SURGICAL STABILIZATION FOR DEGENERATIVE LESIONS OF THE LUMBAR SPINE IN PATIENTS WITH REDUCED BONE MINERAL DENSITY: A SYSTEMATIC LITERATURE REVIEW

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Objective. To analyze methods contributing to the improvement of clinical and radiological outcomes of surgical stabilization of the lumbar spine in conditions of reduced bone mineral density (BMD).
Material and Methods. A search for publications presenting the results of clinical studies of surgical treatment of patients with degenerative lesions of the lumbar spine and reduced BMD was conducted in English and Russian in the MEDLINE and Russian Science Citation Index (RSCI) databases using key words "osteoporosis", "osteopenia", "spinal surgery", "spinal fusion" and related terms in titles and abstracts with a search depth of 20 years. After applying the inclusion and exclusion criteria, 17 clinical studies were selected for analysis.
Results. Among the large number of techniques and implant-associated factors affecting the success of surgical intervention for degenerative lesions of the lumbar spine and reduced BMD, high-quality clinical studies have proven the effectiveness of expandable screws, spinal fusion with cortical screw placement and cement augmentation with polymethyl methacrylate.
Conclusion. The combination of techniques for cortical pedicle screw placement, cement augmentation and the use of expandable screws makes it possible to achieve results in surgical treatment of patients with degenerative lesions of the lumbar spine with reduced BMD comparable with those in patients with normal BMD. Of particular importance is the preoperative assessment of the regional state of bone tissue, which should be carried out using quantitative CT or MRI studies.
Key Words: degenerative lesions of the lumbar spine, bone mineral density, osteoporosis, osteopenia.
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Osteoporosis is a multifactorial disease characterized by a decrease in the T-score of bone mineral density (BMD) by 2.5 or more standard deviations from the mean values for young healthy subjects [1]. Its incidence reaches 19.8–26.9 % among women and 9.6–14.1 % among men [2]. The number of patients suffering from osteoporosis in the Russian Federation is approximately 16 million. The urgency of this issue is determined by not only the increased risks of pathologic fractures and disability and mortality associated with them, but also by the influence of osteoporosis on the rates of unsatisfactory outcomes of surgical treatment of patients with degenerative disc disease.

The incidence of osteopenia and osteoporosis among patients undergoing surgical lumbar spinal fusion is 43.6 % and 14.9 %, respectively, and in patients over the age of 50, the occurrence of osteoporosis reaches 32.4 %. [4, 5]. Multilevel stabilizing surgery in patients with low bone quality is associated with an increased risk up to 13 % for early complications (pedicle fractures, compression fractures of the adjacent segment) and up to 38 % for late complications (pseudoarthrosis, screw loosening, junctional kyphosis, degenerative changes and compression fractures of the adjacent segment) [6]. Nowadays, there are no generally accepted clinical guidelines for the surgical treatment of patients with degenerative lesions of the lumbar spine and reduced BMD.

The objective is to analyse the techniques contributing to the improvement of clinical and radiological outcomes of surgical stabilization of the lumbar spine in conditions of reduced BMD.

Material and Methods

We have conducted a search in the MEDLINE and Russian Science Citation Index (RSCI) databases for clinical trial results in English and Russian concerning surgical treatment of patients with degenerative lumbar spine lesions under condition of reduced bone mineral density (BMD), including an assessment of clinical and radiological outcomes. The search was performed using the following keywords: "osteoporosis", "osteopenia", "spine surgery" and "spinal fusion" and related terms in titles and abstracts. According to the described search strategy, 251 articles were identified and verified for compliance with the inclusion and exclusion criteria.

Inclusion criteria:

1) original clinical retrospective or prospective studies;

2) most patients in the study cohort underwent surgery for a symptomatic degenerative lesion of the lumbar spine with instrumentally confirmed reduced bone mineral density. Its criterion was

the T-score of dual-energy X-ray absorptiometry (DEXA) equal to -1.0 or lower (the density values from CT data were not used when selecting papers as the main ones due to the lack of a standardized measurement technique in preoperative planning, and as a result made it impossible to objectively compare the studies);

3) the clinical and/or radiological outcomes of treatment were assessed, followed by statistical analysis.

Exclusion criteria:

1) biomechanical studies performed in animals, cadaver or computer models, or case studies or case series;

2) the ICD diseases that were indications for spine surgery have not been quantified, or the study groups for them were statistically significantly heterogeneous;

3) degenerative lesions in the lumbar spine were the indication for surgery in less than half of the patients in the study cohort. The main reasons for surgery were vertebral fractures, tumors or inflammatory spondyloarthropathy;

4) there was no data on the BMD of the subjects studied, or it did not match the criteria for osteoporosis or osteopenia;

5) surgical treatment was performed not on the lumbar spine in most patients;

6) there was no evaluation of the clinical and/or radiological outcomes of treatment;

7) there was no statistical processing of the results;

8)the full-text version of the article was not available.

After using the inclusion and exclusion criteria, 16 clinical trials were included in the analysis. The general methodology of searching for clinical trials is illustrated in Fig.

The search depth was 20 years. The level of evidence in the conducted study was 4 (OCEBM Levels of Evidence Working Group, The Oxford 2011 Levels of Evidence).

Results

Accurate assessment of BMD is an essential stage of preoperative preparation. DEXA is the gold standard for quantifying BMD, correlating mainly with the risk of pathological fractures and the potential benefits of prescribed conservative treatment [7]. In the context of surgical planning, this technique has several disadvantages. The presence of a summation effect in the region of interest prevents us from evaluating the condition of the trabecular bone alone, and the result may be affected by concomitant osteosclerosis, which invariably accompanies degenerative disc disease [8]. An alternative is the software module for analysing the trabecular bone structure (Trabecular Bone Score, TBS). Clinical studies have shown that TBS predicts bone strength better than conventional DEXA. However, it remains an indirect method for evaluating trabecular bone [9]. A direct evaluation of the density of trabecular bone can be achieved using CT and MRI studies. According to DEXA, the T-scores for the vertebrae only explain 48 % of the variation in the regional density of trabecular bone in the Hounsfield units (HU) [10]. Quantitative computed tomography (QCT) is used to perform a volumetric analysis of trabecular bone in terms of mineral density units (mg/cm). This technique effectively predicts the strength of transpedicular fixation, surpassing the accuracy of conventional densitometric values [11]. The BMD measured by CT is statistically significantly associated with the rate of loosening of screws and pseudoatrosis [12–14]. The high correlation between HU values and T-scores from DEXA allows us to determine the presence of osteoporosis or osteopenia based on CT findings alone. The mean value of trabecular bone density, measured by CT scans in three regions of interest (ROI) in the shape of an ellipse in the middle of the L1–L4 vertebral bodies and next to the end plates in patients with normal bone density, osteopenia and osteoporosis, according to DEXA, was 133.0 ± 37.6, 100.8 ± 24.5 and 78.5 ± 32.4 HU, respectively. Meanwhile, the lower limit of the 95 % confidence interval of normal bone density was 118.4 HU, and it was 93.1 HU for osteopenia [10]. Therefore, in the context of upcoming surgery, patients with a trabecular bone density of less than 120 HU and 90 HU in the vertebrae of interest can be considered to have osteopenia and osteoporosis, respectively. Unlike MRI, the main disadvantage of QCT is the high radiation exposure. Among the various assessment techniques used in MRI, relaxometry with a quantitative assessment of bone quality (Vertebral Bone Quality, or VBQ) has the greatest practical significance. The technique is based on a change in the signal in T1-weighted images (T1-WI), as the normal trabecular bone is replaced by bone marrow adipose tissue. It represents the ratio between the signal intensity of the trabecular bone in the vertebral body and the signal intensity of cerebrospinal fluid at the same level. VBQ is an influential risk factor in clinical trials, affecting the probability of screw loosening [15]. The predictive accuracy of VBQ may surpass HU [16]. Just as with HU, VBQ strongly correlates with T-scores of densitometry. The optimal diagnostic criteria for osteopenia and osteoporosis are VBQ values of 2.56 and 2.83, respectively [17]. In this case, an inverse correlation is observed, since the adipose involution of trabecular bone is characterized by increased signal intensity on T1-WI. In this regard, an MRI scan can effectively complement QCT during the preoperative assessment of bone quality.

A prerequisite for successful surgical outcomes when performing decompression and stabilization procedures on the lumbar spine is appropriate immobilization of the affected segment until a complete interbody fusion has formed. Therefore, the initial strength, which is provided intraoperatively, is essential for prevention of pseudoarthritis. The most common technique of posterior stabilization is the use of pedicle screws in combination with interbody fusion. Failures of posterior stabilization in osteoporosis are characterized by the loosening, cutting-out or pulling-out of screws. Consequently, the main existing prevention techniques are aimed at modifying

the design and placement techniques of pedicle screws.

The strength of the screw fixation generally depends on the contact area of the screw and the degree of compression of the bone in the walls of the screw channel. These parameters can be affected by the diameter, length and shape of the rod and the thread of screw as demonstrated in several biomechanical research. Among all the techniques for modifying the design of pedicle screws, only expandable screws have been clinically studied in patients with reduced BMD. In a controlled clinical trial with 24-month follow-up of patients with osteoporosis after lumbar spinal fusion, the rate of interbody block formation was significantly higher (92.5 % and 80.5 %, respectively) and frequency of loosening was lower (4.1 % and 12.9 %, respectively) in the group using expandable screws compared to conventional screws [18]. In comparison with fenestrated screws and cement augmentation, transpedicular fixation with expandable screws in patients with reduced BMD allows for similar clinical and radiological outcomes. Meanwhile, the risks of complications associated with cement extravasation are completely excluded [19]. In a lower-quality, non-controlled trial of the use of expandable screws for osteoporosis, satisfactory clinical outcomes were seen. Over 35 months of follow-up, the rate of maintained stability in the operated segment was 86 % [20]. While the improvement in clinical and radiological outcomes is significant, there is currently no evidence to suggest that the use of expandable screws leads to an increase in the number of implant-associated complications.

Despite the fact that laboratory studies have shown the importance of a set of parameters in pedicle screw placement techniques, including methods for pedicle preparation and trajectory change, as well as the use of double screws, the cortical placement method with reduced BMD was clinically examined. In an independent variant, the trajectory of the screw insertion through the cortical bone means its passage in the mediolateral and caudocranial direction only through the compact bone tissue of the vertebra without engaging the trabecular bone of the body that is first to loose strength in osteoporosis [21]. The BMD in the area of cortical bone trajectory of screw fixation is considerably higher than in the area of conventional anatomical one (parallel to the course of the pedicle) [22, 23]. The placement of cortical screws in combination with interbody fusion is characterized by a special variant of the median approach, MIDLIF (Midline Lumbar Interbody Fusion). This technique requires a much lower degree of dissection of soft tissues than with conventional methods. Transforaminal lumbar interbody fusion in conditions of osteoporosis using a conventional trajectory result in a significantly higher incidence of screw loosening than with a cortical trajectory (28.13 % and 6.50 %, respectively). Nevertheless, radiological and clinical outcomes do not differ [24]. According to a recent randomized clinical trial, the cortical trajectory in osteoporosis can improve short-term clinical outcomes at a follow-up point of 3 months. As for the evaluation after one year, the number of loose screws is considerably less than with the conventional trajectory [25]. The shorter duration of the surgery, the less blood loss volume and the muscle injury during the MIDLIF contribute to the rapid activation of patients that is particularly important for osteoporosis. In patients with osteoporosis who have undergone lumbar fusion with MIDLIF and have been followed for three years, the overall rate of stable bone block is 90.5 %, and their quality of life improves significantly [26]. Due to this experience, MIDLIF may be regarded as a promising alternative to conventional technique. The clinically studied methods of modifying the design and placement techniques of screws are summarized in Table 1.

One of the most widely applied methods of increasing the strength of the posterior fixation is pedicle screw cement augmentation. The use of polymethyl methacrylate (PMMA) has a greater evidence base than other biocompatible compositions. There are two main tech-

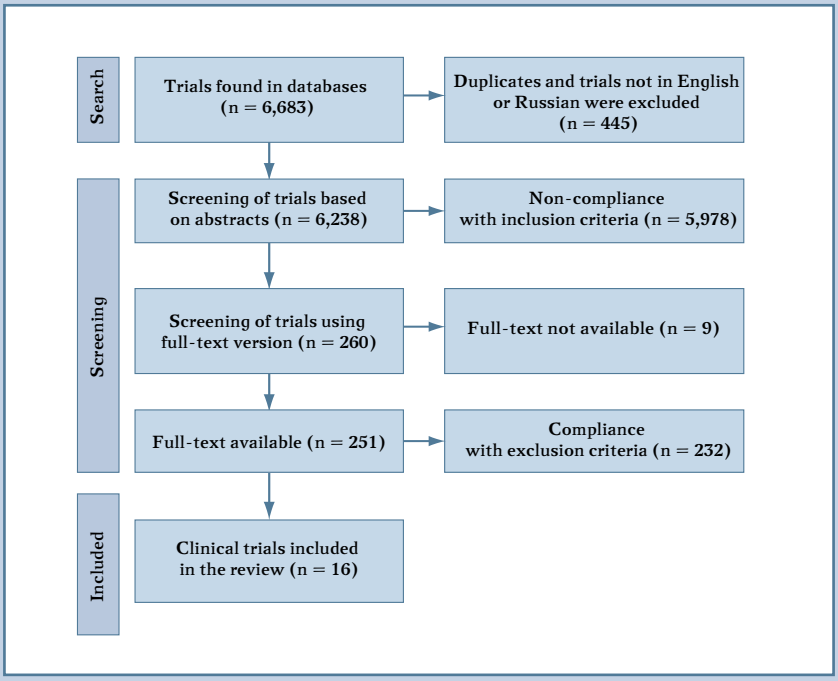

Fig.
Methodology for searching clinical trials

niques of cement augmentation: pre-filling of the screw channel with material and its injection into cannulated pedicle screws.

The use of PMMA has been widely studied in clinical practice. Pre-filling screw channels with PMMA, followed by the placement of high-strength screws, is an effective technique for preventing loosening and implant-associated complications in cases of osteoporosis [27]. In non-controlled retrospective and prospective studies, the use of PMMA with cannulated screws in patients with osteoporosis for transpedicular fixation combined with posterolateral or interbody fusion has been shown to practically eliminate the risk of screw loosening and, in the vast majority of cases, significantly improve clinical outcomes [28–32]. In case of surgery for spondylolisthesis in conditions of osteoporosis, minimally invasive transforaminal interbody fusion (MIS-TLIF) using PMMA allows for a better degree of reduction and angle of segmental lordosis than without augmentation [33]. In cases of extended instrumentation system (3 or more levels) and osteoporosis, the use of cement augmentation significantly reduces the rate of screw loosening (0.89 % vs 8.46 % in the control group). Most cases of screw loosening are found on the cranial or caudal segments of the instrumentation. Selective cement augmentation of the end vertebrae may be useful in case of increased number of operated levels, considering the high rate of PMMA extravasation (34.52 %) [34]. Meanwhile, unilateral cement augmentation ensures clinical outcomes that are no worse than those achieved with bilateral augmentation, while reducing the amount of surgery duration, blood loss and the incidence of cement leakage [35]. The clinical experience of using PMMA for degenerative lesions of the lumbar spine and reduced BMD is given in Table 2.

In cases of reduced BMD, there are increased risks of postoperative implant-associated complications, including junctional fractures and kyphosis development in the long term. For example, the risk of proximal junctional kyphosis (PJK) in osteoporosis increases by 2.5 times [36]. The presence of osteoporosis reinforces the negative effect of an excessive proximal junctional angle in the form of an increased risk of PJK by 66.4 % with each additional degree [37]. One of the principles for decreasing the probability of these complications is load reduction on each fixation point and junctional mobile segments. Clinical prevention techniques for PJK with reduced BMD have been studied only in a small number of articles. In non-controlled trials, preventive vertebroplasty of the proximal adjacent segment efficiently prevents the development of fractures in the postoperative period [27, 38]. According to domestic studies, vertebroplasty and pediculolaminar fixation are both effective techniques for preventing fractures of the superjacent vertebra. In case of osteoporosis, radical correction of lumbar hypolordosis and sagittal imbalance should be avoided, since this in some cases increases the risks of complications [39]. Clinically studied prevention techniques for PJK are given in Table 3.

Discussion

Nowadays, despite a large number of studies on the surgical treatment of spinal pathology associated with reduced bone mineral density, no unified approach to instrumentation has been developed for this cohort of patients. This is mostly due to the prevalence of experimental biomechanical studies on animals, cadavers or computer models that are heterogeneous in design. Only a small number of clinical trials are performed in a cohort of patients with instrumentally confirmed reduced BMD. An insufficient number of clinical trials aggravates the identification of factors significantly affecting the success of surgery. Undoubtedly, augmentation with PMMA cement is the most widely studied technique in clinical trials. The benefit of this increases with the decrease in BMD. Analysis of the available data reveals a significant reduction in the incidence of both pseudoarthrosis and screw loosening with the use of cement augmentation in patients with osteoporosis. Also, a minimization of postoperative implant-associated complications is observed. The improvement of radiological and clinical outcomes can be achieved through the use of conventional techniques or fenestrated screws. These screws have the advantage of reducing the risk of cement extravasation. Additional factors related to the design and placement of pedicle screws with proven clinical efficacy are expandable screws and their placement along a cortical trajectory. The use of expandable screws in high-quality clinical trials is safe in the context of the risk of implant-associated complications and provides better stability in conditions of reduced BMD than conventional pedicle screws. The technique of median cortical fixation with interbody fusion not only improves the rates of successful arthrodesis, but it also results in less muscle injuries and revision of the posterior support structures during the surgical approach. This contributes to the earlier activation of patients after surgery. The combination of preventive vertebroplasty and laminar fixation of junctional segments is efficient in the prevention of PJK. Considerably less attention has been paid to the use of interbody implants in case of reduced bone mineral density in the existing range of clinical trials, which is a promising area for research. The appropriateness of using described surgical techniques should be determined by an accurate preoperative assessment of the regional density of trabecular bone. Therefore, quantitative CT or MRI scans are more preferable than standard densitometry. The guideline for making a decision about whether to use the techniques described above is based on a reduction in bone density of 90–120 HU or less, as determined by volumetric analysis of bone density using MSCT scans.

Conclusion

The combination of techniques for cortical pedicle screw placement, cement augmentation and the use of expandable screws allows for achieving results in surgical treatment of patients with

Table 1
Clinical trials of modifications of design and pedicle screw placement techniques in conditions of reduced BMD

Trial	Design	Surgical treatment	Study groups / cohort	Outcomes	Conclusions
Modification of pedicle screw design					
Wu et al. [18]	RCT of 157 patients with osteoporosis and symptomatic lumbar spinal stenosis	Single- or multilevel transpedicular fixation with or without interbody arthrodesis/posterolateral fusion	Main (80): expandable pedicle screws; control (77): conventional pedicle screws without additional cement augmentation	Number of loose screws (24 months): 20 vs 48 ($p < 0.001$); number of screw fractures (24 months): 2 vs 0 ($p = 0.34$); interbody block rate (24 months): 92.5 % vs 80.5 % ($p = 0.048$); ODI (12 months): 11.4 % vs 14.6 % ($p < 0.001$) in the study and control groups, respectively	Expandable screws surpass traditional ones in clinical and radiological outcomes in patients with osteoporosis after decompression and stabilization surgery of the lumbar spine
Gazzeri et al. [19]	RCT of 40 patients with osteopenia or osteoporosis who had fractures or degenerative pathology of the lumbar spine requiring surgical stabilization	Single- or multilevel transpedicular fixation without discectomy and interbody arthrodesis	Main (20): expandable screws without cement augmentation; control (20): cannulated screws with augmentation with 1.5–3.0 ml of PMMA per screw	ODI (24 months): 23.8% vs 22.9% ($p = 0.79$); VAS (24 months): 2.9 vs 3.0 points ($p = 0.67$); satisfaction with the treatment outcomes 90 % vs 85 % ($p = 0.58$) in the main and control groups, respectively. In all cases, the operated segment was stable after 24 months of follow-up	Expandable screws are equal to cannulated screws in clinical and radiological efficiency and completely eliminate the risks associated with cement extravasation
Cook et al. [20]	Retrospective analysis of 145 cases of lumbar spinal fusion for degenerative pathology, fractures, tumour lesions	Single- or multilevel transpedicular fixation with expandable screws without discectomy and interbody arthrodesis	21 of 145 patients had osteoporosis. 17 of them had degenerative disc disease of the lumbar spine as an indication for surgery	With an mean follow-up period of 35 months, the rate of stability of the operated segment in osteoporosis was 86%	Expandable screws provide satisfactory surgical outcomes in conditions of osteoporosis where the use of conventional screws is associated with a high risk of loosening
Modifications to pedicle screw placement techniques					
Liu et al. [24]	RCT of 70 patients with osteoporosis and degenerative disc disease of the lumbar spine	Single- or two-level interbody fusion using a cortical screw trajectory (MIDLIF) or conventional transforaminal interbody fusion (TLIF)	Main (31): interbody fusion using MIDLIF; control (32): conventional TLIF	Number of loose screws (18 months): 6.50% vs 28.13 % ($p = 0.03$); depth of cage subsidence (18 months): 2.49 vs 3.01 mm ($p = 0.02$) in the main and control groups, respectively; the incidence of interbody block did not differ significantly	The cortical screw trajectory provides similar clinical outcomes and better segment stability for lumbar fusion in conditions of osteoporosis compared to the conventional one
Ding et al. [25]	RCT of 124 patients with osteoporosis and degenerative disc disease of the lumbar spine	Single-level interbody fusion using a cortical screw trajectory (MIDLIF) or conventional transforaminal interbody fusion (TLIF)	Main (62): interbody fusion with MIDLIF; control (62): conventional TLIF	Number of loose screws (12 months): 3 vs 14 ($p = 0.006$) in the main and control groups, respectively; the incidence of interbody block and clinical outcomes did not differ significantly	The cortical screw trajectory provides similar clinical outcomes and better segment stability for lumbar fusion in conditions of osteoporosis compared to the conventional one

The end of the Table 1

Clinical trials of modifications of design and pedicle screw placement techniques in conditions of reduced BMD

Noh, Zhang [26]	Retrospective analysis of 200 patients with osteopenia and degenerative disc disease of the lumbar spine	Single- or multilevel interbody fusion using a cortical screw trajectory (MIDLIF)	Division into groups depending on the number of operated segments. On average, patients in each group had a reduced BMD specific for osteopenia	The overall incidence of interbody block 3 years after surgery is 90.5 %. There were no reported cases of implant-associated complications. All patients had a statistically significant improvement in the VAS, ODI, SF-36	Cortical screw trajectory provides satisfactory clinical and radiological outcomes when performing lumbar fusion in conditions of osteopenia

RCT — randomized controlled trial; PMMA — polymethyl methacrylate; BMD — bone mineral density.

degenerative lesions of the lumbar spine with reduced BMD, that are not worse than ones in patients with normal BMD. It is particularly important to perform a preoperative assessment of the regional state of bone tissue that should be performed using quantitative CT or MRI scans.

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.

Table 2
Clinical trials of the use of PMMA in conditions of reduced BMD

Trial	Design	Surgical treatment	Study groups / cohort	Outcomes	Conclusions
Cement augmentation of pedicle screws					
Alvarez-Galovich et al. [28]	Prospective analysis of 89 patients over 65 years of age with osteoporosis and degenerative disc disease of the lumbar spine	Single- or multilevel transpedicular fixation with augmentation of cannulated PMMA screws and posterolateral spinal fusion with autologous bone	All studied patients met the criteria for osteoporosis and had symptomatic degenerative disc disease of the lumbar spine	During follow-up (12–40 months), there were no clinical or radiological signs of bone block non-union. 90 % of patients had an improvement in ODI of 15 % or more	PMMA cement augmentation is a safe and effective technique for lumbar fusion in elderly patients with osteoporosis
Dai et al. [29]	Prospective analysis of 43 patients with osteoporosis and degenerative disc disease of the spine, fractures or ankylosing spondylarthritis	Single- or multilevel transpedicular fixation with augmentation of cannulated PMMA screws and posterolateral spinal fusion with autologous bone	32 of 43 patients had symptomatic degenerative disc disease of the lumbar spine as indication for surgery	Over a mean follow-up period of 15.7 months, there were no cases of screw loosening or postoperative implant-associated complications. All patients showed regression of neurological symptoms and a statistically significant improvement in the VAS ($p = 0.018$) and ODI ($p = 0.025$)	PMMA cement augmentation with cannulated screws in conditions of osteoporosis improves structure stability and reduces the risk of implant-associated complications
Piñera et al. [30]	Prospective analysis of 23 patients over 70 years of age with osteoporosis and symptomatic degenerative spinal instability of the lumbar spine	Single- or multilevel transpedicular fixation with augmentation of cannulated PMMA screws and posterolateral spinal fusion with autologous bone	All studied patients met the criteria for osteoporosis and had symptomatic degenerative disc disease of the lumbar spine	At the control point of 6 months all patients had signs of intertransverse block union. In 3 cases, resorption was observed at the cement-screw border. There were no cases of implant-associated complications; 90% of patients had an ODI improvement of 15% or more	PMMA cement augmentation is a safe and effective technique for lumbar fusion in elderly patients with osteoporosis
Wang et al. [31]	Retrospective analysis of 128 patients with osteoporosis and degenerative disc disease of the spine, fractures or ankylosing spondylarthritis	Single- or multilevel transpedicular fixation with augmentation of cannulated PMMA screws with or without interbody/posterolateral spinal fusion with autologous bone	97 of 128 patients had symptomatic degenerative disc disease of the lumbar spine as indication for surgery	Over a mean follow-up period of 42.4 months, there were no cases of screw loosening that required revision. All patients showed a bone block union and a statistically significant improvement in the VAS ($p < 0.001$) and ODI ($p < 0.001$)	PMMA augmentation of cannulated screws is safe and effective in patients with osteoporosis with indication for instrumented surgery
Moon et al. [32]	Prospective analysis of 37 patients with osteoporosis and symptomatic degenerative lumbar spinal stenosis	Single- or multilevel transpedicular fixation with augmentation of cannulated PMMA screws and transforaminal interbody fusion	All studied patients met the criteria for osteoporosis and had symptomatic degenerative disc disease of the lumbar spine	Over a mean follow-up period of 23.3 months, the incidence of interbody block was 91.9 %. Screw loosening was observed in only 1 case. In all cases, there was a statistically significant decrease in the severity of pain in the leg and back according to the VAS after surgery	The use of PMMA is a safe and effective option for surgery for lumbar degenerative disc disease in conditions of osteoporosis
Wang et al. [33]	Retrospective analysis of 88 patients with osteoporosis and symptomatic spondylolisthesis of the lumbar spine	Single-level minimally invasive transforaminal interbody fusion (MIS-TLIF) with transpedicular fixation	Main (36): MIS-TLIF with transpedicular fixation by fenestrated screws; control (52): MIS-TLIF with transpedicular fixation by conventional screws	Incidence of complete interbody block: 96.0 % vs 90.4 % ($p = 0.684$); ODI (after surgery): 22 % vs 22 % ($p = 0.951$); VAS in the leg (after surgery): 1.19 vs 1.06 ($p = 0.202$); grade of spondylolisthesis: 7.04 % vs 13.12 % ($p < 0.001$); lumbar lordosis: 52.39° vs 47.08° ($p = 0.010$) in the main and control groups, respectively	In conditions of osteoporosis and in the presence of spondylolisthesis with similar clinical outcomes, PMMA augmentation allows achieving greater degrees of reduction and correction of the lumbar lordosis
Tang et al. [34]	Prospective analysis of 93 patients with osteoporosis and multilevel (3 or more levels requiring surgery) degenerative disc disease of the lumbar spine	3- or 4-level transforaminal (TLIF) or posterior (PLIF) interbody fusion with transpedicular fixation	Main (46): TLIF/PLIF with transpedicular fixation and PMMA augmentation; control (47): TLIF/PLIF with transpedicular fixation without PMMA augmentation	Number of loose screws: 3/336 vs 33/390 ($p < 0.001$); surgery duration: 303.07 min vs 268.72 min ($p = 0.010$) in the main and control groups, respectively. Postoperative the VAS and ODI scores did not differ significantly	Cement augmentation provides better stability in multilevel lumbar fusion in conditions of osteoporosis, but extends surgery duration and is associated with risks of cement extravasation. Selective cemented augmentation of end vertebrae may be useful to reduce the risk of complications.
Liu et al. [35]	Non-randomized comparative trial of 50 patients with osteoporosis and spondylolisthesis of the lumbar spine	Single-level transforaminal interbody fusion (TLIF) with transpedicular fixation by cannulated screws	Main (46): TLIF with transpedicular fixation and unilateral PMMA augmentation; control (47): TLIF with transpedicular fixation and bilateral PMMA augmentation	There is statistically significant clinical improvement after surgery according to VAS and ODI scores in all cases, with no difference between groups; in all cases a complete bone block was formed; surgery duration: 186.1 min vs 204.4 min; blood loss: 183.0 ml vs 236.4 ml in the main and control groups, respectively	Unilateral cement augmentation provides equal clinical and radiological effectiveness compared to bilateral one with less surgery duration and blood loss

PMMA — polymethyl methacrylate; BMD — bone mineral density.

Table 3

Clinically studied techniques for the prevention of proximal junctional kyphosis in conditions of reduced BMD

Trial	Design	Surgical treatment	Study groups / cohort	Outcomes	Conclusions
Techniques for strengthening the ends of the structure to prevent proximal junctional kyphosis					
Aydogan et al. [27]	Retrospective analysis of 49 patients with osteoporosis and degenerative disc disease of the spine, fractures or tumor lesions	Single- or multilevel transpedicular fixation with cemented vertebroplasty of the adjacent segment	29 of 49 patients had symptomatic degenerative disc disease of the lumbar spine as indication for surgery	Over a mean follow-up period of 37 months, there were no cases of fractures of the proximal or distal adjacent segments	Cement vertebroplasty of vertebrae adjacent to instrumentation is an effective technique for preventing proximal junctional kyphosis when performing lumbar fusion in conditions of osteoporosis
Basankin I.V. et al. [39]	Prospective analysis of 140 patients with osteoporosis and degenerative deformity of the lumbar spine	Multilevel instrumental fixation with correction of frontal and sagittal imbalances	Group I (36): correction of lumbar lordosis up to 30°; Group II (23): correction of lumbar l ordosis up to 30° + proximal laminar fixation; Group III (20): complete correction with preventive proximal vertebroplasty; Group IV (60): complete correction	Partial correction of lumbar lordosis and laminar fixation provide the smallest number of cases of proximal junctional kyphosis — by 16–28 % compared to other groups ($p = 0.001$). In the absence of prevention techniques and complete correction, the incidence of kyphosis is significantly higher compared to other techniques ($p < 0.050$)	Partial correction of lumbar lordosis, laminar fixation and preventive vertebroplasty are effective techniques for the prevention of proximal junctional kyphosis

BMD — bone mineral density.

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