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Substantiation and development of an optimal method of minimally invasive posterior interbody stabilization of vertebrae using distraction cages in patients with lumbar spondylolisthesis

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Objective to improve the effectiveness of treatment of patients with lumbar spondylolisthesis, the authors substantiated and developed a novel method of minimally invasive posterior interbody vertebral stabilization (MIPIVS) using distraction cages.

Materials and methods: A clinical prospective comparative (controlled) single-center interventional cross-section study was conducted with a subsequent observation phase, as well as preliminary modeling and development of a novel intervention method. The biomechanical model was used to determine the possibility of restoring the functional state of the spine using distraction cages, and the stress-strain state of the structures was analyzed. The clinical part of the study involved 21 patients aged 35 to 68 (Me=56 [LQ=50; UQ=65]) years (15 women and 6 men), divided into three groups: the study group (n=4) treated with the author's method of MIPIVS (patent application No. a202302383 dated May 18, 2023), a comparison group (n=10) with the standard method of MIPIVS, a control group (n=7) treated with other methods of interbody spondylodesis. Patients were examined according to standard protocols. Logistic and statistical analyses were performed using standard nonparametric methods at a critical level of $p < 0.05$. The principles of bioethics and biomedicine were observed.

Results: Before and after surgical treatment of patients with degenerative spondylolisthesis of the lumbar spine, the size of the spinal canal was studied and the dynamics of neurological disorders was assessed. The authors developed a novel method of minimally invasive posterior interbody stabilization of vertebrae using distraction cages and determined the possibility of restoring the value of segmental lordosis, parameters of spinal-pelvic balance and sagittal contour of the spine as indicators of the functional state of the spine using a biomechanical model. The analysis also included assessment of the stress-strain state within the "transpedicular structure – spinal motion segment – distraction cage" system.

Conclusions: The proprietary method of MIPIVS using distraction cages, which has been substantiated and developed, will help to improve the effectiveness of treatment for patients with lumbar spondylolisthesis. Further research prospects include clinical testing of the author's MIPIVS method.

Key words: *spondylolisthesis; treatment; operation; surgery; minimally invasive posterior interbody stabilization of the spine*

Lumbar spondylolisthesis (LS) remains a significant issue in spinal surgery [1–5]. In cases where conservative treatment failed, surgical intervention was typically employed. However, the development of minimally invasive techniques has improved patient management with LS by reducing hospital stays and enhancing rehabilitation outcomes [6–10].

The application of minimally invasive posterior interbody vertebral stabilization (MIPIVS), either as a standalone procedure or using distraction cages, represents a promising approach that aligns with current trends toward preserving normal anatomy and minimizing surgical trauma [11].

The necessity for implementing and refining minimally invasive approaches is driven by numerous

global geopolitical crises. The war in Ukraine poses not only a challenge to the national healthcare system but is also associated with a rising incidence of traumatic spinal injuries and multiple post-traumatic and degenerative disorders, including spondylolisthesis [12, 13].

The impact of war extends to healthcare logistics, leading to limited access to medical devices and the need for especially meticulous provisioning during surgical procedures. Preference is given to techniques that achieve the desired clinical outcomes with shorter operation times and lower resource consumption compared to extensive surgical interventions. In this context, the justification and development of effective minimally invasive surgical techniques—such as MIPIVS



with distraction cages (**Fig. 1**)—constitute a highly relevant objective.

Numerous medical centers are developing and implementing minimally invasive methods of interbody (particularly posterior) vertebral stabilization in cases of LS [14]. Traditional and minimally invasive posterior approaches are commonly used due to their acceptable fusion rates and low complication levels. However, these approaches are limited by the extent of dural and spinal nerve root retraction, and they carry the risk of iatrogenic injury to the paravertebral muscles and disruption of the posterior ligamentous complex. Anterior approaches, which allow bypassing the spinal canal, cauda equina, and spinal nerve roots, are associated with abdominal and vascular complications, while lateral approaches carry a risk of injury to the lumbar plexus and gluteal muscle [15].

Therefore, improving the surgical treatment of spondylolisthesis, particularly through the use of MIPIVS, remains a relevant clinical challenge.

Objective: To enhance the effectiveness of treatment for patients with lumbar spondylolisthesis by employing minimally invasive posterior interbody vertebral stabilization using distraction cages.

Materials and methods

Study design

A clinical, prospective, comparative (controlled), single-center cross-sectional interventional study was conducted (**Fig. 2**).

Using a biomechanical model with distraction cages, the study assessed the potential for restoring segmental lordosis, spinal-pelvic balance parameters, and sagittal spinal alignment as indicators of spinal functional status. It also analyzed the stress-strain condition within the system "transpedicular construct – spinal motion segment – distraction cage" [16] in the Biomechanics Laboratory of the Sytenko Institute of Spine and Joint Pathology, National Academy of Medical Sciences of Ukraine.

The clinical study included patients with degenerative spondylolisthesis of the lumbar spine and neurocompressive disorders who underwent inpatient treatment in Neurosurgery Department No. 2 between 2017 and 2024, followed by dynamic outpatient monitoring at the clinic of the Municipal Non-Commercial Enterprise of the Kharkiv Regional Council "Regional Clinical Hospital" (Kharkiv).

The research was conducted at the Department of Neurosurgery of Kharkiv National Medical University.

The study complied with the principles of bioethics and biomedicine (ethics and bioethics committee Minutes No. 7 of Kharkiv National Medical University, dated October 10, 2017).

Study Participants

The clinical study involved 21 patients (15 women and 6 men), aged 32 to 68 years (median age – 56 (50; 65) years), divided into three groups: study group (n=4), where the author's technique of MIPIVS was applied (patent application No. a202302383 of 18.05.2023) (**Fig. 3**); comparison group (n=10), where the standard



Fig. 1. The Designed distraction cage

MIPIVS technique was used (**Fig. 4**); control group (n=7), where other interbody fusion techniques were employed (**Fig. 5**).

Inclusion Criteria:

- diagnosed degenerative spondylolisthesis of the lumbar spine accompanied by neurocompressive disorders such as neurogenic intermittent claudication, lower limb paresis (3–4 points), and segmental sensory disturbances (L4–L5, L5–S1);
- age range: 32–68 years;
- surgical treatment:
 - for the study group: the proposed MIPIVS technique using titanium distraction cages;
 - for the comparison group: traditional MIPIVS technique;
 - for the control group: alternative methods of lumbar interbody spinal fusion.

Exclusion Criteria:

- Age over 75 years;
- absence of neurological symptoms or neurocompressive disorders such as lower limb paresis (1–2 points) or limb plegia;
- severe somatic and concomitant neurological pathology, vascular disorders of the lower extremities, etc.;
- patient refusal to participate in the study.

Patients were examined according to standard protocols. The type and stage of spondylolisthesis were determined, as well as the degree of sagittal imbalance and associated neurocompressive and biomechanical disorders. This allowed for the calculation of the required intraoperative correction of lordosis to achieve optimal biomechanical compensation, etc.

Following preoperative preparation, minimally invasive surgery was performed using a standard technique with the application of an interbody distraction cage. On the first postoperative day, in the absence of contraindications, patients underwent follow-up radiographic examination to evaluate the extent of correction and calculate key biomechanical parameters (lordosis angle, sacral slope, pelvic tilt variability, and pelvic incidence relative to the sagittal vertical axis).

This article contains some figures that are displayed in color online but in black and white in the print edition.

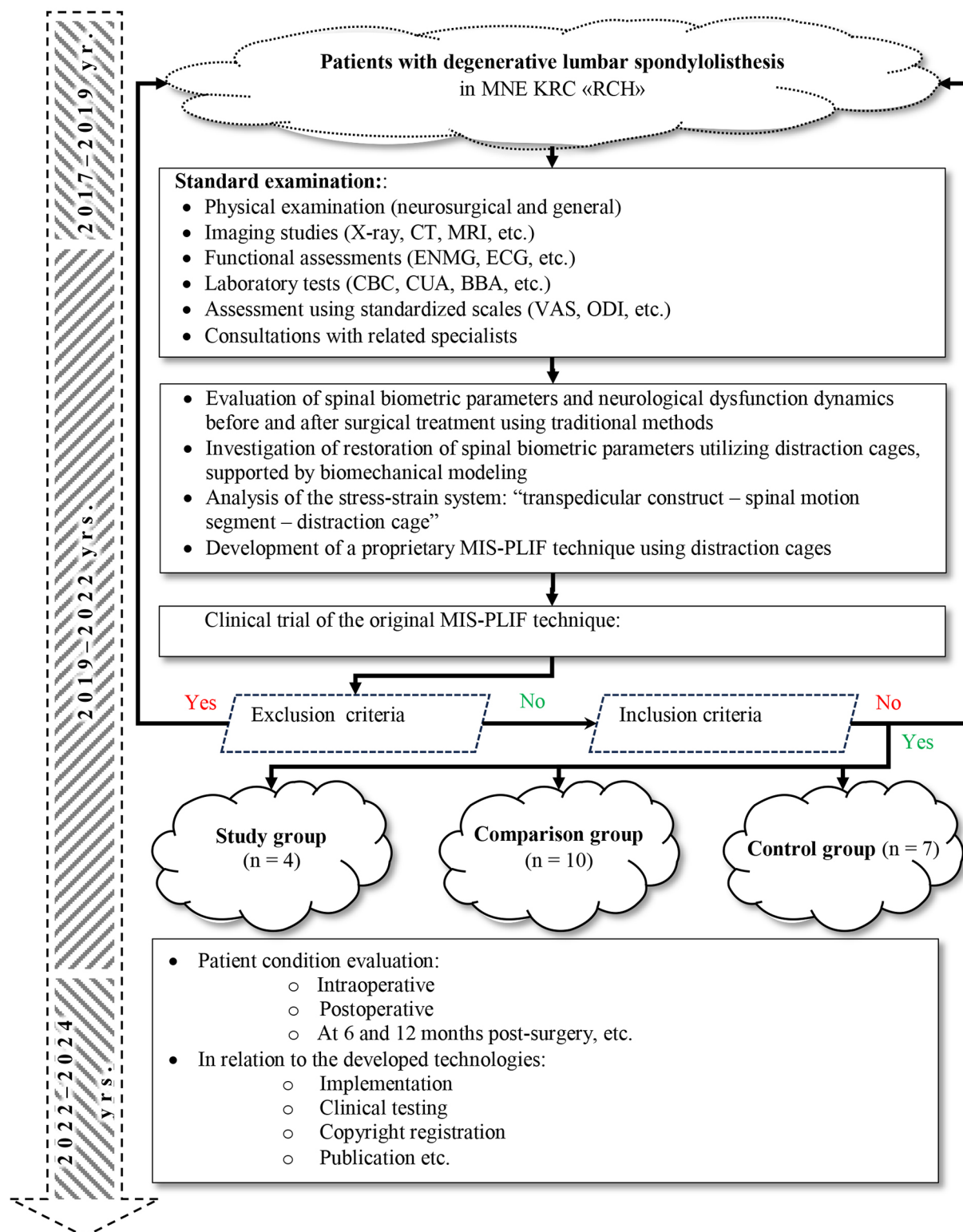


Fig. 2. Study Design:

MNE KRC «RCH»– Municipal Non-Commercial Enterprise of the Kharkiv Regional Council "Regional Clinical Hospital"; CT – computed tomography (X-ray); MRI – magnetic resonance imaging; ENMG – electroneuromyography; ECG – electrocardiography; CBC – complete blood count; CUA – clinical urinalysis; BBA – biochemical blood analysis; VAS – visual analogue scale; ODI – Oswestry Disability Index; MIS-PLIF – minimally invasive surgery posterior lumbar interbody fusion.

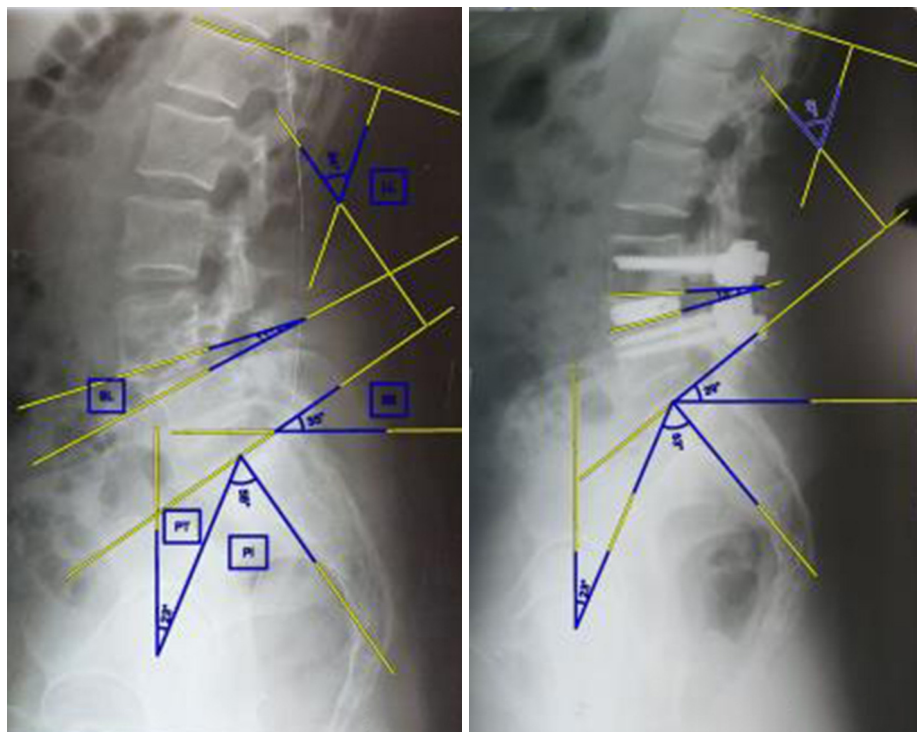


Fig. 3. Radiographic control before and after surgery using the minimally invasive posterior interbody vertebral stabilization technique with titanium distraction cages

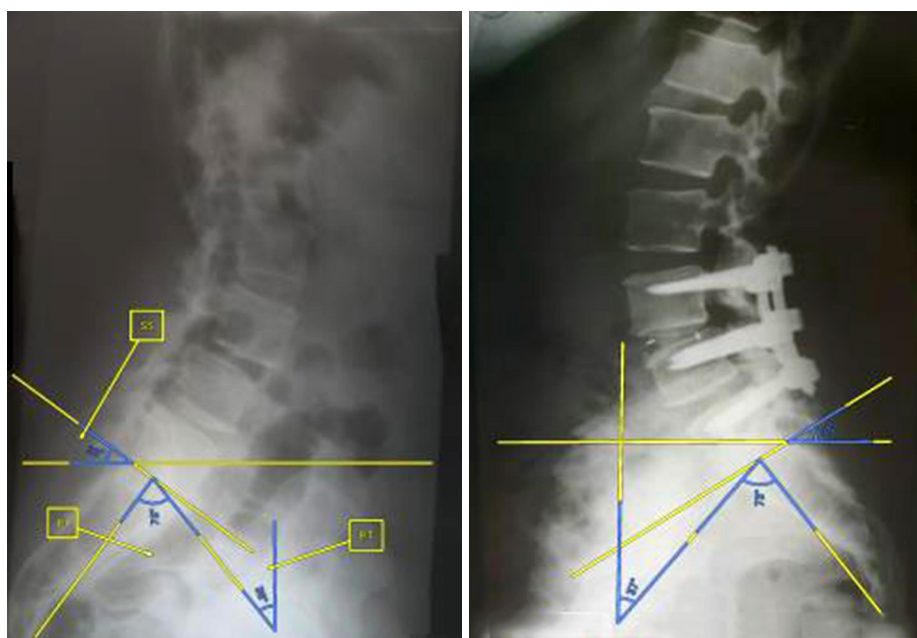


Fig. 4. Radiographic control before and after surgery using the traditional minimally invasive posterior interbody vertebral stabilization (MIPIVS) technique

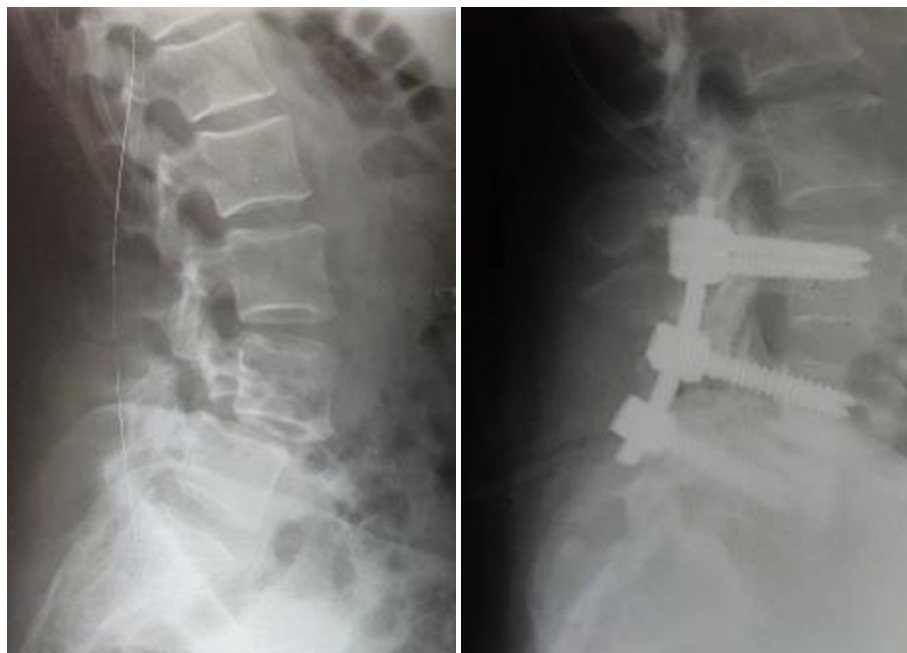


Fig. 5. Radiographic control before and after surgery using alternative methods of lumbar interbody spinal fusion

A neurological assessment was conducted to evaluate postoperative changes in neurological status, pain intensity using the Visual Analogue Scale (VAS), and functional status based on the Oswestry Disability Index (ODI).

On postoperative day 30, in the absence of contraindications, follow-up magnetic resonance imaging (MRI) was performed to assess the formation of primary bone fusion, along with a clinical and neurological examination, pain assessment via VAS, and functional status evaluation using the ODI.

Statistical Analysis

Data systematization and logical-statistical analysis were carried out using standard methods with a critical significance level of $p < 0.05$. Since the data distribution deviated from normal, nonparametric statistical methods were applied. The central tendency was described using the median (Me), and variability was expressed through the determination of the lower (LQ) and upper (UQ) quartiles. The significance of pairwise intergroup differences was assessed using the Mann–Whitney U test. Frequency indicators (both absolute and relative) were compared using Fisher's exact test.

Results and discussion

Among the clinically significant parameters, the key outcome indicators were evaluated, including complaints and medical history, physical examination data (general condition, level of consciousness), duration of the surgery, surgical approach, closure of the surgical wound, intraoperative radiation exposure to medical personnel and patients, volume of intraoperative blood loss and hemotransfusion, postoperative drainage, length of hospital stay, and the incidence of complications (radiculitis, radicular dysfunction, foot flexor weakness, pain during flexion and extension of the foot, paresthesia, motor disorders, incomplete spinal fusion, pseudoarthrosis, dural tears, major vascular

injuries, neural structure damage, surgical site infection, paravertebral muscle atrophy, postoperative bleeding, cerebrospinal fluid leakage, venous thromboembolism), screw loosening, malposition of surgical hardware, reoperation, body mass index, lordosis angle, lifestyle, progression of disorders, duration of conservative treatment, pain reduction after surgery, percentage of displacement before and after surgery, increase in intervertebral space, height of the foraminal opening, disability according to the ODI, and others.

The study groups were comparable in terms of age, gender ratio, anthropometric, clinical-anamnestic, and physical characteristics ($p > 0.05$) (**Table 1**).

The surgical parameters were more favorable in the main group (**Table 2**).

The incidence of complications was the lowest in the study group (**Table 3**). No cases of postoperative hemorrhage, cerebrospinal fluid leakage, venous thromboembolism, paravertebral muscle atrophy, incomplete spondylodesis, dural injury, screw loosening, malposition of surgical hardware, neural structure damage, major vascular injury, or surgical site infection were recorded in this group. Only one reoperation was performed due to pseudoarthrosis.

Data have been obtained confirming the effectiveness of the author's method of MIPIVS using distraction cages in patients with degenerative spondylolisthesis of the lumbar spine.

The significance of this approach lies in the ongoing search within spinal surgery for optimal treatment methods that combine effective deformity correction with segmental spinal stability while reducing the incidence of postoperative complications. Minimally invasive technologies, particularly the use of transpedicular fixation and interbody cages, are currently considered among the most promising directions in the surgical management of degenerative spinal disorders [17–19].

Table 1. Clinical and anthropometric characteristics of patients with lumbar spine spondylolisthesis

Parameter	Study group (n = 4)	Comparison group (n = 10)	Control group (n = 7)	Total (n = 21)
Age, years	50 [37;53]	63 [50;66]	59 [53;60]	50 [37;53]
Men	1 (25%)	4 (40%)	1 (14%)	6 (29%)
Women	3 (75%)	6 (60%)	6 (86%)	15 (71%)
Body mass index, kg/m ²	32 [28;34]	32 [28;34]	32 [28;34]	32 [28;34]
General condition	RS	RS	RS	RS
Consciousness	Clear	Clear	Clear	Clear
Achilles reflex	Weakend	Weakend	Weakend	Weakend
Tenderness	Present	Present	Present	Present
Lasègue sign	Positive	Positive	Positive	Positive
Wassermann sign	Positive	Positive	Positive	Positive
Hypoesthesia	Present	Present	Present	Present
Hyperesthesia	Present	Present	Present	Present
Meningeal signs	Absent	Absent	Absent	Absent
Plantar signs	Absent	Absent	Absent	Absent
Coordination	Preserved	Preserved	Preserved	Preserved
Paresis	Present	Present	Present	Present

Note: RS – relatively satisfactory.

Table 2. Surgical parameters for lumbar spine spondylolisthesis surgery

Parameter	Study group (n = 4)	Comparison group (n = 10)	Control group (n = 7)	Total (n = 21)
Hospital length of stay, days	13 [11;18]	9 [7;12]	11 [6;22]	10 [7;15]
Duration of surgery, minutes	180 [180;180] #	180 [160;210]	360 [240;480]	180 [180;215]
Duration of surgical approach, minutes	30 [30;30] *#	60 [60;60]	60 [60;90]	60 [30;60]
Duration of surgical wound closure, minutes	10 [8;10] *#	40 [40;40]	45 [40;50]	40 [12;40]
Duration of intraoperative radiation exposure of medical personnel, seconds	92 [87;93]	93 [90;95]	87 [81;90]	91 [87;94]
Total intraoperative radiation exposure of medical personnel, mSv:	0,22 [0,19;0,23]	0,25 [0,21;2,18]	0,20 [0,08;0,26]	0,23 [0,20;0,48]
Surgeon at the patient's side, mSv	0,08 [0,07;0,08]	0,09 [0,07;1,05]	0,07 [0,03;0,09]	0,08 [0,07;0,18]
Assisting staff at medium distance, mSv	0,06 [0,05;0,07]	0,07 [0,07;0,09]	0,06 [0,02;0,08]	0,07 [0,06;0,08]
Other personnel at a greater distance, mSv	0,03 [0,03;0,04]	0,05 [0,04;0,08]	0,04 [0,01;0,05]	0,23 [0,20;0,48]
Intraoperative patient exposure, mSv	2 [1;4]	1 [1;2]	1 [1;5]	2 [1;3]
Intraoperative blood loss, ml	100 [100;100] *#	200 [200;300]	500 [400;600]	200 [100;400]
Haemotransfusion	Not performed	1 (10%)	Not performed	1 (5%)
Haemotransfusion volume, ml	–	600 [600;600]	–	600 [600;600]
Postoperative drainage	Not performed	3 (30%)	1 (14%)	4 (19%)
Postoperative drainage volume, ml	–	0 [0;300]	0 [0;300]	0 [0;0]

Table continued 2. Surgical parameters for lumbar spine spondylolisthesis surgery

Parameter	Study group (n = 4)	Comparison group (n = 10)	Control group (n = 7)	Total (n = 21)
Pain reduction after surgery, difference score	4 [4;4]#	3 [3;4]	2 [1;2]	3 [3;4]
Displacement, %:				
preoperatively	20 [20;25]	17,5 [10;30]	25 [20;30]	20 [15;30]
postoperatively	5 [5;5]	5 [0;15]	15 [0;25]	5 [0;15]
Sagittal vertical axis displacement, cm:				
preoperatively	10 [8;11]	10 [7;12]	10 [8;12]	10 [8;12]
postoperatively	5 [4;6]	6 [5;7]	6 [5;8]	6 [5;7]
Pelvic tilt angle, deg:				
preoperatively	50 [49;52]	50 [48;53]	58 [56;60]	54 [50;57]
postoperatively	52 [51;53]	52 [50;55]	60 [58;62]	56 [54;58]
Pelvic incidence angle, deg:				
preoperatively	19 [18;20]	24 [22;27]	30 [29;33]	25 [23;27]
postoperatively	16 [15;17]	22 [20;25]	28 [26;30]	25 [19;23]
Sacral slope angle, deg:				
preoperatively	31 [30;32]	30 [28;33]	30 [28;32]	31 [30;32]
postoperatively	34 [33;35]	32 [30;35]	33 [31;35]	33 [31;35]
Increase in intervertebral space, mm	10 [9;11] *	8 [5;9]	11 [8;12]	9 [7;10]
Increase in foraminal height, mm	2,1 [2,0;2,1]	2,2 [1,9;2,2]	1,9 [1,8;1,9]	2,1 [1,9;2,2]
Duration of conservative treatment, months	12 [12;12]	12 [3;18]	12 [12;18]	12 [6;18]
Duration of rehabilitation, months	6 [6;6]	6 [6;12]	12 [6;18]	6 [6;12]
Dynamics of ODI disability, score	10 [10;15]	15 [10;25]	18 [10;20]	15 [10;20]

Note: * – statistically significant difference from the comparison group ($p < 0.05$); # – the difference from the control group is statistically significant ($p < 0.05$).

Table 3. Incidence of complications following surgical intervention for lumbar spine spondylolisthesis

Parameter	Study group (n = 4)	Comparison group (n = 10)	Control group (n = 7)	Total (n = 21)
Postoperative hemorrhage	–	3 (30%)	1 (14%)	4 (21%)
Postoperative cerebrospinal fluid (CSF) leakage	–	1 (10%)	–	1 (5%)
Venous thromboembolism	–	–	–	–
Atrophy of the paravertebral muscles	–	10 (100%)	1 (14%)	11 (52%)
Radiculitis with dysfunction of spinal nerve roots, manifested as:	1 (25%)	3 (30%)	1 (14%)	5 (24%)
Autonomic disturbances:				
Frequency	4 (100%)	10 (100%)	2 (29%)	16 (76%)
Duration (weeks)	1	1	1	1
Hypoesthesia:				
Frequency	1 (25%)	4 (40%)	1 (14%)	6 (29%)
Duration (weeks)	1	1	1	1

Table continued 3. Incidence of complications following surgical intervention for lumbar spine spondylolisthesis

Parameter	Study group (n = 4)	Comparison group (n = 10)	Control group (n = 7)	Total (n = 21)
Pain during foot flexion and extension:				
Frequency	1 (25%)	3 (30%)	1 (14%)	5 (24%)
Duration (weeks)	1	1	1	1
Paresthesia:				
Frequency	4 (100%)	3 (30%)	1 (14%)	8 (38%)
Duration (weeks)	1	2	2	2
Weakness of foot flexors:				
Frequency	–	2 (20%)	1 (14%)	3 (14%)
Duration (weeks)	–	4	4	4
Screw loosening	–	1 (10%)	1 (14%)	2 (10%)
Malposition of surgical hardware	–	1 (10%)	1 (14%)	2 (10%)
Incomplete spinal fusion (insufficient spondylodesis)	–	1 (10%)	1 (14%)	2 (10%)
Dural sac injury	–	2 (20%)	–	2 (10%)
Damage to neural structures	–	2 (20%)	–	2 (10%)
Injury to major blood vessels	–	–	–	–
Surgical site infection	–	1 (10%)	1 (14%)	2 (10%)
Reoperation	1 (25%)	1 (10%)	–	2 (10%)

The results of our study demonstrated that patients in the study group, who underwent surgery using the author's technique, showed more pronounced positive dynamics in functional recovery compared to the standard treatment and control groups. Pre- and postoperative assessments revealed a significant reduction in pain intensity on the VAS. In the study group, pain levels decreased by an average of 4 points, while in the comparison group the reduction was 3 points, and in the control group — 2 points (the differences were statistically significant). Furthermore, assessment of functional status using the Oswestry Disability Index (ODI) showed marked improvement in the main group (a reduction of 10 points), indicating more effective restoration of the spinal motion segment and minimal limitations in daily activities.

A critically important outcome is the restoration of intervertebral disc height following surgery, as this parameter is key to ensuring the stability and functionality of the spinal motion segment. In the study group, postoperative increase in intervertebral disc height averaged 10 [9;11] mm, which was higher than that observed in the comparison group (8 [5;9] mm, $p < 0.05$). Restoration of disc height plays a decisive role in reducing nerve structure compression, thereby alleviating neurological deficits and pain symptoms. Another essential aspect is the preservation of spinopelvic balance, a major factor in achieving a sustained positive clinical outcome. According to the collected data, the correction of sacral and pelvic tilt

angles was most optimal in the main group, further supporting the effectiveness of the applied technique in ensuring biomechanical stability.

The assessment of intraoperative parameters demonstrated that the use of distraction cages significantly reduced the duration of the surgical procedure and hospitalization, as well as the volume of blood loss. The average operative time in the study group was 180 [180;180] minutes, which aligns with the standard parameters for MIS-PLIF (minimally invasive surgery posterior lumbar interbody fusion) and was significantly shorter ($p < 0.05$) compared to the control group, where the operative time was 360 [240;480] minutes. The reduction in operative time directly contributes to a decreased risk of intraoperative complications such as blood loss and infectious complications. Intraoperative blood loss in the study group was considerably lower—100 [100;100] ml—compared to the comparison group, which recorded 200 [200;300] ml ($p < 0.05$), and the control group, where blood loss amounted to 500 [400;600] ml ($p < 0.05$). This reduction minimizes the need for blood transfusions and lowers the risk of hypovolemic shock.

An analysis of postoperative complications revealed the lowest incidence in patients treated using the authors' proprietary technique. Specifically, no cases of paravertebral muscle atrophy were observed in the study group, while the incidence in the comparison group was 100% and 50% in the control group ($p < 0.05$). This outcome is attributed to the fundamentally

different surgical access technique, indicating that the minimally invasive approach significantly reduces the risk of iatrogenic damage to the musculo-ligamentous apparatus and promotes improved postoperative recovery.

The rate of postoperative bleeding was 27% and 33% in the comparison and control groups, respectively, whereas no such cases were observed in the main group ($p < 0.05$). A significant reduction in the risk of radiculitis with spinal nerve root dysfunction was also of clinical importance. This complication occurred in only 25% of cases in the main group, compared to 30% in the comparison group and 50% in the control group ($p < 0.05$).

These findings are consistent with contemporary studies demonstrating the advantages of minimally invasive techniques in the treatment of degenerative spondylolisthesis. Such methods reduce the risk of surgical complications, improve postoperative outcomes, and shorten the rehabilitation period. In particular, significant improvement in sagittal balance parameters has been observed in patients who underwent treatment with distraction cages within the MIS-PLIF framework [20, 21].

Conclusions

1. The dimensions of the vertebral canal were studied, and the dynamics of neurological impairments were assessed following surgical treatment of patients with degenerative lumbar spondylolisthesis using a traditional approach.

2. The magnitude of segmental lordosis, spine-pelvic balance parameters, and sagittal spinal contour were determined as indicators of spinal functional status before and after traditional surgical treatment in patients with degenerative lumbar spondylolisthesis.

3. A proprietary method of MIPIVS using distraction cages was substantiated and developed.

4. Criteria for evaluating the effectiveness of the proposed MIPIVS method with distraction cages were identified.

5. Using a biomechanical model, the potential for restoring segmental lordosis, spine-pelvic balance parameters, and sagittal spinal contour—as indicators of spinal functional condition—was assessed. Additionally, the stress-strain state of the system “transpedicular construct – spinal motion segment – distraction cage” was analyzed.

Prospects for further research

Clinical validation of minimally invasive posterior interbody stabilization using distraction cages in patients with lumbar spondylolisthesis is planned.

Disclosure

Conflict of Interest

The authors declare no conflict of interest.

Ethical Standards

All procedures performed on patients in the course of this study complied with the ethical standards of the institutional and national research ethics committees and with the 1964 Helsinki Declaration and its subsequent amendments or comparable ethical standards.

Informed Consent

Informed consent was obtained from all individual participants included in the study.

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