SURGICAL TREATMENT OF POSTTRAUMATIC KYPHOSIS OF THE LUMBAR SPINE: COMPENSATORY CHANGES AND DYNAMICS OF SAGITTAL BALANCE

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Objective. To analyze clinical and radiological results of staged surgical interventions in the treatment of patients with posttraumatic kyphosis of the lumbar spine and to identify a mechanism of deformity compensation.

Material and Methods. The data obtained from the case histories of 42 patients operated on for clinically significant posttraumatic kyphosis at the L3 and L4 vertebral levels were studied. Patients underwent staged surgical interventions in one surgical session. Demographic data and radiological results of surgical treatment were evaluated.

Results. As a result of surgical interventions, local kyphosis was corrected on average by 29.66° ± 13.83° from 15.48° ± 13.04° to -14.19° ± 8.85°. After correction of posttraumatic kyphosis, statistically significant changes in the parameters of sagittal curvatures of the spine were revealed: an increase in thoracic kyphosis (TK) and lumbar lordosis (LL), changes in the parameters of the spinopelvic balance PT and SS with a p-level < 0.05, as well as in the global angle ($p < 0.001$) were noted. According to the GAP scale, 26 (61.9 %) patients moved to a more balanced category. A correlation ($r = 0.45$; $p < 0.05$) was found between the indices of local kyphosis and the GAP scores before surgery. The total duration of all surgical stages was 318 [150; 600] minutes, and blood loss was 677 [150; 1800] ml. In 9 (21.4 %) patients, 12 intra- and postoperative complications were noted.

Conclusion. The main compensatory mechanisms of posttraumatic deformities with the apex at L3 and L4 vertebrae are a decrease in thoracic kyphosis, the thoracolumbar lordosis and pelvic retroversion. Staged surgical treatment for posttraumatic spinal deformities significantly improves the parameters of the spinopelvic and global sagittal balance. It ameliorated the sagittal profile of patients in 61.9 % of cases and was accompanied by moderate duration of surgery and intraoperative blood loss and an acceptable number of complications.

Key Words: posttraumatic kyphosis; sagittal balance; staged operations.

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According to the expert consensus [1], posttraumatic deformities are “a condition where the spine injury induces deformity in any plane and results in pain and impaired function with or without neurological deficits”.

Posttraumatic lumbar deformities are represented with kyphosis associated with post-traumatic changes in the L3 and L4 vertebrae, since out of all five lumbar vertebrae L1 and L2 functionally belong to the thoracolumbar junction, and L5 fractures and their consequences are rare and not discussed in this study. Injuries to the lower lumbar vertebrae are much less common than injuries to the thoracolumbar junction and thoracic spine. Thus, according to Magerl et al. [2], L3 and L4 vertebral fractures account for 7.8 % and 4.0 % of thoracic and lumbar vertebral injuries, respectively. Nonetheless, clinically significant posttraumatic lumbar deformities are more common: according to our data, lumbar kyphosis accounts for 22.0 % of posttraumatic deformities of the thoracic and lumbar vertebrae.

Lumbar lordosis is the base parameter forming the sagittal balance of the trunk. Rigid local post-traumatic kyphotic deformities change the magnitude of lumbar lordosis, which is followed by compensatory changes of the spine in the adjacent segments and is reflected in the spinopelvic balance of the trunk. Therefore, changes in the main parameters of posture are manifested by global balance disorders – adverse and energetically unfavorable, transcending the cone of economy [3, 4].

The indicators of compensatory changes typical for lumbar deformities associated with degenerative disc diseases are well studied and are considered to be criteria for evaluating the severity of these deformities. For example, the SRS Schwab balance modifiers (PT, SVA, PI-LL) are a reflection of compensatory changes and are associated with patient quality of life indicators, but these are mean absolute parameters [5]. In the literature there are known scales for evaluating multifactorial relative indicators of the balanced distribution of lumbar

lordosis, pelvic anteversion, and global balance, individualized according to the corresponding indicators of the "ideal" spine, for example, GAP – Global Alignment and Proportion [6] (appendix). We believe that such scales and their individual components can be used in the evaluation of acquired non-degenerative deformities, including post-traumatic ones, both to form indications for surgical reconstruction and to evaluate the achieved correction as well as to predict the risk of mechanical complications [7].

The majority of posttraumatic kyphotic deformities of the lumbar spine are consequences of type A3 and A4 injuries (according to AO Spine) and are manifested by a deficit in the anterior height of the vertebral segment and sometimes clinically significant narrowing of the spinal canal caused by displaced craniodorsal body fragments, which is the substrate of neurological disorders. Errors and complications during surgical treatment of severe lumbar vertebral injuries in the acute period are also reasons for posttraumatic kyphosis. Recurrences of posttraumatic kyphosis associated with failure of posterior transpedicular fixation are most common, and pseudarthrosis associated with failure of anterior fixation is considerably rarer. The main reasons for such complications are the overestimation of the possibilities of posterior short-segment transpedicular fixation in cases of severe traumatic events of the lumbar vertebral bodies and adjacent discs, especially in young patients, as well as unreasonable laminectomy in uncomplicated injury, which critically destabilizes the affected spinal segment.

Reconstructive surgery for lumbar posttraumatic kyphosis involves restoration of anatomical parameters of the anterior column (enhancing anterior segment height) and stable circular fixation, sequentially performed in one surgical session of anterior corrective fusion (anterior decompression when indicated) and transpedicular fixation. Due to the anatomical features at the apex of the lumbar lordosis, this treatment pattern has no alternative.

We believe that after corrective surgery for post-traumatic deformity, if the local kyphosis factor is excluded, it is possible to record changes in the parameters of sagittal curvatures of the spine, spinopelvic and global balance that define compensatory changes in the posttraumatic spine.

The objective is to analyze clinical and radiological results of staged surgical interventions in the treatment of patients with posttraumatic kyphosis of the lumbar spine and to identify a mechanism of deformity compensation.

Study design: a monocenter retrospective study.

Material and Methods

The data of case histories of 42 patients (22 women, 20 men) with clinically significant posttraumatic deformities who underwent surgery from 2017 to December 2022 were used as the material of the study.

Patients with posttraumatic kyphosis at the level of the L3 and L4 vertebrae were included in the study. Exclusion criterion: inability to independently hold a standing posture.

All patients underwent one-stage (in one surgical session) or staged (2- and 3-stage) procedures. The correction of kyphosis at the L3 and L4 levels was performed by anterior corrective fusion through the left retroperitoneal approach. The peculiarity of anterior surgery is the position of the patient on the back on the operating table. After resection of the lumbar vertebral body with adjacent discs, the correction of kyphosis and reconstruction of lumbar lordosis are performed by gradual deformation (extension) of the surgical table with the top at the level of kyphosis under radiological control to the proper values. The resulting defect is replaced with an implant combined with bone autograft in the position of deformity correction; if indicated, anterior decompression of the nerve roots of the cauda equina is performed by resection of the craniodorsal part of the vertebral body. Transpedicular fixation of the appropriate level is performed as a second stage in the same surgical session, and if necessary, additional correction of residual deformity is performed (Fig. 1).

In the case of posterior bone and bone-metal blocks as barriers to the deformity correction, mobilization in the form of facetectomy or removal of instrumentation was performed as an additional stage (Fig. 2).

The follow-up period was the entire duration of the patients' admission to the hospital. Pre- and postoperative radiological and clinical parameters (age, gender, number of surgical stages, total time of surgery stages, and blood loss volume) were evaluated. The Clavien – Dindo scale [8] was also used to evaluate complications (any variation from the normal course of the postoperative period was included).

Profile radiography of the spine from the skull to the middle third of the thighs was performed in normal posture standing in two planes. The analysis of obtained radiological data included the study of the parameters of sagittal curvatures of the spine, spinopelvic balance, and global sagittal balance.

The sagittal contour of the spine was assessed according to the following parameters: local kyphosis (LK) at the level of post-traumatic deformity according to Cobb; thoracic kyphosis (TK) T4–T12; thoracolumbar angle (TL) T1–L2; and lumbar lordosis (LL) L1–S1. Lower lumbar lordosis (Low LL) was measured as follows: from the L4 superior endplate to S1 in the case of posttraumatic kyphosis at the level of L2–L3 vertebrae; from the L3 superior endplate to S1 in the case of kyphosis at L3–L4. Spinopelvic balance was evaluated by standard PI, PT, SS, and PI-LL, and global balance was assessed by measuring SVA, global tilt (GT), and C7 vertical tilt (C7VT); GT = PT + C7VT [9].

We analyzed the sagittal profile status and proportionality in all patients according to the GAP scale [6] by the sum of the scores of its four components (RPV – relative pelvic version, RLL – relative lumbar lordosis, LDI – lordosis distribution index, RSA – relative spinopelvic alignment) and age correction factor: 0–2 – proportional; 3–6 – moderately

disproportional; greater than 7 – grossly disproportional.

The correlation between the magnitude of local kyphosis and GAP values before and after surgery was analyzed.

Statistical techniques

Indicator descriptions are expressed as median [first quartile; third quartile] (MED [Q1; Q3]) for continuous data, and the number of events and frequency for binary and categorical data. Most of the continuous indicators (82 %) were distributed abnormally according to the Shapiro – Wilk test and in a heteroscedastic manner according to Fisher's F-test. As a result, the Mann – Whitney U-test (a non-parametric statistical test) was used to verify the hypothesis of equality of numerical characteristics of sampling distributions of continuous indicators in the compared groups. Comparisons of continuous indicators before and after surgery were performed by the Wilcoxon signed-rank test. The Spearman's rank correlation coefficient was calculated and scatter plots were constructed to study pairwise connections. Binary and categorical indicators were compared between groups using Fisher's exact test, and using the McNemar's test before and after surgery. Only two-tailed tests were used. Multiple comparisons were corrected using the Benjamini – Hochberg method. Verification of statistical hypothesis was performed at the critical significance value of $p = 0.05$, i.e., the difference was considered statistically significant if $p < 0.05$. Statistical estimations were performed in IDE RStudio (version 2023.09.1 Build 494, USA) in R (version 4.1.3, Austria).

Results

The studied group of patients consisted of 20 women and 22 men, mean age 45.2 ± 14.6 (23 to 78 years). The duration of injury ranged from 6 to 38 months; seven patients had recurrence of posttraumatic deformity after unsuccessful previous surgery in the acute period of injury. Neurological signs were found in 12 (28 %) patients and presented with radiculopathy (n = 6; 14 %) and polyradicular compression syndrome (n = 6; 14 %).

Fig. 1
Radiographs and MSCT of patient R., male, 45 years old: **a** – posttraumatic kyphosis of L3–L4 (3°) associated with a previous burst fracture (A4 according to AOSpine) of the L4 vertebral body, posttraumatic stenosis of the spinal canal, radiculopathy of the L4 on both sides; **b** – the result of a 2-stage surgery in one surgical session (anterior decompression, anterior corrective fusion of the L3–L5 and transpedicular fixation of the L3–L5), correction of kyphosis, restoration of lumbar lordosis and clearance of the spinal canal were achieved; regression of neurological symptoms

Surgeries. All 42 patients underwent procedures through combined approaches in one surgical session: 29 patients underwent two-stage surgery (anteroposterior) and 13 patients underwent three-stage surgery (posteroanteroposterior), including a total of 97 stages. Six patients with polyradicular compression syndromes underwent anterior decompression during the anterior stage. The mean total time of all stages in the study group was 318 min [150; 600]. The mean total blood loss volume of all stages was 677 ml [150; 1,800]. Blood loss of more than 30% of total blood volume was noted in 7 (16 %) patients and was associated with anterior decompression.

Radiological findings before and after surgery. The correction of kyphotic posttraumatic deformity at the level of the L3 and L4 vertebrae was 29.66° ± 13.83°, and kyphosis was corrected from a mean of 15.48° ± 13.04° to -14.19° ± 8.85°. There was a statistically significant increase in LL and TK after deformity correction, while there was no change in Low LL. Postoperative changes in spinopelvic balance were observed as a change ($p < 0.05$) in PT and SS scores. Statistically significant changes in global balance after surgery were identified: GT and C7VT; there were no significant changes in SVA (Table 1).

Correlation of the degree of local kyphosis correction was obtained with the indices of changes in thoracic kyphosis (ΔTK), lumbar lordosis (ΔLL), thoracolumbar angle (ΔTL), and global tilt (ΔGT), as well as with the indices of spinopelvic balance (ΔPT, ΔSS, and ΔPI-LL) ($p < 0.001$; Table 2).

GAP indicators. Mean GAP scores before and after correction of thoracolumbar kyphosis statistically significantly decreased from 5 [3.00; 7.75] to 1 [0.00; 3.00] points, respectively ($p < 0.001$). Moreover, statistically significant changes were observed in the indicators associ-

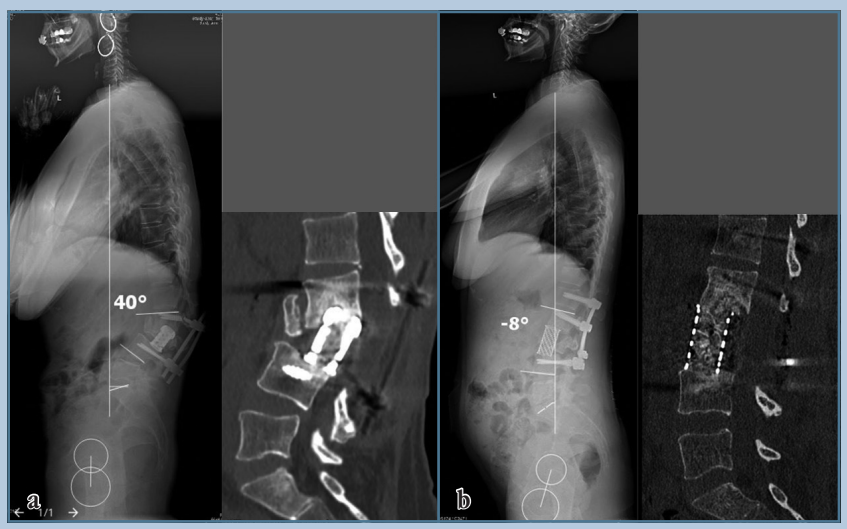

Fig. 2
Radiographs and MSCT of patient M., female, 40 years old: **a** – posttraumatic kyphosis of the L2–L4 (40°) after a previous VCR-type surgery, pseudoarthrosis, failure of the transpedicular instrumentation; **b** – the result of a 3-stage surgery in one surgical session (removal of the transpedicular instrumentation, installation of screws in the L1–L2–L4 vertebrae; removal of the telescopic implant, correction of kyphosis and anterior fusion with a mesh implant and bone autografts; installation of the transpedicular instrumentation, additional correction of kyphosis and posterior fusion of the L2–L4); correction of kyphosis is achieved, lumbar lordosis is restored; circular fixation of L1–L2–L4

ated with optimization of lumbar lordosis RLL and LDI and global balance RSA (Table 3).

The postoperative transition between the categories "proportional," "moderately disproportionate," and "grossly disproportionate" was marked by a decrease in the degree of disproportionality: there were 8 (19.0 %) "proportional" patients before surgery, and 28 (66.7 %) patients without signs of imbalance after surgery. Patients with moderately (n = 20; 47.6 %) and grossly (n = 14; 33.3 %) disproportionate GAP scores showed a shift of 26 (61.9 %) patients to the more balanced category in the postoperative period. The shift trends between GAP scores are reflected in the diagram of contingency (Fig. 3).

Correlations of local kyphosis and GAP scores. A significant ($p < 0.05$) positive moderate strength ($r = 0.45$) correlation was found (Fig. 4), when studying the relationship between LK indices and preoperative GAP scores before surgery

Complications. According to the Clavien – Dindo scale, 12 complications (1 intraoperative, 11 postoperative; Table 4) were reported in 9 (21.4 %) patients. Three patients suffered more than one complication.

Complication grade 3b (complication requiring surgery under general anesthesia) is represented by three cases of early deep surgical site infection. One intraoperative complication was shown by retroperitoneal extravasation of urine because of intraoperative (unwilled) injury of the left ureter. The patient underwent urgent nephrostomy and retroperitoneal drainage, followed by planned reconstructive surgical treatment in a specialized urological unit. Surgical site infections of the posterior approach wounds required staged revision surgeries using the vacuum-assisted closure of the wound technique; transpedicular grafts were preserved in all cases.

Discussion

The focus in the specialized literature on spinal cord injuries and their consequences is naturally shifted towards studies reflecting the issues of biomechanics, diagnosis, and treatment of thoracolumbar injuries due to their high incidence and practical importance for public health care. The issues of lower lumbar vertebral injuries are covered more modestly in the literature and mainly represent the treatment strategies for vertebral fractures in the acute period of injury [10, 11]. Biomechanics, surgical treatment of posttraumatic deformities of the lumbar spine, and its outcomes are provided as fragments of studies of posttraumatic deformities of the thoracic and lumbar spine in general [12–14].

Injuries to the lumbar vertebrae and their consequences as posttraumatic kyphosis grossly disrupt the anatomy of the lower lumbar spine and lumbar lordosis in general. This triggers a mechanism of compensatory responses on the part of posture, the attrition of which results in clinical manifestations of spinal deformity as pain and functional insufficiency (a clinical case is given in Fig. 5).

Literature sources dedicated to sagittal balance and compensation mechanisms of lumbar spine deformities mostly analyze degenerative changes. However, Barrey et al. [15] point out that the patterns of kyphosis compensation mechanisms are universal: reduction of thoracic kyphosis, hyperextension and retrolisthesis of adjacent segments, and pelvic retroversion in the case of lumbar localization of deformity. Lamartina and Berjano [16] consider thoracic lordosis and pelvic retroversion to be the mechanism of compensation for local lumbar deformity. A.E. Shulga et al. [17] showed that hyperextension of the thoracic spine and pelvic retroversion in the form of changes in sagittal parameters (a decrease in SS and an increase in PT) are typical for posttraumatic deformities at the L3–L5 level with a decrease in lumbar lordosis of less than -17.5°.

In our study, the technique of identifying the mechanism of compensation for posttraumatic kyphosis of the lum-

Table 1
Comparison of indicators of sagittal spinal curvatures, global and spinopelvic balance before and after surgery (n = 42)

Indicator	Before surgery M ± SD (MIN – MAX)	After surgery M ± SD (MIN – MAX)	Differences MED [95% CI] SMD [95% CI]	Wilcoxon test, p value
Indicators of sagittal spinal curvatures				
LK, degrees	10.50 [6.00; 22.00] 15.48 ± 13.04 (0–60)	-13.50 [-20.00; -10.00] -14.19 ± 8.85 (-32–9)	29.00 [28.00; 29.50] 2.66 [2.07; 3.25]	<0.001
TK, degrees	26.00 [16.25; 37.75] 27.38 ± 16.22 (-18–55)	30.00 [22.25; 40.00] 31.43 ± 13.06 (6–61)	-4.00 [-4.50; -3.50] -0.27 [-0.70; 0.15]	0.011
TL, degrees	4.00 [2.00; 13.75] 5.88 ± 11.39 (-27–28)	5.00 [1.00; 11.00] 6.21 ± 9.56 (-11–36)	-0.50 [-1.00; -0.50] -0.03 [-0.46; 0.40]	0.602
LL, degrees	-39.50 [-49.50; -28.00] -38.36 ± 17.36 (-68–16)	-47.00 [-57.75; -42.25] -49.29 ± 11.28 (-76–-30)	9.50 [9.00; 9.50] 0.75 [0.30; 1.19]	<0.001
Low LL, degrees	-44.50 [-49.5; -31.5] -40.38 ± 14.21 (-64–0)	-38.50 [-50.00; -34.25] -39.21 ± 18.73 (-67–60)	1.50 [1.00; 2.00] -0.07 [-0.50; 0.36]	0.508
Indicators of global sagittal balance				
SVA, mm	1.25 [-0.92; 3.42] 3.44 ± 9.63 (-6–50)	0.00 [-1.95; 2.48] 1.21 ± 8.23 (-6–50)	1.45 [1.25; 1.65] 0.25 [-0.18; 0.68]	0.072
GT, degrees	17.00 [11.00; 22.00] 17.88 ± 11.24 (-3–55)	14.00 [8.00; 18.00] 12.79 ± 6.81 (0–28)	4.00 [3.50; 4. 00] 0.55 [0.11; 0.98]	<0.001
C7VT, degrees	1.00 [-1.00; 4.00] 1.74 ± 5.25 (-9–19)	-1.00 [-3.00; 2.00] -0.31 ± 4.23 (-9–15)	2.00 [2.00; 2.00] 0.43 [0.00; 0.86]	0.021
Indicators of spinopelvic balance				
PT, degrees	17.00 [12.00; 20.00] 16.71 ± 7.74 (4–36)	14.50 [7.25; 17.75] 13.33 ± 7.08 (0–31)	2.00 [2.00; 2.50] 0.46 [0.02; 0.89]	0.006
SS, degrees	33.50 [27.50; 38.00] 33.31 ± 9.24 (13–56)	37.00 [31.25; 40.75] 36.79 ± 7.80 (22–55)	-2.50[-3.00; -2.00] -0.41 [-0.84; 0.03]	0.011
PI-LL, degrees	9.00 [0.25; 19.00] 11.38 ± 16.19 (-17–58)	-1.00 [-5.00; 8.00] 0.76 ± 9.47 (-23–17)	9.00 [9.00; 10.00] 0.80 [0.36; 1.25]	<0.001

bar spine is based on the registration of changes in the parameters after the sagittal profile of the spine, spinopelvic and global balance returned to parameters similar to the initial, pre-injury parameters by corrective surgery and exclusion of the local kyphosis factor. Sufficient correction of local posttraumatic kyphosis and restoration of lumbar lordosis were reached during the surgery. The study of changes in radiological parameters before and after surgery showed a statistically significant decrease in thoracic kyphosis and pelvic retroversion according to SS and PT ($p < 0.05$), as well as a significant change in the global tilt (GT; $p < 0.001$). GT is an integral indicator combining the parameters of the sagittal profile and spinopelvic balance that is not sensitive to the patient's voluntary posture. It was found that the Low LL values did not change significantly before and after surgery. It could be suggested that the segments adjacent to the kyphotic vertebrae would also undergo reversed changes after surgery. Nonetheless, changes of the thoracolumbar

Table 2
Correlations between the magnitude of local kyphosis correction (LKpreOP – LKpostOP = 29.66° ± 13.83°) and the difference in radiological parameters before and after surgery (n = 42)

Indicator	PreOP – PostOP M ± SD (MIN – MAX)	Spearman's rank correlation coefficient with LK (r) correction	Value of correlation significance (p)
TK, degrees	-4.00 [-9.75; 3.00] -4.05 ± 9.23 (-24.00–14.00)	0.79	<0.001
TL, degrees	0.00 [-5.00; 3.75] -0.33 ± 10.94 (-34.00–26.00)	0.51	<0.001
LL, degrees	9.00 [3.00; 15.00] 10.93 ± 12.03 (-10.00–46.00)	0.73	<0.001
Low LL, degrees	3.50 [-9.00; 8.75] -1.17 ± 23.45 (-122.00–36.00)	0.24	0.127
SVA, mm	1.50 [-1.82; 4.45] 2.22 ± 11.66 (-39.00–48.80)	0.31	0.047
GT, degrees	3.00 [0.00; 8.50] 5.10 ± 8.89 (-6.00–35.00)	0.69	<0.001
C7VT, degrees	1.50 [-1.00; 5.00] 2.05 ± 5.65 (-11.00–18.00)	0.39	0.010
PT, degrees	1.00 [-1.00; 5.50] 3.38 ± 6.71 (-7.00–20.00)	0.62	<0.001
SS, degrees	-1.00 [-8.00; 1.00] -3.56 ± 7.62 (-21.00–12.00)	0.55	<0.001
PI-LL, degrees	9.00 [1.00; 15.00] 10.62 ± 12.43 (-8.00–47.00)	0.65	<0.001

angle adjacent to kyphosis take occur, and changes of the lower lumbar angle do not, still the pelvic position changes. This may indicate a prolonged activation of the compensatory mechanism of hyperextension of the adjacent segment, probably associated with the anatomical loss of part of the mobile lumbar spine at the levels of L3 and L4.

The correlation between the magnitude of local kyphosis correction (ΔLK = 29.66° ± 13.83°) and perioperative statistically significant changes ($p < 0.001$) of these radiological parameters was high (according to the Chaddock scale) with the change of thoracic kyphosis ($r = 0.79$) and thoracolumbar angle ($r = 0.51$) adjacent to the kyphosis apex, and medium correlation strength with the change of pelvic parameters PT ($r = 0.62$), SS ($r = 0.55$), and PI-LL ($r = 0.65$), as well as GT ($r = 0.69$). Furthermore, there was a slight correlation with SVA score ($r = 0.31$; $p < 0.05$), but no correlation with Low LL. These data show compensatory changes in the lumbar spine, such as a pronounced change in the thoracolumbar region adjacent to the post-traumatic deformity and thoracic kyphosis, as well as less pronounced pelvic retroversion, which in the studied group resulted in only minor changes in the global balance by SVA but had a statistically significant and pronounced effect on the GT index.

The restoration of a balanced sagittal profile is one of the main goals in the surgical treatment of acquired deformities in adults. In our study, we have assessed groups of operated patients using the GAP scale, which is interesting both from the position of evaluating the proportionality of the spine on the whole and in the correlation of certain parameters with the ideal, individualized by the PI index [18]. Sun et al. [19] used statistical techniques to demonstrate the advantage of GAP in predicting the outcome of lumbar spine deformity correction over alternative techniques, such as the Roussouly classification. The analysis of the individual components of the GAP scale provides an assessment of lumbar kyphosis and hypolordosis correction (both hypocorrection and hypercorrection) using indices such as LDI and RLL. Pre- and postoperative GAP scores showed a progressive shift of 26 (61.9 %) patients to a more balanced category. One patient who shifted from the proportional to the moderately disproportionate group was an exception associated with postoperative hypercorrection of the lumbar lordosis. The use of the GAP scale and its components for preoperative planning of lumbar lordosis reconstruction can provide intraoperative guidelines for correction of local kyphosis that is most justified in patients with Roussouly posture types I and II and constitutional lumbar relative hypolordosis, since hypercorrection of lordosis is less favorable for the treatment outcome than hypocorrection [20].

We also revealed that the preoperative local kyphosis magnitude was positively correlated with the GAP value: the more pronounced the posttraumatic kyphosis, the more pronounced the sagittal imbalance is (Fig. 4).

The practical significance of the identified mechanisms of deformity compensation includes the possibility of using

Table 3
Gap indicators (n = 42)

Indicator	Before surgery	After surgery	p value
GAP, points	5 [3; 7.75] 5.52 ± 3.44 (0–13)	1 [0; 3] 1.93 ± 2.10 (0–7)	<0.001
RPV, values			
Anteversion	0 – 22(52.4 %)	0 – 29 (69.0 %)	0.245
Optimal position	1 – 4 (9.5 %)	1 – 6 (14.3 %)	
Moderate retroversion	2 – 13 (31.0 %)	2 – 7 (16.7 %)	
Severe retroversion	3 – 3 (7.1 %)	3 – 0	
RLL, values			
Hyperlordosis	–	–	0.001
Optimal lordosis	0 – 16 (38.1 %)	0 – 27 (64.2 %)	
Moderate hypokyphosis	2 – 13 (31.0 %)	2 – 13 (31.0 %)	
Severe hyperkyphosis	3 – 13 (31.0 %)	3 – 2 (4.8 %)	
LDI, values			
Hyperlordosis	0 – 11 (26.2 %)	0 – 36 (85.7 %)	<0.001
Optimal lordosis	1 – 1 (2.4 %)	1 – 0	
Moderate hypolordosis	2 – 1 (2.4 %)	2 – 1 (2.4 %)	
Severe hypolordosis	3 – 29 (69.0 %)	3 – 5 (11.9 %)	
RSA, values			
Negative	–	–	0.006
Optimal	0 – 24 (57.1 %)	0 – 38 (90.5 %)	
Moderate	1 – 12 (28.6 %)	1 – 4 (9.5 %)	
positive	3 – 6 (14.3 %)	3 – 0	
Severe positive	–	–	
Categories			
0-2, proportional	8 (19.0 %)	28 (66.7 %)	<0.001
3-7, moderately disproportional	20 (47.6 %)	12 (28.6 %)	
> 7, grossly disproportional	14 (33.3 %)	2 (4.8 %)	

RPV – relative pelvic version; RLL – relative lumbar lordosis; LDI – lordosis distribution index; RSA – relative spinopelvic alignment.

Table 4
Intraoperative and postoperative complications

Complication	Complication grade	Number, n (%)
Early deep surgical site infection	3b	3 (7.1)
Extravasation of urine	3b	1 (2.3)
Anemia requiring transfusion	2	5 (11.9)
Lower extremity venous thrombosis	2	2 (4.7)
Transient ischemic attack	2	1 (2.3)
Total		12 (28.3)

them as a criterion for making decisions on the treatment strategy.

We consider simultaneous multistage surgeries as the treatment of choice for posttraumatic lumbar kyphosis: corpectomy of the kyphotic vertebra, anterior corrective fusion, and posterior transpedicular fixation. The use of the anterior corrective fusion technique when indicated provides correction of posttraumatic kyphosis of any magnitude. Since the surgery is performed in the supine position and correction of kyphosis is performed by postural extension by changing the angle of the surgical table, the option of gradual postural correction of kyphosis and restoration of lumbar lordosis under radiological control to proper ranges is available. The deformity component in the frontal plane (lateral tilt and lateral listhesis) concomitant with severe kyphosis in some cases was resolved after correction of kyphosis and restoration of vertebral segment height, and did not require additional alteration of the surgical technique.

A lot of the writing about surgery for deformities in adults discusses on how traumatic staged surgeries can be and how they are different from “single approach” surgeries like three-column osteotomies of the spine. One might suppose that the technically more traumatic staged surgeries may be characterized by prolonged duration, blood loss volume, and complication rates. The results of our study do not support these expectations.

In our study, the total surgery duration (based on the sum of all stages) was 318 min [150; 600], and blood loss volume was 677 ml [150; 1,800]. Nevertheless, in three-column osteotomies (especially VCR [5]) that is an alternative to staged treatment, blood loss volume and surgery duration are much higher than our data. Suk et al. [21] reported 215 min of surgery and blood loss volume of 1,930 ml; Oneil et al. [22] – 521 min and 1,800 ml; Lazennec et al. [23] – 128 min and 1,280 ml of blood loss, respectively.

Complications in spinal deformity surgery continue to be a considerable problem. In the case of three-column osteotomies, they can reach 46 % according to a multicenter study by Bianco et al.

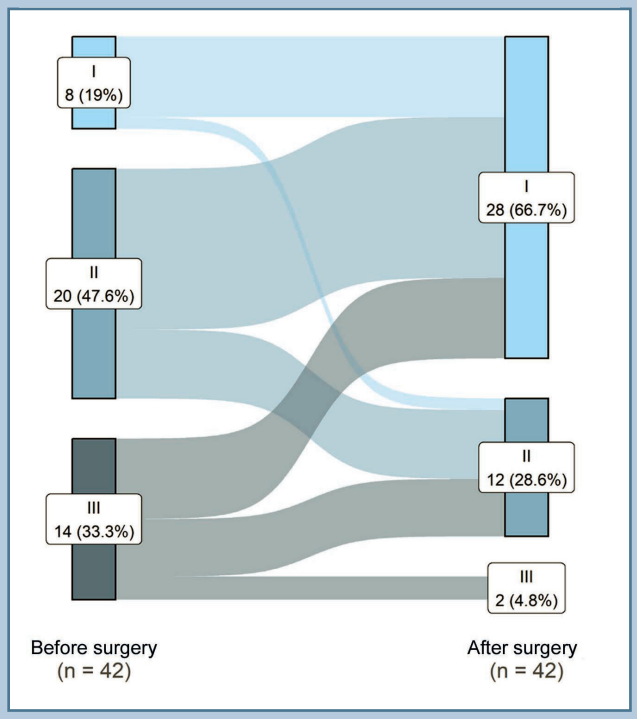

Fig. 3
The conjugation diagram reflects the trend of shift from group to group in accordance with the GAP scale: I – balanced type (0–2 points); II – moderately disproportionate type (3–6 points); III – grossly disproportionate type (<7 points)

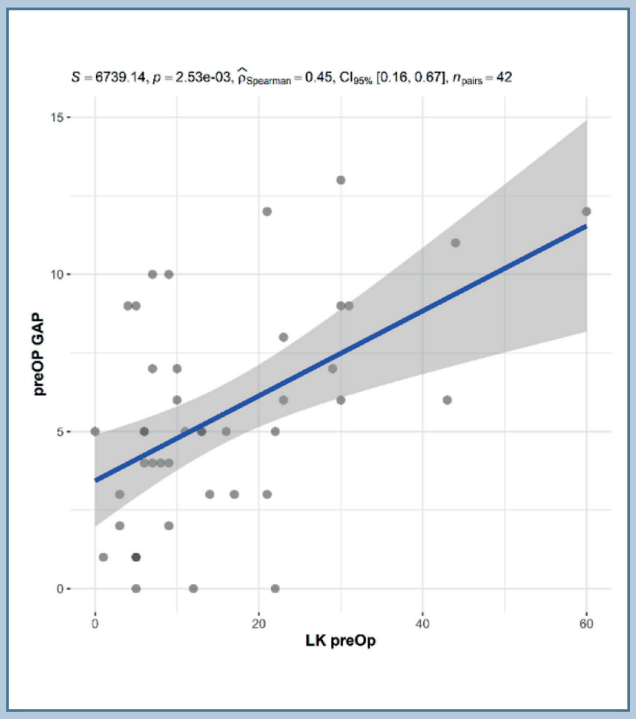

Fig. 4
Scatter plot for preOP LK and preOP GAP correlation scores

[24]. Mundis et al. [25] observed no significant difference in the occurrence of serious complications between two groups undergoing three-column osteotomies at the lumbar level and a combined anteroposterior approach (35.3 % and 41.2 %).

There were 12 complications in 9 (21.4 %) patients in our group. The Clavien – Dindo scale highlights the most prognostically significant complications (grade 3b), 4 (9.4 %) of which were identified. There were no neurological complications. There was a case of ureteral injury, a very rare intraoperative complication in spine surgery [26]. It can be retrospectively said that the complication was associated with gross retroperitoneal fibrotic changes at the apex of the kyphosis; it was not detected intraoperatively and manifested on the day 5 after surgery. We differentiated the diagnosis of retroperitoneal fluid mass detected on MRI between pseudomeningocele, lymphocele, and extravasation of urine. The complication was detected by excretory urography.

Conclusion

The main compensatory mechanisms of posttraumatic deformities with apex at L3 and L4 are a decrease in thoracic kyphosis, lordosis of the thoracolumbar spine, and pelvic retroversion.

Staged surgical treatment of posttraumatic deformities of the lumbar spine provides significant improvement in spinopelvic and global sagittal balance. The use of anterior corrective fusion at the levels of L3 and L4 vertebrae improved the sagittal profile of patients in 61.9 % of cases.

The staged surgical technique, along with moderate duration of surgery and intraoperative blood loss, results in an acceptable number of complications.

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

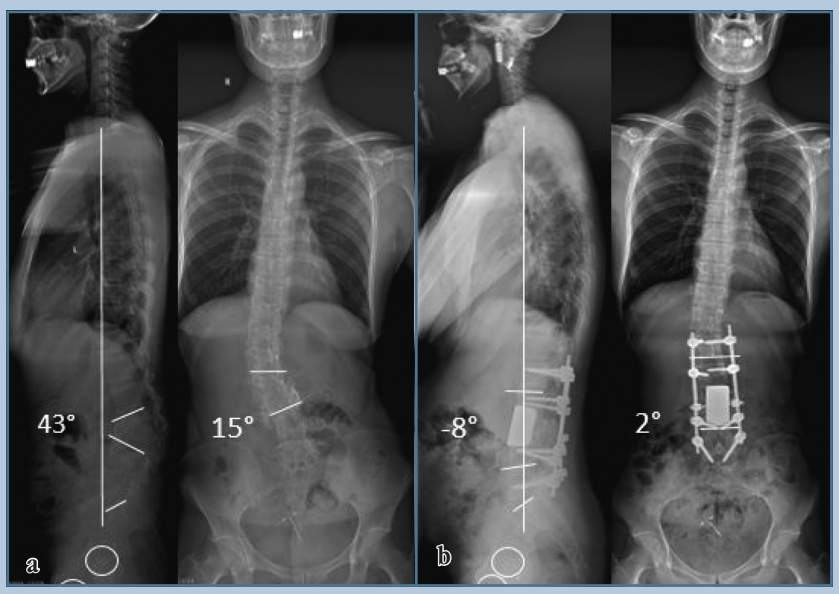

Рис. 5
Radiographs of patient I., female, 32 years old, deformity history – 12 years: **a** – posttraumatic kyphosis of the L2–L3 (43°) with left-sided tilt of the L2–L4 (15°) associated with a previous burst fracture (A4 according to AOSpine) of the L3 vertebral body; TK – 0°, LL – 18°, PI - 52°, PT – 18°, SS – 34°, SVA – 2.2 cm, GT – 19°; GAP – 7 points (grossly disproportionate); post-traumatic stenosis of the spinal canal, polyradiculopathy because of compression of the cauda equina roots; ODI – 60, VAS – 7; **b** – the result of a 3-stage surgery one year after (facetectomy of the L2–L3, anterior decompression, anterior corrective fusion L2–L4 and transpedicular fixation L1–L2–L4–L5); correction of kyphosis and lateral tilt was achieved; LK – 8°, TK – 22°, LL – 38°, PI – 52°, PT – 15°, SS – 37°, SVA – 0.7 cm, GT – 10°; GAP – 3 points (moderately disproportionate); regression of neurological symptoms; ODI – 20, VAS – 2

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Appendix

Procedure for calculating sagittal imbalance according to GAP [6]

Parameters	Categories	Points	Type of proportionality
RPV = measured SS – ideal SS; ideal SS = PI 0.59 + 9	< -15 – severe retroversion	3	0–2 – proportional; 3–6 – moderately disproportionate; more than 7 – severely disproportionate
	15–7.1 – moderate retroversion	2	
	7-5 – optimal position	0	
	> 5 – anteversion	1	
RLL = measured LL – ideal LL; ideal LL = PI 0.62 + 29	< -25 – severe hypolordosis	3	
	25–14.1 – moderate hypolordosis	2	
	14–11 – optimal lordosis	0	
	> 11 – hyperlordosis	3	
LDI = L4–S1 LL/L1–S1 LL 100	< 40% – severe hypolordosis	2	
	40–49% – moderate hypolordosis	1	
	50–80% – optimal lordosis	0	
	> 80% – hyperlordosis	3	
RSA = measured GT – ideal GT; ideal GlobalTilt = PI 0.48 – 15	> 18 – severly positive	3	
	18–10.1 – moderately positive	1	
	10–7 – optimal	0	
	< -7.1 – negative	1	
Age, years	< 60 – adults	0	
	> 60 – elderly	1	

RPV – relative pelvic version; RLL – relative lumbar lordosis; LDI – lordosis distribution index; RSA – relative spinopelvic alignment.

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