ANALYSIS OF THE CAUSES OF SUBSIDENCE OF MODERN EXPANDABLE CAGES FOR VERTEBRAL BODY REPLACEMENT IN THE SURGICAL TREATMENT OF THORACOLUMBAR SPINE INJURIES

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Objective. To analyze the causes of subsidence of modern support cages for vertebral body replacement in the early postoperative period after surgical treatment of thoracolumbar spine injuries.

Material and Methods. A retrospective analysis of the data of 46 patients operated on in a single surgical session for unstable injuries of the thoracolumbar spine using a telescopic extendable vertebral body cage was performed. The degree of cage subsidence was assessed according to the criteria of Marchi et al.: penetration of the implant into the body of the adjacent cranial or caudal vertebral by 25% – grade 1,25–50% – grade 2, 50–70% – grade 3, 75–100% – grade 4. A comparative assessment of demographic, clinical, and radiographic parameters was performed in patients with and without cage subsidence within one year after surgery.

Results. Implant subsidence was detected in 76.5% ($n = 13$) of patients intraoperatively and in 23.5% ($n = 4$) after 4 months during an outpatient appointment. Subsidence into the cranial body prevailed (76%, $n = 13$). The anterior/posterior sequence of surgery stages combined with osteopenia and osteoporosis dominated in the study group (83.3%, $n = 10$). Quantitative parameters such as age, segmental angle, ROI in HU, surface contact area index, as well as qualitative parameters such as female gender, period of injury, and its low-energy nature had statistically significant differences between the study and control groups ($p < 0,05$). The augmentation of the screws and the length of fixation did not affect the formation of subsidence, but were associated with its magnitude.

Conclusion. The use of modern expandable body replacement cages for reconstruction of the anterior spinal column leads to their subsidence in some cases. Patient age, female gender, reduced bone density, the area of the bone-implant contact, anterior/posterior stabilization, and the late period of injury significantly affect the formation of subsidence when using expandable vertebral body replacement cages. A mean implant-to-vertebral endplate contact area ratio of less than 0.4 is a promising predictor of subsidence which requires further study.

Key Words: anterior fusion; anterior column reconstruction; vertebral body implant; Hydrolift; expandable cage; 360° fusion; circumferential stabilization; implant subsidence, implant-associated mechanical complications; distractible cage.

Please cite this paper as: *Lastevskiy AD, Anikin KA, Akhmetyanov ShA, Borisov NN, Kuchuk LE, Nazarov ZhA, Rerikh VV. Analysis of the causes of subsidence of modern expandable cages for vertebral body replacement in the surgical treatment of thoracolumbar spine injuries. 2025;22(4):6–18. In Russian. DOI: http://dx.doi.org/10.14531/ss2025.4.6-18*

An anterior corrective spinal fusion in various options remains one of the most common surgical techniques in the world, including for injuries to the thoracolumbar spine [1]. Combined (anterior and posterior) surgical stabilization is one of the best options for treating unstable spinal injuries and their complications [2, 3]. The European guidelines for the treatment of thoracolumbar fractures, developed by the German Society for Orthopaedics and Trauma Surgery (DGOU – Deutsche Gesellschaft für Orthopädie und Unfallchirurgie (in German)) [2], include morphological modifiers (degree of vertebral body destruction, degree of intervertebral disc damage) that suggest anterior reconstruction when indicated for types A2, A3, A4, B2, and C according to AO Spine.

The classification of osteoporotic fractures (OF) and the treatment strategy developed by a team of German authors from the DGOU recommend anterior column reconstruction for OF 4 and OF 5 fractures using vertebral body replacement implants [4]. This technique is applicable in the setting of marked, unreducible collapse of the vertebral body, even in cases of three-column instability. Spiegl et al. [5] recommend combined 360° stabilization for elderly patients with acute or subacute trauma accompanied by significant destruction of the posterior vertebral body wall and for patients with severe segmental kyphosis of more than 20°.

The sequence of surgical steps (anterior–posterior or posterior–anterior), the extent of posterior fixation, the volume of vertebral body resection, and methods to enhance the primary fixation strength of implantable devices, as well as the applicability of vertebral body replacement technology in osteoporosis, are a subject of ongoing debate [2, 6]. During the past two decades, the understanding of the biomechanics of anterior fixation has undergone a significant transformation. The evolution of anterior fixation implants traces a path from simple static mesh cages to contemporary telescopic expandable systems. The latter allows for reconstruction of the anterior column height using a maximally sparing approach, ensuring adequate primary fixation stability and sufficient load-bearing support throughout the entire period of interbody bone block formation [7–9]. From a biomechanical point of view, the load-bearing and load-sharing capabilities of expandable implants are significantly higher than those of static (mesh) implants [9]. The articles focus on the high clinical and radiological effectiveness of expandable body replacement implants in surgical reconstruction of the anterior support column for spinal injuries [6, 7, 10].

Quite optimistic early studies on the clinical and radiological outcomes of treatment with body replacement implants [11] were followed by more critical studies indicating the need to improve this technique [12, 13]. A serious obstacle for surgeons is the reduction in bone mineral density (BMD) of the vertebrae, which complicates the achievement of the desired outcomes during surgery [14]. In 30–80% of cases, dissatisfaction with treatment outcomes persists associated with mechanical complications in the form of cage subsidence into the adjacent vertebral bodies; in such cases, the extent of subsidence ranges from 2 to 7 mm [7, 10, 12, 14] (Fig. 1).

The consequences of cage subsidence can range from asymptomatic loss of segment height and reduction of the segmental index to narrowing of the intervertebral foramen, foraminal stenosis, development of sagittal lumbopelvic imbalance, and development of pseudarthrosis [15]. Efforts to develop spinal interbody implants with optimal biomechanical fixation characteristics are ongoing at many spine research centers. Articles on the effectiveness of expandable support vertebral body replacement implants for thoracolumbar injuries are controversial [16]. There are also few studies in the current literature focused on subsidence. The issues of predicting subsidence of support vertebral body replacement implants remain unresolved.

The objective is to analyze the causes of subsidence of modern support cages for vertebral body replacement in the early postoperative period after surgical treatment of thoracolumbar spine injuries.

Study design: retrospective, single-center, case-control study [17].

Material and Methods

This study consisted of patients who underwent surgery between 2018 and 2022 at the Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan of the Russian Ministry of Health for unstable thoracolumbar injuries. Inclusion criteria: adult patients with a history of uncomplicated spinal injuries who underwent circumferential instrumented stabilization using a transpedicular instrumentation system and an anterior expandable vertebral body replacement implant of hydraulic type, which belongs to the category of modern dynamic vertebral body replacement devices. Exclusion criteria comprised spinal injuries associated with DISH syndrome, ankylosing spondylarthritis, neoplastic or infectious lesions, and age under 15 years.

According to the mechanism of injury in the total sample (n = 46), patients were divided as follows: traffic accidents – 13.0% (n = 6), catatraumas – 39.1% (n = 18), falls from standing height – 26.0% (n = 12), weight lifting – 2.2% (n = 1), and other mechanisms of injury – 9.5% (n = 9). The sample consists of 71.7% cases of vertebral fractures (n = 33), 13.0% (n = 6) cases of post-traumatic kyphosis, and 15.2% (n = 7) cases of avascular osteonecrosis of the vertebral body secondary to pre-existing trauma. In 93.4% of cases (n = 43), corpectomy was performed at the T12, L1, and L2 levels. The structure of injuries was dominated by burst fractures of types A4/A3 according to AO Spine [18] – 89.1% of cases (n = 41). The patients were ranked according to the period of spinal injury: 54.3% (n = 25) underwent surgery in the acute period (up to 3 weeks), 21.7% (n = 10) in the intermediate period (from 3 weeks to 3 months), and 21.9% (n = 11) in the late period (more than 3 months). Three groups were distinguished according to the stage of approaches in surgery: anterior/posterior (A/P) – 63.0% (n = 29), posterior/anterior (P/A) – 26.1% (n = 12), posterior/anterior/posterior (P/A/P) – 10.9% (n = 5).

During the analysis of the total sample (n = 46), a study group (Group 1; n = 17) with radiographic evidence of subsidence of the vertebral body replacement cage was identified. The following criteria were used for evaluation: displacement of the implant into the adjacent cranial and/or caudal vertebra at 25% of the disc height – grade 0, 25–50% – grade 1, 50–70% – grade 2, 75–100% – grade 3 [19]. The rest of the patients in the sample were included in the control group (Group 2; n = 29).

Women prevail in the study group (4:13) and men prevail in the control group (16:13). The age in the groups varied in a statistically significant way and was 57 [52; 65] years and 44 [35; 52] years, respectively (p = 0.007; Table 1).

During reconstruction of the anterior column, all patients underwent anterior bisegmental fusion with autogenous bone grafts from resected vertebral bodies and ribs, which were placed around the vertebral body replacement cage. If rigid segmental kyphotic deformity was found, detected by bolster lateral radiograph, the first step was anterior mobilization, correction with an operating table bolster, and anterior bisegmental spinal fusion. In the first and second groups, rigid deformities requiring three-stage correction were identified in one and four cases, respectively. In such cases, the first stage included mobilization at the level of fibrous-bony fusion of the facet joints and placement of pedicle screws. The second stage consisted of reconstructing the anterior column using corpectomy and vertebral body replacement with an expandable implant. The surgery was completed with posterior fixation. The extent of correction was determined based on preoperative multislice computed tomography (MSCT) data. Independently of the surgery type, the segmental alignment

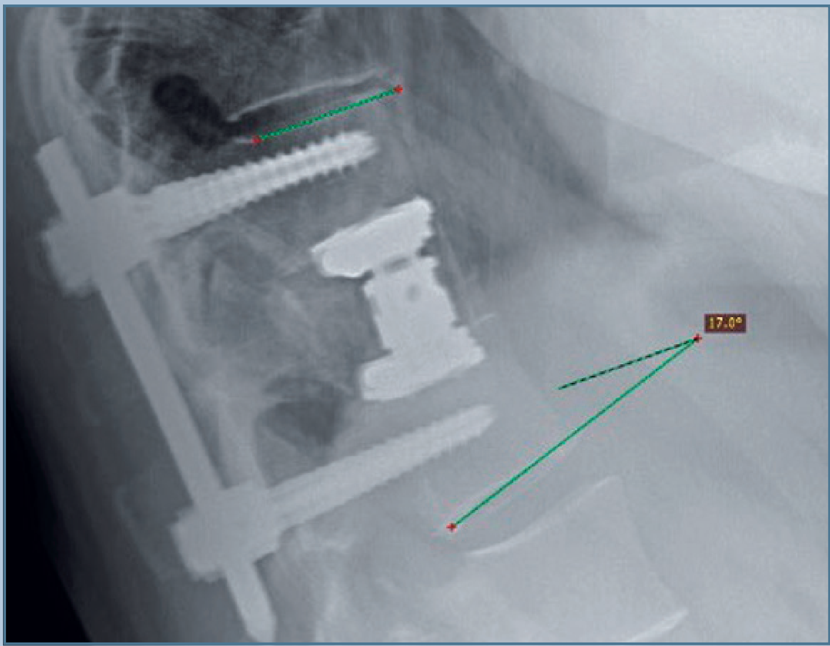

Fig. 1
Subsidence of expandable cage into the caudal vertebral body

was corrected using an operating table bolster; additional distraction using the cage by means of its elevation was not used, considering the possibility of injury to the vertebral endplates. The intended height of the interbody space was calculated as half the sum of the heights of adjacent segments. The indication for anterior column reconstruction was a load sharing classification (LSC) score of 7 or higher [20]. Flexible deformities in "fresh" cases were surgically corrected at the first stage from the posterior approach, with posterior correction and transpedicular stabilization. At the second stage of the same surgery, anterior lumbar interbody fusion was performed.

In both groups, demographic and epidemiological parameters were studied, along with the trabecular bone density of adjacent vertebral bodies using the technique by Zaidi et al. [21], the ratio of the mean area of the cranial and caudal support surfaces of the cage to the mean area of the vertebral endplates: contact surface area (A/B ratio, cm^3) [22] (Fig. 2), and the degree of implant subsidence according to Marchi [19]. The evaluated spondylometric parameters are given in Table 1.

The outcomes of treatment were analysed based on radiological data obtained upon admission, immediately after surgery, and 4, 8, and 12 months after surgery. Spondylometric data corresponding to 8 and 12 months after surgery are not included in the study, as there were no new cases of subsidence during this period.

Statistical analysis. Descriptive characteristics are given as median and first and third quartiles (Me [Q1; Q3]). For the comparable groups with and without implant subsidence, no continuous indicators were identified that simultaneously corresponded to the normal distribution law according to the Shapiro–Wilk Test, therefore the Mann–Whitney U Test was used for comparison. The Chi-Square Test was used to compare qualitative nominal, rank and dichotomous parameters. To identify the strength of the correlation between quantitative variables, Spearman's correlation coefficients and the achieved significance value were calculated. Statistical hypotheses were verified at a critical significance value of $p = 0.05$, i.e., the difference was considered statistically significant if $p < 0.05$. All statistical calculations were conducted in Statistica 12.

Results

There were no statistically significant differences in the study groups in terms of indicators such as days of hospital stay, duration of surgery, blood loss volume, morphology of injury (according to AO Spine), and spondylometric parameters such as anterior and posterior segment height before and after surgery, 4 months after surgery (Table 1). Cage subsidence in Group 1 was detected in 76.5% ($n = 13$) of patients intraoperatively during radiographic control after interbody cage implantation and elimination of spinal extension with an operating table bolster. In 23.5% ($n = 4$) of cases, subsidence was not found during admission and was detected 4 months later during an outpatient appointment. Further follow-up examinations 8 and 12 months after surgery did not reveal any additional cases of cage subsidence.

Subsidence into the cranial vertebral body was the most common, accounting for 76.5% ($n = 13$) of cases. No simultaneous subsidence into both vertebral bodies was found (Table 2).

In both Group 1 and Group 2, the anterior/posterior (A/P) surgical sequence was the most common (Table 3). Within this A/P cohort, osteopenia (T-score between 1.0 and 2.5) and osteoporosis (T-score < 2.5) were identified in 83.3% ($n = 10$) of patients in Group 1 and in 35.2% ($n = 6$) of patients in Group 2. The extent of subsidence for the A/P type of surgery reached maximum values compared to the P/A and P/A/P types (Fig. 3).

Subsidence was more frequently observed in patients who underwent surgery in the acute and late periods of injury (Table 3). In the acute injury period, slight subsidence of 2–3 mm (grade 0–1 according to Marchi) prevailed, while all severe subsidence of 5–8 mm (grade 2–3 according to Marchi) was detected with-

Table 1

Intergroup comparison of clinical and radiological quantitative parameters in study groups, Me [Q1; Q2]

Parameters	Total sample (n = 46)	Group 1 (n = 17)	Group 2 (n = 29)	Mann–Whitney U test; p-value; Group 1 vs. Group 2
Age, years	50 [36; 60]	57 [52; 65]	44 [35; 52]	0.007
Duration of hospital stay, days	14 [12; 17]	14 [12; 15]	14 [12; 18]	0.64
Injury period, days	24.5 [9; 90]	32.0 [10; 163]	18.0 [9; 63]	0.21
Surgery duration, min	147.5 [130; 175]	135.0 [125; 160]	155.0 [140; 180]	0.1
Blood loss, ml	200 [150; 300]	200 [150; 350]	250 [150; 300]	0.77
Bisegmental angle before surgery, degrees	17.0 [10; 22]	17.0 [12; 22]	17.0 [10; 22]	0.60
Bisegmental angle after surgery, degrees	4.5 [7; 0]	5.0 [7; 10]	4.0 [7; 0]	0.86
Bisegmental angle after 4 months, degrees	3.0 [0.5; 5.5]	5.0 [3; 10]	2.0 [0; 4]	0.005
Bisegmental angle after 8 months, degrees	1.5 [0; 5.5]	4.0 [1; 10]	0.0 [0; 5]	0.12
Anterior height before surgery, mm	25.0 [17; 28]	23.0 [15; 28]	26.0 [20; 28]	0.53
Posterior height before surgery, mm	29.5 [26; 34]	29.0 [23; 31]	31.0 [27; 35]	0.24
Anterior height after surgery, mm	35.5 [30; 43]	32.0 [27; 39.5]	36.5 [34; 43]	0.07
Posterior height after surgery, mm	34.0 [29; 38]	30.5 [27.5; 35]	35.0 [32; 39]	0.004
ROI of cranial body before surgery	133.5 [99; 181]	99.0 [72; 116]	143.0 [126; 192]	0.001
ROI of caudal body before surgery	116.0 [95; 161]	95.0 [62; 103]	136.0 [110; 169]	0.009
Subsidence after surgery, mm	–	2 [2; 3]	–	–
Subsidence after 4 months, mm	–	4 [3; 6]	–	–
Subsidence after 8 months, mm	–	5 [3; 6]	–	–
Subsidence after 12 months, mm	–	5 [3; 7]	–	–
Contact area of surfaces, cm^3	0.50 [0.41; 0.58]	0.40 [0.34; 0.41]	0.56 [0.51; 0.60]	0.00001

in 12 months after surgery in patients operated on in the late period of injury using the A/P technique (Figs. 3, 4).

The extent of fixation does not statistically significantly affect the formation of subsidence (Table 3), but intragroup analysis has shown that it did affect the extent of subsidence (Fig. 5). It tended to progress in the study group immediately after surgery and 4 and 12 months later and amounted to 2 [2; 3], 4 [3; 6], 5 [3; 6], and 5 [3; 7] mm, respectively. In Group 1, 82.4% (n = 14) of patients showed signs of decreased BMD according to both densitometry data and the ROI indicator in HU units (Table 3). There is a statistically significant ($p < 0.05$) correlation between the detection of cage subsidence and the value of the T-score. It should be mentioned that the ROI value in the cranial/caudal vertebral bodies differed statistically significantly in the intergroup comparison (Table 1). Intragroup analysis showed a statistically insignificant slight correlation between the ROI of the cranial and caudal vertebral bodies and the degree of vertebral

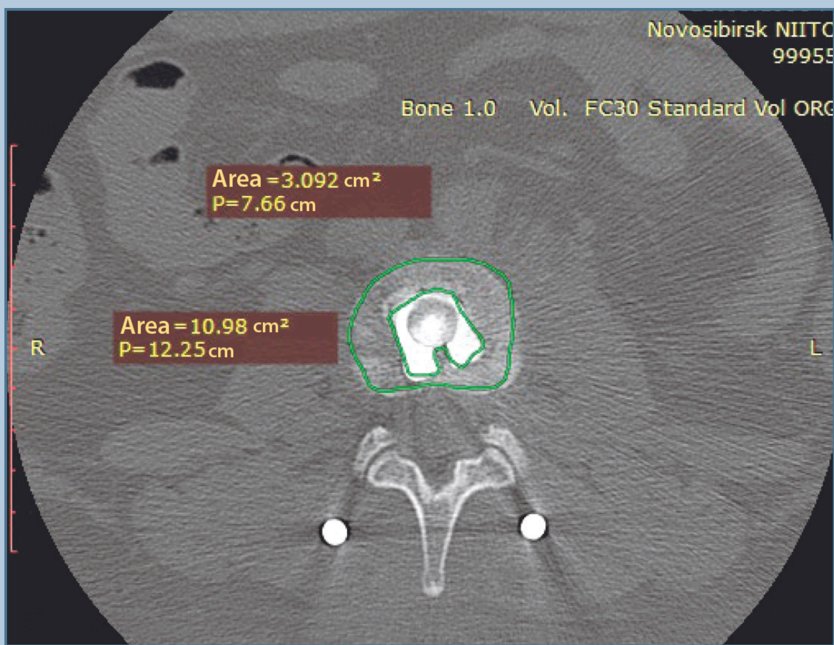

Fig. 2
Measurement of the surface area of the implant footplate and the area of the vertebral body endplate at the level of the cranial vertebra

Table 2

The degree of subsidence into the adjacent vertebral bodies according to Marchi et al. [19], % (n)

Degree according to Marchi	Cranial subsidence	Caudal subsidence
0	11.8 (2)	–
1	29.4 (5)	5.9 (1)
2	5.9 (1)	5.9 (1)
3	29.4 (5)	11.8 (2)

Table 3

Intergroup comparison of rank parameters

Parameters	Group 1 (n = 17)	Group 2 (n = 29)	p-value (χ^2)
Gender			
Males	23.5% (4)	55.2%(16)	0.03
Females	76.5% (13)	44.8%(13)	
Sequence of surgery stages			
Anterior/posterior	70.6% (12)	58.6% (17)	0.63
Posterior/anterior	23.5 % (4)	27.6% (8)	
Posterior/anterior/posterior	5.9% (1)	13.8% (4)	
Mechanism of injury			
Traffic accidents	0	20.7% (6)	0.03
Catatrauma	23.5% (4)	48.3% (14)	
Weight lifting	5.9% (1)	0	
Fall from standing height	41.2% (7)	17.2% (5)	
Another mechanism of injury	29.4% (5)	14.0% (4)	
Extent of fixation			
Short-segment	65.0% (11)	69.0% (20)	0.76
Extended	35.3% (6)	31.0% (9)	
Period of injury			
Acute	41.2% (7)	62.0% (18)	0.30
Intermediate	23.5% (4)	21.0% (6)	
Late	35.3% (6)	17.2% (5)	
Morphology			
Injury	59.0% (10)	79.0% (23)	0.12
Post-traumatic kyphosis	11.8% (2)	13.8% (4)	
Osteonecrosis of the vertebral body	29.4% (5)	7.0% (2)	
Corpectomy level			
T12	53.0% (9)	31.0% (9)	0.40
L1	23.5% (4)	35.0% (10)	
L2	17.6% (3)	27.6% (8)	
Other	5.8% (1)	7.0% (2)	
Bone density			
T-score greater than −1	17.6% (3)	65.5% (19)	0.004
T-score −1 to −2.5	41.2% (7)	24.1% (7)	
T-score less than −2.5	41.2% (7)	10.3% (3)	

subsidence over a period of 4 months (Table 4, Fig. 6). The "period of injury" factor showed a high statistically significant positive correlation with the degree of subsidence (Table 4).

A significant criterion is the ratio of the mean contact area of the cage footplates to the mean area of the vertebral body endplates, which was 0.40 [0.34; 0.41] and 0.56 [0.51; 0.60] in Group 1 and Group 2, respectively (p <0.001; Fig. 7, Table 1).

Using Spearman's rank correlation test, a statistically significant (p <0.001) inverse correlation (ρ = 0.5–0.9) was found between the values of the S contact A/B ratio and cage subsidence (mm) immediately after surgery and 4 months later (Table 5, Fig. 8). There was no significant correlation with spondylometric indicators. This is probably associated with the small sample size.

Post-operative changes in spondylometric parameters have a statistically significant slight or moderate correlation with the "subsidence" parameter in the study group in the post-operative period (Table 6).

An analysis of the parameters four months after surgery indicates that the degree of subsidence has a weakly positive effect on the degree of segmental kyphosis in the postoperative period (Fig. 9).

Patients with bone cement-augmented pedicle screw fixation in the study group predictably predominated compared to the control group: 35.3% (n = 6) and 3.4% (n = 1), respectively. It should be mentioned that its contribution to preventing subsidence is controversial. Patients with screw augmentation in the study group had more severe subsidence values (Fig. 10). This fact requires further study on larger samples.

There were no patients in the study group with signs of instability or disruption of the transpedicular system, or with signs of osteolysis around the screws over the 12-month follow-up period.

Discussion

In the course of time, critical material has been accumulated in the literature

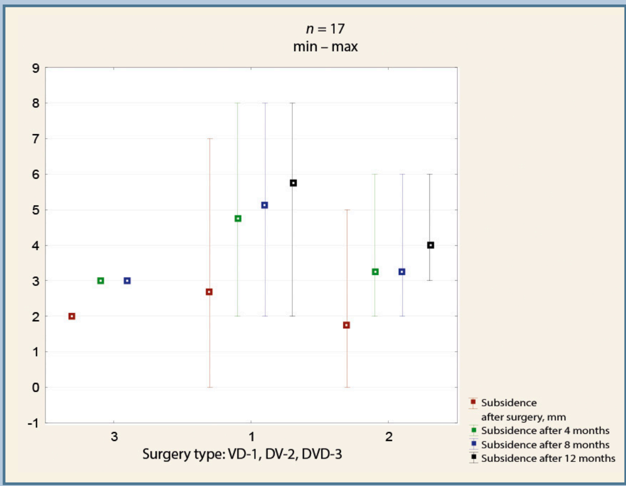

Fig. 3
The impact of the surgery stage on subsidence extent

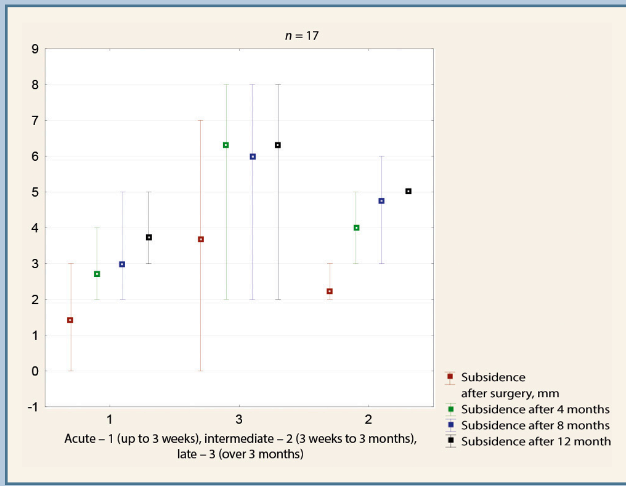

Fig. 4
The correlation between subsidence extent and period of injury

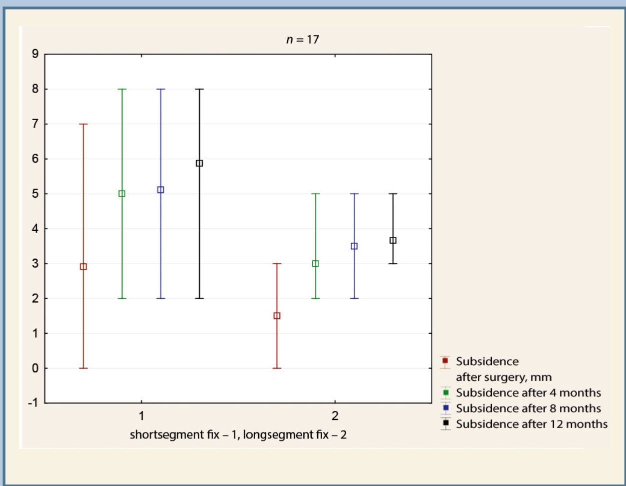

Fig. 5
The correlation between subsidence extent and the extent of fixation

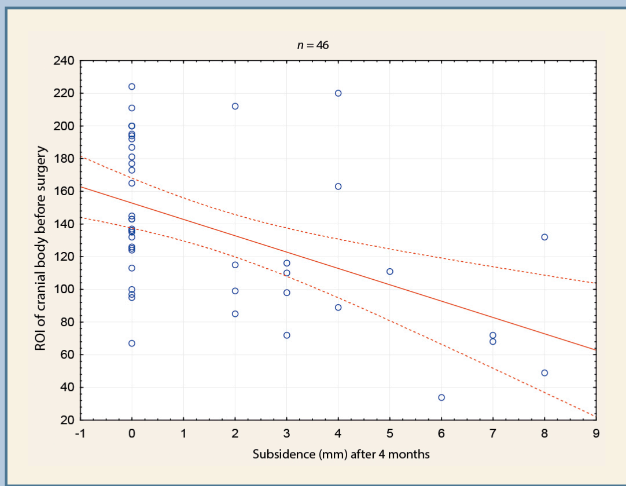

Fig. 6
Scatterplot. Variables: ROI (region of interest) values of the cranial body and subsidence extent

on the reasons for unsatisfactory surgical outcomes in the treatment of spinal injuries such as cage subsidence, which occurs in 25–50% of cases in the postoperative period [7, 23]. The mean extent of subsidence in the early postoperative period varies from 5.5 ± 2.7 to 9.3 ± 5.1 mm [7]. The primary risk factors include excessive distraction of the anterior column [7], excessive or inadequate curettage of the endplate [24], insufficient bone-implant contact area [25], low BMD [23], an inadequate volume of osteoinductive material [7], central placement of the implant [26], mismatch between the footplate inclination angle of the cage and the segmental lordotic angle [27], and short-segment posterior instrumentation [23].

From a biomechanical point of view, the problem of interbody space reduction is associated with a mismatch between the internal resistance of bone tissue and the load applied by the interbody implant to the vertebral endplate. Bone density is described by Young's modulus, which is determined by the structure of trabecular and cancellous bone. Additionally, an important factor is the stress applied to the vertebral endplate [28]. If the telescopic cage is overdistracted, the height of the segment exceeds the required height, result-

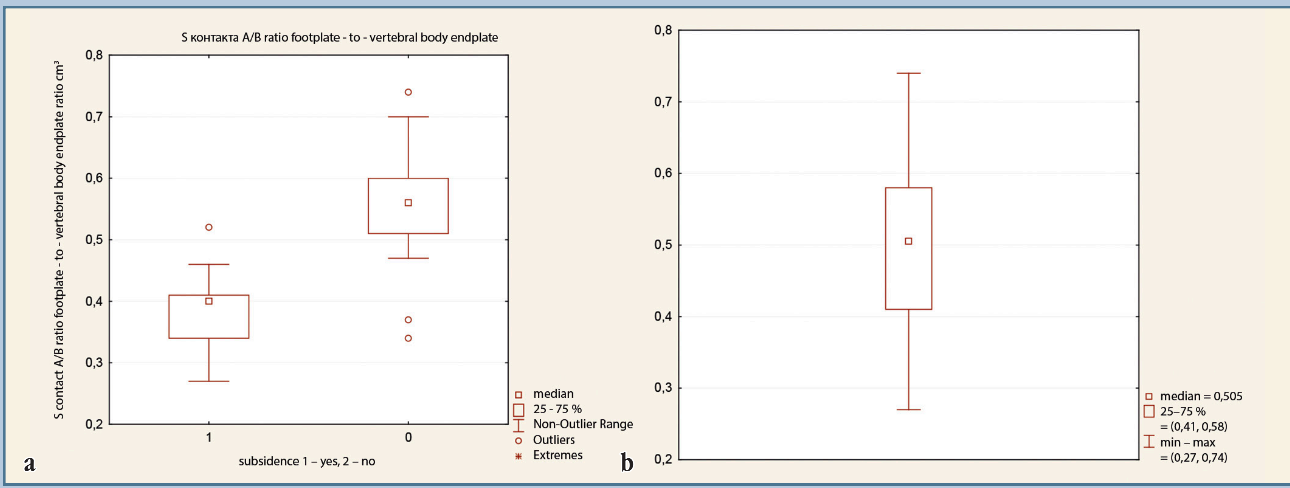

Fig. 7
The value of the ratio of the mean surface area of the implant footplates to the mean surface area of the vertebral body endplate (S contact A/B ratio): **a** – in study groups; **b** – in the total sample ($n = 46$)

ing in increased pressure on the endplate. Since the total force applied to the intervertebral space is constant under normal axial load conditions, the applied pressure is defined by the ratio of the contact surface area of the implant to the vertebral body. The wider footplates of the implant spread the force over a larger area, reducing both the mean and maximum stress. This would typically increase the possibility that the force applied during patient verticalization will cause bone deformity within the elastic zone, i.e., below the yield point of the bone tissue in the endplate region of the vertebral body, thereby reducing the risk of implant subsidence [29].

We have received confirmation in our study that female gender, age, period of injury, and its low-energy nature are parameters that indirectly indicate a decrease in bone density, which, according to the literature, is a cornerstone in the development of subsidence.

The A/P sequence of the surgery stages with reduced bone density provides

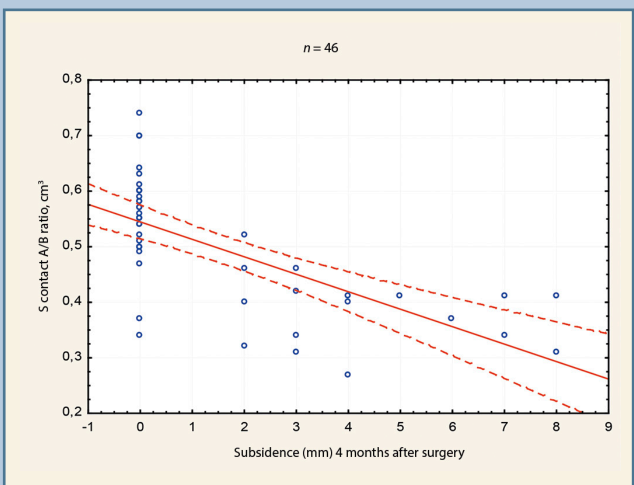

Fig. 8
Scatterplot for the parameters “S contact A/B ratio” and “subsidence extent”

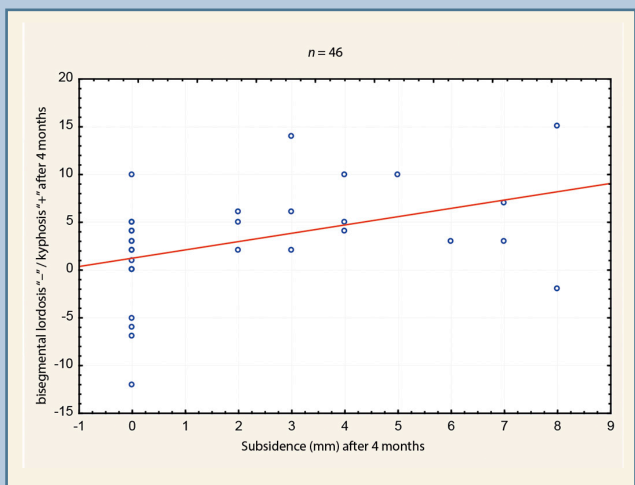

Fig. 9
Scatterplot. Variables: segmental kyphosis/lordosis and subsidence extent 4 months after surgery

Table 4

Correlation of subsidence and quantitative parameters

Parameters	Spearman's rank correlation test (subsidence after 4 months)
ROI (region of interest) of the cranial body before surgery	–0.33
Subsidence after 4 months	1.00
ROI (region of interest) of the caudal body before surgery	–0.38
Age	0.53
Hospital stay, days	0.15
Period of injury, days	0.80
Blood loss	0.06

Significant correlation at $p < 0.001$ ($n = 17$).

all the conditions for intraoperative cage subsidence, either when correcting hyperextension with the operating table bolster or when incorrectly repositioning the patient into the prone position before the posterior stage.

It is confirmed by biomechanical studies that the contact area between the implant and the bone is critical for the initial stability of fixation. Nevertheless, some contradictions have been identified in the specialized literature. Thus, a study by Lau et al. [7] showed a statistically significant ($p = 0.046$) influence of parameter value of S contact A/B ratio of less than 0.5 on the subsidence of the body replacement implant, as diagnosed in the first month after surgery. Reinke et al. [30] conducted a retrospective study of 20 patients with type A2 and A4 injuries using implants with a mean S contact A/B ratio of 0.81. There were no significant clinical or radiological adverse outcomes in patients with one-year follow-up. Meanwhile, the authors do not assert that the use of implants with a large contact area significantly affects the frequency of implant subsidence; additional study is required to investigate this issue. Terai et al. [13] studied the use of large-contact-area body replacement implants in 69 patients with osteoporotic fractures of the thoracolumbar ($n = 35$) and lumbar ($n = 34$) spine. The mean age in the first group was 76.5 ± 5.9 years, and 75.1 ± 7.2 years in the second group. Implant subsidence of more than 2 mm was found in both groups in the early postoperative period in 46% and 44% of cases, respectively. Five patients required revision surgery for progression of subsidence and increasing kyphosis. The authors stated that during anterior column reconstruction in patients with osteoporosis, the contact area between the cage and bone may not be a significant factor affecting implant subsidence, and doubted the significance of the "implant/bone contact area" parameter on implant subsidence.

Ulrich et al. [31] have identified that bone density, as assessed in HU, has a dominant influence on body replacement cage subsidence and loss of reduction. If HU is less than 110, the 100% subsidence with a range of 8 ± 2 mm is revealed. The authors recommend measuring HU before surgery and using additional techniques to augment adjacent endplates with bone cement for patients with HU <180. We have affirmed this data. In the older group of patients with reduced BMD, the HU values of adjacent vertebral bodies were significantly lower compared to the control group, which is consistent with the established view in the literature.

Modular cages made of PEEK material are reported in the literature as an alternative to titanium body replacement cages. Having a Young's modulus of 3.5 GPa, PEEK material, compared to titanium (110 GPa), has an advantage and provides optimal load sharing at the level of fixed segments. The elastic modulus of PEEK is close to that of bone tissue (12 GPa). Thus, according to Wolff's law, a PEEK cage should provide less stress shielding and create conditions for coossification [32].

The literature suggests several measures to prevent potential subsidence

Table 5

The correlation strength of between the surfaces contact area (S contact A/B ratio), spondylometric parameters, and subsidence

Parameters	Spearman's rank correlation test; S contact A/B ratio, cm^3
Bisegmental kyphosis before surgery, degrees	–0.10
Bisegmental lordosis after surgery, degrees	0.02
Bisegmental lordosis "–" / kyphosis "+" after 4 months	–0.41
Bisegmental lordosis after 8 months, degrees	–0.47
Anterior height before surgery, mm	0.07
Posterior height before surgery, mm	0.12
Anterior height after surgery, mm	0.16
Posterior height before surgery, mm	0.19
Subsidence after surgery, mm	–0.56
Subsidence after 4 months, mm	–0.73
Subsidence after 8 months, mm	–0.70
Subsidence after 12 months, mm	–0.68
S contact A/B ratio, cm^3	1.00

Significant correlation at $p < 0.001$.

Table 6

The correlation strength between spondylometric parameters and subsidence

Parameters	Bisegmental posterior height after surgery, mm	Bisegmental anterior height after surgery, mm	Subsidence after surgery, mm	Bisegmental lordosis after surgery, degrees
Bisegmental posterior height after surgery, mm	1.00	0.94	−0.44	−0.27
Bisegmental anterior height after surgery, mm	0.94	1.00	−0.38	−0.28
Subsidence after surgery, mm	−0.44	−0.38	1.00	−0.13
Bisegmental lordosis after surgery, degrees	−0.27	−0.28	−0.13	1.00

Spearman's rank correlation test; significant correlation at $p < 0.001$ ($n = 17$).

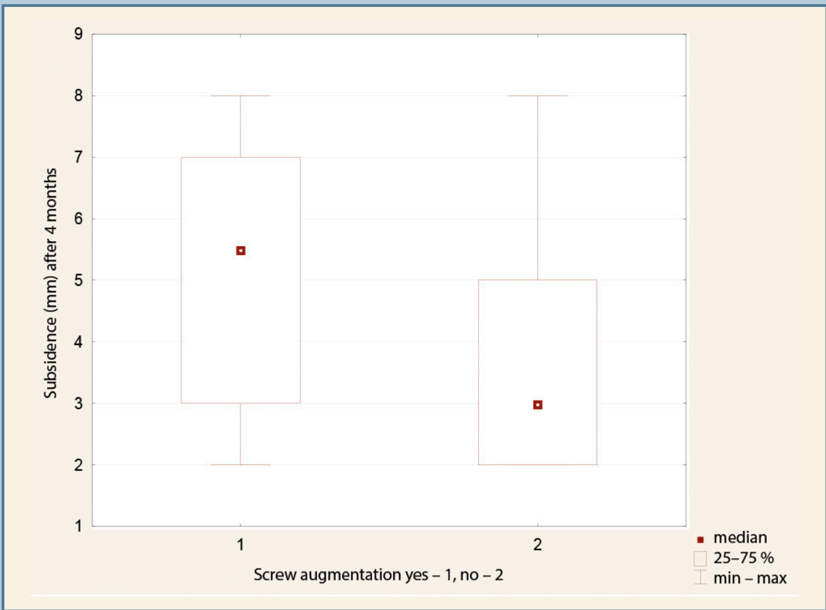

Fig. 10

The impact of screw augmentation on subsidence extent

of support implants in osteoporosis, including avoiding implant overdistraction [28]; using wide rectangular footplates to increase the contact area [25, 29], anterior bone cement augmentation of vertebral bodies beneath the footplates [15, 33]; planning the implant's footplate inclination angle to match the anatomical contour of the vertebral endplate [34, 35]; and performing transpedicular fixation extended at least two levels above and below the corpectomy level [7, 23].

We did not find a significant effect of augmentation of pedicle screws with bone cement and the extent of posterior instrumentation on the onset of subsidence, but we did find a correlation between these parameters and the extent of subsidence.

Using the findings and evidence from the literature, we can say that the factors causing subsidence can be divided into three groups: those associated with biology at the fixation site, those associated with surgical technique, and those associated with the biomechanics of fixation. By thorough preoperative planning with consideration of indications and contraindications, surgeons with appropriate backgrounds can reduce the first and second groups of possible reasons. The biomechanics of fixation therefore require more complex configurations and can be adjusted, for example, by using support cages with a personalized elasticity module for the contact surfaces. A combination of factors such as patient age, reduced bone density, insufficient implant/bone contact area, anterior/posterior stabilization, and late injury have a significant impact on the formation of subsidence when using expandable body replacement implants. This implies that modern industrial expandable body replacement cages have limitations when used in patients with osteoporosis, and beyond these limitations, subsidence occurs, even when all possible risk factors are accounted. Therefore, for patients with reduced BMD in anterior column reconstruction, it is likely that implants with fundamentally different biomechanical characteristics will be required.

Limitations of the study. The study did not include sagittal balance parameters due to the majority of patients with acute injury.

Conclusion

The use of modern expandable body replacement cages in anterior spinal column reconstruction results in their subsidence in a number of cases, which is more common in women, mainly in the cranial body, and arises more often either intraoperatively or between stages of the surgery. The period of injury affects the onset of subsidence and correlates highly with its extent. If subsidence is found in the early postoperative period, its progression is reported within one year after surgery. The sequence of stages in circumferential fixation does not inherently influence the occurrence of subsidence; therefore, for patients with osteoporosis undergoing circumferential fixation, it is advisable to perform the posterior approach as the first stage. Implant subsidence has a significant effect on segmental kyphosis in the postoperative period. A ratio of less than 0.4 between the mean contact area of the implant surface and the vertebral body endplate is a significant indicator for predicting subsidence and requires further study.

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.

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Received 15.11.2024
Review completed 11.11.2025
Passed for printing 25.11.2025

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