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PREDICTION OF THE RISKS OF DEVELOPING CLINICALLY SIGNIFICANT FRONTAL IMBALANCE IN SURGICAL TREATMENT OF SEVERE FORMS OF IDIOPATHIC SCOLIOSIS WITH A PRIMARY THORACIC SCOLIOTIC CURVE

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Objective. To create a multifactorial model for predicting the risks of developing clinically significant frontal imbalance in surgical treatment of severe idiopathic scoliosis based on the identification of predictors influencing the main clinical parameters of trunk asymmetry.
Material and Methods. The results of surgical treatment of 288 patients with severe forms of idiopathic scoliosis with a primary thoracic scoliotic curve of types 1, 2, 3 according to Lenke (mean 97.6° ± 15.5° according to Cobb) who underwent surgery in 1999–2019 using posterior segmental instrumentation with hook, hybrid and transpedicular fixation, were analyzed. There were 243 female (84.4 %) and 45 male patients (15.6 %). The average age of patients at the time of surgery was 15.3 [10–39] years. The average postoperative follow-up period was 3.5 [2.0–19.5] years. The analysis included clinical and radiological data obtained in the preoperative, postoperative and late postoperative periods. Predictors of the occurrence of frontal imbalance (the distance from the plumb line to the navel and intergluteal fold more than 15 mm, the tilt of the shoulder girdles more than 5° and the tilt of the scapula more than 15°) were identified by building single- and multivariate logistic regression models.
Results. In the total cohort, 41 (14.2 %) patients with clinically significant frontal imbalance were identified, including 10 (3,0 %) – with an increase in the distance from the plumb line to the umbilicus of more than 15 mm, 12 (4.2 %) – with an increase in the distance from the plumb line to the intergluteal fold of more than 15 mm, 8 (2.8 %) – with a shoulder girdle tilt of more than 5°, and 11 (3.8 %) – with a scapular tilt of more than 15°. A significant predictor of the risk of developing frontal imbalance was determined as postoperative thoracic scoliotic curve of more than 63°. Multiplicative predictors of the risk of frontal imbalance were identified: postoperative increase in the distance from the plumb line to the umbilicus by more than 15 mm and a tilt of the shoulder girdles by more than 5° with a sensitivity of 88.9 % and 100.0 %, and a specificity of 89.5 % and 100.0 %, respectively ($p < 0.001$).
Conclusion. Identification of multiplicative predictors of the risk of frontal imbalance allows predicting the risk of increasing the distance from the plumb line to the navel by more than 15 mm and the risk of shoulder girdle tilt by more than 5°. To eliminate the risk of frontal imbalance, it is necessary to strive for maximum correction of the thoracic scoliotic curve. When planning surgical treatment using transpedicular fixation for the correction of severe thoracic scoliosis, it is necessary to take into account the patient's gender and the presence of concomitant neurosurgical, cardiological and pulmonological pathology to prevent shoulder girdle imbalance.
Key Words: severe idiopathic scoliosis, frontal imbalance, predictors, logistic regression, prognosis.
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Today, clinical prediction of possible treatment outcomes is becoming increasingly important in the diagnosis and treatment of many diseases. The concept of Clinical Prediction Tools is used to make decisions based on a variety of clinical and paraclinical data in order to predict a specific clinical outcome, stratify patient risk, or suggest specific individual examination and treatment tactics. These instruments have traditionally been created using a combination of linear statistics, subjective clinical experience, and patient data. In order to reduce subjectivity in decision-making, artificial intelligence is starting to be introduced with a very large and extensive input of raw patient data [1].

It is necessary to consider consistency between the patient's expectations and possible outcomes when planning the surgical treatment [2].

The accurate prediction of the possible surgical outcome in patients with severe idiopathic scoliosis, with a primary scoliotic curve greater than 80° according to Cobb, is particularly important, as the treatment strategy in this case differs from the standard one and the risks of complications and unsatisfactory outcomes are significantly increased [3].

The achievement of optimal initial correction of the primary scoliotic curve

is not always equal to a satisfactory surgical outcome. Many additional factors should be considered, including frontal and sagittal balance, the dynamics of physiological kyphosis and lordosis, the risk of junctional kyphosis, postoperative progression (loss of the achieved correction of spinal deformity), the risk of violation of integrity of instrumentation, and changes in the shape of the back surface [4]. Chan et al. [5] reported that patients or their parents choose to aquaint with informed consent for surgical treatment more than one time together with the surgeon and even with the use of visual aids. Even though the risks of mortality and neurological complications are of greatest concern, patients lay the responsibility for other complications and unsatisfactory outcomes of surgical treatment of scoliosis on surgeons, despite informed consent for surgical treatment. Sieberg et al. [2] pointed out that the preoperative factors influencing the surgical outcomes of idiopathic scoliosis have not been adequately studied to date. The issue of the importance of the frontal balance arose together with the beginning of surgical treatment of scoliosis and resulted in the different classifications, the development of which continues to this day [6].

The clinical manifestations of frontal imbalance patients focus on are primarily the remaining trunk asymmetries after surgery. Patient's acceptance of the outcome is related to their preoperative self-esteem, age, and mental health [7].

The objective is to create a multivariate model for predicting the risks of developing clinically significant frontal imbalance in surgical treatment of severe idiopathic scoliosis based on the identification of predictors influencing the main clinical parameters of trunk asymmetry.

Material and Methods

A retrospective single-center cohort nonrandomized controlled study was conducted. It included the results of surgical treatment of 288 patients with severe forms of idiopathic scoliosis with a primary thoracic scoliotic curve of types 1, 2, and 3 according to Lenke (mean 97.6° ± 15.5° according to Cobb) who underwent surgery in 1999–2019 using posterior segmental instrumentation with hook, hybrid, and transpedicular fixation. There were 243 (84.4 %) female and 45 (15.6 %) male patients. The mean age of patients at the time of surgery was 15.3 [10–39] years. The mean postoperative follow-up period was 3.5 [2.0–19.5] years.

173 (60.3 %) patients had no comorbidities, 2 (0.7 %) patients had neurosurgical pathology (syringomyelia and Chiari malformation), 14 (4.9 %) patients had cardiovascular pathology, and 14 (4.9 %) patients had impairment of respiratory function. There were 34 (11.8%) gastrointestinal pathologies and 50 (17.4 %) other comorbidities.

We assessed the data of medical history, orthopedic examination, radiographs of the spine (C7–S1 standing in the anteroposterior and lateral views, as well as in the position of lateral flexion to the curvature side before surgery), orthopedic examination data, and radiographs of the spine in the standing position in two views after surgery and at the end of the follow-up period.

We evaluated frontal balance according to four basic clinical parameters with threshold values exceeding which indicated, from our point of view, postoperative frontal imbalance [3]:

I: distance from the plumb line (from the jugular notch of the sternum) to the navel to the right or left by more than 15 mm;

II: distance from the plumb line (from the spinous process of the C7 vertebra) to the intergluteal cleft to the right or left by more than 15 mm;

III: imbalance of the shoulder girdles more than 5°;

IV: imbalance of blades more than 15°.

We performed statistical analysis of 398 clinical and radiological signs to identify relevant factors (predictors) affecting the surgical outcomes. Predictors of the frontal imbalance risk were identified by building univariate and multivariate logistic regression models. The quality of models was evaluated by ROC-analysis.

Continuous indicators of age, weight, height, spirometry, slopes, imbalances, displacements, plumb lines, spinal stretch, primary curve, countercurvature, torsion, lordosis, blood loss, and others were tested for conformity to normal distribution by the Shapiro-Wilk test. Only 2 (5.3 %) of the 38 indicators (primary curve with slope towards deformity, $p = 0.891$; countercurvature with slope towards deformity, $p = 0.450$) met the normal-theory test. Median and interquartile range (MED [Q1; Q3]) were estimated as main descriptive statistics for continuous data, and mean ± standard deviation (M ± SD), minimum and maximum values (MIN–MAX) were estimated as additional statistics. The number and proportion in the total group were calculated to describe binary and categorical data. Primary curve values between time points preoperatively, postoperatively, and in the long-term follow-up were compared by the Wilcoxon signed-rank test.

Predictors of all four clinical threshold parameters describing non-optimal surgical outcomes were identified by logistic regression. Paired numerical associations of covariates with goals were identified by the construction of univariate models. Multivariate logistic regression models were constructed from poorly correlated covariates (Spearman's rank correlation coefficient $r < 0.3$) using the backward stepwise regression. The predictive properties of multivariate models were studied by ROC analysis.

Statistical hypothesis were tested at the critical significance value of $p = 0.05$, i.e., a difference was considered statistically significant if $p < 0.05$. Statistical calculations were performed in the IDE RStudio (version 2023.09.1 Build 494) in R (version 4.1.3 of 2022-03-10).

Results

The initial primary scoliotic curve was mean 97.6° ± 15.5° by Cobb and was reduced to 42.9° ± 18.2° after surgical treatment ($p < 0.001$). Lumbar countercurvature was observed in 156 (53 %) patients; its magnitude (36.8° ± 17.6°) decreased to 29.8° ± 13.9° ($p < 0.001$)

after surgical treatment and increased to 41.2° ± 17.6° ($p < 0.001$; Table 1) at the end of the follow-up period.

A pronounced correction of the primary scoliotic curve was achieved as a result of surgical treatment, and the loss of its correction at the end of the follow-up period was statistically insignificant. Patients with lumbar countercurvature showed an increase in lumbar countercurvature at the end of the follow-up period, attributed to the significant number of cases of using laminar screw fixation in the lumbar spine. A decreased thoracic kyphosis and lumbar lordosis were observed in the early postoperative period, with a slight recovery at the end of the follow-up period. It is necessary to point out that the mean thoracic kyphosis in these patients was higher than the physiological standard, and therefore its reduction did not result in thoracic lordosis in the majority of patients. The recovery of frontal balance according to radiographs was noted throughout the follow-up period. Nevertheless, a clinical increase in the distance of the plumb line from the intergluteal cleft was found that, apparently, can be associated with some increase in the lumbar countercurvature with preservation of the correction of the primary scoliotic curve (Table 1).

In accordance with the threshold parameters we selected, patients were identified with their exceedance at the end of the follow-up period.

The data on the course of the basic radiological parameters in patients with frontal balance values above the clinical thresholds are given in Table 2.

All clinical disorders of frontal balance (except for shoulder girdles imbalance) occur with a residual primary scoliotic curve of more than 50° at the end of the follow-up period and loss of correction of lumbar countercurvature. The preoperative distance from the centroid of the T1 vertebral body to the central sacral line was more than 9 mm in all patients with the resulting frontal imbalance. Postoperative tilt of the lower instrumented vertebra was greater than 10° in all patients (except for the group with shoulder girdles imbalance). Therefore, the clinical manifestations of frontal imbalance emerge with insufficient correction of the primary scoliotic curve, loss of countercurvature correction, and are followed by trunk displacement. Imbalance of the shoulder girdles may occurr independently from other frontal balance disorders.

By building univariate and multivariate logistic regression models, the most relevant univariate and multivariate predictors of the occurrence of clinical frontal imbalance as an increased distance from the plumb line to the navel of more than 15 mm were revealed (Table 3).

The main risk of this condition was when the residual magnitude of the primary scoliotic curve was greater than 112° during functional test. This significant univariate predictor correlates with the residual magnitude of scoliotic curve after surgery, which is more than 63°. The residual magnitude of scoliotic curve is an indirect indication of both the initial degree of the deformity and its mobility and the degree of surgical effect.

Multivariate (correlated) predictors of risk were determined to improve predictive ability. The risk of imbalance development was increased by patients' age over 18.4 years (by 33.3 times) and the initial distance from the centroid of the T1 vertebra from the central sacral line more than 9.5 mm (8.6 times).

To analyze the predictive properties of the multivariate regression model of frontal imbalance using ROC-analysis, the best sum of sensitivity (88.9 %) and specificity (89.5 %) was found for the threshold value of the probability of frontal imbalance (distance from the plumb line to the navel greater than 15 mm) – 20.6 %.

The obtained threshold value was used to predict the risk of frontal imbalance (distance from the plumb line to the navel more than 15 mm; Fig. 1) in patients with a model-calculated probability of frontal imbalance greater than 20.6 %.

Table 1

Changes of the main radiological indicators in all patients

Indicators	Before surgery in standing position, M ± SD	After surgery, M ± SD	At the end of follow-up, M ± SD
Primary curve, degrees	97.6 ± 15.5	42.9 ± 18.2*	45.4 ± 17.5
Torsion according to Sullivan, degrees	40.7 ± 11.8	17.0 ± 9.4*	18.5 ± 9.3
Countercurvature, degrees	33.6 ± 14.0	29.8 ± 13.9*	41.2 ± 17.6*
Thoracic kyphosis, degrees	49.7 ± 29.2	30.1 ± 16.1*	32.4 ± 17.5*
Lumbar lordosis, degrees	65.6 ± 15.0	51.7 ± 11.8*	54.2 ± 12.6*
Distance from the plumb line to the navel, mm	14.3 ± 11.7	11.2 ± 6.2*	1 2.3 ± 5.9
Distance from the plumb line to the intergluteal cleft, mm	15.9 ± 13.31	10.1 ± 6.7*	18.5 ± 9.3*
Shoulder girdle imbalance, degrees	4.5 ± 2.9	4.7 ± 2.0	3.8 ± 1.5
Scapular imbalance, degrees	9.6 ± 5.3	8.4 ± 3.3	7.8 ± 3.7
Distance of the centroid of the T1 vertebral body from the central sacral line, mm	11.1 ± 15.1	2.8 ± 7.7*	1.2 ± 3.9*

* Values are statistically different at $p < 0.05$.

The predictive ability of the obtained multivariate model was verified using the available raw data with a known final outcome. 47 patients had a high risk of clinical frontal imbalance as an increased distance from the plumb line to the navel greater than 15 mm (Table 4).

Therefore, by verifying the derived model on the available data (with a known prior outcome), we were able to accurately predict the risk of clinical frontal imbalance in 8 out of 12 patients, and in 34 out of 35 cases we correctly predicted zero risk.

By constructing univariate logistic regression models, we have found relevant univariate predictors of the onset of clinical frontal imbalance as an increased distance from the plumb line to the intergluteal cleft of more than 15 mm (Table 5).

The most relevant risk predictors for persistence or aggravation of clinical frontal imbalance were a pronounced initial anterior imbalance, increasing the risk of postoperative abnormalities by 32.5 times, and posterior imbalance, increasing the risk by 19.4 times. Postoperative tilt of the lower instrumented vertebra more than 19° is relevant, increasing the risk by 19.1 times.

The magnitude of the primary scoliotic curve in the lateral flexion to the curvature side of more than 79.5° increases the risk by 5.8 times.

There were no multiplicative, uncorrelated significant predictors of the onset of clinical frontal imbalance as increased distance from the plumb line to the intergluteal cleft greater than 15 mm in patients.

By building univariate and multivariate logistic regression models, the most relevant univariate and multivariate predictors of the risk of shoulder girdle imbalance greater than 5° were identified (Table 6).

A postoperative magnitude of scoliotic curve (more than 63° in this case) was a common factor influencing both shoulder girdle imbalance and other indicators of frontal imbalance, increasing the risk by 19.5 times. The other relevant factor was transpedicular fixation in the correc-

Table 2
Changes of the main radiological parameters in patients with frontal imbalance

Parameters	Primary curve before surgery in standing position, degrees (M ± SD)	Primary curve in lateral flexion to the curvature side, degrees (M ± SD)	Primary curve after surgery, degrees (M ± SD)	Primary curve at the end of follow-up, degrees (M ± SD)	Countercurvature, degrees (M ± SD)	Countercurvature after surgery, degrees (M ± SD)	Countercurvature at the end of follow-up, degrees (M ± SD)	Distance from the centroid of the T1 vertebral body to the central sacral line before surgery, mm (M ± SD)	Lower instrumented vertebra tilt after surgery (M ± SD)
The distance from the plumb line to the navel >15 mm (n = 10)	111.30 ± 23.30	97.00 ± 28.62	62.30 ± 30.00*	62.50 ± 24.40	44.80 ± 22.20	30.90 ± 14.50*	45.90 ± 22.30**	14.20 ± 11.20	14.30 ± 8.10
The distance from the plumb line to the intergluteal cleft >15 mm (n = 12)	107.00 ± 20.60	93.33 ± 22.98	56.80 ± 28.80*	59.30 ± 21.60*	46.80 ± 21.00	41.90 ± 26.10*	46.00 ± 19.50*	9.30 ± 11.90	12.90 ± 8.30
Shoulder girdle imbalance >5° (n = 8)	106.10 ± 15.80	89.50 ± 17.20	45.10 ± 23.30*	50.90 ± 19.60	40.20 ± 15.90	31.50 ± 14.00*	32.30 ± 13.10	11.60 ± 7.37	5.70 ± 4.80
Scapular imbalance >15° (n = 11)	110.60 ± 22.40	92.70 ± 28.80	66.90 ± 21.50*	66.10 ± 21.17	30.30 ± 12.70	32.40 ± 7.40*	37.40 ± 7.90	13.80 ± 18.70	10.90 ± 9.30

* Differences are significant in comparison to the value before surgery; ** differences are significant in comparison to the value after surgery, i.e. at $p < 0.05$.

tion of spinal deformity, increasing the risk by 18.7 times.

In order to improve predictive ability, multivariate (maximally independent of others) predictors of risk were determined. These included male gender (6.3-fold increase in risk) and comorbidities such as syringomyelia and Chiari malformation, cardiovascular disease, and pulmonological disorders (8.8-fold increase in risk).

To analyze the prognostic properties of the multivariate regression model for the development of shoulder girdle imbalance, the best combined sensitivity (100 %) and specificity (100 %) values for the threshold value of the probability of shoulder girdle imbalance greater than 5° – 50 % were determined using ROC-analysis.

Using the obtained threshold value, the risk of shoulder imbalance was predicted for patients with a model-calculated probability of shoulder girdle imbalance more than 50 % (Fig. 2).

The predictive ability of the multivariate model was verified using the available initial data with a known final outcome. 63 patients had a high risk of shoulder girdle imbalance greater than 5° (Table 7).

Therefore, by validating the model on the available data (with a known outcome), it was possible to correctly predict the risk of a shoulder girdle imbalance greater than 5° and its nonexistence in all patients, which can be explained by the overfitting of the model due to the small number of cases of shoulder girdle imbalance greater than 5°.

By building univariate and multivariate logistic regression models, the most significant univariate and multivariate predictors of the risk of scapular imbalance of more than 15° were revealed (Table 8).

The main significant risk factor was an initial scapular imbalance of more than 12.5°, increasing the risk 49.9-fold. A postoperative increase in the primary scoliotic curve by 10° is associated with a 1.79 [1.34; 2.37] fold increase in the odds of scapular imbalance greater than 15°, all other variables being equal in a multivariate model.

Postoperative lower instrumented vertebral tilt greater than 21.5° increased the risk by 26 times.

It is worth pointing out that the onset of scapular imbalance of more than 15° is associated with their initial severe distortion and depends on the degree of correction of the primary scoliotic curve and horizontalization of the lower instrumented vertebra as a result of surgical treatment.

There were no multiplicative significant predictors of scapular imbalance greater than 15° in all patients in the multivariate logistic regression model.

Limitations. Small number of imbalance events, limiting the possibility of constructing multivariate models and overfitting.

Clinical case study. Patient S., 16 years old, presented with idiopathic severe thoracic scoliosis, mitral valve prolapse, and decreased pulmonary capacity up to 55 %.

Using ROC-analysis, we calculated a risk value for frontal imbalance (curve value at lateral flexion less than 112°, residual curve less than 63°, age under 18 years, distance from T1 centroid less than 9.5 mm) of 15.6 % that is lower than the threshold value (20.6 %), and the risk of shoulder imbalance (concomitant cardio- and pulmonological pathology, male patients, and use of transpedicular fixation) of 74 %, exceeding the threshold value of 50 %, despite pronounced correction of the primary scoliotic curve (Fig. 3–5).

After verticalization in the postoperative period, the shoulder girdle imbalance was clinically and radiologically 35° to the right. There was no pronounced frontal imbalance (plumb line in front along the navel, 10 mm posteriorly to the right of the intergluteal cleft; Figs. 4, 5).

Discussion

The urgency to statistically reasonably predict the surgical outcomes of idiopathic scoliosis was updated in the paper by Schwab et al. [8]. A classification of adult scoliosis with the definition of significant threshold parameters for predicting treatment outcomes and prognostic models was created, permitting the detection of the risk of complications with an accuracy of up to 71 %.

The need to accurately predict the scoliosis treatment outcome during the surgical planning process, including mathematical assessment of the three-

Table 3

The main predictors of the onset of clinical frontal imbalance in the form of an increased distance from the plumb line to the navel by more than 15 mm

Covariates	Univariate models		Multivariate models	
	OR [95 % CI]	p	OR [95 % CI]	p
The magnitude of the primary scoliotic curve in the lateral flexion of more than 112°	40.0 [5.2; 856.4]	<0.001*	–	–
The magnitude of the primary scoliotic curve of more than 63° after surgery	19.5 [3.3; 165.89]	<0.001*	–	–
Age over 18.4 years	33.3 [3.6; 790.5]	<0.001*	22.1 [1.4; 1490.3]	<0.001*
The distance of the centroid of the T1 vertebra from the central sacral line of more than 9.5 mm	8.6 [2.0; 48.5]	<0.001*	7.8 [1.7; 43.5]	<0.001*

* Statistically significant predictors (statistically verified dependence of the risk of occurrence of the distance from the plumb line to the navel of more than 15 mm on the identified predictors).

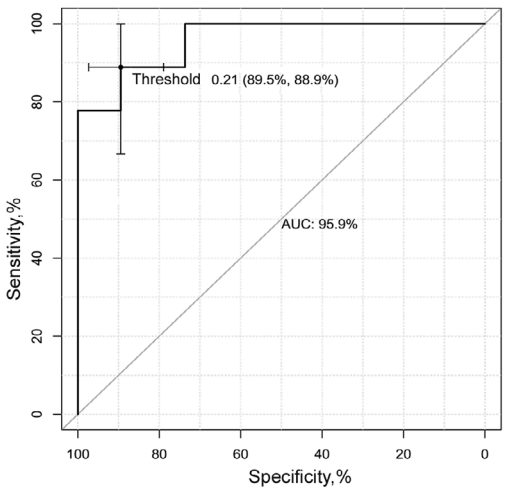

Fig.1
ROC curve of a multivariate model for the onset of clinical frontal imbalance in the form of an increase in the distance from the plumb line to the navel by more than 15 mm

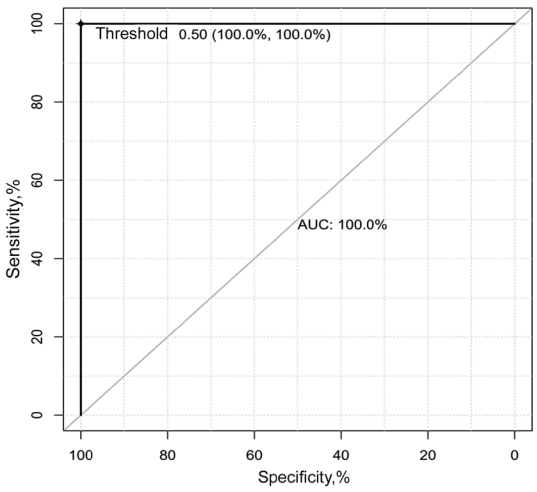

Fig. 2
ROC curve of a multivariate model for shoulder girdle imbalance of more than 5°

dimensional shape of the patient's trunk, is emphasized by Assi et al. [9].

Wondra et al. [10] have developed algorithms to predict adverse outcome parameters in adult symptomatic lumbar scoliosis, such as "major complications", repeated surgery, and readmission. The probability of complications was 38.7 %, 30.1 % and 28.5% with real data of 41.4 %, 20.77 %, and 17.2 %, respectively. The authors point out that customized prediction models contribute to optimal decision-making in surgical planning by both a surgeon and a patient.

Pasha et al. [11] have tried to predict the three-dimensional outcomes of idiopathic scoliosis correction. Given the preoperative data, the prediction accuracy was 64 %, and given the planned surgery, it was 75 %.

Sieberg et al. [2] found that the major factors that may influence patient satisfaction (based on the results of the SRS-30 questionnaire) with the surgical outcomes of idiopathic scoliosis are preoperative mental health, pain, and the expectation of certain surgical outcomes.

An essential component of the surgical outcome of severe idiopathic scoliosis is the improvement of the patient's trunk shape. Gardner et al. [12] pointed out that the surgical strategy for adolescent idiopathic scoliosis is to restore the trunk symmetry. This involves minimization of both the curve degree and the angles between the sides of the trunk, as well as restoring normal thoracic kyphosis. The ISIS2 system was used to evaluate changes in trunk shape. The ability to consider postoperative trunk shape changes with a patient provides a personalized approach to predicting the surgical outcome.

To create a multivariate model for predicting the risks of developing clinically significant frontal imbalance during surgery for severe idiopathic scoliosis, we have assessed the most prominent clinical and radiological parameters traditionally used in our hospital. The clinical examination included measurement of anthropometric data quantifying trunk asymmetry [13]. According to the Scoliosis Research Society definition,

Table 4
Contingency of a multivariate model of the onset of clinical frontal imbalance in the form of an increased distance from the plumb line to the navel by more than 15 mm

	Distance of more than 15 mm	Distance of less than 15 mm	Total
Probability of the distance of more than 15 mm	8 (true positive prediction)	4 (false positive prediction)	12
Probability of the distance of less than 15 mm	1 (false negative prediction)	34 (true negative prediction)	35
Total	9 (distance of more than 15 mm)	38 (distance of less than 15 mm)	47

Table 5
The main predictors of the onset of clinical frontal imbalance in the form of an increased distance from the plumb line to the intergluteal cleft of more than 15 mm

Covariates	Univariate models	
	OR [95 % CI]	p
The distance from the plumb line to the intergluteal cleft of more than 17.5 mm before surgery	32.5 [6.4; 212.0]	<0.001*
The distance from the plumb line to the navel of more than 17.5 mm	19.4 [3.1; 174.1]	<0.001*
The tilt of the lower instrumented vertebra of more than 19° after surgery	19.1 [3.6; 114.7]	<0.001*
The magnitude of the primary scoliotic curve in the lateral flexion of more than 79.5°	5.8 [1.6; 27.5]	<0.001*

* Statistically significant predictors (statistically verified dependence of the risk of occurrence of the distance from the plumb line to the intergluteal cleft of more than 15 mm on the identified predictors).

frontal compensation (frontal balance) is the vertical alignment of the centroid of the C7 vertebra above the central sacral line [14]. Nowadays, the frontal balance (along with sagittal balance) is considered to be a more significant factor than the magnitude of scoliosis correction. I.E. Nikityuk and S.V. Vissarionov [15] prove in their study that patients with idiopathic scoliosis have a non-optimal movement pattern, presumably because of sensory processing disorder; therefore, there is a disturbance of the postural control system in the postoperative period. In order to achieve the ultimate goal of an optimally balanced spine, many classifications have been and are being created to select levels of fixation and fusion extension [16]. We tried to quantify the clinical parameters of trunk asymmetry, indicating frontal balance after surgery for severe idiopathic scoliosis.

It has been found that the initial magnitude of the scoliotic curve, its mobility, and the magnitude of correction have a pronounced effect on the frontal balance. Thus, the maximum primary correction in severe idiopathic scoliosis is still essential, and it is impossible to achieve optimal postoperative frontal balance without reaching it. According to our data, the residual scoliotic curve after surgery should not exceed 63°, and when its magnitude in functional tests is higher (more than 80°), it is vital to plan surgery to achieve pronounced correction, despite the initial magnitude of scoliosis. The patient's age over 18 years and initial frontal subcompensation (on radiological examination) greater than 9.5 mm have a pronounced impact on the risk of frontal imbalance. We managed to create a multivariate model for predicting the risk of clinical frontal imbalance in the form of an increased distance from the plumb line to the navel of more than 15 mm with a prediction accuracy of 88.9 %, tested on the existing surgical outcomes of 47 patients.

The scapular imbalance also depended on the magnitude of the spinal deformity correction. This parameter was also influenced by the lower instrumented vertebral tilt over 21.5°. Nevertheless, it was impossible to identify multiplicative relevant predictors by which it would be feasible to predict the risk of pronounced scapular imbalance in the postoperative period during preoperative examination.

The risk factors for the onset of pronounced shoulder girdle imbalance should be considered as a separate matter. We assessed only the clinical manifestation of this condition without analyzing a variety of radiological predictors such as the clavicle angle, neck tilt, difference of the coracoid processes, costoclavicular angles, and others described in the literature on the shoulder girdle balance. However, even a clinical postoperative imbalance of the shoulder girdle may indicate decompensation and the requirement of repeated surgery [17]. Only the clinical distortion of the shoulder girdle in degrees was assessed. Since the clinical examination data from 1998 were analyzed, the anterior and posterior angles of the axilla and trapezius muscles were not considered. We attempted to determine maximally independent of

Table 6
The main predictors of the onset of a shoulder girdle imbalance of more than 5°

Covariates	Univariate models		Multivariate models	
	OR [95 % CI]	p	OR [95 % CI]	p
Application of transpedicular fixation	18.7 [2.0; 180.4]	<0.001*	–	–
The magnitude of the primary scoliotic curve of more than 63° after surgery	19.5 [3.3; 165.6]	<0.001*	–	–
Male gender	6.3 [1.2; 30.0]	<0.001*	22.1 [1.4; 1490.3]	<0.001*
The presence of comorbidity (syringomyelia and Chiari malformation, cardiovascular pathology, pulmonological pathology)	8.8 [2.0; 48.5]	<0.001*	7.6 [1.7; 43.7]	<0.001*

* Statistically significant distinct predictors (statistically verified dependence of the risk of occurrence of shoulder girdle imbalance of more than 5° on the identified predictors).

Table 7
Contingency of a multivariate model of the onset of shoulder girdle imbalance of more than 5°

	Shoulder girdle imbalance of more than 5°	Shoulder girdle imbalance of less than 5°	Total
Probability of shoulder girdle imbalance of more than 5°	3 (true positive prediction)	0 (false positive prediction)	3
Probability of shoulder girdle imbalance of less than 5°	0 (false negative prediction)	63 (true negative prediction)	63
Total	3 (Shoulder girdle imbalance of more than 5°)	63 (Shoulder girdle imbalance of less than 5°)	66

Table 8
The main predictors of the onset of shoulder girdle imbalance of more than 15°

Covariates	Univariate models	
	OR [95 % CI]	p
Scapular imbalance of more than 12.5° before surgery	49.90 [10.20; 369.60]	<0.001*
The primary scoliotic curve after surgery, with an increase by 10°	1.79 [1.34; 2.37]	<0.001*
The tilt of the lower instrumented vertebra of more than 21.5° after surgery	26.00 [4.30; 161.90]	<0.001*

* Statistically significant predictors (statistically verified dependence of the risk of onset of shoulder girdle imbalance of more than 15° on the identified predictors).

each other factors that influence the risk of shoulder girdle imbalance in the postoperative period. It emerged that transpedicular fixation results in the risk of pronounced shoulder girdle imbalance. It provides a better correction of the scoliotic curve. Nevertheless, in comparison with laminar fixation, a more rigid fixation may more often result in shoulder girdle imbalance that is consistent with the literature data [17]. A large residual scoliotic curve also affects the possible imbalance of the shoulder girdle. Despite the conclusions of some authors on the lack of gender influence [16], we have identified an association of an increased risk of shoulder girdle imbalance with the male gender (by 6.3 times). The presence of neurosurgical, cardiological, and pulmonological pathologies also affected the risk of developing shoulder imbalance, increasing it by 8.8 times. In order to estimate the risk of severe shoulder girdle imbalance, a multivariate model was created that could predict potential risks with 100 % accuracy when examining the surgical outcomes of 66 patients.

Therefore, when predicting the risks of clinical frontal imbalance in the surgical treatment of severe idiopathic scoliosis with the primary thoracic scoliotic curve, it is essential to use both treatment strategies and options to achieve maximum correction of the scoliotic curve considering the age of patients, the initial deformity degree, its mobility, and compensation. During the application of transpedicular fixation, it is essential to consider the risks such as male gender and comorbidities of neurosurgical, cardiological, and pulmonological origin.

Conclusion

For severe idiopathic scoliosis surgery with a primary thoracic scoliotic curve, multiplicative predictors of frontal imbalance risk can predict with 88.9 % sensitivity the risk of an increased distance of more than 15 mm between the plumb line and the navel and with 100 % sensitivity the risk of a shoulder girdle imbalance of more than 5°. It is important to achieve maximum correction of the thoracic scoliotic curve, especially in the presence of other considerable risk factors (patients older than 18 years old, residual scoliosis on functional tests greater than 80°, initial frontal subcompensation) to exclude the risk of frontal imbalance.

The gender of patients and the presence of comorbid neurosurgical, cardiologic, and pulmonological pathologies should be considered when planning surgical treatment using transpedicular fixation in the correction of severe thoracic scoliosis to prevent the onset of shoulder imbalance.

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.

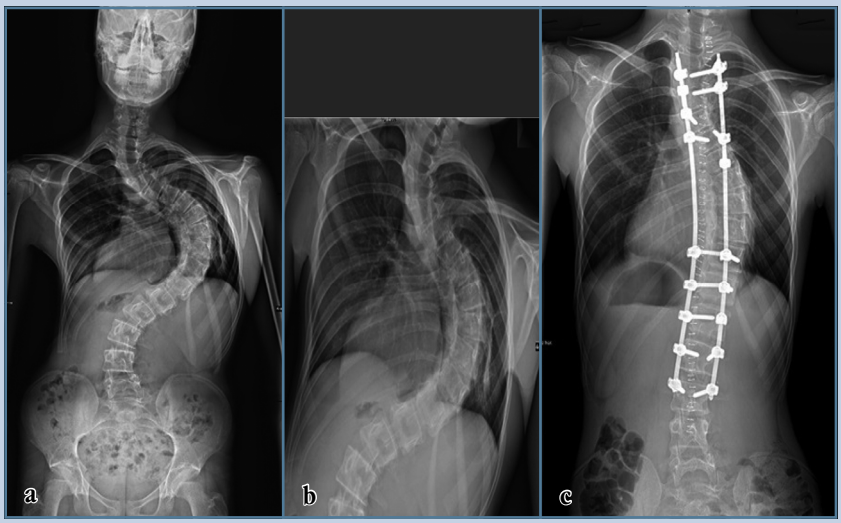

Fig. 3
Radiographs of patient S., 16 years old: **a** – the primary thoracic scoliotic curve of 117° before surgery, radiographically there is no shoulder girdle imbalance, the distance from the T1 centroid to the central sacral line is 5 mm; **b** – the primary curve with lateral flexion is 100°; **c** – the primary thoracic scoliotic curve of 41° after surgery, shoulder girdle imbalance is 35° to the right

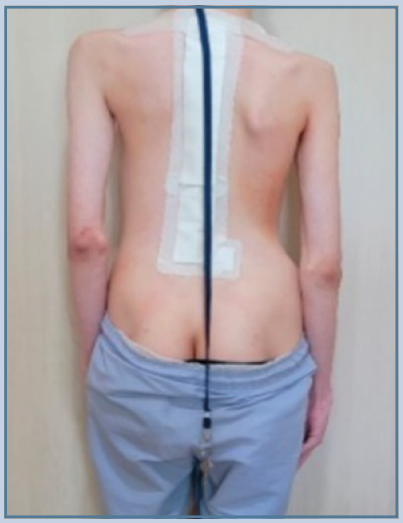

Fig. 4
The distance from the plumb line to the intergluteal cleft is 10 mm

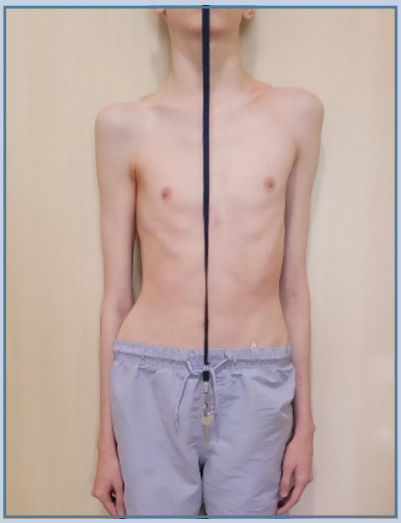

Fig. 5
Clinical shoulder girdle imbalance is 35° to the right, the plumb line in front along the navel

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