards

Conflict of interest Dr Goulet has received a scholarship from the Medtronic research chair in spinal trauma at Université de Montréal. Andréane Richard-Denis has received a scholarship and research grants from the Fonds de recherche du Québec—Santé, an investigator-initiated research grant from Medline Industries, and a research grant from Praxis Spinal Cord Institute. Dr Petit reports no financial disclosure. Mr Diotalevi has received a salary support from the Medtronic research chair in spinal trauma at Université de Montréal. Dr Mac-Thiong is chairholder of Medtronic research chair in spinal trauma at Université de Montréal, owns stocks and is a board member in Spinologics, and has received a scholarship and research grants from the Fonds de recherche du Québec—Santé, an investigator-initiated research grant from Medline Industries, educational grants from Medtronic and Depuy-Synthes, as well as research grants from the U.S. Department of Defense—Congressionally directed medical research programs, Craig H. Neilsen Foundation, from Social Sciences and Humanities Research Council, Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council, Praxis Spinal Cord Institute, and Vertex Pharmaceutical.

Ethical approval All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional ethical research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

References

1. Wilson JR, Cadotte DW, Fehlings MG (2012) Clinical predictors of neurological outcome, functional status, and survival after traumatic spinal cord injury: a systematic review. J Neurosurg Spine. https://doi.org/10.3171/2012.4.AOSPINE1245
2. Wilson JR, Grossman RG, Frankowski RF, Kiss A, Davis AM, Kulkarni AV, Harrop JS, Aarabi B, Vaccaro A, Tator CH, Dvorak M, Shaffrey CI, Harkema S, Guest JD, Fehlings MG (2012) A clinical prediction model for long-term functional outcome after traumatic spinal cord injury based on acute clinical and imaging factors. J Neurotrauma. https://doi.org/10.1089/neu.2012.2417
3. Mputu P, Beauséjour M, Richard-Denis A, Thompson C, Mac-Thiong JM (2018) Early predictors of neurological recovery after traumatic spinal cord injury: a systematic review.
4. van Middendorp JJ, Hosman AJ, Doi SA (2013) The effects of the timing of spinal surgery after traumatic spinal cord injury: a systematic review and meta-analysis. J neurotrauma. https://doi.org/10.1089/neu.2013.2932
5. Skeers P, Battistuzzo CR, Clark JM, Bernard S, Freeman BJC, Batchelor PE (2018) Acute thoracolumbar spinal cord injury: relationship of cord compression to neurological outcome. J Bone Jt Surg Am. https://doi.org/10.2106/jbjs.16.00995
6. Dvorak MF, Noonan VK, Fallah N, Fisher CG, Finkelstein J, Kwon BK, Rivers CS, Ahn H, Paquet J, Tsai EC, Townson A, Attabib N, Bailey CS, Christie SD, Drew B, Fourney DR, Fox R, Hurlbert RJ, Johnson MG, Linassi AG, Parent S, Fehlings MG (2015) 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. https://doi.org/10.1089/neu.2014.3632
7. Reinhold M, Audige L, Schnake KJ, Bellabarba C, Dai LY, Oner FC (2013) AO spine injury classification system: a revision proposal for the thoracic and lumbar spine. Eur spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc. https://doi.org/10.1007/s00586-013-2738-0
8. Hiyama A, Watanabe M, Katoh H, Sato M, Nagai T, Mochida J (2015) Relationships between posterior ligamentous complex injury and radiographic parameters in patients with thoracolumbar burst fractures. Injury. https://doi.org/10.1016/j.injury.2014.10.047
9. Radcliff K, Su BW, Kepler CK, Rubin T, Shimer AL, Rihn JA, Harrop JA, Albert TJ, Vaccaro AR (2012) Correlation of posterior ligamentous complex injury and neurological injury to loss of vertebral body height, kyphosis, and canal compromise. Spine. https://doi.org/10.1097/BRS.0b013e318240fcd3
10. Whiteneck G, Gassaway J (2012) The SCIRehab project: what rehabilitation interventions are most strongly associated with positive outcomes after spinal cord injury? J Spinal Cord Med. https://doi.org/10.1179/2045772312y.0000000083
11. Fehlings MG, Rao SC, Tator CH, Skaf G, Arnold P, Benzel E, Dickman C, Cuddy B, Green B, Hitchon P, Northrup B, Sonntag V, Wagner F, Wilberger J (1999) The optimal radiologic method for assessing spinal canal compromise and cord compression in patients with cervical spinal cord injury. Part II: results of a multicenter study. Spine. https://doi.org/10.1097/00007632-199903150-00023
12. McCormack T, Karaikovic E, Gaines RW (1994) The load sharing classification of spine fractures. Spine. https://doi.org/10.1097/00007632-199408000-00014
13. Cantor JB, Lebwohl NH, Garvey T, Eismont FJ (1993) Nonoperative management of stable thoracolumbar burst fractures with early ambulation and bracing. Spine. https://doi.org/10.1097/00007632-199306150-00004
14. Wilcox RK, Boerger TO, Allen DJ, Barton DC, Limb D, Dickson RA, Hall RM (2003) A dynamic study of thoracolumbar burst fractures. J bone Jt Surg Am. https://doi.org/10.2106/00004623-200311000-00020
15. Yugue I, Aono K, Shiba K, Ueta T, Maeda T, Mori E, Kawano O (2011) Analysis of the risk factors for severity of neurologic status in 216 patients with thoracolumbar and lumbar burst fractures. Spine. https://doi.org/10.1097/BRS.0b013e3181f58d56
16. Gupta R, Mittal P, Sandhu P, Saggar K, Gupta K (2014) Correlation of qualitative and quantitative MRI parameters with neurological status: a prospective study on patients with spinal trauma. J Clin Diagn Res. https://doi.org/10.7860/jcdr/2014/9471.5181
17. Diotalevi L, Bailly N, Wagnac É, Mac-Thiong J-M, Goulet J, Petit Y (2020) Dynamics of spinal cord compression with different patterns of thoracolumbar burst fractures: Numerical simulations using finite element modelling. Clin Biomech 72:186–194
18. Skiak E, Karakasli A, Harb A, Satoglu IS, Basci O, Havitcioglu H (2015) The effect of laminae lesion on thoraco-lumbar fracture reduction. Orthop Traumatol Surg Res. https://doi.org/10.1016/j.otsr.2015.02.011
19. Ozturk C, Ersozlu S, Aydinli U (2006) Importance of greenstick lamina fractures in low lumbar burst fractures. Int Orthop. https://doi.org/10.1007/s00264-005-0052-0
20. Panjabi MM, Crisco JJ, Vasavada A, Oda T, Cholewicki J, Nibu K, Shin E (2001) Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. Spine. https://doi.org/10.1097/00007632-200112150-00012
21. Boisclair D, Mac-Thiong JM, Parent S, Petit Y (2013) Compressive loading of the spine may affect the spinal canal encroachment of burst fractures. J Spinal Disord Tech. https://doi.org/10.1097/BSD.0b013e318246b180
22. Kaminski L, Cordemans V, Cernat E, M'Bra KI, Mac-Thiong JM (2017) Functional outcome prediction after traumatic spinal cord injury based on acute clinical factors. J Neurotrauma. https://doi.org/10.1089/neu.2016.4955
23. Fehlings MG, Vaccaro A, Wilson JR, Singh A, D WC, Harrop JS, Aarabi B, Shaffrey C, Dvorak M, Fisher C, Arnold P, Massicotte EM, Lewis S, Rampersaud R (2012) Early versus delayed decompression for traumatic cervical spinal cord injury: results of the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS). PLoS ONE. https://doi.org/10.1371/journal.pone.0032037
24. Mabray MC, Talbott JF, Whetstone WD, Dhall SS, Phillips DB, Pan JZ, Manley GT, Bresnahan JC, Beattie MS, Haefeli J, Ferguson AR (2016) Multidimensional analysis of magnetic resonance imaging predicts early impairment in thoracic and thoracolumbar spinal cord injury. J Neurotrauma. https://doi.org/10.1089/neu.2015.4093
25. Ahuja CS, Schroeder GD, Vaccaro AR, Fehlings MG (2017) Spinal cord injury-what are the controversies? J Orthop Trauma. https://doi.org/10.1097/BOT.0000000000000943
26. Bourassa-Moreau E, Mac-Thiong JM, Feldman DE, Thompson C, Parent S (2013) Non-neurological outcomes after complete traumatic spinal cord injury: the impact of surgical timing. J Neurotrauma. https://doi.org/10.1089/neu.2013.2957

27. Burke JF, Yue JK, Ngwenya LB, Winkler EA, Talbott J, Pan J, Ferguson A, Beattie M, Bresnahan J, Haefeli J, Whetstone W, Suen C, Huang MC, Manley GT, Tarapore PE, Dhall SS (2016) 182 Ultra-early (%3c12 Hours) decompression improves recovery after spinal cord injury compared to early (12–24 H) decompression. Neurosurgery. https://doi.org/10.1227/01.neu.0000489751.59414.45

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.