RETROSPECTIVE ANALYSIS OF RESTORATION OF THE ANATOMY OF THE DAMAGED THORACIC AND LUMBAR SPINAL MOTION SEGMENT USING TRANSPEDICULAR REPOSITIONING DEVICE

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Objective. To carry out a retrospective analysis of the restoration of the anterior and posterior vertebral body heights and the elimination of deformation of the anterior spinal canal wall caused by thoracic and lumbar spine injury, based on the data of spiral computed tomography (SCT).
Material and Methods. The study analyzed SCT data and case histories of 50 patients with thoracolumbar spinal cord injury operated on at different times after injury: up to 10 days – Group 1 and 11–30 days – Group 2. All patients underwent spinal reposition using a transpedicular device. The preoperative and postoperative SCT parameters were compared with the initial ones, which were calculated. The restoration of vertebral body heights and the elimination of deformation of the anterior spinal canal wall were compared in two groups depending on the distraction of interbody spaces and changes in the angle of segmental deformity.
Results. In Group 1, the anterior and posterior dimensions of the vertebral body were restored, on average, by 95.3 ± 1.9 and 96.9 ± 1.4 % of the initial height; in Group 2 – by 87.4 ± 4.2 and 96.6 ± 1.8 %, respectively. The maximum restoration of the anterior dimensions of the vertebral bodies was achieved with distraction of the anterior interbody spaces closer to 100 % of the original size in the first and second groups. The maximum recovery of the posterior dimensions of the vertebral bodies was obtained by distraction of the posterior interbody spaces by 97 % or more of the original dimensions. The maximum elimination of the displacement of bone fragments from the spinal canal was obtained by distraction of the interbody spaces to a distance close to 100 % of the initial one, and when the obtained angle of segmental deformity coincided with the initial one.
Conclusion. In the first 10 days after the injury, a greater percentage of the restoration of the anterior and posterior vertebral body heights and a decrease in the deformation of the anterior wall of the spinal canal were obtained. It was possible to maximally eliminate the deformation of the anterior wall of the spinal canal and restore the height of the anterior and posterior walls of the damaged vertebra by approaching the obtained dimensions of interbody spaces and the angle of segmental deformity to the initial ones.
Key Words: spinal cord injury, segmental deformity, transpedicular reposition.
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Spinal cord injury surgery should effectively correct post-traumatic spinal deformity, promote neurological recovery and reduce the risk of complications [1, 2]. An indirect decompression in spinal surgery is the decompression of the neural structures of the spinal canal by distraction and ligamentotaxis without removing the compressing tissue. For this purpose, various repositioning maneuvers are used, which help to achieve adequate recovery of the damaged spinal segment [3, 4].

A good long-term result with minimal complications can only be achieved if the biomechanical principles for restoring the spinal axis, shape and dimension of the spinal canal are followed [5, 6]. Transpedicular systems are considered the optimal means for performing indirect decompression and fixation [7, 8]. A.A. Afaunov et al. [9] point to the effectiveness of indirect decompression due to ligamentotaxis. Distraction combined with ligamentotaxis may reduce compression of the spinal canal contents by up to 50 % [10].

One of the major surgical steps in the treatment of post-traumatic deformities of the thoracic and lumbar spine is indirect decompression of the spinal canal with estimated segmental and global recovery of the spinal axis [11]. This is due to the fact that the best treatment outcomes are observed when restoring the balance of the spinal column [12], the calculation of which requires reference to X-ray pelvic parameters [13], which cannot be obtained in patients in the acute period of complicated injury. No clear instructions are given in the literature what targets it is necessary to be guided on when restoring the anatomy of a damaged spinal segment. On the one hand, the distraction of the vertebrae with transpedicular fixation device partially eliminates the spinal stenosis. On the other hand, excessive distraction can result in greater injury to the facet joints [14]. During the reposition of the damaged vertebra, the restoration of its posterior dimensions is used as a basis when maximum distraction efforts are applied to the fibrous-ligamentous elements of the middle osteoligamental column [15].

To reconstruct the angle of kyphotic deformity, segmental reference values are used, which are based on models obtained by Stagnara et al. [16]. The calculations of the angles of deformity correction suggested by the authors are approximate, if we consider the individual diversity of the anatomy of the spine depending on the posture types according to Rossoully [17]. Clinical decision-making in the case of thoracic and lumbar spine injuries is under the following parameters of radiographic measurement: the Cobb angle, the Gardner segmental deformity angle, and the percentage of compression of the anterior part of the vertebral body [18]. The range of angles offered for the evaluation of post-traumatic segmental deformity makes it difficult to estimate the treatment outcomes [19, 20].

The restoration of the original anatomy of the damaged thoracic or lumbar spine segment was carried out with closed decompression of the spinal canal using the transpedicular system, estimated using the proposed radiographic measurement and calculations, as the aim of this study.

The objective is to retrospectively analyze the restoration of the anterior and posterior vertebral body heights and the elimination of the anterior spinal canal wall deformation caused by thoracic and lumbar spine injuries, based on the data of spiral computed tomography (SCT).

Material and Methods

Patients

The material for the study was pre- and postoperative SCT scans of 50 patients (31 men, 19 women) with spinal cord injuries of the thoracic and lumbar spine (the most cranial damaged vertebra was T8, the most caudal – L3). The study consisted of patients with a fracture of only one vertebra. Any deformations or abnormalities of adjacent vertebral bodies were excluded. Control SCT scans were performed within a week after surgery.

The average age of the patients was 29.4 ± 1.5 years. According to the AO classification, four patients had injuries of type A3, 37 ones had injuries of type A4, five patients had injuries of type B2, and four patients had injuries of type C. The severity of spinal cord injury was determined using the ASIA scale, which revealed type A in one patient, type B in two patients, type C in 17 patients, type D in 14 patients, and type E in 11 patients.

Techniques

All patients underwent posterior approach surgeries. Using a repositioning device for transosseous transpedicular osteosynthesis, the restoration of the height of the damaged vertebra and closed decompression of the spinal canal were performed. In all cases, the damaged and two adjacent vertebrae were included in the repositioning device that allowed the multi-plane deformity to be eliminated in a metered manner.

Due to a number of factors, the patients were operated on at different times after the injury. Thus, due to this fact and in accordance with the purpose of the study, the patients were divided into 2 groups. In Group 1 (n = 27), surgeries were performed within the first 10 days; and in Group 2 (n = 23) from the 11th to the 30th day. The formed groups are comparable in terms of spinal injury types. A multiplanar reconstruction (DICOM format) was created of preoperative and postoperative SCT with the help of the RadiAnt software. In the mid-sagittal plane, measurements were made of the damaged vertebra, as well as of the vertebrae located cranially and caudally from it and four adjacent discs (Fig. 1). The height of the anterior (La) and posterior (Lp) bodies of damaged and adjacent vertebrae was measured on computer scans (usually these settings are referred to as AVH and PVH in the literature), as well as the anterior (Mta) and posterior (Mtp) dimensions of interbody spaces (the damaged vertebral body with adjacent discs). The extent deformation of the anterior wall of the spinal canal (X) due to dislocated bone fragments of the damaged vertebra was defined (the distance from the line along the posterior surface of the bodies of vertebrae adjacent to the damaged one to fragments displaced into the spinal canal). The dimensions of the upper cortical plate of the body of the subjacent vertebra (Y) and the angle of segmental deformity (α), which is formed by the lower cortical plate of the body of the superjacent vertebra and the upper cortical plate of the body of the subjacent vertebra, were measured. It would be optimal to study the deficiency of the lumen of the spinal canal during a closed decompression. Nevertheless, an additional laminectomy performed in some patients does not permit us to reliably assess it.

To restore the presumed original anatomy of the spine, vertical anterior (La calc.) and posterior (Lp calc.) dimensions of the damaged vertebral bodies (the half-sum of the vertical dimensions of the bodies of adjacent vertebrae) and the anterior (Mta calc.) and posterior (Mtp calc.) dimensions of interbody spaces (the average dimensions of the damaged vertebra + the sum of the disc dimensions a segment above and below the damaged vertebra) were measured; the angle of segmental deformity was also calculated according to the formula:

$$\sin - 1\times (|\text{Mta calc.}| - |\text{Mtp calc.}|)/|Y|.$$

The proposed angle of segmental deformity was chosen by us due to its usability in calculations (a trigonometric function is applied to a triangle, where the legs are the difference between the interbody spaces and Y). This angle captures the damaged vertebral body with adjacent discs, which are often damaged; the angle is similar to the Cobb. The preoperative and postoperative dimensions of the damaged vertebral bodies and the dimensions of the interbody spaces were estimated as a percentage of the calculated or initial dimensions, which were taken as 100 %. Ventral compression of the spinal canal was evaluated in millimeters, and the angle of segmental deformity was assessed in degrees.

Statistical data processing was carried out using the statistical software package SPSS Statistic ver. 23.

Results

Evaluation of the distribution of characteristics using graphical methods and statistical tests.
There was a normal distribution of characteristics (La1, Lp1, Mta1, Mtp1, X1) in both groups before surgery. This is confirmed by the graphs and the significance of Shapiro – Wilk's test (from 0.08 to 0.70). The average dimensions were assessed with a 95 % confidence interval. The estimated average dimensions of the vertebral bodies and interbody spaces before the procedure are shown in Table 1, along with the amount of displacement of bone fragments from the vertebral body towards the spinal canal. Table 2 demonstrates the same parameters evaluated after the procedure.

It can be seen from these tables that, as a result of frame reduction, the restoration of the height of the damaged vertebra and the reformation of the anterior wall of the spinal canal in both groups are observed. Furthermore, these processes are less effective in Group 2 (Table 2).

The restoration of anterior (ΔLa) and posterior (ΔLp) body dimensions of damaged vertebrae depending on time (T) after injury. To evaluate the effect of time after surgery on the restoration of the anterior dimensions of the vertebra ΔLa = La2 - La1, the Student's t-test for unpaired samples was used. The significance level of the Levene test for equality of variances is 0.16. This confirms the equality of variances. The value of the T-test is 4.6 at $p < 0.001$; the significance of the Mann – Whitney U-test is < 0.001. This indicates a more efficient restoration of the anterior wall of the damaged vertebra in patients operated on at an early date (Fig. 2). In correlation analysis, average feedback was obtained. The Pearson correlation coefficient r = -0.48 at $p < 0.001$.

While assessing the effect of time after injury on the restoration of the posterior dimensions of the vertebral body ΔLp = Lp2 - Lp1, no statistical differences were found between the two groups (Fig. 3). The significance level of the Levene test for equality of variances is 0.27. The value of the T-test is -0.17 at $p < 0.78$. The significance of the Mann – Whitney U-test is 0.4. The Pearson correlation coefficient indicates a weak relationship: r = -0.21 at $p = 0.04$.

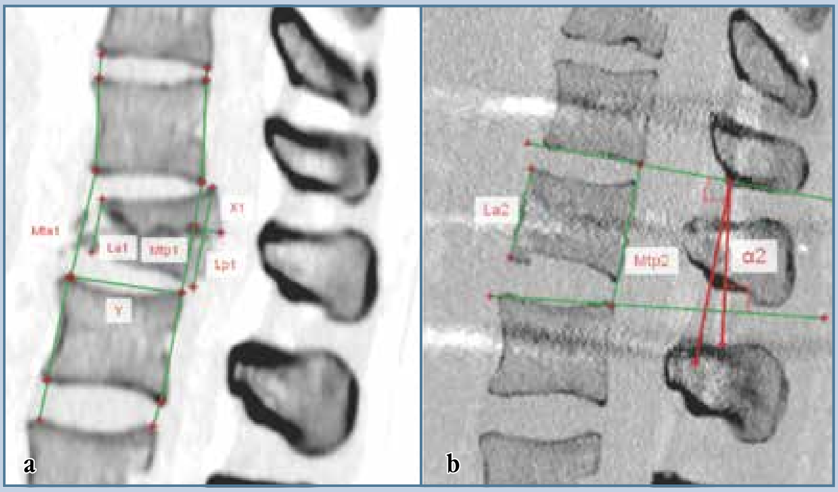

Fig 1
Measurement of the damaged segment of the spine in the midsagittal plane according to the SCT data in the DICOM format on the example of a fracture of the L1 vertebral body: **a** – before surgery; **b** – after surgery

Restoration of anterior (La2) and posterior (Lp2) vertebral body dimensions during distraction of anterior (Mta2) and posterior (Mtp2) interbody spaces. The anterior dimensions La2 of vertebral bodies had significantly greater recovery when the anterior interbody spaces Mta2 were distracted in Group 1. The value of the Student's t-test is 3.64 at $p = 0.001$. The significance of the Mann – Whitney U-test is < 0.001.

Fig. 3a indicates that the maximum recovery of the anterior dimensions of vertebral bodies is achieved by distraction of the anterior interbody spaces to a distance close to 100 % of their original dimension in groups 1 and 2. Moreover, further distraction (more than 100 %) of the anterior interbody spaces does not affect the restoration of the anterior dimensions of the vertebral body. A direct and strong correlation was achieved when restoring the dimensions of the anterior vertebral wall (La2) depending on the distraction of the anterior interbody spaces Mta2: r = 0.683 at $p < 0.01$.

The maximum recovery of the posterior dimensions of the vertebral bodies (Lp2) was achieved with distraction of the posterior interbody spaces (Mtp2) by 97% or more of the original dimensions (Fig. 3b). The changes in the two groups are statistically insignificant; the Student's t-test is 1.72 at $p = 0.091$. The significance of the Mann–Whitney U-test is 0.09. The Pearson correlation coefficient indicates an average direct correlation: r = 0.523 at $p < 0.01$.

Evaluation of the eliminated (ΔX) and remaining (X2) deformation of the anterior wall of the spinal canal depending on the distraction of the anterior (Mta2) and posterior (Mtp2) interbody spaces. In Group 1, the reformation of the anterior wall of the spinal canal was more efficient ($p < 0.03$). Meanwhile, during distraction of the anterior interbody spaces by a distance of 95 % of the initial dimension of the anterior interbody spaces, the maximum displacement of bone fragments from the spinal canal in the ventral direction was achieved. During further distraction, the remaining deformation of the spinal canal did not change substantially (Fig. 4). In Group 2, the displacement of bone fragments from the spinal canal in the ventral direction was raised appreciably with an increase in distraction up to 93 % of the initial dimension of the anterior interbody space. Further distraction of the anterior interbody spaces did not essentially affect the reformation of the anterior wall of the spinal canal.

The residual deformation of the anterior wall of the spinal canal after distraction of the anterior interbody spaces is shown in Fig. 4b. In the case of distraction of the anterior interbody spaces up to 95 % of the initial value, the residual deformity of the anterior wall of the spinal canal is reduced. If there is further distraction, it does not change significantly in both groups. A weak inverse correlation was identified between the residual deformation of the anterior wall of the spinal canal (X2) and distraction of the anterior interbody spaces (Mta2): the Pearson correlation coefficient (r) = -0.295 at $p = 0.03$.

During distraction of the posterior interbody spaces, it was revealed that in Group 1, the reformation of the anterior wall of the spinal canal was more efficient ($p < 0.01$). Meanwhile, it was possible to resolve the deformation of the spinal canal as much as possible with distraction of the posterior interbody spaces by 102–105 % of the initial dimension of the posterior interbody spaces (Fig. 5). A weak correlation was found for a decrease in ventral compression depending on the increase in the dimensions of the posterior interbody spaces: $r = 0.355$ at $p = 0.01$.

The remaining ventral compression is considerably reduced in Group 2 with distraction of the posterior interbody spaces of more than 94 % of the original length. Further distraction of the posterior interbody spaces does not significantly impact the remaining ventral compression (Fig. 5b). In Group 1, deformation of the anterior wall of the spinal canal is efficiently and uniformly resolved with the onset of distraction. Minimal ventral compression was achieved by distraction of the posterior interbody spaces by 102–105 % of the initial length. A weak inverse correlation with the residual deformation of the anterior wall of the spinal canal during distraction of the posterior interbody spaces was observed: $r = -0.312$ at $p = 0.03$.

The influence of the angle during the reposition of the damaged segment of the spine on the deformation of the anterior wall of the spinal canal. The angle $\Delta\alpha$ is the difference between the measured and the initial angle α, which possesses positive and negative values. If the measured angle α on the control SCT is greater than the initial one, then the difference possesses negative value. Fig. 6 represents the linear dependence of the ventral compression removal value on the angle $\Delta\alpha$. In Group 1, $\Delta\alpha$ approaches 0°. In Group 2, the achieved angle of segmental deformity α was on average 2° less than the initial one.

The linear dependences of the residual anterior deformation of the spinal canal X2 on $\Delta\alpha$ are displayed in Fig. 6b. The residual deformity of X2 grows with an increase in the difference between the initial and corrected angle α, especially in Group 2. In Group 1, when $\Delta\alpha$ is close to 0°, the residual deformation of the spinal canal is also minimal. Thus, when resolving the deformity of the damaged segment of the spine in the thoracic and lumbar spine, in addition to the amount of distraction of the interbody spaces, it is essential to consider the segmental deformity angle α. If the angle of the resolved segmental deformity approaches the initial angle α, the deformation of the anterior wall of the spinal canal becomes minimal.

Discussion

Type A3 and A4 spinal injuries are unstable according to the AO classification. They are often followed by a considerable stenosis of the spinal canal caused by dislocated fragments of the vertebral body, which can result in compression of the spinal cord, a medullary cone, cauda equina or a combination thereof [21]. A complete direct decompression of the contents of the spinal canal and anterior reconstruction may also be achieved with the help of anterior approaches. Nevertheless, this is a surgically more complex technique and it is associated with complications [22]. The corrective possibilities provided by the technologies of the anterior systems proved insufficient to correct relatively small local kyphotic and scoliotic deformities [23]. The best functional outcomes are achieved with dorsal interventions, and the best correction is obtained with combined approaches [24]. In the case of unstable injuries of the thoracic and lumbar spine, posterior deformity correction is applied for two spinal motion segments with simultaneous distraction and reposition to resolve

Table 1

Average dimensions of the anterior and posterior vertebral bodies, interbody spaces and deformations of the anterior wall of the spinal canal before surgery in two groups

Group	La1	Lp1	Mta1	Mtp1	X1
1	59.6 ± 4.0	91.7 ± 1.6	72.1 ± 4.0	84.5 ± 2.5	8.1 ± 0.9
2	59.7 ± 4.0	91.2 ± 3.2	70.4 ± 3.4	84.3 ± 2.4	7.2 ± 1.1

Table 2

Average dimensions of the anterior and posterior vertebral bodies, interbody spaces and deformations of the anterior wall of the spinal canal after surgery in two groups

Group	La2	Lp2	Mta2	Mtp2	X2
1	95.3 ± 1.9	96.9 ± 1.4	93.1 ± 7.2	98.5 ± 2.0	3.5 ± 0.8
2	87.4 ± 4.2	96.6 ± 1.8	92.1 ± 2.8	95.7 ± 2.4	4.0 ± 0.9

spinal canal stenosis and restore the height of the body of the damaged vertebra [25, 26].

To evaluate the damaged segment of the spine and decompression of the spinal canal after manual reduction and indirect decompression, various criteria are used: the anterior height of the damaged vertebra, the angle of the wedge of the body of the damaged vertebra, and the percentage of spinal canal stenosis [27]. The effect of prognostic factors associated with postural and instrumental reduction on the restoration of vertebral height and kyphosis angle in fractures of the thoracolumbar spine was considered [28]. The following factors were favorable and prognostic for better recovery of the kyphosis angle: the time before surgery up to 4 days, the types of A3 and A4 fractures and the level of fracture at the L2 level.

In our study, the transpedicular spinal system "Synthesis" was applied for the reposition of the damaged segment of the spine [29]. Intermediate screws are used in it for reposition, which, according to Tong et al. [30], improves the surgical outcomes. In the process of indirect decompression of the spinal canal due to ligamentotaxis, a partial restoration of the dimensions of the damaged vertebra occurs as well as kyphotic deformity is being resolved; and patients without neurologic or with partial neurologic impairment don't need laminectomy any more [31]. Alobaid et al. [32] believe that the restoration of the normal height of the vertebral column provides deformity correction in the sagittal and frontal planes. During spinal reduction, the height of the damaged vertebra could not be restored when the compression of the vertebra was more than 2/3 of its actual height [33]. Using distraction and ligamentotaxis after posterior spinal instrumentation, approximately 50% reduction in spinal canal stenosis can be achieved [34]. The efficiency of distraction correlated with the preoperative percentage of spinal canal compression [35]. If the correction of traumatic deformity during distraction is achieved more in the disc than in the bone, an anterior approach is additionally performed [36].

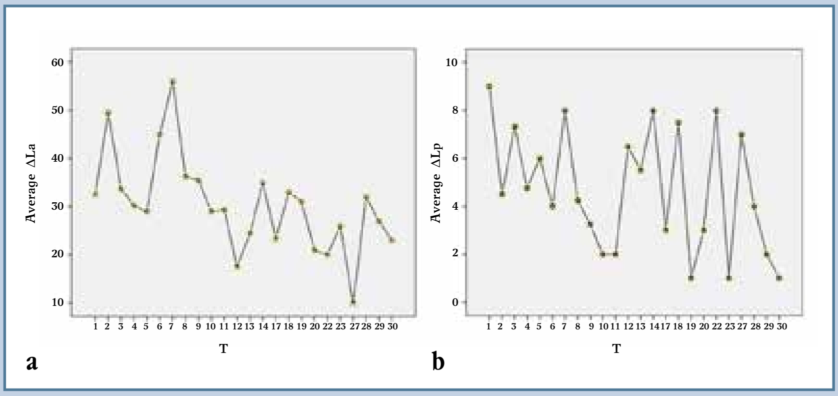

Fig 2
Restoration (in percent) of the height of the anterior ΔLa **(a)** and posterior ΔLp **(b)** walls of the damaged vertebra depending on time (T) after injury

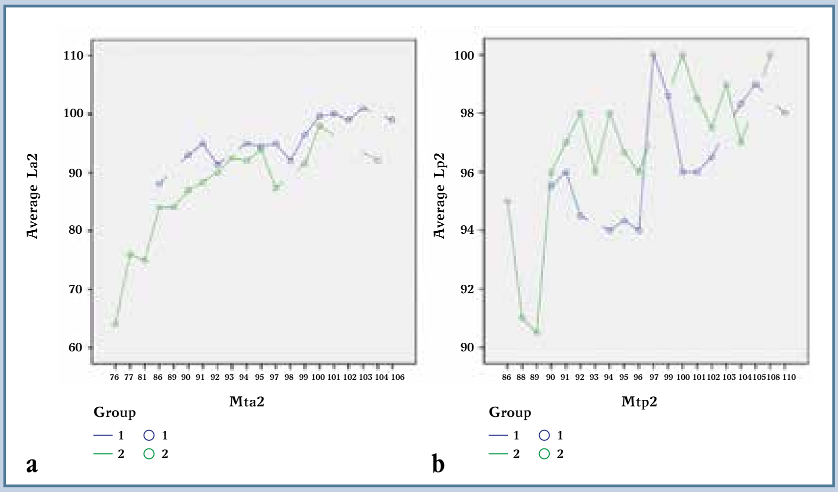

Fig 3
Restoration (in percent) of the anterior La2 **(a)** and posterior Lp2 **(b)** dimensions of the vertebral bodies with distraction of the anterior Mta2 and posterior Mtp2 interbody spaces

It is essential to perform right correction of spinal deformity to avoid excessive stretching of the spinal cord in case of long-standing deformities [37]. An excessive distraction of the spine during deformity correction is the main cause of distraction iatrogenic spinal cord injury [38]; in the case of long-standing deformity with rupture of the anterior longitudinal ligament or ankylosis, it is frequently accompanied by vascular injuries [39]. The safe limits of distraction were studied in animals: in the goat model, distraction was 11.80 ± 3.65 mm [40], in pig models, spinal cord injury developed with distraction of the thoracolumbar spine by 20.2 ± 4.7 mm [41].

Spinal distraction is a part of the surgical technique. To restore the height of the vertebral body and achieve indirect decompression of the spinal canal by ligamentotaxis, axial distraction is approximately 3–5 mm [42]. Regardless of whether it was used before or after the correction of kyphosis, distraction was an effective tool for the dislocation

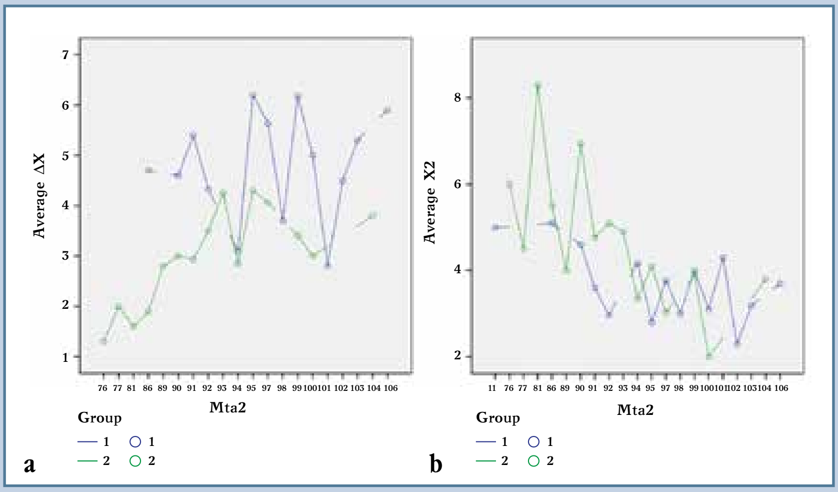

Fig 4
Influence of distraction (in percent) of the anterior interbody spaces Mta2 on the displacement of bone fragments ΔX from the spinal canal in ventral direction, in mm **(a)**, and on the remaining deformation of anterior wall of the spinal canal X2, in mm **(b)**

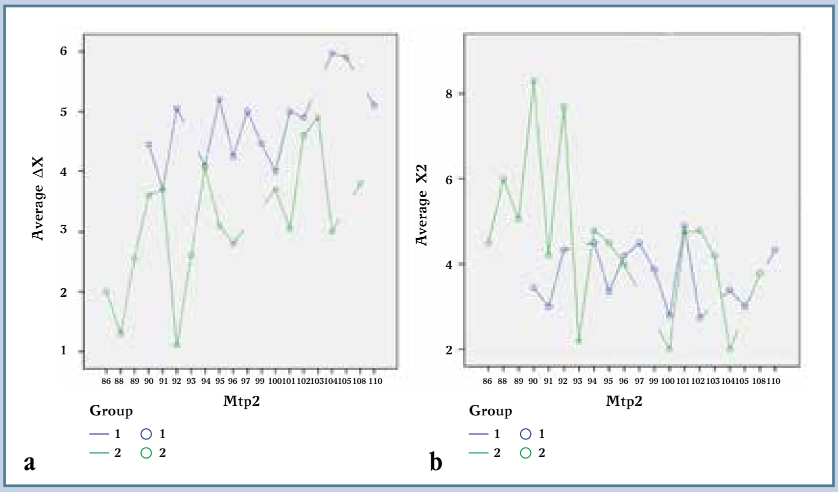

Fig 5
Influence of the distraction (in percent) of the posterior interbody spaces Mtp2 on the displacement of bone fragments ΔX from the spinal canal in ventral direction, in mm **(a)**, and on the remaining deformation of anterior spinal canal wall X2, in mm **(b)**

of bone fragments from the spinal canal [43]. Nevertheless, excessive extension of the damaged motion segment without distraction may cause the displacement of the intracanal fragment [44]. The dimension of the bone fragment is the main factor determining the efficiency of reduction due to the tension of the posterior longitudinal ligament [45]. If the width of the intracranial bone fragment was more than 75 % of the transverse diameter of the spinal canal and the height was more than 47 % of the height of the damaged vertebrae, the deformation of the spinal canal did not decline when ligamentotaxis was performed. An injury to the posterior longitudinal ligament interferes with the reposition of bone fragments of the body of the damaged vertebra [46].

An essential factor influencing the resolution of local post-traumatic deformity is the time elapsed since the fracture of the vertebrae [47]. If the post-traumatic deformity is not resolved within 72 hours, then the malposition is fixed and adhesions develop in the spinal canal [48]. According to A.A. Afaunov et al. [49], with spinal cord injury in the lower thoracic and lumbar spine for up to 10 days, the high efficiency of closed repositioning decompression during transpedicular fixation provides for the rejection of decompressive laminectomy.

To correct the deformity, Farcy et al. [50] used the sagittal index as an angle (between the lower endplate of the superjacent vertebral body and the lower endplate of the damaged vertebral body) adjusted for the normal sagittal contour at the level of deformity. The following initial data were used to assess the normal sagittal contour: -5° in the thoracic spine, 0° in the thoracolumbar joint, and +10° in the lumbar spine. This approach does not consider the frequently damaged lower disc, which is involved in the formation of post-traumatic kyphotic deformity. The restoration of the segmental deformity angle promotes the physiological position of the spinal cord since the anterior-posterior diameter and the spinal cord length change during flexion and extension [51]. The segmental deformity angle α, chosen by us for measurements and calculations, is close to the Cobb angle, which is recognized as the most reliable when measuring spinal deformities [52]. The proposed calculation of the dimensions of interbody spaces and the segmental deformity angle in estimating the reposition of the spine reduces the margin of error in the restoration of the local sagittal profile.

Conclusion

The analysis of SCT examinations conducted for spinal cord injury of the

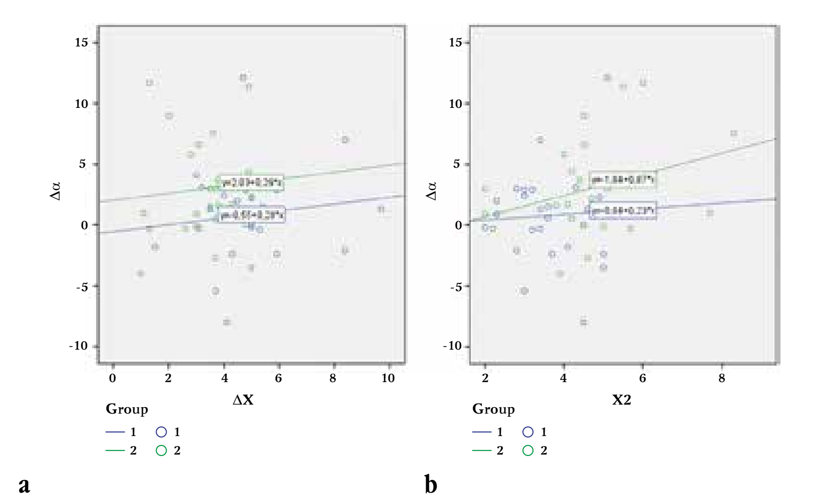

Fig 6
Difference between postoperative and calculated angles of segmental deformity (Δα), in degrees, depending on the displacement of bone fragments ΔX from the spinal canal in ventral direction, in mm **(a)**, and on the remaining deformation of anterior wall of the spinal canal X2, in mm **(b)**

thoracolumbar spine indicates a decrease in the possibility of frame reduction of damaged vertebrae with an increase in the time before surgery.

The restoration of the anterior and posterior heights of the damaged vertebral bodies depends on the distraction of the anterior and posterior interbody spaces. The maximum restoration of the anterior dimensions of the vertebral bodies is obtained by distraction of the anterior interbody spaces to a distance close to 100 % of the calculated (initial) dimension in groups 1 and 2. Additionally, further distraction of the anterior interbody spaces does not affect the restoration of the anterior dimensions of the vertebral body. The maximum recovery of the posterior dimensions of the vertebral bodies is reached by distraction of the posterior interbody spaces by 97% or more from the initial calculated dimensions of the posterior interbody spaces.

During distraction of the anterior interbody spaces at a distance of 95 % of the initial dimension, the maximum displacement of bone fragments from the spinal canal in the ventral direction was achieved. The extension of distraction did not significantly change the residual deformation of the spinal canal. It was feasible to maximally resolve the deformation of the anterior wall of the spinal canal by distraction of the posterior interbody spaces up to 102–105 % of the initial estimated dimension.

The minimal deformation of the anterior wall of the spinal canal during the reposition of the spine was gained when the achieved angle of segmental deformity corresponded with the initial angle.

The study had no sponsors. The authors declare that they have no conflict of interest.

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