



Correlation between preoperative characteristics of lumbar segments and late postoperative clinical outcomes of lumbar total disc arthroplasty and transforaminal lumbar interbody fusion in railway workers

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Abstract

Introduction Long-term clinical outcomes can be optimized based on degeneration mechanisms of microstructural changes in the supporting elements of the spine and an objective assessment of the severity of pathological changes and the extent of surgical intervention.

The **objective** was to explore the relationship between preoperative age, behavioral, physiological, professional characteristics of patients, morphological and radiological parameters of the lumbar segments and long-term surgical outcomes of railway workers with degenerative diseases of the spine treated with lumbar total disc arthroplasty (LTDA) and transforaminal lumbar interbody fusion (TLIF) to objectify indications for the use.

Material and methods Surgical outcomes of 223 railway workers with single-segment lumbar degenerative disease treated with LTDA ($n = 64$) and TLIF ($n = 159$) between 2015 and 2018 were retrospectively reviewed. Univariate logistic regression analysis was used to identify and evaluate the influence of various risk factors on poor clinical outcomes.

Results A long-term poor outcome of lumbar LTDA was associated with age > 40 years, body mass index $> 28 \text{ kg/m}^2$, smoking, posterior osteophytes, dynamic sagittal angle over 10° , decreased interbody height of $> \frac{1}{2}$ of the overlying one, Pfirrmann disc degeneration greater than stage III, A. Fujiwara facet joint osteoarthritis greater than stage II, the apparent diffusion coefficient (ADC) less than $1200 \text{ mm}^2/\text{sec}$, facet angle $> 60^\circ$, tropism of the facet joint, cellular density of the nucleus pulposus $< 1500 \text{ cells/mm}^3$, collagen types X and XI. For TLIF, the factors included body mass index over 28 kg/m^2 , smoking, category III energy expenditure at work, dynamic linear translation $< 4 \text{ mm}$, facet angle $< 60^\circ$.

Discussion The findings suggested systematization of patients considering the severity of preoperative degenerative changes in the lumbar segments providing an optimal choice of surgical strategy and prediction of the postoperative follow-up.

Conclusion A unified choice of surgical technology, a comprehensive analysis of preoperative age, behavioral (smoking), physiological (BMI), professional (level of energy expenditure) parameters, morphological and radiological characterization of the lumbar segments were essential for effective treatment of clinical symptoms in the late postoperative period in railway workers with single-level degenerative disease of the lumbar segments.

Keywords: railway workers, lumbar spine, total disk replacement, transforaminal lumbar interbody fusion, risk factors, choice of surgical strategy

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INTRODUCTION

Pain in the back and lower extremities is one of the most common health disorders among the adult population of industrialized countries [1]. Degeneration in the supporting elements including intervertebral discs (IVD) and facet joints (FJ) is the main cause of the condition [2]. There is a variety of clinical and morphological forms of this pathology due to asymmetric changes in the IVD and FJ [3]. Surgical technologies are being developed aimed at improving the quality of life and restoring the preoperative functional status [4]. Along with the annual increase in the number of spinal interventions, there is an increase in poor surgical outcomes being associated with adverse events and with the lack of unified surgical algorithms for groups with similar morphological and radiological criteria [5].

This suggests a high social role of the problem in a professionally active cohort of patients, including railway workers [6]. High axial loads on the spinal column, twisting movements, vibration, and psychoemotional stress are recorded in the anamnesis of these patients [5, 6]. Occupational medicine deals with the preconditions for the development of an optimal strategy for specialized neurosurgical care [7]. Mechanisms of degeneration at the level of microstructural changes in the supporting elements of the spine are to be thoroughly explored for an objective assessment of the severity of pathological changes and the choice of the extent of surgical intervention to optimize long-term clinical outcomes [8].

No studies reporting the relationship between preoperative morphological and radiological changes and long-term clinical outcomes of patients including in railway workers could be identified in specialized databases such as Scopus, Pubmed, and Elibary. This circumstance prompted us to conduct this study.

The **objective** was to explore the relationship between preoperative age, behavioral, physiological, professional characteristics of patients, morphological and radiological parameters of the lumbar segments and long-term surgical outcomes of railway workers with degenerative diseases of the spine treated with lumbar total disc arthroplasty (LTDA) and transforaminal lumbar interbody fusion (TLIF) to objectify indications for the use.

MATERIAL AND METHODS

Methodology

A retrospective study was based on the perioperative data of 588 railway workers included in a single updated patient database [9] who underwent a lumbar spine surgery between September 2015 and September 2018. The project was supported by the grant of the Russian Science Foundation “Molecular signaling cascades and their effect on nutrient transport through the intercellular matrix for intervertebral disc regeneration” (Chief Research Officer: V.A. Byvaltsev, project No. 15-15-30037) (Fig. 1).

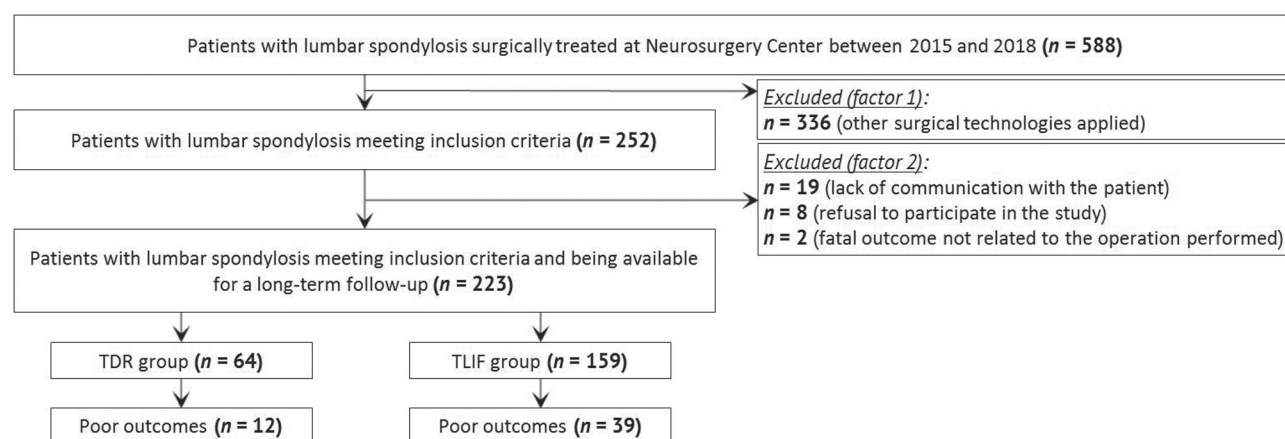


Fig. 1 Flow chart of the study

Total disk replacement (TDR) and transforaminal lumbar interbody fusion (TLIF) were performed for 252 (42.9 %) patients. A comprehensive analysis was available for 223 (88.5 %) patients with a five-to-seven-year follow-up.

Inclusion criteria: patients who were railway workers with single-segment degenerative diseases surgically treated using the TDR and TLIF techniques.

Exclusion criteria: previous lumbar surgery, the need for multilevel interventions, the presence of concurrent lumbar pathology of traumatic, inflammatory, or tumor origin.

General data on patients in the groups are presented in Table 1.

Table 1

Characteristics of patients in the study groups

Parameter		TDR (<i>n</i> = 78)	TLIF (<i>n</i> = 184)
Age, years, Me (Q ₂₅ ;Q ₇₅)		35 (29;45)	43 (37;55)
BMI, kg/m ² , Me (Q ₂₅ ;Q ₇₅)		24.5 (22.5;27.6)	26.7 (23.9;29.3)
Gender	males, <i>n</i> (%)	49 (62.8)	113 (61.4)
	females, <i>n</i> (%)	29 (37.2)	71 (38.6)
Smoking, <i>n</i> , %		26 (33.3)	59 (32.1)
Categories of work by level of energy consumption	Ia, <i>n</i> (%)	7 (8.9)	16 (8.7)
	Ib, <i>n</i> (%)	13 (16.7)	31 (16.8)
	IIa, <i>n</i> (%)	18 (23.1)	43 (23.4)
	IIb, <i>n</i> (%)	21 (26.9)	59 (32.1)
	III, <i>n</i> (%)	19 (24.4)	35 (19)
Follow-up observation, mo., Me (Q ₂₅ ;Q ₇₅)		71 (65;83)	74 (67;85)

Current conditions: All patients were affiliated with JSC Russian Railways and underwent neurosurgical treatment and were followed up by specialists at the RZD-Medicine Clinical Hospital (Irkutsk).

Description of the medical intervention

Total discectomy, bilateral foraminotomy and mandatory resection of the posterior longitudinal ligament was performed in the TDR group using a left-sided pararectal retroperitoneal approach. The M6-L prosthesis (Spinal Kinetics, Switzerland) was used. It consisted of ultra-high-molecular-weight polyethylene fibers arranged in multiple layers around a polycarbonate-urethane polymer core and through titanium alloy endplates with keels to provide fixation to the upper and lower vertebral bodies. Spinal canal reconstruction was performed in the TLIF group using a minimally invasive intermuscular approach or an open midline approach, followed by transforaminal interbody fusion and transpedicular fixation.

Outcomes

Factors potentially influencing long-term poor clinical outcomes were explored. The parameters were included in a univariate statistical analysis to identify reliable risk factors for poor outcomes in patients undergoing TDR and TLIF for single-segment degenerative lumbar spine diseases:

- (1) Patient age;
- (2) Body mass index;
- (3) Smoking;

- (4) Work category based on energy expenditure;
- (5) Presence of posterior osteophytes;
- (6) Sagittal angle (°);
- (7) Linear displacement in the segment (mm) [10];
- (8) Interbody space size (mm) [11];
- (9) IVD degeneration graded by C. Pfirrmann [12];
- (10) DS degeneration graded by A. Fujiwara [13];
- (11) Measured diffusion coefficient (MDC) (mm^2/sec) [14];
- (12) Facet angle (deg);
- (13) Presence of DS tropism [15];
- (14) IVD cell density (cells/mm^3);
- (15) Immunohistochemical changes in the IVD tissue (extracellular matrix and cell nuclei) [16].

Neurological status, the back and lower extremity pain, functional status measured with ODI, quality of life assessed with SF-36, and treatment outcome measured with the Macnab scale were assessed during the postoperative follow-up.

The long-term outcome was considered poor (TDR = 12 cases, TLIF = 27) in case of simultaneous verification of the VAS pain level > 20 mm, ODI > 20 %, SF-36 < 30 scores, and a poor outcome as evaluated with the Macnab scale.

Outcome recording methods

Radiological data were obtained using a DuoDiagnost digital X-ray system (Philips, USA), an 80-slice Aquilion Prime MSCT scanner (Toshiba, Japan), and a Magnetom Essenza 1.5T MRI scanner (Siemens, Germany). Diffusion coefficient maps were generated from diffusion-weighted magnetic resonance imaging (DWI) sequences using the ADCmap plugin (<http://web.stanford.edu/~bah/software/ADCmap>) in Osyrix (R) software.

Morphological analysis was performed using fragments of IVD tissue (nucleus pulposus region). They were fixed in 10 % formaldehyde, decalcified in formic acid, and stained with hematoxylin and eosin and safranin O (Sigma-Aldrich, USA). Histological preparations were examined using a Zeiss AxioVert A1, Axiocam 506 color microscope, and quantitative assessment was performed in the Fiji program (NIH) using the Automatic Cell Counting module. Cell density was expressed as the number of cells per mm^3 .

Three-dimensional structure of aggrecan and collagens in the extracellular matrix of the IVD was explored at the Ultramicroanalysis Shared Use Center of the Linguistic Institute of the Siberian Branch of the Russian Academy of Sciences (<http://www.lin.irk.ru/copp/rus/>). For immunohistochemical analysis, tissue fragments were fixed in 4 % paraformaldehyde (Sigma-Aldrich, USA). A panel of primary IgG antibodies from Abcam (USA) was used to identify key components of the intervertebral disc extracellular matrix.

The following antibodies were used in the work: mouse antibodies to collagen I (ab90395) at a dilution of 1:200; rabbit antibodies to collagen II (ab34712) at a dilution of 1:200; mouse antibodies to collagen X (ab49945) at a dilution of 1:200; rabbit antibodies to collagen XI alpha 2 (ab196613) at a dilution of 1:200; rabbit antibodies to aggrecan (ab186414) at a dilution of 1:200.

For visualization, secondary IgG antibodies labeled with Alexa Fluor® 594 (Abcam, USA) were used, which were directed to both rabbit (ab150080) and mouse (ab150116) antibodies. Cell nuclei were stained with Hoechst 33342 (Life Sciences, USA). The prepared slides were embedded in Prolong Gold (Life Sciences, USA) and scanned using an LSM-710 laser confocal microscope (Carl Zeiss, Germany). The resulting Z-stacks were analyzed using Imaris 7.2.3 (Bitplane AG, Switzerland) and ZEN (Carl Zeiss, Germany) software.

Statistical Data Processing

Statistical analysis was performed using Statistica for Windows (version 13.5). General patient information and postoperative outcomes are presented as median and first and third quartile values (Me (Q25;Q75)). Univariate logistic regression analysis was used to identify unadjusted associations between risk factors for poor clinical postoperative outcomes and various preoperative variables. Between-group comparisons of categorical variables were performed using Fisher's exact test, and continuous variables were compared using Student's t-test. Collinearity of covariates was analyzed using the Pearson correlation coefficient. Risk factors with a p -value < 0.05 were considered significant. The study was approved by the Ethics Committee of the Irkutsk Scientific Center of Surgery and Traumatology (protocol No. 10 dated August 31, 2015).

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RESULTS

T1- (Fig. 2a) and T2- (Fig. 2b) weighted images, as well as sagittal ADC maps (Fig. 2c) were explored. This analysis revealed characteristic visual patterns that may be significant for diagnosing degenerative diseases of the lumbar spine. ADCs are presented in a full dynamic color scale using the Jet palette, which allowed for the creation of a bright and informative image. Additionally, 65 % transparent ADC maps were superimposed on the corresponding T2-WI (Fig. 2d), which improved the perception of anatomical localization and made the data more accessible for analysis.

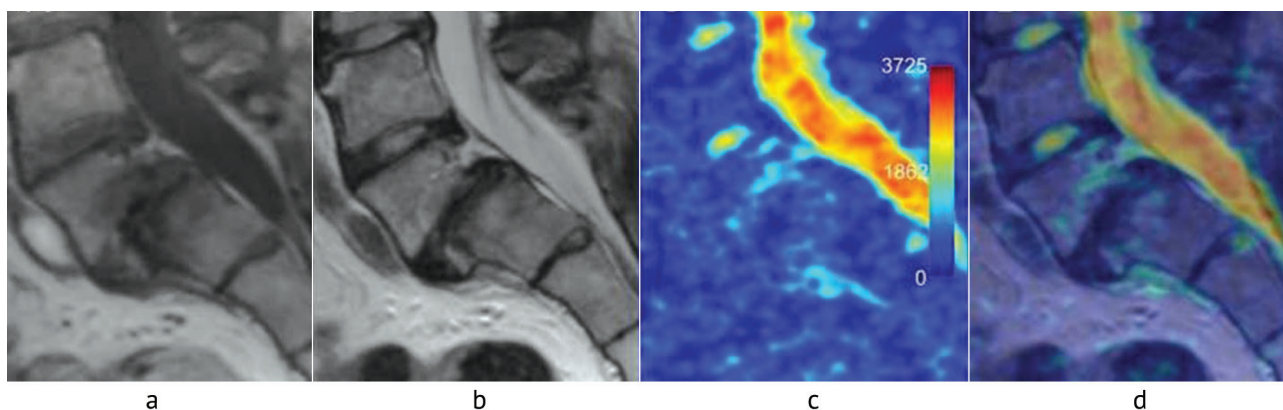


Fig. 2 A clinical example of a 39-year-old patient (TLIF group), plotting maps of the measured diffusion coefficient: (a) T1-weighted image shows a hypointense signal; (b) T2-weighted image shows a hyperintense signal; (c) the ADC map shows a hyperintense signal; (d) superposition of the ADC map on the T2 image shows the anatomical location of areas with increased diffusion, corresponding to the Modic 1 change boundary.

The nucleus pulposus area was measured for cellular density in all cases. The analysis revealed a pattern of low cellular density with the highest ADC values. For example, Figure 3 shows the morphological data of a patient in the TDR group with a nucleus pulposus cellular density of 1562 cells/mm³ (Fig. 3a) and an ADC value of 1377 mm²/sec. In this case, Safranin-O staining for glycosaminoglycans (Fig. 3b) confirmed a mild degree of IVD tissue degeneration, which correlated with the nucleus pulposus ADC cell density values.

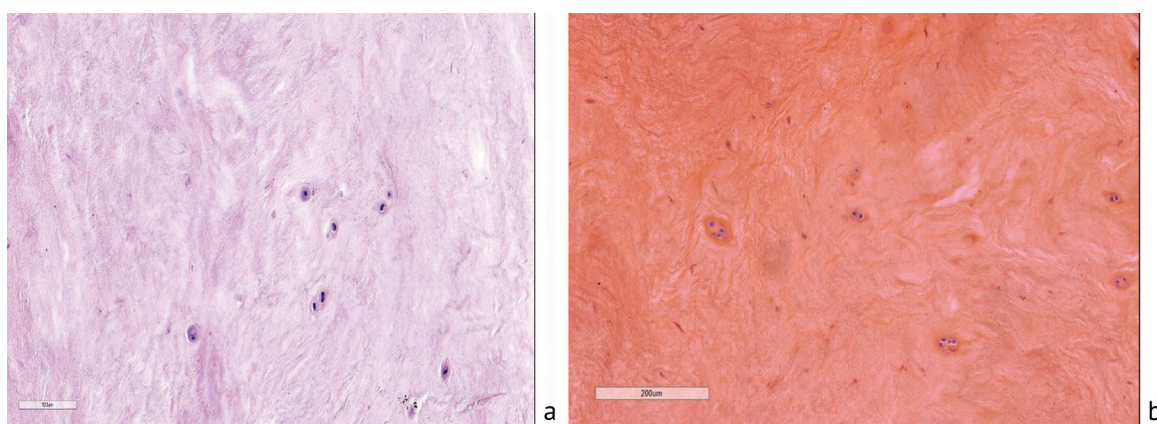


Fig. 3 Clinical example of a 33-year-old patient (TDR Group) showing: (a) micrograph of histological examination of the nucleus pulposus area, stained with hematoxylin and eosin, magnification $\times 200$; (b) micrograph of histological examination of the nucleus pulposus area, stained with safranin-O for glycosaminoglycans, nuclei stained with hematoxylin and eosin, magnification $\times 200$

All patients were characterized by degenerative changes in the structure of the extracellular matrix (Fig. 4 and 5) with zones of lumpy decay and lysis of the components (aggrecan, collagen I and II). Cases with more intense destructive changes were associated with the appearance of collagens in the composition of the intercellular substance that are not characteristic of the composition of the intervertebral disc (collagen X and XI).

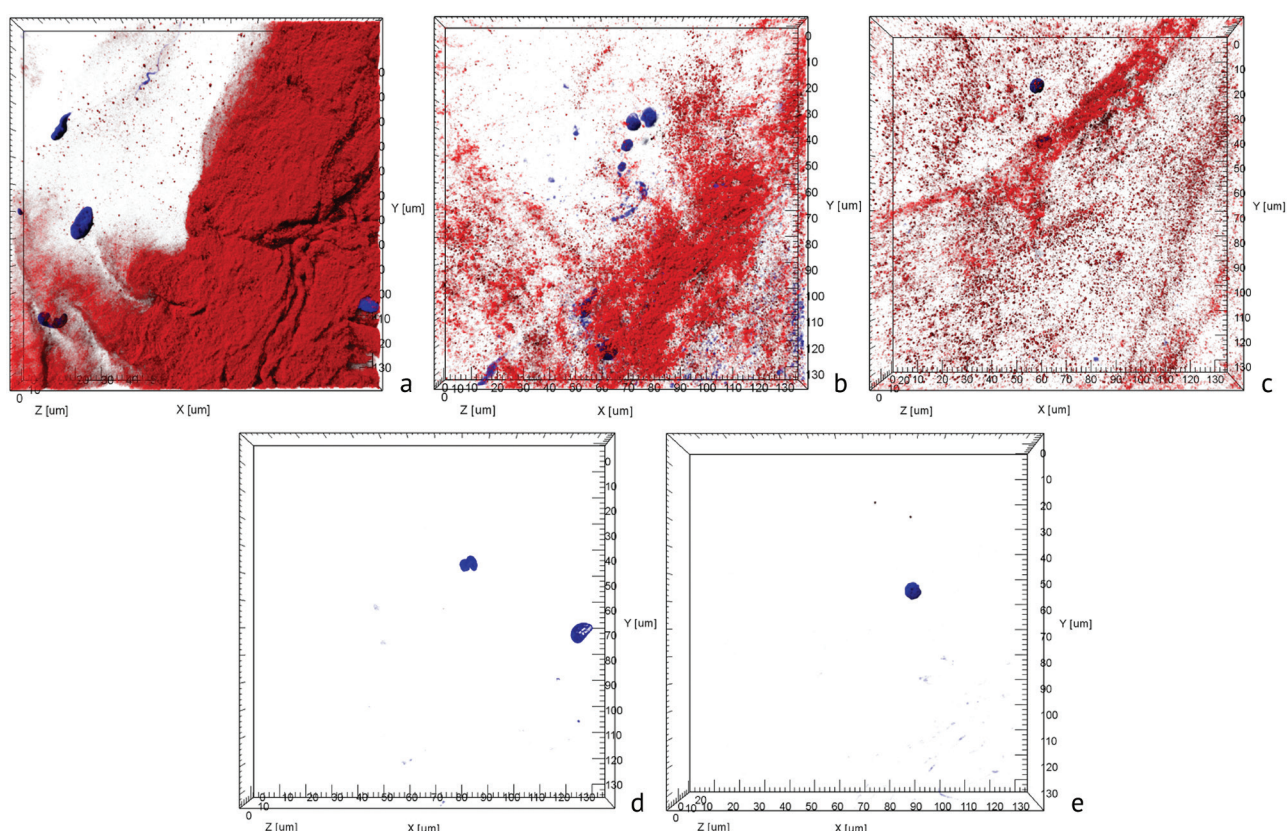


Fig. 4 A clinical case of a 39-year-old patient (TDR Group). Laser confocal microscopy of IVD tissue. Three-dimensional reconstruction of Z-stacks, visualization mode — shadow projection. Immunohistochemical staining of the nucleus pulposus (detectable component of the IVD — Alexa Fluor® 594, red; cell nuclei — Hoechst 33342, blue) for aggrecan (a), collagen type I (b) and collagen type II (c), collagen types X (d) and XI (e) were not detected

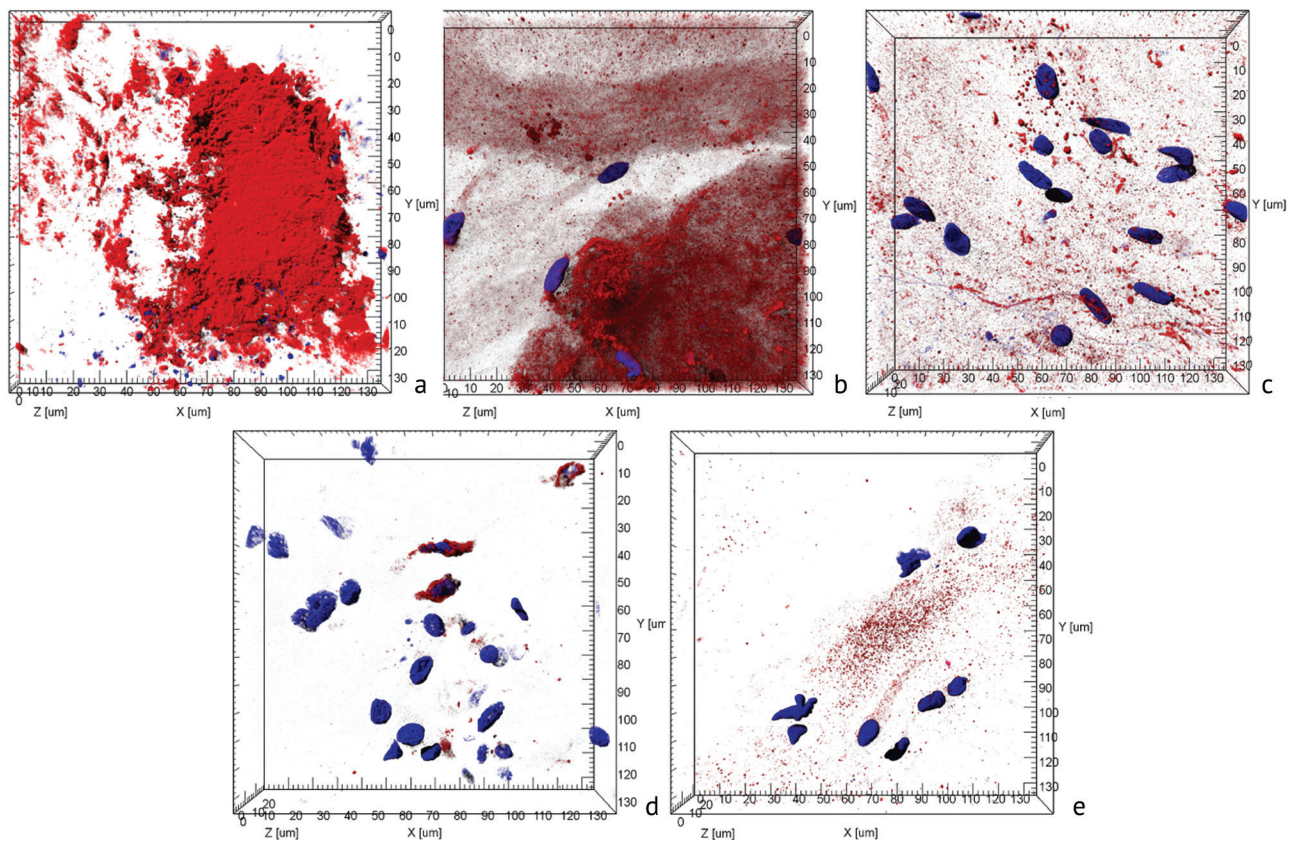


Fig. 5 A clinical example of a 46-year-old patient (TLIF Group). Laser confocal microscopy of IVD tissue. Three-dimensional reconstruction of Z-stacks, visualization mode — shadow projection. Immunohistochemical staining of the nucleus pulposus (detectable component of the IVD — Alexa Fluor® 594, red; cell nuclei — Hoechst 33342, blue) for aggrecan (a), collagen type I (b) and collagen type II (c), collagen types X (d) and XI (e) were detected in the tissue

Long-term clinical parameters were available in 82.1 % (64/78) of patients in subgroup I and in 86.4 % (159/184) of patients in subgroup II (Table 2).

Table 2

Long-term clinical data of patients included in the study

Parameter		TDR (n = 64)	TLIF (n = 159)
VAS pain, mm, Me (25;75)	Lower limbs	14 (8;21)	17 (9;22)
	Lumbar spine	29 (19;44)	30 (18;46)
Functional status measured with ODI, %, Me (25;75)		28 (18;40)	30 (16;42)
Quality of life measured with SF-36, score, Me (25;75)	Physical component score	35.23 (33.38;42.19)	32.17 (30.23;36.55)
	Mental component score	34.54 (30.66;39.93)	33.89 (29.93;37.19)
The result of the operation measured with the Macnab score, n, %	Excellent	20 (31.25)	15 (9.4)
	Good	19 (29.7)	58 (36.5)
	Fair	13 (20.3)	47 (29.6)
	Poor	12 (18.75)	39 (24.5)
Impaired muscle strength, n (%)		2 (3.125)	9 (5.7)
Sensory disorders, n (%)		19 (29.7)	52 (32.7)
Complications graded by Dindo – Clavien	Mild adverse events (Grade I, II, IIIA), n (%)	7 (10.9)	21 (13.2)
	Severe complications (Grade IIIB, IV and V), n (%)	2 (3.125)	9 (5.7)

Patients with degenerative diseases of the lumbar spine who had a poor outcome, of those available for a long-term follow-up, accounted for 18.75 % (12/64) in subgroup I and 24.5 % (39/159) in subgroup II. Factors associated with the risk of a poor outcome were identified using univariate logistic regression analysis (Table 3).

Table 3

Risk factors influencing poor long-term outcome in the patients studied

Parameter	TDR (n = 64)			TLIF (n = 159)		
	Poor outcome (n = 12)	Satisfactory outcome (n = 52)	p	Poor outcome (n = 39)	Satisfactory outcome (n = 120)	p
	OR (95 % CI)	SE		OR (95 % CI)	SE	
Age over 40	11.2 (2.2–57.3)	0.8	0.031	0.9 (0.4–1.8)	0.3	0.216
Body mass index over 28 kg/m ²	15 (1.8–124.9)	1.1	0.015	3.3 (1.4–7.6)	0.4	0.031
Smoking	36.6 (4.2–313.6)	1.1	0.013	5.0 (2.1–12.2)	0.4	0.018
Energy expenditure category III	0.4 (0.09–2.5)	0.8	0.427	11.0 (4.7–25.6)	0.4	0.005
Presence of posterior osteophytes	41 (4.7–352.9)	1.1	0.024	0.9 (0.4–1.9)	0.3	0.439
Dynamic sagittal angle greater than 10°	32.1 (5.7–178.4)	0.8	0.019	1 (0.5–2.1)	0.3	0.549
Dynamic linear translation less than 4 mm	1.2 (0.2–7.1)	0.8	0.622	14.5 (6.1–34.4)	0.4	0.009
Decrease in the height of the interdiscal space by more than ½ of the overlying one	11.1 (2.5–48.4)	0.7	0.007	1.4 (0.7–3.0)	0.3	0.148
Pfirsman disc degeneration greater than stage III	47 (7.9–277.6)	0.9	0.009	0.9 (0.4–1.9)	0.3	0.513
A. Fujiwara facet joint osteoarthritis greater than stage II	46.2 (5.3–400.6)	1.1	0.002	1.2 (0.6–2.5)	0.3	0.318
ADC less than 1200 mm ² /sec	275 (22.8–3309.1)	1.2	0.001	1.3 (0.6–2.7)	0.3	0.245
Facet angle > 60°	60 (9.6–373.6)	0.9	0.018	0.8 (0.4–1.8)	0.3	0.812
Facet angle less than 60°	1.5 (0.3–7.0)	0.7	0.629	8.7 (3.7–19.9)	0.4	0.014
Verified tropism of the facet joint	21 (3.9–111.2)	0.8	0.004	0.9 (0.4–1.9)	0.3	0.791
Cellular density of the nucleus pulposus < 1500 cells/mm ³	10 (2.3–42.9)	0.7	0.021	1.2 (0.5–2.4)	0.3	0.772
The presence of collagen types X and XI detected by IHC testing	10.2 (2.0–52.2)	0.8	0.011	0.8 (0.4–1.8)	0.3	0.829

Note: OR, odds ratio; 95 % CI, 95 % confidence interval; SE, standard error of the odds ratio; IVD, intervertebral disc; FJ, facet joint; MDC, measured diffusion coefficient; NP, nucleus pulposus; IHC, immunohistochemistry

A univariate analysis of various factors on the risk of poor long-term clinical outcomes in patients with single-level degenerative disease of the lumbar spine treated with TDR and TLIF showed the following results. Poor long-term clinical outcomes in TDR patients were associated with:

- Age over 40 years ($p = 0.031$);
- Body mass index over 28 kg/m² ($p = 0.015$);
- Smoking ($p = 0.013$);
- Presence of posterior osteophytes ($p = 0.024$);
- Dynamic sagittal angle over 10° ($p = 0.019$);
- Decreased interdiscal space height by more than ½ of the overlying one ($p = 0.007$);
- Pfirsman disc degeneration greater than stage III ($p = 0.009$);

- Fujiwara facet joint osteoarthritis greater than stage II ($p = 0,002$);
- ADC value $< 1200 \text{ mm}^2/\text{sec}$ ($p = 0.001$);
- Facet angle of 60° or more ($p = 0.018$);
- Presence of facet tropism ($p = 0.004$);
- Cellular density of the nucleus pulposus $< 1500 \text{ cells/mm}^3$ ($p = 0.021$);
- Presence of collagen types X and XI detected by IHC ($p = 0.011$).

The risk of poor long-term clinical results in TLIF patients after can be associated with:

- Body mass index greater than 28 kg/m^2 ($p = 0.031$);
- Smoking ($p = 0.018$);
- Work category according to the level of energy expenditure III ($p = 0.005$);
- Dynamic linear translation less than 4 mm ($p = 0.009$);
- FJ angle less than 60° ($p = 0.014$).

Therefore, the criteria for poor clinical follow-up in case of single-level lumbar degenerative disc disease were:

- TDR: age over 40 years, BMI $> 28 \text{ kg/m}^2$, smoking, presence of posterior osteophytes, dynamic sagittal angle $> 10^\circ$, decrease in interdiscal space by more than $\frac{1}{2}$ of the overlying one, Pfirrmann disc degeneration greater than stage III, Fujiwara facet joint osteoarthritis greater than stage II, ADC value $< 1200 \text{ mm}^2/\text{sec}$, facet angle $> 60^\circ$, presence of DS tropism, cellular density of nucleus pulposus $< 1500 \text{ cells/mm}^3$, presence of collagen types X and XI, detected by IHC;
- TLIF: BMI $> 28 \text{ kg/m}^2$, smoking, energy expenditure level III work category, dynamic linear translation less than 4 mm , facet angle $< 60^\circ$.

DISCUSSION

The study first demonstrated the relationship between a comprehensive assessment of patient characteristics including preoperative age, behavioral (smoking), physiological (BMI), and occupational (energy expenditure) parameters, as well as morphological and radiological aspects of lumbar segments, and long-term clinical outcomes of lumbar TDR and TLIF. The findings facilitated grading of the patients based on the severity of preoperative degenerative changes in the lumbar segments, optimal selection of surgical strategies and prediction of postoperative outcomes.

The intervertebral disk and the spinal joint, as supporting elements of the spinal motion segment (SMS), are specific and vulnerable anatomical structures subject to involutional processes and degenerative changes, which can be aggravated by increased physical activity and microtrauma [17, 18]. Developing symptomatic degenerative disease of the SMS is the main cause of persistent neurological symptoms and is associated with a high incidence of disability [19].

Morphological studies of the IVD and DS tissues provided valuable information on the pathophysiological mechanisms and histopathological changes that are difficult to diagnose by neuroimaging methods in cases of minor and moderate changes [20, 21]. Evaluation of the prognostic value of microstructural degenerative transformations in the tissues of the IVD has the potential for the development of unified surgical approaches aimed at selecting surgical technologies taking into account grouped morphological and radiological features [22, 23].

There are publications reporting relationship between various signs of degeneration of the IVD without the assessment of the relationship between long-term clinical outcome and the surgical strategy. Kilitci et al. reported a high correlation between the degree of degeneration of the IVD according to MRI data and the severity of histological degenerative changes in the posterior longitudinal ligament [20]. Middendorf et al. suggested that MRI-based degeneration grades do not correlate with cartilage mechanics [24]. Bečulić et al. suggested a correlation of radiological and early clinical postoperative findings [8]. The authors confirmed a statistically significant correlation of histological signs of degenerative changes in the IVD with motor and sensory disorders, pain and the degree of disability in patients who underwent microsurgical removal of a disc herniation at a six-month follow-up.

Prospective, randomized multicenter studies are required to confirm the obtained results. The identified patterns may not be strictly specific to railway workers, and additional objectification might be required.

Limitations of the study included:

- 1) retrospective single-center nature of the study;
- 2) exploring the results of interventions in railway workers with special working conditions;
- 3) lack of analysis of the relationship between morphological and radiological data on the outcome of treatment in the early period;
- 4) study of the results of exclusively single-segment surgical interventions on the lumbar spine;
- 5) lack of analysis of other risk factors (psychosomatic status, comorbidities, duration of the disease, opioid intake, changes in adjacent lumbar segments, etc.);
- 6) lack of assessment of the relationship between production factors and degenerative disc diseases, as well as on long-term clinical and radiological outcomes;
- 7) lack of economic analysis of the financial costs of lumbar TDR and TLIF.

CONCLUSION

Railway workers with symptomatic single-segment degenerative disease of the lumbar spine need to comprehensively assess the severity of degenerative changes (IVD, DS) and the degree of workload.

Lumbar total arthroplasty can be offered for moderate IVD degeneration (Pfirrmann disc degeneration greater than stage III, ADC value $< 1200 \text{ mm}^2/\text{sec}$, which corresponds to cellular density of nucleus pulposus $< 1500 \text{ cells/mm}^3$, absence of collagen types X and XI, to be detected by IHC) and DS changes (Fujiwara facet joint osteoarthritis greater than stage II, DS angle $< 60^\circ$, no tropism), in the absence of posterior osteophytes, a dynamic sagittal angle $< 10^\circ$, and preservation of the interbody space height of more than $\frac{1}{2}$ of the overlying one.

Single-level transforaminal lumbar fusion can be performed in other cases (BMI $< 28 \text{ kg/m}^2$, dynamic linear translation $> 4 \text{ mm}$, facet angle $> 60^\circ$).

Conflict Interests The authors declared no potential conflicts of interest with respect to the authorship and/or publication of this article.

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Ethical Approval The study was conducted in accordance with the Declaration of Helsinki and approved by the Local Ethics Committee of the Irkutsk Scientific Center of Surgery and Traumatology (Protocol No. 10 dated August 31, 2015).

Informed Consent The patients gave informed consent for publication of the findings without identification.

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