FEATURES OF THE COURSE OF COMPLICATED INJURY OF THE LOWER CERVICAL SPINE DEPENDING ON THE TIMING OF SURGICAL DECOMPRESSION OF THE SPINAL CORD

I.A. Statsenko, M.N. Lebedeva, A.V. Palmash, V.L. Lukinov, V.V. Rerikh
Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, Novosibirsk, Russia

Objective. To determine the influence of the urgency of performing surgical decompression of the spinal cord (SC) on the course of acute and early periods of complicated injury of the lower cervical spine.

Material and Methods. The results of treatment of 75 patients with acute complicated injury of the lower cervical spine with ASIA A and ASIA B severity of spinal cord injuries were retrospectively analyzed. Two groups were formed, depending on the timing of surgical decompression of the spinal cord after injury. Group I included 33 patients in whom the SC decompression was performed within the first eight hours after the injury, and Group II included 42 patients in whom the SC decompression was performed in more than eight hours after the injury.

Results. The mean age of patients in Group I was 29 [25; 39] years, in Group II – 35 [30; 42] years ($p = 0.129$). There were 31 (94.0 %) male patients in Group I and 38 (90.5 %; $p > 0.999$) in Group II. The time from the moment of injury to decompression of the spinal cord was 6.1 [5.0; 7.5] hours in Group I and 16.9 [11.8; 39.6] hours in Group II ($p < 0.001$). Pneumonia developed in 55 % [38 %; 70 %] of patients in Group I and in 86 % [72 %; 93 %] of patients in Group II ($p = 0.004$). The duration of pneumonia in Group I was 18 [8; 20] days, and in Group II – 28 [20; 39] days ($p < 0.001$). It was shown that the risk ratio for developing pneumonia in patients with delayed decompression of the spinal cord was 2.08 [1.17; 3.67] times higher ($p = 0.01$). The duration of mechanical ventilation in Group I was 12 [7; 17] days versus 19 [11; 26] days in Group II ($p = 0.001$). Maintaining the target blood pressure levels ≥ 85 mm Hg was required in 73 (97.3 %) patients with a duration of hemodynamic support of 6 [3; 10] days in Group I versus 10 [5; 15] days in Group II ($p = 0.019$). It was shown that SC decompression within the first eight hours after injury reduced the proportion of patients with a SOFA score of 4 points or more by 20 % in the acute period and by 42 % by the fifth day of the early period of injury. Positive dynamic in neurological status was recorded in 30.0 % [17.0 %; 47.0 %] of patients in Group I and only in 2.0 % [0.0 %; 12.0 %] of patients in Group II ($p < 0.001$). The duration of treatment in the ICU was 20 [16; 25] days in Group I and 29 [23.5; 41.75] days in Group II ($p = 0.001$). The total length of hospital stay was 38 [27; 46] days in Group I versus 57 [45.75; 67.50] days in Group II ($p < 0.001$). Mortality was recorded only in Group II and amounted to 5.3 %.

Conclusion. Decompression and stabilization surgery within the first eight hours after the injury, together with a complex of intensive care measures for acute complicated injury of the lower cervical spine have a significant positive effect on the course of the acute and early periods of traumatic SC disease.

Key Words: complicated spinal injury, spinal cord injury, respiratory complications, duration of mechanical ventilation, hemodynamic support, SOFA scale, mortality.

Please cite this paper as: *Statsenko IA, Lebedeva MN, Palmash AV, Lukinov VL, Rerikh VV. Features of the course of complicated injury of the lower cervical spine depending on the timing of surgical decompression of the spinal cord. Russian Journal of Spine Surgery (Khirurgiya Pozvonochnika). 2024;21(2):13–26. In Russian.*

DOI: http://dx.doi.org/10.14531/ss2024.2.13-26.

Lower cervical spine injuries with spinal cord (SC) compression result in severe neurological impairment, and sometimes in fatal outcomes [1, 2]. Combined treatment for such injuries always includes surgical interventions performed for decompression and stabilization. In academic literature, there are different opinions on the optimal time for such interventions. There is an established view that the period of 24–36 hours is a critical time interval within which shortening of time to decompression can improve neurological outcomes, while delayed SC decompression causes a rapid and persistent decrease in motor function recovery [3, 4]. Under the most recent guidelines, early SC decompression is required that is defined as surgery performed within 24 hours after injury [5]. When analyzing the effect of SC decompression time on clinical outcomes in patients with SC injury, most researchers consider changes in neurological status over time [4, 6]. Thus, Burke et al. [7] compared the efficacy of decompression performed within 12 hours, 12–24 hours, and later than 24 hours after injury. 88.8 % of patients who underwent surgery within 12 hours demonstrated the regression of neurological impairment at discharge vs 38.4% of patients who received delayed SC decompression. The results of meta-analyses published in 2020 and 2021 indicate the efficacy of SC decompression performed within 8 hours after injury, with no increase in the number of complications and the duration of total hospital stay [8, 9]. However, several papers provide opposite results. Thus, a trial performed by Liu et al. [10] revealed deterioration in the neurological status in the early SC decompression group in comparison to the late SC decompression group: 6.6 % and 0.7 %, respectively ($p < 0.001$). Similar results were obtained by the authors for the analysis of the incidence of adverse outcomes: 7.1 % and 2.1 % ($p = 0.003$). At the same time, no significant differences were found in the duration of mechanical ventilation, the incidence of infectious and vascular complications [10].

Thus, the analysis of published research data indicates that there are sufficient publications assessing the efficacy of early SC decompression in regard to the neurological outcome. However, the issues of the effect of SC decompression time on the severity of the patients' condition during intensive care in the ICU after surgical treatment are covered to a lesser extent, and this became the objective of our work.

The objective is to analyze the effect of the urgency of surgical SC decompression on the course of the acute and early periods in patients with complicated lower cervical spine injury.

Material and Methods

We performed a retrospective analysis of treatment results obtained from 75 patients with acute complicated lower cervical spine injury who received specialized surgical care at the Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan in the period from December 2014 to November 2023.

Inclusion criteria: single complicated lower cervical spine injury, ASIA A and B SC injury severity, SC surgical decompression, and need for mechanical ventilation.

Non-inclusion criteria: concomitant injury, multiple injury, C1–C2 SC injury, age over 60, viral pneumonia, and secondary immunodeficiency.

There were no exclusion criteria in this research.

Patients were divided into two groups depending on the time of surgical decompression after SC injury: Group I (main) included 33 patients who underwent SC decompression within 8 hours after injury; and Group II (comparison) included 42 patients with SC decompression performed in the period over 8 hours after injury.

The research was approved by the Local Ethics Committee (extract No. 008/24 from protocol 004/24 dated May 17, 2024).

Intergroup comparison was performed for the following parameters: gender, age, mechanism of injury, SC injury severity, presence of comorbidities, nature and incidence of complications, gas exchange parameters, duration of mechanical ventilation, nature and duration of hemodynamic support, heart rate variability (HRV), severity of patients' condition and organ dysfunction severity, changes of neurological status over time, results of radiological diagnostics, duration of ICU stay, duration of hospital stay, and mortality rate.

Monitoring of mechanical ventilation parameters and extended hemodynamic monitoring were carried out during the research. Ventilation monitoring included the following: respiratory rate (RR), tidal volume (TV), respiratory minute volume (RMV), forced respiratory volume (FV), inspiratory pressure (Pinsp), positive end-expiratory pressure (PEEP), static compliance (Cstat), and airway resistance (Raw). Extended hemodynamic monitoring was carried out by the method of impedance cardiography using a Nicom Reliant device (Israel); the following parameters were registered: systolic blood pressure (BPsys), diastolic blood pressure (BPdia), mean blood pressure (BPm), cardiac output (CO), cardiac index (CI), stroke volume (SV), and total peripheral resistance (TPR).

HRV was registered using a Poly-Spectrum.NET device (Russia) with the appropriate software. Registration was performed for 5 minutes with the patient at rest, in lying position.

SC injury severity was assessed according to the American Spinal Injury Association (ASIA/IMSOP) classification [11]; severity of patients' condition was assessed using the APACHE II score [12]; and organ dysfunction severity was assessed using the SOFA score [13].

Control points: upon admission, Day 1, 3, 5, 7, 10, 15, 20, and 30 in the ICU.

Statistical calculations were carried out in the Rstudio software (version 0.99.879 – © 2009–2016 RStudio, Inc., USA, 250 Northern Ave, Boston, MA 02210 844-448-121).

Because of the small number of parameters that were suitable for the parametric Student's t-test, continuous variables were compared using non-parametric rank tests: the Mann – Whitney U-test and the Wilcoxon signed-rank test.

Descriptive statistics for continuous data are presented as median [Q1; Q3]; binary data – as the number of elements (events, complications, etc.), sample proportion [lower bound of 95 % CI; upper bound of 95 % CI] was calculated according to Wilson's formula; for each level of categorical data, the number of patients at the level (proportion of the total number of patients in the group) is provided. The Wilcoxon test was used to perform statistical tests of hypotheses about the equality of sample distributions for continuous parameters at different time points. Predictors were identified using logistic regression models.

Statistical hypotheses were tested at 0.05 critical value of significance level, that is, the difference was considered statistically significant when $p < 0.05$ was achieved.

Results

Male patients of working age prevailed in both groups. The mean age of patients in Group I was 29 [25; 39] years, in Group II – 35 [30; 42] years; $p = 0.129$. There were 31 (94.0%) male patients in Group I and 38 (90.5%) male patients in Group II; $p > 0.999$. The most common causes of injury in the overall sample were dive-related injury in 36 (48.6%) patients, road traffic accidents in 18 (24.3 %) patients, and fall from height in 12 (16.2 %) patients, with no statistically significant differences between groups.

Distribution of patients in groups according to the SC injury severity is provided in Table 1.

Injury in the area of C5–C6, C6, and C6–C7 was the most common: 38 (51.3 %) cases in the overall sample, with no statistically significant differences between groups ($p > 0.999$).

Arterial blood gas parameters at admission in the setting of spontaneous breathing before the start of oxygen support in groups were as follows: Group I: PaO_2 – 89.0 [76.0; 140.5] mm Hg, $PaCO_2$ – 41.0 [38.5; 42.25] mm Hg, oxygenation index (OI) – 400.0 [366.0; 423.0]; Group II: PaO_2 – 87.0 [80.5; 103.5] mm Hg, $PaCO_2$ – 37.0 [34.0; 44.0] mm Hg, OI – 323.0 [287.75; 361.0]. In an intergroup analysis of the presented gas exchange parameters, statistically significant differences were obtained only for OI values that were lower in Group II ($p = 0.015$). OI values in the range 100–200 at the preoperative stage were registered in one (3.0 %) patient in Group I; there were no OI values below 200 in Group II, however, OI values in the range 200–300 were registered in 6 (14.3 %) patients. The identified abnormal gas exchange could indicate the presence of acute diffuse lung damage, i.e. acute respiratory distress syndrome (ARDS) that was confirmed by MSCT results of the thoracic organs at this research stage: diffuse strengthening of the pulmonary pattern due to vascular component, symmetrical shadows, as well as decreased aeration of lung tissue.

All patients underwent urgent surgical decompression and stabilization. The time from the injury to SC decompression was characterized by statistically significant differences and amounted to 6.1 [5.0; 7.5] hours in Group I and 16.9 [11.8; 39.6] hours in Group II ($p < 0.001$). Duration of the surgical intervention was 240 [200; 280] min in Group I and 225 [196; 256] min in Group II ($p = 0.278$). Intraoperative blood loss was 300 [150; 400] mL in Group I, and 175 [100; 300] mL in Group II ($p = 0.029$). During SC surgical decompression, none of the patients experienced complications that could have an effect on the further injury course.

Follow-up and treatment after the surgical stage were carried out in the ICU. All patients received prolonged mechanical ventilation in accordance with the concept of protective mechanical ventilation.

Analysis of OI values on Day 1 of the follow-up and treatment in the ICU demonstrated that 1 (3.0 %) patient in Group I had OI below 200 mm Hg, and 7 (21.2 %) patients had OI in the range 200–300 mm Hg. Upon that, the injury in all patients with OI below 300 mm Hg was caused by diving into shallow water. All other patients in Group I with similar and other mechanisms of injury had OI of 300 mm Hg higher. OI values below 200 mm Hg in Group II were registered in 4 (9.5 %) patients on Day 1 of treatment in the ICU; the injury was caused by diving into shallow water in three of them, and one patient was involved in a traffic accident. There were 9 (21.4 %) patients with OI in the range 200–300 mm Hg in Group II; only two of them were caused by dive-related injury. In other cases, OI values were 300 mm Hg and higher.

68 (90.7 %) patients in the overall sample underwent tracheostomy to ensure adequate sanitation of the tracheobronchial tree: on Day 3 [2; 3] of postoperative follow-up in Group I, and on Day 2 [2; 3] in Group II ($p = 0.323$).

To assess the effect of early SC decompression on the incidence of respiratory complications, a comparative intergroup analysis was performed (Table 2) that revealed a statistically significant difference in the incidence of all complications, except for purulent tracheobronchitis that was a typical complication for the analyzed injury.

A comparative intergroup analysis of the duration of pneumonia course demonstrated a statistically significant difference: 18 [8; 20] days in Group I vs 28 [20; 39] days in Group II ($p < 0.001$). It should be mentioned that the period before SC decompression in patients with pneumonia was 11 [7.5; 32.5] hours vs 7 [7.85; 12.5] hours in cases with no pneumonia ($p = 0.019$).

Analysis of the time of pneumonia development was carried out using the method of constructing Kaplan–Meier curves (Fig. 1).

In the main group, pneumonia was most often registered on Day 4–12 of follow-up; the first case was diagnosed on Day 4. In the comparison group, pneumonia was more often diagnosed on Day 4–9, and in two patients – even on Day 1 of ICU stay. Results of the analysis revealed that there was a 2.08-fold [1.17; 3.67] risk ratio for developing pneumonia in patients in the comparison group vs patients of the main group ($p = 0.01$). Pneumonia resolved by Day 20 in 13 (72 %) patients of the main group, and only in 9 (27 %) patients of the comparison group; $p = 0.031$.

Univariate logistic regression models helped to identify individual significant predictors of pneumonia development: duration of mechanical ventilation ($p = 0.001$), time of transition to the assisted mode of ventilation ($p = 0.004$), ASIA B neurological deficit ($p = 0.004$), ASIA A neurological deficit ($p = 0.004$), duration of ICU stay ($p = 0.005$), and positive changes in neurological status over time ($p = 0.009$).

It was demonstrated that increased duration of mechanical ventilation by three days ($p = 0.001$) is associated with a 1.6-fold [1.3; 2.2] increase in possibility of pneumonia development; increased time before transition to the assisted mode of ventilation by three days was associated with a 2.0-fold [1.3; 3.3] increase in possibility of pneumonia development; severity of neurological impairment (ASIA A) was associated with a 5.87-fold [1.79; 20.81] increase in possibility of pneumonia development; increased ICU stay duration by three days was associated with a 1.3-fold [1.1; 1.5] increase in possibility of pneumonia development; positive changes in neurological status over time were associated with a 0.16-fold [0.04; 0.62] decrease in possibility of pneumonia development.

Comparative intergroup analysis of the incidence of pulmonary sepsis revealed no statistically significant dif-

Table 1

Distribution of patients by severity of spinal cord injury

Injury severity	Group I (n = 33)	Group II (n = 42)	p value
ASIA A, n (%)	24 (72.7)	36 (85.4)	0.246
ASIA B, n (%)	9 (27.3)	6 (14.6)	0.246

Comparisons of causes of injury were performed using Fisher's exact two-tailed test.

ference ($p = 0.249$), however, all three cases of its development were registered in patients of the comparison group.

The duration of mechanical ventilation in Group I was significantly less than in Group II and amounted to 12 [7; 17] days and 19 [11; 26] days, respectively ($p = 0.001$).

Hemodynamic support during the preoperative examination in order to achieve target values of BPm ⩾ 85 mm Hg was required in 13 (39.4 %) patients in Group I and 21 (51.0 %) patients in Group II; it included infusion therapy and vasopressor agents. Choosing medications at this stage was based on HR. Norepinephrine 0.02 % was used at a dose of 0.08 [0.04; 0.12] μg/kg/min in Group I, and 0.125 [0.08; 0.22] μg/kg/min in Group II ($p = 0.126$); dopamine 0.5 % was used at a dose of 3.0 [2.55; 4.15] μg/kg/min in Group I, and 3.46 [3.23; 4.66] μg/kg/min in Group II ($p = 0.905$). At the stage of surgical treatment, the number of patients who required BP adjustment increased to 65.3 %. Following surgical treatment, maintaining target values of BPm ⩾ 85 mm Hg was carried out in the ICU; it was required in 73 (97.3 %) patients.

Adding of advanced hemodynamic monitoring on Day 1 of follow-up in the ICU allowed identifying three types of hemodynamic disorders. 62.5 % of patients had decreased TPR with normal CI values; 25.0 % of patients demonstrated both decreased TPR and decreased CI; in 12.5 % of patients, hypotension was caused by decreased CI only. The duration of hemodynamic support was characterized by significant differences between the groups: 6 [3; 10] days in Group I vs 10 [5; 15] days in Group II ($p = 0.019$).

The severity of patients' condition according to the APACHE II score on admission demonstrated no statistically significant differences and was 7 [5; 9] points in Group I vs 7 [7; 9] points in Group II ($p = 0.072$). Upon that, organ dysfunction severity assessed using SOFA score demonstrated statistically significant intergroup differences: 2 [0; 3] points in Group I vs 3 [2; 4] points in Group II ($p = 0.022$).

The results of intergroup comparative analysis using the APACHE II and SOFA scores at subsequent stages of our research are provided in Table 3.

Analysis using the SOFA score revealed that the highest organ dysfunction severity based on the sum of cumulative points was registered on Day 1 and 3 in Group I, and on Day 1–5 in Group II. Moreover, statistically significant intergroup differences indicating a higher severity of organ dysfunction in Group II were observed on Day 5 of follow-up.

The severity of patients' condition in Group I provided in points of the APACHE II score was stable during the first 10 days and significantly lower than that in Group II at all stages of the research.

As the result of the correlation analysis, a high positive correlation between the SOFA points and the duration of ICU stay was established on Day 30 of follow-up ($r = 0.77$; $p < 0.001$), with mean positive correlation on Day 15 ($r = 0.64$; $p < 0.001$) and Day 20 ($r = 0.57$; $p < 0.001$).

Table 2

Nature and incidence of respiratory complications in study groups

Complications	Group I (n = 33)	Group II (n = 42)	Fisher's exact two-tailed test	
	n % [95 % CI]	n % [95 % CI]	OR [95 % CI]	p value
Pneumonia	18 55 [38; 70]	36 86 [72; 93]	0.2 [0.1; 0.7]	0.004*
Acute respiratory distress syndrome	13 39 [25; 56]	27 66 [51; 78]	2.9 [1.0; 8.6]	0.035*
Obstruction of the main bronchi	1 3 [1; 15]	12 29 [18; 44]	12.9 [1.7; 581.6]	0.004*
Hydrothorax	11 33 [20; 50]	25 61 [46; 74]	3.1 [1.1; 9.1]	0.021*
Atelectasis of the lung	7 21 [11; 38]	22 54 [39; 68]	4.2 [1.4; 14.2]	0.008*
Purulent tracheobronchitis	30 91 [76; 97]	40 98 [87; 100]	3.9 [0.3; 214.9]	0.318

CI — confidence interval; OR — odds ratio; * statistically significant difference.

Changes in HRV parameters over time were registered in 10 patients of the overall sample (Table 4); they demonstrated that decreased temporal and spectral components of HRV, as well as the prevalence of the VLF component in the total spectral power, proportion of which was more than 60 % in the acute period and more than 50 % in the early period of injury, indicate increased activity of the central circuit of heart rate regulation, as well as high stress in regulatory systems and low adaptive abilities of the cardiovascular system in patients with complicated spinal injury.

Positive changes in the neurological status over time were observed in 11 (15.0 %) patients in the overall sample: 10 patients in Group I – 30.0 % [17.0 %; 47.0 %] vs only 1 patient in Group II – 2.0 % [0.0 %; 12.0 %]; p < 0.001. In Group I, four patients demonstrated a transition of SC injury severity from ASIA A to B, and six patients – from ASIA B to C. In Group II, positive changes in the neurological status over time corresponded to a transition of SC injury severity from ASIA B to C.

We used univariate and multivariate logistic regression models to determine predictors of neurological impairment regression.

Univariate logistic regression models helped to identify individual significant predictors of neurological impairment regression in all patients included in this research: ASIA A SC injury (p = 0.001); ASIA B SC injury (p = 0.001); period from the injury to the start of intensive care (p = 0.006); period from the injury to SC decompression (p = 0.008); SC injury at C6 level (p = 0.024); and duration of hemodynamic support (p = 0.029).

It was found that ASIA A SC injury was associated with a 0.08-fold [0.02; 0.33] decrease in the probability of neurological impairment regression; ASIA B SC injury was associated with a 12.25-fold [3.05; 56.67] increase in the probability of neurological impairment regression; period from the injury to the start of intensive therapy of less than 4.65 hours was associated with a 9.9-fold [2.3; 68.98] increase in the probability of neurological impairment regression; period from the injury to SC decompression of less than 8.2 hours was associated with a 17.83-fold [3.12; 337.74] increase in the probability of neurological impairment regression; SC injury at C6 level was associated with a 5.52-fold [1.18; 24.81] increase in the probability of neurological impairment regression; and an increase in hemodynamic support duration by one day was associated with a 0.82-fold [0.67; 0.95] decrease in the probability of neurological impairment regression.

Multivariate logistic regression models revealed multiplicative significant predictors of neurological impairment regression: ASIA B SC injury (p = 0.001), and

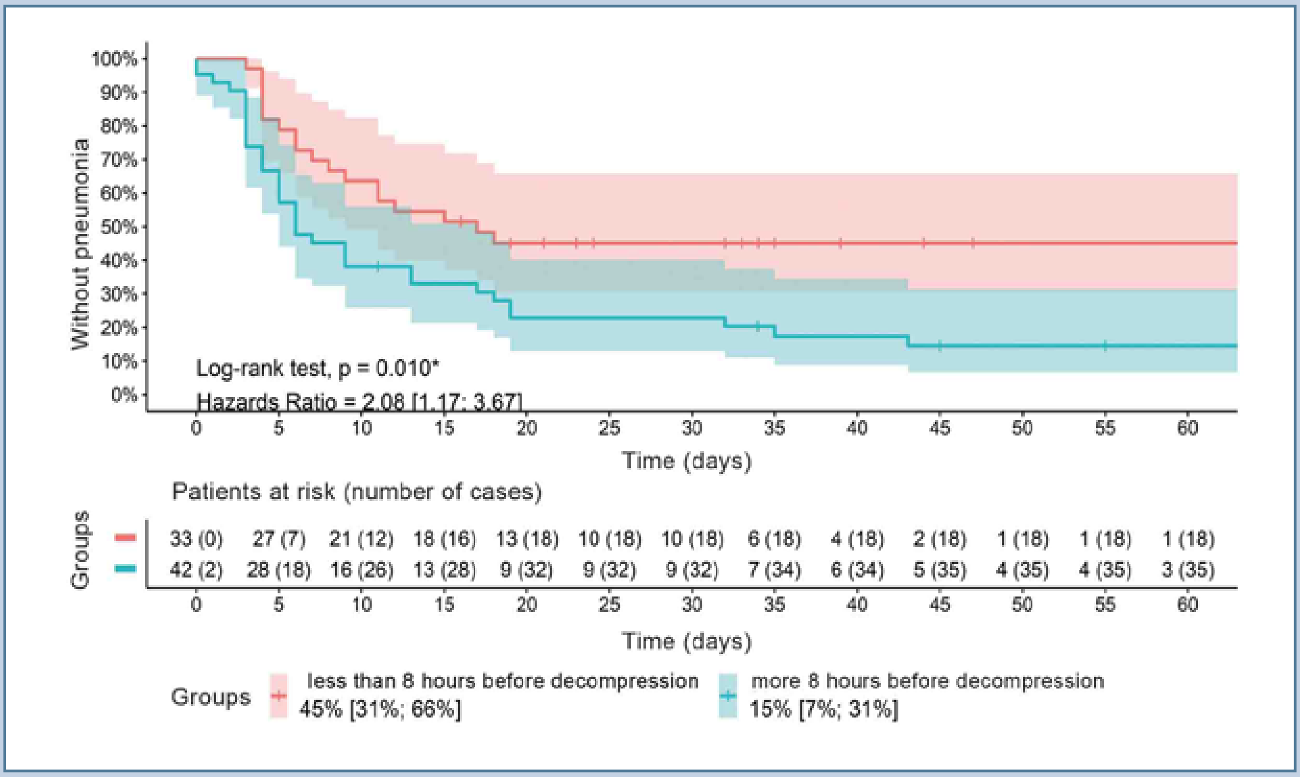

Fig. 1
Timing of pneumonia development in study groups

the period from the injury to the start of intensive care (p = 0.006). It was found that ASIA B SC injury was associated with an 18.76-fold [3.59; 150.75] increase in the probability of neurological impairment regression; and the period from the injury to the start of intensive care of less than 4.65 hours was associated with a 15.18-fold [2.7; 154.33] increase in the probability of neurological impairment regression. Using ROC analysis, this multifactorial model was found to have the best sensitivity (100.0 %) and specificity (59.4 %) for a threshold value of the probability of neurological impairment regression of 9.0 %.

Fatal outcomes were registered in 4 (5.3 %) patients of Group II who had severe SC injury (ASIA A). Intergroup comparison of the mortality rate revealed no statistically significant difference (p = 0.126). In two cases, death was caused by a combination of pulmonary sepsis associated with severe hospital-acquired pneumonia and abdominal sepsis developed associated with acute non-calculous cholecystitis. In one case, death was caused by pulmonary sepsis; in another case, it was an acute hemorrhagic cerebrovascular event.

Considering the absence of statistically significant differences in the incidence of fatal outcomes in groups, a comparative analysis was carried out for two types of outcomes: favorable – 71 (94.7 %) patients, and fatal – 4 (5.3 %) patients.

It was found that patients with poor outcomes had a statistically significant difference in regard to age in comparison to patients with favorable outcomes: 53.5 [48.0; 56.0] years and 33.0 [26.0; 41.5] years, respectively (p = 0.01). There was also a significant difference in the time of admission to the emergency room: 30.0 [11.0; 57.5] hours and 5.5 [2.4; 13.5] hours (p = 0.037), as well as in the period from the injury to SC decompression: 34.25 [13.88; 68] hours and 9.20 [6.5; 19.75] hours (p = 0.41).

Logistic regression was used to determine predictors of fatal outcomes.

Univariate logistic regression models helped to identify individual significant predictors of poor outcomes: duration of mechanical ventilation (p = 0.002); duration of ICU stay (p = 0.003); duration of hemodynamic support (p = 0.037); patient's age (p = 0.002); coronary heart disease (p = 0.003); chronic heart failure (p = 0.012); and SC injury at C3–C4 level (p = 0.04). It was found that duration of mechanical ventilation longer than 52 days was associated with a 140-fold [7.97; 6,116.91] increase in probability of fatal outcome; ICU stay duration over 55.5 days was associated with a 69-fold [4.85; 1,970.09] increase in probability of fatal outcome; duration of hemodynamic support of more than 7 days was associated with a 3.19-fold [1.5; 11] increase in probability of fatal outcome; age over 51.5 years was associated with a 69-fold [4.85; 1,970.09] increase in probability of fatal outcome; coronary heart disease was associated with a 70-fold [4.92; 1,998.46] increase in probability of fatal outcome; chronic heart failure was asso-

Table 3

Assessment of intergroup comparative analysis using the APACHE II and SOFA scores

Follow-up period, days	Group I (n = 33)	Group II (n = 42)	Comparison by Mann–Whitney U test	
	MED [IQR]	MED [IQR]	MED [95% CI]	p value
APACHE II score				
1	7 [6.00; 9.00]	8 [7.00; 9.75]	1 [0.00; 2.00]	0.037*
3	7 [5.75; 7.25]	9 [7.00; 10.00]	2 [1.00; 2.00]	<0.001*
5	7 [5.00; 7.50]	9 [7.00; 10.00]	2 [1.00; 3.00]	<0.001*
7	7 [6.00; 8.75]	8 [7.00; 10.00]	2 [1.00; 2.00]	0.002*
10	7 [5.00; 7.00]	8 [7.00; 10.00]	2 [1.00; 2.00]	0.001*
15	5 [5.00; 7.00]	8 [7.00; 10.00]	2 [1.00; 3.00]	<0.001*
20	5.5 [5.00; 7.00]	8 [6.00; 9.50]	1 [1.00; 3.00]	0.002*
25	7 [5.00; 7.00]	8 [7.00; 9.00]	1 [0.00; 2.00]	0.128
30	7 [5.00; 7.00]	8 [6.75; 8.25]	1.91 [0.00; 4.00]	0.022*
SOFA score				
1	3 [3.00; 5.00]	4.0 [3.00; 5.00]	1 [0.00; 1.00]	0.124
3	3 [2.00; 4.00]	4.0 [3.00; 5.00]	1 [0.00; 1.00]	0.052
5	2 [1.00; 3.00]	4.0 [3.00; 5.00]	2 [1.00; 2.00]	<0.001*
7	2 [1.00; 3.00]	3.0 [2.00; 4.00]	1 [0.00; 1.00]	0.100
10	1 [0.00; 2.00]	2.0 [1.00; 4.00]	1 [1.00; 2.00]	<0.001*
15	1 [0.00; 1.75]	2.0 [1.00; 3.00]	1 [1.00; 2.00]	<0.001*
20	1 [0.00; 1.00]	2.0 [1.00; 3.00]	1 [0.00; 2.00]	0.005*
25	1 [1.00; 1.00]	1.5 [1.00; 2.25]	1 [0.00; 1.00]	0.132
30	1 [1.00; 1.00]	2.0 [1.00; 2.00]	–	–

MED – median; IQR – interquartile range; CI – confidence interval; * statistically significant differences.

ciated with a 20.67-fold [2.37; 444.19] increase in probability of fatal outcome; and SC injury at C3–C4 level was associated with a 23.33-fold [0.8; 704.15] increase in probability of fatal outcome.

ICU stay duration was 20 [16; 25] days in Group I and 29 [23.5; 41.75] days in Group II ($p = 0.001$), total hospital stay duration was 38 [27; 46] days in Group I and 57 [45.75; 67.5] days in Group II ($p < 0.001$).

It should be mentioned that all the results of this research were obtained in the setting of the same approach to intensive care in both groups according to the algorithms provided (Fig. 2 and 3).

Discussion

Traumatic injuries of the vertebral column are quite common; however, issues associated with these injuries are still debatable, especially those related to the management of patients with severe injuries [14]. We analyzed the course of acute and early periods of complicated lower cervical spine injury with SC compression considering the urgency of performing decompression and stabilization surgeries. Our research involved only patients with an isolated lower cervical spine injury in order to minimize the possible effect of other injuries on the course of SC traumatic injury.

It is known that acute SC injury is characterized by early respiratory dysfunction that affects all levels of the respiratory system [15]. Results of this research demonstrated that even during admission to the hospital, there were signs indicating the presence of acute lung injury, ARDS, which is manifested by impaired gas exchange and typical MSCT findings in the lungs. The corresponding signs were registered in 3.0% of the main group, and in 14.3 % of the comparison group. We assessed the severity of acute lung injury by the OI values that corresponded to mild and moderate ARDS.

The data obtained are fully consistent with the results of recent experimental studies that revealed congestion in the pulmonary capillaries 6 hours after injury; pulmonary alveoli filled with erythrocytes and serous extravasate 12 hours after injury; hemorrhages and edema in pulmonary interstitium and alveoli 24 hours after injury [16–18]. Since the most common cause of injury in the overall sample of patients was diving into shallow water (49.3 %), it would be reasonable to assume that probable aspiration could be a primary damaging factor in the pathogenesis of ARDS, as well as the cause of pneumonia development; according to the research literature [19–21], pneumonia associated with this mechanism of injury is registered in 42.5 % of cases.

Even more convincing evidence indicating the presence of diffuse lung injury in the analyzed category of patients was obtained during mechanical ventilation on day 1 after injury, when signs of ARDS were registered in 24.2 % of cases in the main group, and in 57.1 % in the comparison group ($p < 0.001$). The OI values indicated that all these patients had mild or moderate lung injury. Follow-up over time revealed typical radiological signs of ARDS, i.e. ground-glass opacity zones in 39.0 % of patients in Group I, and in 67.0 % of patients in Group II ($p = 0.022$). The results obtained are consistent with the conclusions of earlier clinical trials that demonstrated two common types of respiratory complications with underlying SC injury: acute lung injury and ARDS as its most severe form; these complications develop because of both the injury and pneumonia, shock, aspiration, and sepsis [22–24].

It is known that the development of respiratory complications is the most common complication after SC injury.

Table 4

Heart rate variability indicators

Indicator/norm	Follow-up period					
	Day 1	Day 3	Day 5	Day 7	Day 10	Day 15
Statistical indicators						
Heart rate/60–80 beats per minute	68.6 ± 7.8	70.0 ± 5.4	73.0 ± 9.8	71.4 ± 7.7	69.2 ±6.6	65.9 ± 9.3
RRmin, ms	755.0 ± 147.5	710.3 ± 151.8	792.8 ± 100.9	792.0 ± 92.3	645.6 ± 69.3	808.0 ± 62.8
RRmax, ms	1052.3 ± 139.6	1014.1 ± 133.6	1029.3 ± 109.8	976.8 ± 87.1	936.4 ± 154.1	1041.0 ± 100.4
SDNN / 60 ± 6 ms	55.0 ± 19.5	38.3 ± 11.8	35.0 ± 11.3	32.1 ± 12.7	38.5 ± 8.3	31.2 ± 12.6
RMSSD / 27 ± 12 ms	28.6 ± 10.0	24.3 ± 12.5	25.6 ± 10.0	23.7 ± 14.2	25.2 ± 8.2	25.6 ± 15.0
pNN50 / 29,00 ± 19,55 %	6.9 ± 5.9	5.5 ± 5.2	9.0 ± 9.6	5.3 ± 7.3	2.8 ± 2.9	6.9 ± 9.3
Spectral indicators						
TP / 3,466 ± 1,018 ms^2/Hz	2574.3 ± 1375.8	969.7 ± 492.3	1279.8 ± 813.7	666.3 ± 400.4	1231.0 ± 289.6	645.4 ± 323.8
VLF / 765 ± 410 ms^2/Hz	1716.8 ± 1068.6	589.1 ± 338.7	713.1 ± 532.7	383.2 ± 248.9	623.8 ± 240.2	332.2 ± 192.2
LF / 1,170 + 416 ms^2/Hz	536.5 ± 334.6	207.4 ± 124.9	252.8 ± 182.9	106.0 ± 36.3	330.0 ± 204.4	179.8 ± 128.2
HF / 975 ± 203 ms^2/Hz	320.8 ± 205.4	173.0 ± 126.0	326.4 ± 283.2	173.2 ± 170.3	277.2 ± 175.4	133.8 ± 76.2
LF/HF / 1.5–2.0	2.1 ± 1.1	1.5 ± 0.5	1.4 ± 0.9	1.9 ± 1.4	2.0 ± 1.4	1.6 ± 0.5
SI, 1/s^2	101.5 ± 68.9	258.9 ± 220.2	207.6 ± 131.8	322.7 ± 190.3	136.3 ± 46.2	207.9 ± 41.0

Moreover, about 30 % of all fatal outcomes in cases of SC injury are caused by respiratory complications, with pneumonia being the most common complication at all stages of SC injury course [25] that has major effect on the duration of hospital stay and neurological outcomes in such patients [26, 27]. In our research, pneumonia development was registered in 72 % of patients. However, SC decompression within 8 hours after injury statistically significantly (by 31 %) reduced both the incidence of pneumonia and the duration of the pathologic process. The analysis performed also revealed a 2.08-fold [1.17; 3.67] increase in the risk ratio for pneumonia development with delayed SC decompression ($p = 0.01$).

Associated with both the injury and infectious comorbidities, breathing mechanics disorders in the analyzed category of patients determines the need for mechanical ventilation [28]. The total duration of mechanical ventilation in the main group was significantly lower. A small number of cases of mechanical ventilation discontinuation failure were also registered: 3.0 % in the main group vs 7.1 % in the comparison group.

It is known that two mechanisms of damage to nervous tissue are involved in case of SC injury, primary and secondary. Secondary damage that can aggravate the baseline injury usually includes hypoxia and hypotension. In relation to the current understanding of the pathogenesis of SC injury, hypotension episodes in the acute phase of injury reduce SC perfusion and lead to slower neurological recovery or to its absence [29]. Therefore, the principal goal of treatment is to maintain BPm level of 85–90 mm Hg within 7 days after the SC injury. Intensive hemodynamic management is required to maintain the recommended BP values. Vasopressor agents are commonly used, and they may lead to corresponding complications [30, 31].

In regard to the overall sample of patients, we followed the available international guidelines. Moreover, expanded monitoring of hemodynamic parameters allowed identifying three types of hemodynamic disorders, as well as determining a possible personalized approach, with appropriate medications in a relevant dose in order to achieve target BP values considering the established hemodynamic profile for the patient. The results obtained are consistent with the opinion of other researchers that hypotension is a spectrum of hemodynamic profiles; it is very important to consider this factor when making treatment decisions [32, 33].

We found that hemodynamic support depended on the urgency of surgical SC decompression and was statistically significantly shorter when the surgery is performed within 8 hours after injury. This result was certainly due to not only the timely elimination of SC compression, but also the earliest possible start of treatment for hemodynamic disorders. Upon that, it was the achievement of hemodynamic stability at the hospital admission that allowed performing decompression and stabilization surgeries as early as possible.

There are reports that SC injuries result in severe systemic inflammatory response that contributes to organ dysfunction [34]. To determine the severity of patients' condition and to measure organ dysfunction, we used the SOFA and APACHE II scores; both are widely used in global ICU practice [35, 36]. An intergroup comparison revealed that the total SOFA score and the same APACHE II score were statistically significantly lower in patients of the main group at most stages of the research.

To our opinion, the results obtained for severity of condition and organ dysfunction are determined by the fact that patients in Group I had a significantly lower number of respiratory complications, both infectious and non-infectious ones. The duration of hemodynamic support was also important; it was statistically significantly shorter in Group I. It is the parameters in the scores indicating respiratory and cardiovascular dysfunction that were significant for calculating the total scores.

Patients who underwent early decompression surgery had better improvement of the baseline neurological status; in some cases, by two grades of the ASIA impairment score [37, 38]. This research demonstrated that early surgical decompression was associated with favorable neurological recovery in 30.3 % of patients vs 2.0 % of patients who received delayed SC decompression ($p < 0.001$). The results of multivariate regression analysis revealed that the early start of combined intensive treatment for organ dysfunctions, along with the early SC decompression, are significant predictors of regression of the baseline neurological deficit using the ASIA score.

Our research demonstrated that the ICU stay duration and the total duration of hospital stay have statistically significant differences between groups ($p = 0.001$) and confirm the benefits of early surgical decompression and stabilization.

It is known that patients with SC injuries are at high risk of fatal outcomes. Recent trials revealed that in-hospital mortality in the analyzed category of patients ranged from 5.0 % to 12.6 % [14, 36]. There are reports on the mortality rate in patients with tetraplegia that can reach 22.0 %. Meanwhile, respiratory complications and cardiovascular causes (OR = 39.03: 95 % CI = 8.29–183.89) were significant risk factors associated with poor outcomes [39]. The mortality rate of 5.3 % in our research is closer to the lowest values presented in research literature sources. All fatal outcomes were observed in patients with ASIA A SC injuries who underwent SC decompression surgery within the period of more than 8 hours after the injury. Severe infectious complications were the cause of fatal outcomes in 75.0 % of cases.

Conclusion

The results obtained during this research allow thinking that the earliest possible surgical decompression and stabilization in combination with the earliest possible start of combined intensive treatment have a significant positive effect on the acute and early periods of SC injury course; these measures help to reduce the number of respiratory complications and the severity of organ dysfunctions, shorten the duration of mechanical

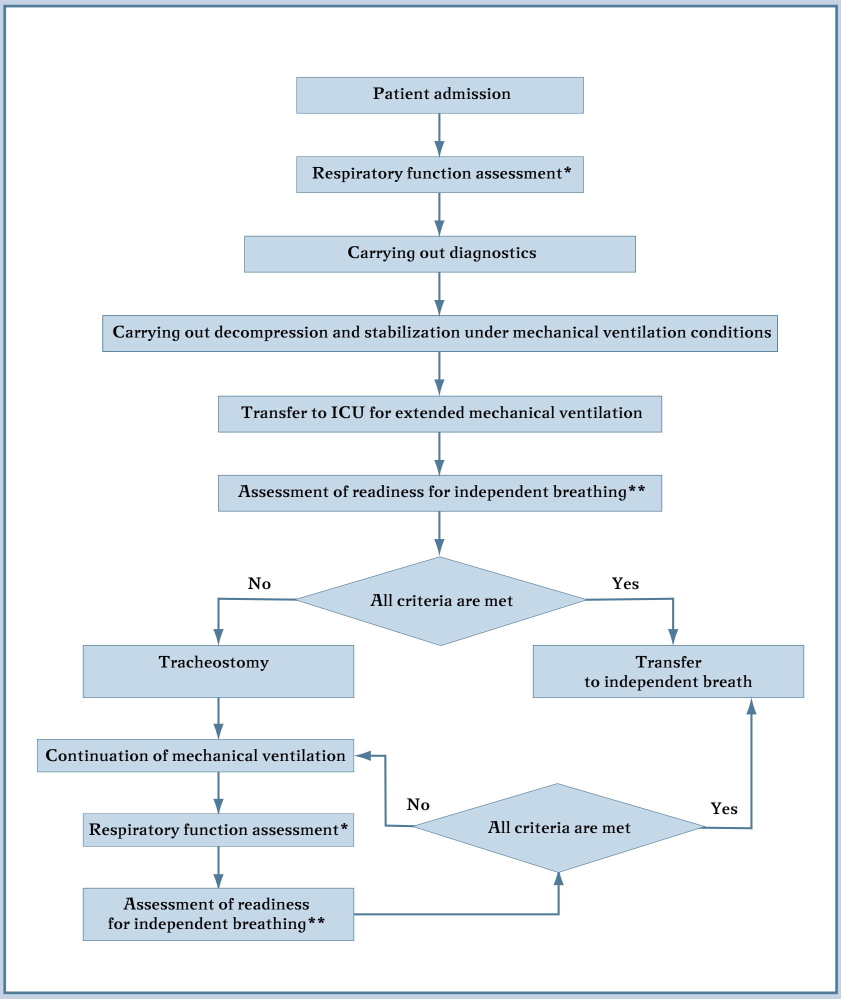

Fig. 2
Algorithm for determination whether patients are ready for independent breathing:
* assessment of the respiratory system function: respiratory rate, SpO_2, gas composition and acid-base ratio of arterial blood; functional state of the diaphragm using ultrasound (diaphragm thickness during forced breathing (DTFB), diaphragm excursion during forced breathing (DEFB), diaphragm excursion during spontaneous breathing (DESB);
** criteria for the patient's readiness for independent breathing: general criteria (absence of depression of consciousness and pathological breathing rhythms, complete cessation of the action of muscle relaxants and other medication that depress breathing, absence of signs of shock, stable hemodynamics, absence of an active infectious process); respiratory criteria (mechanical ventilation in auxiliary ventilation modes with respiratory support parameters at Pinsp 6–10 mbar and PEEP 5–8 mbar, oxygenation index > 300, SpO_2 > 95 % when using FiO_2 < 40 %); additional criteria (values of the functional state of the diaphragm DTFB, DEFB, DESB must exceed the values recorded at the time of admission)

ventilation and hemodynamic support, reduce the ICU follow-up and treatment duration, the total duration of hospital stay, and mortality rate.

The study had no sponsors. The authors declare that they have no conflict of interest.
The study was approved by the local ethics committees of the institutions. All authors contributed significantly to the research and preparation of the article, read and approved the final version before publication.

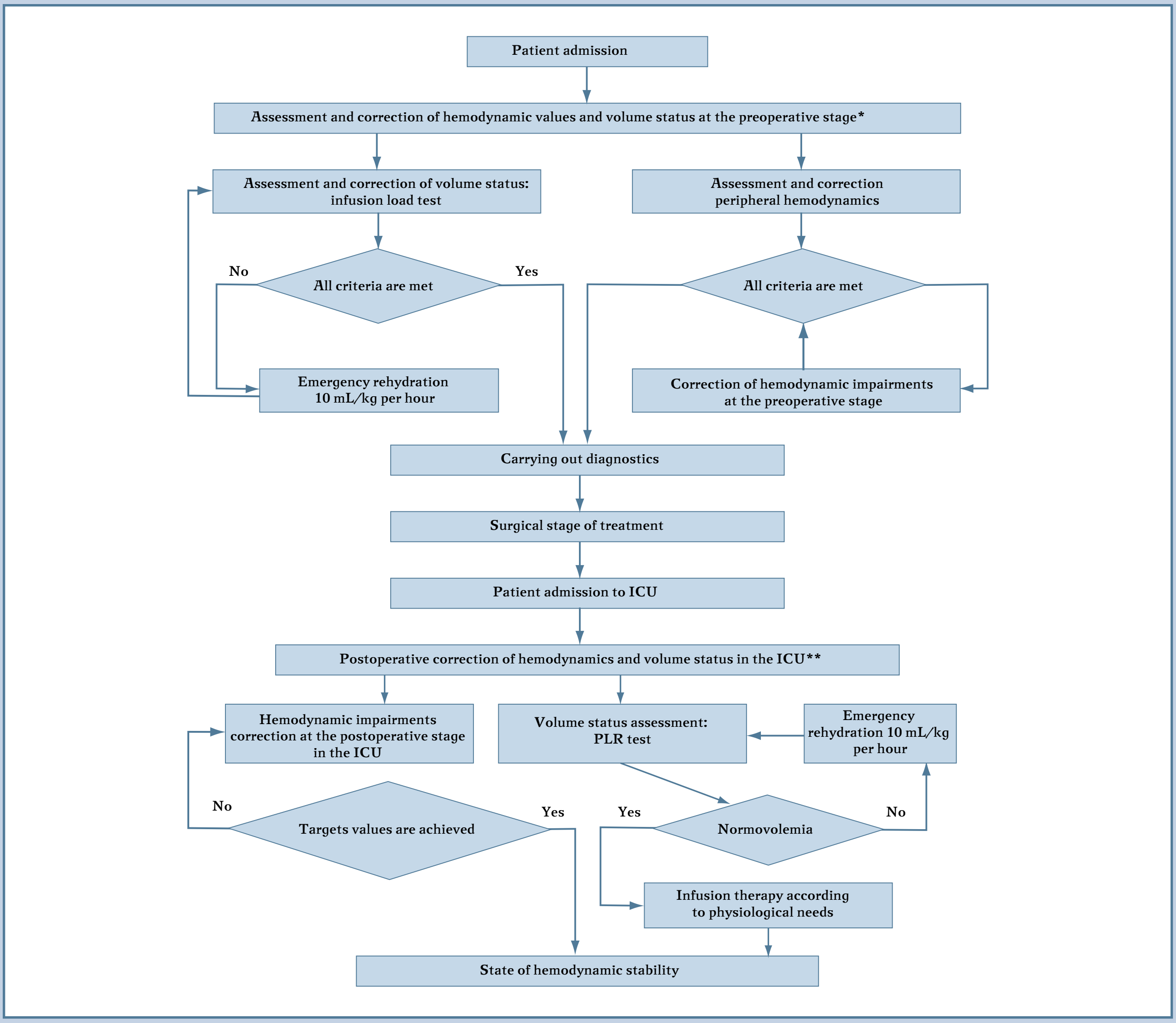

Fig. 3

Algorithm for hemodynamic stabilization: * assessment of volume status (test with infusion load – intravenous administration of a crystalloid solution at the rate of 3 mL/kg for 5–10 minutes); assessment and correction of hemodynamics at the preoperative stage (target values of mean blood pressure ⩾ 85 mm Hg and heart rate ⩾ 65 beats per minute: in registration of mean blood pressure ⩽ 85 mm Hg and heart rate ⩾ 65 beats per minute – norepinephrine is prescribed in a dosage of 0.01–0.50 µg/kg; in registration of mean blood pressure ⩾ 85 mm Hg and heart rate ⩽ 65 beats per minute – dopamine is prescribed in a dosage of 1.0–10.0 µg/kg per minute; in mean blood pressure ⩽ 85 mm Hg and heart rate ⩽ 65 beats per minute – norepinephrine 0.01–0.50 µg/kg is prescribed in combination with dopamine 1.0–10.0 µg/kg per min); ** assessment and correction of systemic hemodynamics values at the postoperative stage in the ICU (target values: mean blood pressure 85–95 mm Hg; heart rate 65–80 beats per minute; CI 2.5–4.0 L/min/m^2; TPR 800–1,200 dyn*s/cm^{-5}); the type of hemodynamic impairment and the option of drug correction are determined based on central hemodynamics indicators (type 1: CI indicators 2.5–4.0 L/min/m^2 and TPR ⩽ 800 dyn*s/cm^{-5} – dopamine is prescribed at a dosage of 1.0–10.0 µg/kg per min with heart rate values ⩽ 65 beats per minute; norepinephrine is prescribed at a dose of 0.01–0.50 µg/kg with heart rate values ⩾ 65 beats per min; type 2: CI ⩽ 2.5 L/min/m^2 and TPR 800–1,200 dyn*s/cm^{-5} – dobutamine 1.0–10.0 µg/kg per min is prescribed; type 3: CI ⩽ 2.5 L/min/m^2 and TPR ⩽ 800 dyne*s/cm^{-5} – dobutamine is prescribed 1.0–10.0 µg/kg per minute in combination with norepinephrine 0.01–0.50 µg/kg); assessment and correction of volume status: Passive leg raising (PLR test) – if SV increases by 10% or more, emergency rehydration is prescribed at rate of 10 mL/kg/h in addition to previously prescribed therapy; if the increase is less than 10%, infusion therapy is carried out in volume of physiological needs taking into account pathological losses

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Address correspondence to:
Statsenko Ivan Anatolyevich
Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan,
17 Frunze str., Novosibirsk, 630091, Russia,
Stacenco_i@mail.ru

Received 15.05.2024
Review completed 30.05.2024
Passed for printing 04.06.2024

Ivan Anatolyevich Statsenko, anesthesiologist-intensivist of the intensive care unit, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0003-2860-9566, Stacenco_i@mail.ru;
Maya Nikolayevna Lebedeva, DMSc, Head of Research Department of Anesthesiology and Reanimatology, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0002-9911-8919, MLebedeva@niito.ru;
Aleksey Viktorovich Palmash, anesthesiologist-intensivist of the intensive care unit, Novisibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0002-2454-477X, alexpslmasph@gmail.com;
Vitaliy Leonidovich Lukinov, PhD in Physics and Mathematics, leading researcher, Department of organization of scientific research, Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0002-3411-508X, vitaliy.lukinov@gmail.com;
Viktor Viktorovich Rerikh, DMSc, Prof., Head of the Research Department of Spine Pathology, Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, 17 Frunze str., Novosibirsk, 630091, Russia, ORCID: 0000-0001-8545-0024, rvv_nsk@mail.ru.