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Avoiding Spinal Implant Failures in Osteoporotic Patients: A Narrative Review

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Abstract

Study design: Narrative review.

Objectives: With an aging population, the prevalence of osteoporosis is continuously rising. As osseous integrity is crucial for bony fusion and implant stability, previous studies have shown osteoporosis to be associated with an increased risk for implant failure and higher reoperation rates after spine surgery. Thus, our review's purpose was to provide an update of evidence-based solutions in the surgical treatment of osteoporosis patients.

Methods: We summarize the existing literature regarding changes associated with decreased bone mineral density (BMD) and resulting biomechanical implications for the spine as well as multidisciplinary treatment strategies to avoid implant failures in osteoporotic patients.

Results: Osteoporosis is caused by an uncoupling of the bone remodeling cycle based on an unbalancing of bone resorption and formation and resulting reduced BMD. The reduction in trabecular structure, increased porosity of cancellous bone and decreased cross-linking between trabeculae cause a higher risk of complications after spinal implant-based surgeries. Thus, patients with osteoporosis require special planning considerations, including adequate preoperative evaluation and optimization. Surgical strategies aim towards maximizing screw pull-out strength, toggle resistance, as well as primary and secondary construct stability.

Conclusions: As osteoporosis plays a crucial role in the fate of patients undergoing spine surgery, surgeons need to be aware of the specific implications of low BMD. While there still is no consensus on the best course of treatment, multidisciplinary preoperative assessment and adherence to specific surgical principles help reduce the rate of implant-related complications.

Keywords
spine, osteoporosis, bone density, pedicle screws, revision

Introduction

Osteoporosis is the most common bone disorder and affects nearly 200 million people worldwide.[1] Due to an aging population, this number is expected to further increase in the future which in turn is associated with a rise in patients with osteoporotic vertebral fractures.[2] Although the number of patients undergoing spine surgery has increased and an osteoporosis prevalence of up to 20% overall and of 50% in women over 50 years has been shown, only 19.6% of spine

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surgeons report screening their patients' bone health prior to surgery.[1,3]

In osteoporosis, an uncoupling of the bone remodeling cycle leads to a rarefication in trabecular structure, increased porosity of cancellous bone and decreased cross-linking between vertical trabeculae.[4] Patients with osteoporosis demonstrate a high risk for complications of posterior spinal instrumentation with half of surgically treated osteoporotic patients facing surgery-related complications after spine surgery compared to less than one fourth of patients with healthy bone quality.[5] In this regard, complications such as pedicle fractures, screw loosening, pseudarthrosis, adjacent vertebra fractures, proximal junctional kyphosis (PJK), and implant failure with screw loosening rates of over 22% are reported in patients with reduced bone mineral density (BMD).[5,6] Due to the increasing number of patients with osteoporosis undergoing spine surgery, we reviewed the existing literature to provide an update of evidence-based solutions in the preoperative planning and surgical treatment of this patient group.

Load-Bearing Changes in Osteoporotic Vertebrae

Influence of Bone Mineral Density on Pedicle Screw Fixation

As numerous biomechanical studies have shown, osteoporosis is associated with reduced pedicle screw toggle resistance and pull-out strength.[7,8] Both craniocaudal stiffness and pull-out strength result from cortico-cancellous fixation of the screw in the pedicle in 60-80% and to a lesser proportion from fixation in cancellous bone in the vertebral body.[9] While the center of the pedicle has a lower BMD compared to the outer cancellous pedicle layers, patients with osteoporosis show a reduced BMD especially in the outer cancellous layers, in which the screw-bone interface is located, if only a partial cortical screw-bone interface is achieved.[9] The fixation stiffness of pedicle screws correlates significantly more with cancellous bone density than with cortical bone density.[10] As a reduced load bearing surface leads to increased peak loads at the bone-implant contact areas, the risk of local loosening increases and the resulting loads are redistributed, which in turn may cause complete implant failure.[11]

Failure Mechanisms of Posterior Instrumentation in the Osteoporotic Spine

Reduced BMD may cause both early and late posterior spinal instrumentation failure. DeWald and Stanley[12] report a rate of 13% of early complications (<3 months) such as early adjacent compression fractures and pedicle fractures which result from reduced bone quality on the one hand and the use of thicker screws to increase the screw-bone interface on the other. As a pattern of failure in the later postoperative course (>3 months), the development of pseudarthrosis due to a reduced bone-turnover and thus a delayed bony fusion is discussed in patients with osteoporosis.[12,13] The delayed fusion results in an increased rate of implant breakage due to an extended implant load.[14]

Besides septic loosening, several factors are relevant for implant loosening: firstly, a reduced force transmission through the vertebrae due to force redistribution through the implant and a resulting decrease in bone density, and secondly, microfractures of the screw-bone interface due to local overloading at the screw-bone interface,[15] as well as osteolysis due to implant wear are reported as causes for screw loosening.[16] Furthermore, a reduced BMD is associated with an increased risk of adjacent segment fractures and proximal-junctional kyphosis (PJK).[17] As adjacent segment fractures have been shown to be directly associated with decreased Hounsfield unit (HU) values both locally and in general, measuring HUs using computed tomography (CT) imaging preoperatively is helpful in anticipating this complication and adjusting surgical strategies accordingly.[18,19] Furthermore, strategies to reduce the risk of PJK in the treatment of adult spinal deformity include peri-operative optimization of reduced BMD as well as attention to sagittal alignment restoration, especially in the area of the uppermost instrumented vertebra (UIV).[20,21] Thus, the reduction of implant-related complications relies heavily on detailed preoperative planning.

Multidisciplinary Strategies in Osteoporotic Patients

Patients with osteoporosis require special considerations when being evaluated for spine surgery in the treatment of both osteoporotic fractures and degenerative diseases. To date, however, there is a lack of definitive guidelines for the perioperative optimization of low BMD in the setting of spine surgery.

Facilitating Positive Bone Remodeling

While there are no established guidelines for osteoporosis screening, Sardar et al[22] recently published an expert consensus providing recommendations for the assessment and management of osteoporosis in patients undergoing elective spine surgery. They suggest BMD screening in all patients over 65 years independent of risk factors. For patients over the age of 50 years a screening is also necessary if risk factors such as chronic glucocorticoid use, a history of low energy fracture, chronic kidney disease, prior failed spine surgery, vitamin D deficiency, current smoking, or limited mobility amongst others are present. In patients under the age of 50 years, screening should be performed in case of chronic glucocorticoid use, previous low energy fracture, metabolic bone disease, cancer treatment, or chronic kidney disease.[22] While to date, dual-energy x-ray absorptiometry (DXA) imaging has been the clinical standard for measuring BMD, quantitative CT imaging and, more recently, biomechanical computed tomography analysis (BCT) have been investigated increasingly as alternatives and provide additional diagnostic information such as bone strength. Furthermore, in 2019, Ehresman et al[23] introduced the vertebral bone quality (VBQ) score which allows assessment of bone quality using magnetic resonance imaging[24] and recently, there have been first attempts at developing machine learning algorithms predicting bone health status and in finding novel risk factors for reduced BMD in patients requiring spine surgery.[25]

Preoperatively, any modifiable risk factors need to be addressed including adequate calcium and vitamin D intakes, exercise, and cessation of excessive alcohol or smoking.[26,27] Recombinant parathyroid hormone compounds such as teriparatide are recommended as first-line preoperative treatment as they have been shown to decrease complication rates and are associated with higher fusion rates in spine surgery compared with bisphosphonates or no treatment.[22,28]

Increasing Screw Anchorage

Previous studies have shown that screw loosening occurs in over 22% of osteoporotic patients undergoing pedicle screw fixation.[6] Larger-diameter pedicle screws engage with the pedicle cortex more strongly and thus reduce screw toggle while longer pedicle screws allow more threads in the bone.[29] Furthermore, angling pedicle screws toward the subchondral bone near the end plate with a length of 80% of the vertebral body provides maximum insertional torque and pull-out strength in the osteoporotic spine.[30] In the thoracic spine, placing screws in a straight-forward trajectory rather than anatomically also improves screw anchorage. The most robust fixation is achieved in the inferior part of the pedicle.[31] Due to an increased cortical bone contact, cortical screw fixation has been proposed as an effective alternative in patients with lumbar spinal disorders without spondylolysis.[32] By travelling from dorsomedially to ventrolaterally, the cortical trajectory engages more screw threads in cortical bone and thus increases insertional torque.[33] While expandable screws may allow enhanced screw anchorage in the bone, there is a lack of high-quality studies providing sufficient evidence for their clinical benefit especially considering concerns regarding screw breakage and migration.[34] The use of rod reduction devices should be avoided as it decreases screw pull-out.[35]

As increasing pedicle screw length and diameter is limited by the patient's anatomy, further fixation strength may be achieved through augmentation with polymethyl methacrylate (PMMA) or, less frequently, calcium phosphate (CaP).[36] PMMA augmentation does not only increase pull-out strength but also leads to reduced loss of deformity correction as well as higher fusion rates and is therefore indicated in case of severe osteoporosis with T-scores below -3, a CT-based density below 120 HU, low torque intraoperatively, or if fracture reduction is performed using the screw-rod-construct.[19,37] While there are multiple techniques for augmentation, the use of fenestrated screws has been shown to be biomechanically superior to solid-fill techniques and is therefore most common.[38] As it has also been shown that fenestrated screws without PMMA augmentation have similar pullout strength as standard pedicle screws, fenestrated screws may generally be used in patients with proven or suspected low bone quality to avoid the necessity of changing screws.[39]

In all techniques, screw augmentation must be performed under fluoroscopic control to enable early detection of leakage. In the thoracic spine, a PMMA volume of 1-1.5 mL and in the lumbar spine a volume of 1.5-2 mL per screw is recommended.[40] Applying larger volumes does not yield additional anchorage but increases the risk of cement leakage, which occurs in up to 94% of augmented pedicle screws.[41] While leakage almost always remains asymptomatic, it may damage surrounding tissues such as the spinal cord, nerve roots, or blood vessels and leads to symptoms in 2-4% of cases.[41] Further possibly severe complications include thermal nerve root damage, PMMA or fat embolisms as well as unspecific cement reactions.[42,43] However, a recent meta-analysis by Rometsch et al[6] showed a risk of screw loosening of 2.2% after PMMA augmentation compared to 22.5% without augmentation.

Avoiding Junctional Complications

PJK or proximal junctional failure (PJF) are devastating complications after spine surgery and are associated with low BMD.[20] Underlying causes include failure of the posterior tension band, intervertebral disc degeneration, adjacent vertebral fractures, and/or instrumentation failure.[44] While preoperative planning is most important to achieve the best-possible construct stability, there is no single solution to effectively minimize this complication's occurrence. In a survey-based study regarding PJK and PJF management in general, spine surgeons reported contouring the terminal rod into kyphosis and preoperative BMD treatment as the most commonly used techniques in avoiding PJF, followed by transverse process hooks at the UIV and vertebroplasty at the UIV or the UIV plus one segment.[45]

In the osteoporotic spine, there is a clear trend towards higher pedicle screw density and long-segment instrumentation. Longer constructs provide increased points of fixation and thus aid in protecting against junctional or segmental failure.[36] High strains at the construct's end may cause progressive deformity or instrumentation failure. Ending a construct in the cervicothoracic or thoracolumbar junction should be avoided due to their predisposition to kyphotic collapse.[30] To decrease strain on each point of fixation, long-segment constructs are preferable to short-segment posterior instrumentation in both deformity correction and fracture stabilization with the recommendation of three levels of fixation above and below the apex of a deformity and two levels above and below an osteoporotic fracture.[36,37,46] While it is important to restore appropriate sagittal alignment, larger deformity correction is also associated with an increased risk of junctional failure in older patients.[20] As there are no BMD-adjusted alignment goals, surgeons need to aim for patient-specific alignment thresholds.[47] To avoid adjacent segment fractures, prophylactic vertebroplasty of the UIV or the UIV plus one additional vertebra may reduce proximal junctional vertebra collapse and associated reoperation rates especially in the surgical treatment of degenerative pathologies.[48]

Furthermore, posterior construct stiffness may influence mechanical stresses on the proximal junction. While biomechanical studies supporting this notion are still lacking, it is likely that reduced construct stiffness allows for more flexibility and thus reduces junctional stress.[49]

Besides the use of hooks, strategies to achieve a soft landing at the junctional zone include the use of posterior tethers as they allow a gradual transition between the instrumented and non-instrumented levels.[47] Several studies have shown a reduction in PJK rates after band placing even in patients with low BMD.[50]

To increase stability in the lumbosacral region, distal pelvic fixation with iliac and/or sacral screws is superior to fusions ending at L5.[51] Various techniques have been introduced to maximize fusion rates while minimizing construct failure. Optimal sacral screw trajectories with the highest bone quality may be planned using CT-based analysis of HU values.[19] The screws need to be placed tricortically toward the promontory to increase insertional torque.[52] S2 alar iliac screws are increasingly popular as they are associated with at least similar biomechanical stability but lower complication rates compared with traditional iliac screws.[53,54] By providing anterior column support, additional anterior fusion at the L4/L5 or L5/S1 level may improve lumbosacral fusion rates. This is especially important as lumbosacral pseudarthrosis may cause sacral insufficiency fractures.[55]

Regarding interbody devices, the primarily used materials have been titanium and polyetheretherketone (PEEK). While PEEK theoretically lowers the risk of subsidence because its elastic modulus is closer to that of corticocancellous bone, the literature does not clearly favor one material over the other.[56] Advancements in implant materials include surface modifications and hybrid-material devices. However, large-scale studies of their performance are still needed.[56] More recently, patient-specific spinal implants have emerged. These custom implants are based on three-dimensional (3D) modelling of the patient's anatomy and thus allow addressing individual defect dimensions and surgical requirements.[57] To date, the use of these most commonly titanium alloy implants has been limited to anatomically challenging cases and there is a lack of randomized controlled clinical trials proving their superiority over 'off-the-shelf' implants.[57] However, customized 3D implants hold the potential to be a viable alternative in reconstructive spine surgery as they may improve subsidence and pseudarthrosis rates.[58]

In contrast to isolated posterior instrumentation, combined anterior-posterior or anterior-only approaches allow an optimized interbody cage cross-sectional area and thus decreased subsidence, which in turn allows load-sharing and a higher stability of the construct.[59] However, there also is a correlation between anterior instrumentation failure and low BMD.[60,61] To avoid cage subsidence, in preparing the disc space, special attention needs to be drawn towards correct cage placement and preparation of the end plates as both affect cage stability.[36,62] As cage subsidence is mainly caused by axial compression forces, cement augmentation of the adjacent endplates leads to higher construct stability and less reduction loss following vertebral body replacements and therefore should be considered in patients with HU values of 180 or less.[63,64] Furthermore, in anterior-posterior approaches short-segmental posterior instrumentation provides better fixation of the corporectomy level compared to long-segmental instrumentation.[65]

Conclusion and Outlook

Due to a reduction in trabecular structure, increased porosity of cancellous bone and decreased cross-linking between vertical trabeculae patients with osteoporosis are at a higher risk of complications after spine surgery. Thus, BMD plays a crucial role in the fate of patients undergoing spine surgery, which is why surgeons need to be aware of possible risk factors and of the specific implications low bone quality has on the treatment course of affected patients not only in case of an osteoporotic fracture but also in preparing elective spine surgery.

As our review of the existing literature shows, besides new diagnostic tools for better preoperative assessment of bone quality, manifold surgical strategies have evolved. However, to date there is no final consensus on the best course of treatment for this highly challenging patient population. Due to the high rate of complications, there is no doubt that these patients need thorough surgical planning. The literature provides multiple strategies for improving fixation and construct stability and new strategies such as patient-specific implant modelling emerge continuously.

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