GeroScience (2024) 46:3555–3566
https://doi.org/10.1007/s11357-024-01083-6

ORIGINAL ARTICLE

Surgical management of spinal pathologies in the octogenarian: a narrative review

Alexander R. Evans · Joshua Bakhsheshian · Christopher S. Graffeo · Zachary A. Smith

Received: 26 December 2023 / Accepted: 15 January 2024 / Published online: 29 January 2024
© The Author(s), under exclusive licence to American Aging Association 2024

Abstract Optimal management paradigms of spinal pathologies in the octogenarian population are controversial given the higher incidence of comorbidities with concern for poor prognosis and fear of increased complications associated with surgical management. In this narrative review, we aim to detail the complex clinical considerations when approaching odontoid screw fixation/instrumented fusion, spinal decompression, and spinal fusion in the octogenarian. Literature review was conducted via Google Scholar and PubMed databases, with literature selected based on statistical power and clinical relevance to the following pathologies/surgical techniques: odontoid fracture, surgical decompression, and surgical fusion in the octogenarian. The aforementioned pathologies were selected based on prevalence in the advanced-age population in which surgical screening techniques and management remain nonuniform. Preoperative evaluation of the octogenarian patient increasingly includes frailty, sarcopenia, and osteopenia/osteoporosis assessments. In cases of odontoid fracture, conservative management appears to provide beneficial clinical outcomes with lower rates of complication compared to surgery; however, rates of radiographic odontoid fusion are far lower in conservatively managed patients. Regarding surgical decompression and fusion, the presence of comorbidities may be more predictive of outcome rather than age status, with the advent of minimally invasive techniques providing safety and efficacy in the surgical management of this age cohort. Age status may be less pertinent than previously thought in the decision to pursue spinal surgery for odontoid fracture, spinal decompression, or spinal fusion; however, each of these procedures has respective risks and benefits that must be considered within the context of each patient's comorbidity profile.

Keywords Octogenarian · Spine surgery · Odontoid fracture · Fusion · Decompression

A. R. Evans · C. S. Graffeo · Z. A. Smith (✉)
Department of Neurosurgery, University of Oklahoma, Oklahoma City, OK, USA
e-mail: Zachary-A-Smith@ouhsc.edu

J. Bakhsheshian
Department of Neurosurgery, Mayo Clinic, Phoenix, AZ, USA

Introduction

The octogenarian is a rapidly expanding demographic in the USA, expected to grow from 1.9% of the population in 2020 to 4.3% in 2050 [1]. Although many groups have studied general surgical and neurosurgical outcomes in the octogenarian [1–23], there remains little consensus regarding standardized approaches for the surgical management of this patient population. Within the realm of spinal pathology, many look to frailty indices in the guidance of surgical decision-making. Increased frailty

corresponds to higher rates of postoperative complications and mortality [5, 24]. Moreover, frailty has been associated with loss of normal spinal alignment, which subsequently impacts instrumental activities of daily living (IADLs) [25], such as cooking, cleaning, transportation, laundry, and management of finances. As such, these observations emphasize that level of frailty may be an invaluable tool in predicting surgical outcomes and informing clinical decision-making. However, despite the increasing use of clinical decision-making tools such as frailty indices, there remains a clear lack of unanimity in the preoperative screening and surgical management of these patients.

Surgical approaches to spine pathology in the octogenarian can be divided into three main categories: cervical approaches (generally in the case of odontoid fracture), decompression, and fusion. Odontoid fracture is associated with a 5-year mortality rate of up to 18% with even higher complication rates, regardless if managed surgically or conservatively [6]. The authors have also investigated outcomes of decompression for lumbar spinal stenosis (LSS) in this cohort, with some studies reporting clinical improvement to the level of younger patients [7, 9]. In contrast, with moderate-sized fusion procedures, reports have shown prolonged length of stay and nonroutine discharge, particularly with anterior cervical discectomy and fusion (ACDF) [15]. Given the heterogeneous nature of the aforementioned findings, it is our aim to synthesize current recommendations regarding the surgical management of a range of spinal pathologies in the octogenarian, chiefly odontoid screw fixation/instrumented fusion, spinal decompression, and spinal fusion. Further, we hope to provide an overview of these surgical approaches through the lens of the most prevalent spinal pathologies in the octogenarian cohort: odontoid fracture, myelopathy, and degenerative spinal disease (Table 1).

Table 1 Illustrative examples of common spinal pathologies encountered in the octogenarian population with resultant surgical management techniques and complication profiles

	Pathology		
	[a]Odontoid fracture	Myelopathy	Degenerative spinal disease/instability
Pathophysiological mechanism	Hyperextension of the cervical spine, posterior movement of the head and C1 vertebra, leading to fracture of odontoid neck	Spinal cord compression (e.g., primary or metastatic neoplasm, spondylosis or spondylolisthesis, herniated intervertebral disc)	Weakening or atrophy of spinal support muscles (e.g., the multifidus), age-related changes (e.g., spondylolisthesis)
Surgical approaches	C1–2 instrumented fusion or odontoid screw fixation	Decompressive techniques: ACDF, ULBD, posterior cervical discectomy and fusion, posterior cervical laminectomy and fusion	Fusion techniques: ACDF, posterior cervical discectomy and fusion, anterior/posterior/direct lateral/transforaminal lumbar interbody fusion
Complications	Dysphagia, airway compromise (including ARDS, reintubation, tracheostomy placement, pneumonia), infection	Worsening of myelopathy, nonunion, IPD migration, postoperative osteoporotic vertebral fracture, dural tear/CSF leak, dysphagia, pneumonia, atelectasis, infection	Nonunion, postoperative osteoporotic vertebral fracture, dural tear/CSF leak, dysphagia, pneumonia, atelectasis, infection

[a]Only represents type II odontoid fracture and the most frequently encountered mechanism of fracture in the octogenarian. Although the classification of odontoid fracture is clinically pertinent, this remains outside the scope of the current review

Abbreviations: *ARDS* acute respiratory distress syndrome, *ACDF* anterior cervical discectomy and fusion, *ULBD* unilateral laminotomy for bilateral decompression, *IPD* interspinous process device, *CSF* cerebrospinal fluid

The octogenarian

Frailty indices

When considering to operate on an elderly patient, frailty is frequently considered a determining factor of fit for surgery, often measured using a frailty index. The most frequently used indices are the modified frailty index (5-item or 11-item, abbreviated as

mFI-5 or mFI-11, respectively); the fatigue, resistance, ambulation, illness, and loss of weight (FRAIL) scale (and its Korean adaptation (K-FRAIL)); and the metastatic spinal tumor frailty index (MSTFI) [5, 15, 24–29]. The mFI ranges from 0 to 1, calculated as a 1 point for each present risk factor divided by the total number of possible risk factors, and has been associated with increased odds of all adverse events, including mortality, severe complications, prolonged length of hospital stay, and nonroutine discharge, among others [15, 26, 28, 29]; however, patients with a wide range of mFI scores have been observed to improve in the visual analog scales for back and leg pain after lateral lumbar interbody fusion (LLIF) procedures [27], emphasizing the limited clinical utility of this index. Interestingly, the FRAIL scale has been associated with loss of normal spinal alignment, in addition to its association with the parameters of fatigue, resistance, and ambulation [25]. On the other hand, the K-FRAIL scale can categorize patients as robust, pre-frail, and frail, which may be helpful in the delineation of cohorts and prediction of postoperative complication rates in those with degenerative spine disease [24]**.** Further, frailty has been associated with a median survival of 521 days following surgery for type II odontoid fractures compared to 1951 days in non-frail patients [5], highlighting the association frailty may have with decreased survival.

Sarcopenia

Sarcopenia, or the loss of skeletal muscle mass, is frequently evaluated in the octogenarian cohort as prevalence ranges from 10 to16% worldwide [30]. Central sarcopenia is generally assessed using the cross-sectional area of the psoas muscle on computer tomography (CT) imaging at the level of the L3 or L4 pedicle, which can be divided by the vertebral body area and presented as a proportion [24, 31, 32]. Sarcopenia can also be determined via the ratio of fat to muscle in the paraspinal musculature (often utilizing the multifidus muscle) determined on axial MRI of the cervical or lumbar spine. Using this technique, it has been found that patients with increased paraspinal sarcopenia experience a higher level of functional disability in cases of lumbar spinal stenosis and less functional improvement following posterior cervical decompression and fusion (PCDF), in addition to more frequently reporting worsening patient-reported outcome measures [33, 34]. Although sarcopenia has been significantly associated with frailty, it has not been associated with increased length of hospital stay, postoperative complications, or mortality; nevertheless, more studies are required to definitively establish the relationship between sarcopenia, frailty, and adverse events in the elderly population.

Osteopenia and osteoporosis

Further workup prior to spinal surgery in the octogenarian should include assessment for the presence of osteopenia or osteoporosis, as these comorbidities increase the risk for fragility fractures and worsened postoperative outcome. Osteoporosis is one of the most common pathologies experienced by the elderly population, with a worldwide prevalence of 35.3% in women and 12.5% in men [35]. What is more, the prevalence of osteopenia and osteoporosis in adults at a mean age of 63 undergoing lumbar spine fusion surgery has been reported to be as high as 43.6% and 14.9%, respectively [36]. As the risk for the development of osteoporosis increases with age, one can infer that the prevalence of this disease is even higher in the octogenarian and, as such, warrants further clinical investigation.

Postoperative osteoporotic vertebral fracture has been significantly associated with refractory leg symptoms and poor satisfaction in octogenarians undergoing decompression for lumbar canal stenosis [17], which highlights the importance of preoperative assessment with dual x-ray absorptiometry (DEXA) scanning. Especially in high-risk patients, the identification of osteopenia or osteoporosis via DEXA scan may have a significant impact on surgical planning and avoidance of postoperative morbidity. Moreover, online algorithms have been made available that allow for the prediction of osteoporotic fracture, such as the fracture risk assessment (FRAX) tool. This algorithm, which became widely available in 2008, predicts the 10-year likelihood of a major osteoporotic fracture (of the hip, spine, humerus, or wrist), based on age, body mass index (BMI), and the presence of risk factors [37]. Since its inception, this tool has been popularized globally due to accessibility and utility across medical and surgical subspecialties alike [38], which may be advantageous in the setting of screening surgical candidates for likelihood of postoperative fracture. If a patient is deemed high

risk for osteoporotic fracture via the aforementioned screening tools, one may consider preoperative treatment (often with a bisphosphonate or synthetic derivative of human parathyroid hormone (e.g., teriparatide)) to increase the likelihood of spinal fusion while decreasing the likelihood of hardware loosening or postoperative osteoporotic fracture with subsequent reoperation [17, 39].

Age as an indirect risk factor for poor outcome

Many studies have assessed increased age as an independent risk factor for poor surgical outcomes, yet the data remain heterogeneous. Elderly status is associated with higher rates of preexisting comorbidities (such as renal failure, hypertension, and cardiac arrhythmias). These factors have been found to be independently associated with increased length of hospital stay or nonroutine discharge following ACDF [15]. Moreover, spinal range of motion in the lumbar/sacral regions decreases with age, while lumbar lordosis increases with age; this calls into question the use of a standard alignment in all age groups when performing reconstructive lumbar surgery [40] and may also result in less optimal outcomes. Importantly, and contrary to common belief, age itself does not appear to be a contraindication for lumbar spinal surgery [17]. Although not seemingly an independent risk factor for poor surgical outcome, elderly age status has been directly associated with several comorbidities, which emphasizes the possibility that age may be indirectly linked to poor surgical outcome.

Advancements in minimally invasive spinal surgery

Historically, the approach to back pain has been stepwise [41, 42], with initial aims consisting conservative measures such as administration of local anesthetic or steroid injection to lessen pain reception and inflammation, respectively; if pain, nerve compression, or spinal instability is refractory, spinal fusion or decompression may be pursued. Although fusion is generally approached via large soft tissue dissection, minimally invasive options have emerged, mitigating the risk of blood loss and prolonged recovery time. However, it is crucial to consider that surgery is only indicated in the context of particularly bothersome symptoms; further, if indicated, the surgical outcomes of leg pain and disability are generally superior in surgical management versus non-operative treatment [42]. What is more, it has been reported that minimally invasive tubular lumbar decompression has resulted in similar clinical outcomes between octogenarians and younger cohorts, although the older cohorts require longer time to experience clinical benefit [7]. In addition, minimally invasive transforaminal lumbar interbody fusion (TLIF) results in similar neurological outcomes in elderly patients compared to younger cohorts, although degenerative comorbidities such as knee osteoarthritis are significantly associated with decreased activities of daily living (ADL) subscores [43].

Notable advancements of minimally invasive spinal surgery in the last decade can be divided into three domains: the mini-open/percutaneous technique, the tubular technique, and endoscopy. In the mini-open/percutaneous technique, muscle splitting allows for minimal soft tissue dissection with subsequent quick recovery time and limited blood loss. The tubular technique allows for multiple working channels that focus the corridor of visualization, with dilation minimizing trauma to soft tissue and allowing for easy, fine-tuned adjustments to the trajectory of ports. In addition, endoscopy has similar advantages to smaller instruments with direct access to pathology. Overall, there is a consensus that the tubular and endoscopic techniques have early learning curves when compared to the mini-open/percutaneous technique [44]. Regardless, each of these techniques allows for minimal blood loss, lower complication rates, and decreased length of hospital stay and may be considered in those with refractory leg symptoms [44].

Despite the advances in minimally invasive surgical approaches, elective operations do not necessarily equate complication-free, especially in the octogenarian population. In a retrospective cohort study of 95 octogenarian patients, an overall mortality rate of up 8.4% was reported in the context of elective lumbar and cervical spinal fusion surgeries, with a greater proportion of patients experiencing complications for lumbar operations than cervical [13]. Dysphagia is a common postoperative complication of elective spinal surgery [13, 15], which has also been found to be predictive of the development of pneumonia [13]. Within the context of ACDF, dysphagia is one of the most common postoperative complications experienced by elderly and younger cohorts alike [15, 45].

However, elderly patients (defined by Yeshoua et al. as 75 + years of age) have been found to experience dysphagia following ACDF at a significantly higher rate than younger cohorts, ranging from 8.95 to 13.47% of patients across the years of 2016 to 2018 (compared to a range of 3.00% to 3.77% in the young cohort) [46]. In octogenarians, this complication may coexist with increased length of hospital stay and non-routine discharge [15]; nevertheless, further study is required to determine if these factors have a true association. The high incidence of dysphagia following ACDF has led to many developments in minimally invasive spinal surgery, such as the increased use of a zero-profile, stand-alone anterior cervical cage in single-level ACDF, which has demonstrated a high level of safety and efficacy in the literature [47]. What is more, pain improvement has been documented in octogenarians undergoing minimally invasive lumbar spinal surgery, indicating that this patient population can benefit from elective procedures; nonetheless, the potential higher incidence of complications in this cohort must be weighed against the potential benefits [13, 15]. Age status alone does not preclude patients from receiving the aforementioned procedures, as clinical benefit has been documented in advanced-age groups. As such, the risk of comorbidity may be associated with increasing age (not type of procedure), in which smaller decompression procedures should not contain an "age-limit."

Cervical spine pathology and odontoid fracture

Two types of cervical spine operations that are common in octogenarians are anterior/posterior cervical fusion and instrumented odontoid fusion. In cervical spondylosis, age-related degenerative processes may lead to stenosis, myelopathy, or spinal cord injury, especially in those older than 55. Surgical decompression or fusion (via ACDF [47, 48] or posterior instrumented fusion) can alleviate symptoms, with increase in anterior–posterior diameter of the spinal canal between preoperative and postoperative decompression being associated with neurological improvement at 1-year follow-up [49]. On the other hand, traumatic C2 fracture is frequently encountered in this cohort as the prevalence of osteoporosis/osteopenia increases with age. Mortality of C2 fracture in octogenarians has been reported as high as 9.7%, with coexisting bleeding disorders and congestive heart failure being predictive of mortality [50]. Odontoid fracture often accompanies C2 fracture, generally due to hyperextension and subsequent movement of the head and C1 vertebra backwards, causing increased traction and fracture of the odontoid process of C2. The most common subcategory of odontoid fracture is type II, which involves the odontoid neck [51]. In octogenarians, up to 77% of patients presenting with odontoid fracture have a posterior plane of displacement, suggesting a high incidence of forward falls as the cervical spine is hyperextended and the head and C1 vertebra are pushed backwards [6]. Thus, within the context of increased frailty of this age group, it is imperative to consider the nuances of surgical management of odontoid fractures in this patient population.

Odontoid fracture in the octogenarian

Management of odontoid fracture can be divided into conservative or surgical management options. Conservative management requires the placement of a halo immobilization device or cervical collar, whereas surgery generally requires odontoid screw fixation or anterior/posterior instrumented fusion. Odontoid union is generally assessed radiographically, which is much more often achieved with surgical management [2, 6]. However, postoperative complication rates in octogenarians are much higher than in nonoperative management [2, 4, 6], with dysphagia being one of the most frequently experienced postoperative complications in this cohort [2, 3]; of note, it has been reported that 31% of nonoperative patients managed with halo vest immobilization experienced significant airway complication [4, 6], elucidating the nuanced decision-making required when pursuing operative versus conservative management. Further, dysphagia appears to correlate with necessitating reintubation, placement of a tracheostomy [2], or placement of a feeding tube and has been associated with a 14.5-time higher mortality rate. Nonoperative management of octogenarians averages 0.625 complications per patient, whereas an average of 1.72 complications per patient has been observed in operative cases [4]. In addition, length of stay is significantly longer for those undergoing surgery.

Others have found no significant difference in attributable mortality between surgery versus

nonoperative management in this cohort, yet increasing age, degree of odontoid displacement, and requirement of a feeding tube have been found to be the strongest predictors of mortality at 1 year [3, 6]. These associations may be attributed to the higher incidence of frailty in this age group, as median survival of frail elderly patients is comparable whether they receive operative or nonoperative management; conversely, median survival time is much higher in non-frail elderly patients undergoing non-operative management versus non-frail elderly patients undergoing operative management. These findings imply that frailty status may be an independent indicator of clinical outcome in cases of surgery versus nonoperative management [5], regardless of age status.

Overall, the clinical benefit of surgery for odontoid fracture in octogenarians is likely negligible when compared to the risk of complication, even with increased radiologic fusion observed after surgery [2, 5, 6]. Alternatively, some argue that posterior C1–2 fusion by screw construct is a feasible treatment for octogenarians with unstable type II odontoid fractures, given that the degree of odontoid displacement has been associated with increased mortality [3]. Notably, posterior cervical instrumented fusion appears to afford fewer overall complications with a higher healing rate than anterior odontoid screw fixation, albeit at the expense of sacrificing C1–2 rotatory motion [52]. Despite a lack of consensus regarding operative versus nonoperative management of odontoid fracture in octogenarians, it appears that nonoperative options (especially cervical collar) may provide lowered risk of complication and subsequent mortality (Fig. 1); nonetheless, it is crucial to consider frailty status, which may more closely correlate with mortality risk than age status. See Table 2 for further details regarding conservative versus surgical management of odontoid fractures in the octogenarian.

Illustrative case example

An 86-year-old man with a history of medically controlled hypertension and prior open reduction and fixation (ORIF) of the right femur presented to our institution following a ground-level mechanical fall, in which he fell forward and hit his face and right knee without losing consciousness. He reported no neurologic symptoms, including numbness, tingling, or weakness of the extremities. Physical exam revealed right periorbital ecchymosis and eyebrow laceration with no other abnormalities. Pertinent negative physical exam findings included no cervical spine tenderness, step-offs, or notable deformities. Non-contrast sagittal short tau inversion recovery (STIR) magnetic resonance imaging (MRI) and computed tomography (CT) scan of the cervical spine demonstrated a nondisplaced type III odontoid fracture (Fig. 2). Of note, CT brain demonstrated no pathology. Given the absence of odontoid displacement or neurologic symptoms, conservative management was pursued, in which he was subsequently placed in a cervical collar and medically managed with acetaminophen as needed. X-ray of the cervical spine remained stable over the following day, after which he was discharged neurologically intact. He continues to follow-up at our institution and has experienced no further symptomatology.

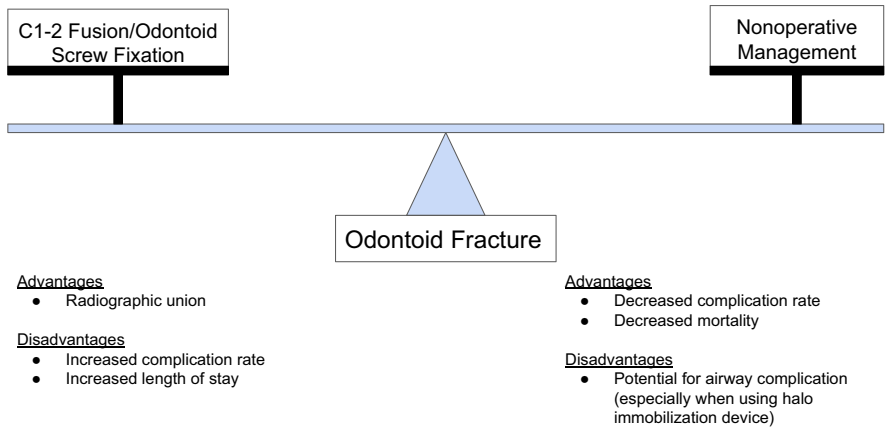

Fig. 1 Visual demonstration of our perceived advantages and disadvantages of surgical fixation versus nonoperative management of odontoid fractures in the octogenarian population, which must be weighed within the context of each patient's unique clinical presentation and comorbidity profile

Table 2 Advantages and disadvantages of varying approaches to odontoid fracture in the octogenarian

Treatment modality	Approach	Advantages	Disadvantages
Conservative	Halo immobilization device	Decreased length of hospital stay compared to surgical measures; decreased number of overall complications compared to surgery	[a]Significant risk for airway complication; decreased chance of radiographic union
	Cervical collar	Decreased length of hospital stay compared to surgical measures; significantly lower risk for airway complication compared to halo device; decreased number of overall complications compared to surgery	Decreased chance of radiographic union; slight risk for airway complication
Surgical	Anterior odontoid screw fixation	Greater chance of radiographic union compared to conservative measures; preservation of the majority C1–2 motion	Increased length of hospital stay; significant chance of postoperative dysphagia
	Posterior cervical instrumented fusion	Greater chance of radiographic union compared to conservative measures; fewer complications than anterior approach with higher healing rate	Increased length of hospital stay; elimination of C1–2 rotatory motion

[a]Airway complication defined as acute respiratory distress, intubation, or pneumonia

Cervical myelopathy and degenerative lumbar disease

Myelopathy may occur due to a variety of pathologies but most often arises due to age-related structural changes of the spinal canal with resultant spinal cord compression. In the elderly population, degenerative cervical disc disease and osteophyte formation become more common, which may lead to radiculopathy via nerve root compression or deterioration of the spinal cord, resulting in degenerative cervical myelopathy (DCM) [53]. DCM generally manifests as paresthesia or hypoesthesia of the limbs, ataxia, loss of coordination, and/or incontinence [54]. These degenerative pathologies are collectively termed spondylosis [54].

In addition, a commonly observed pathology in octogenarians is spondylolisthesis, which is the slippage of one vertebral body over another, also due to degenerative changes related to aging [55]. The natural history of spondylolisthesis remains understudied, although contributing factors are likely female status (via ligamentous laxity and hormonal effects), baseline lumbar/pelvic parameters, and the effect of aging on the intervertebral disc and facet joints [56]. As emphasized above, degenerative spinal disease is seen with frequency in the octogenarian population, in which surgical decompression is a mainstay of therapy. It has been found that patients over the age of 80 experience a significantly higher incidence of overall complications, mortality, hospital readmission, and longer length of stay than younger cohorts; however, similar clinical improvement has been documented between octogenarians and younger patients undergoing decompression [19], which together highlight the subtleties in management of spinal cord compression in this cohort.

Minimally invasive approaches

Minimally invasive approaches to spinal decompression have gained popularity, including indirect decompression techniques of interspinous process devices (IPDs) and direct decompression techniques such as microscopic or endoscopic spine surgery [57]. Indirect decompression techniques can be achieved via the utilization of an interbody graft to restore disc height (such as in the case of ACDF). On the other hand, direct decompression may be achieved

Fig. 2 Sagittal **a** short tau inversion recovery (STIR) MRI and **b** non-contrast CT scan of the cervical spine demonstrating nondisplaced type III odontoid fracture in an 86-year-old male

via microscopic or endoscopic spine surgery. Microscopic spine surgery uses a microscope via soft tissue tubular retraction to decompress the spinal canal [57]. Conversely, endoscopic spine surgery can achieve direct decompression with less associated tissue damage. Originally utilized for disc herniation, this technology has expanded to include decompression for stenosis with or without degenerative spondylolisthesis and has the benefits of minimal tissue dissection and muscular injury, clearer surgical vision, minimal blood loss, less postoperative epidural fibrosis and scarring, faster recovery, improved quality of life, shorter length of hospital stay, and improved cosmesis [57]. Notably, fluoroscopy-guided epidural anesthesia for endoscopic lumbar decompression surgery (of less than 3 levels) has been associated with significantly lower postoperative pain scores up to 48 h with decreased number of patients requiring rescue analgesics in the post-anesthesia care unit (PACU) when compared to general anesthesia, with a similar complication profile [58]. Therefore, conscious sedation for endoscopic spinal decompression may provide superior pain control than general anesthesia, which may be advantageous in avoiding the perioperative complication risk of general anesthesia in advanced-age patients. However, it must be noted that these techniques are novel and, as such, lack the long-term and high-class data of more established approaches.

Decompression in the octogenarian

As spinal surgery trends towards minimally invasive approaches, it is essential to assess how these approaches impact those of differing age groups. Current literature is somewhat heterogeneous, although many believe that octogenarians can benefit from minimally invasive decompression of the spinal canal, despite the increased risk of complication [7, 10]. Not surprisingly, open spinal decompression (e.g., posterolateral arthrodesis) is associated with much higher risk of complication in octogenarians. As in any preoperative assessment, careful evaluation of the patient's coexisting comorbidities is crucial to formulating a proper treatment plan, in which the American Society of Anesthesiologists (ASA) physical status and BMI provide a strong correlation with the highest number of complications [8].

In the context of minimally invasive spinal decompression, the literature appears to conclude that octogenarians can benefit from surgical intervention [7, 10]. Those over 80 have been found to experience significant improvement in patient-reported outcome measures at 6 months following unilateral laminotomy for bilateral decompression (a form of tubular lumbar decompression), similar to younger patients [7]. In addition, awake, transforaminal endoscopic spinal decompression may also offer a safe and efficacious option in the treatment of lumbar degenerative disc disease, with Telfeian and colleagues reporting an improvement in disability and leg pain metrics at 1-year follow-up [10]. However, approaches to cervical decompression may be more nuanced, as Xu and colleagues found that ACDF for multilevel cervical myelopathy resulted in reduced cobb angle of C2–C7 at the cost of increased complication rates when compared to posterior laminoplasty [59]. Altogether, the approach to surgical decompression remains highly

dependent on patient comorbidity profile and spinal level of disease, in which age status may not directly impact patient outcomes.

Illustrative case example

An 81-year-old female with a past medical history of end-stage renal failure secondary to Goodpasture syndrome who was on frequent hemodialysis presented to our institution for the evaluation of cervical spondylotic myelopathy. She reported a 1-year history of weakness in the bilateral lower extremities with accompanying ataxia and increased number of falls. In addition, she reported numbness and tingling in bilateral distal lower extremities. MRI of the cervical spine demonstrated moderate-to-severe spinal canal stenosis and flattening of the ventral cord ranging from the C4 to C7 spinal levels. Upon neurologic examination, she was found to have bilateral Hoffman's sign and a wide-based gait with the inability to perform tandem gait testing. At that time, she was instructed to seek cardiac clearance and DEXA bone density scanning prior to pursuing operative intervention. Following clearance for surgery, she underwent an elective ACDF procedure of the C5–C7 spinal levels, in which she experienced no perioperative complications and was discharged neurologically intact on postoperative day 1. At 2-week follow-up, she reported a significant improvement in her symptoms; however, she suffered a ground-level mechanical fall at home but reported no adverse sequelae. She appeared to be recovering well otherwise and was later lost to follow-up.

Spinal fusion

Lumbar fusion has evolved to include minimally invasive approaches such as percutaneous pedicle screw fixation techniques, lateral approaches for interbody fusion, and midline lumbar fusion with cortical bone trajectory screws [60]. Regarding cervical fusion, the ACDF procedure is frequently used, which historically has been conducted through an open incision. However, this procedure has become less invasive with the advent of tubular retractors, which allow for the manipulation of soft tissue for successful discectomy and fusion [47, 61]. Given these advances, ACDF appears to be a feasible surgical avenue in all ages, with similar recovery ratios reported in elderly patients versus younger cohorts (42.8% versus 51.1%, respectively) [53]. What is more, others have concluded that clinical outcomes support anterior approaches to cervical fusion compared to posterior due to increased ability for the structural correction and restoration of lordosis, while posterior approaches (e.g., posterior cervical discectomy and fusion) may be preferred in cases requiring multilevel decompression and fusion [62].

Fusion in the octogenarian

The complication profile for spinal fusion surgery in the octogenarian cohort appears to be multifaceted. A multitude of factors may impact outcomes, such as comorbidities or spinal level of disease. Interestingly, a higher percentage of octogenarians undergoing lumbar fusion have encountered complications compared to those undergoing cervical fusions (71.4% versus 53.9%, respectively), with the lumbar group demonstrating improved pain, ODI, and 36-Item Short Form Survey (SF-36) scores [13]. However, no significant difference in intraoperative dural tear or CSF leaks has been found in those over 80 compared to younger cohorts. Furthermore, comorbidities that impact heart or hemostatic blood pressure regulation (e.g., renal failure, hypertension, cardiac arrhythmias) may predict ACDF outcome [15], providing a challenge when assessing age as an independent risk factor for poor outcome. Together, these data suggest that increasing age may independently increase the risk for a subset of complications in lumbar fusion surgery but do not represent an associative risk for all complications. In addition, age does not appear to limit clinical improvement in cases of lumbar fusion.

Elective lumbar fusions continue to rise in number, as annual cases increased from 1144 to 2061 between 2004 and 2014. Interestingly, immediate postoperative mortality rates have fluctuated between 0.2 and 1% with length of stay decreasing from 6 to 4.5 days over this time period [16]. Considering that the number of octogenarians continues to rise, lumbar fusion surgery may be trending towards decreasing postoperative complications despite treating an increasing proportion of higher risk patients. Although overall postoperative complication rates may be declining, it has been reported that the proportion of patients experiencing at least one complication increases by 44.6% after the age of 80, with 90-day and 1-year mortality rates increasing by a factor of 3.5 and 2.58, respectively [12]. In addition, bony

union rate following fusion is significantly lower in octogenarians compared to younger patients [14]; however, it is unclear if nonunion impacts patient-reported clinical outcomes, similar to the above discussion of odontoid instrumented fusion. Altogether, age may have an independent impact on mortality rates following spinal fusion surgery [12], yet the complex medical landscape of octogenarian care continues to limit the isolation of age as an independent risk factor for poor outcome.

Conclusion

In this narrative review, we recounted common spinal pathologies encountered by the octogenarian and varying surgical treatment options for these conditions. Current literature indicates that age status may be less pertinent than previously thought in the decision to pursue spinal surgery for odontoid fracture, spinal decompression, or spinal fusion; however, each of these procedures has respective risks and benefits that must be considered within the context of each patient's comorbidity profile. Further study is warranted to isolate age as an independent risk factor for outcome of spinal surgery in this age cohort.

Declarations

Competing interests The authors declare no competing interests.

References

1. Kim TI, Brahmandam A, Skrip L, Sarac T, Dardik A, Ochoa Chaar CI. Surgery for the very old: are nonagenarians different? Am Surg. 2020;86:56–64.
2. Perry A, Graffeo CS, Carlstrom LP, Chang W, Mallory GW, Puffer RC, Clarke MJ. Fusion, failure, fatality: long-term outcomes after surgical versus nonoperative management of type II odontoid fracture in octogenarians. World Neurosurg. 2018;110:e484–9. https://doi.org/10.1016/j.wneu.2017.11.020.
3. Clark S, Nash A, Shasti M, Brown L, Jauregui JJ, Mistretta K, Koh E, Banagan K, Ludwig S, Gelb D. Mortality rates after posterior C1–2 fusion for displaced type II odontoid fractures in octogenarians. Spine. 2018;43:E1077–81. https://doi.org/10.1097/BRS.0000000000002637.
4. Smith HE, Kerr SM, Maltenfort M, Chaudhry S, Norton R, Albert TJ, Harrop J, Hilibrand AS, Anderson DG, Kopjar B, Brodke DS, Wang JC, Fehlings MG, Chapman JR, Patel A, Arnold PM, Vaccaro AR. Early complications of surgical versus conservative treatment of isolated type II odontoid fractures in octogenarians: a retrospective cohort study. J Spinal Disord Tech. 2008;21:535–9. https://doi.org/10.1097/BSD.0b013e318163570b.
5. Carlstrom LP, Helal A, Perry A, Lakomkin N, Graffeo CS, Clarke MJ. Too frail is to fail: frailty portends poor outcomes in the elderly with type II odontoid fractures independent of management strategy. J Clin Neurosci. 2021;93:48–53. https://doi.org/10.1016/j.jocn.2021.08.027.
6. Deng H, Yue JK, Upadhyayula PS, Burke JF, Suen CG, Chan AK, Winkler EA, Dhall SS. Odontoid fractures in the octogenarian: a systematic review and meta-analysis. J Neurosurg Sci. 2016;60:543–55.
7. Shahi P, Song J, Dalal S, Melissaridou D, Shinn DJ, Araghi K, Mai E, Sheha E, Dowdell J, Qureshi SA, Iyer S. Improvement following minimally invasive lumbar decompression in patients 80 years or older compared with younger age groups. J Neurosurg Spine. 2022;37:828–35. https://doi.org/10.3171/2022.5.SPINE22361.
8. Aimar E, Iess G, Mezza F, Gaetani P, Messina AL, Todesca A, Tartara F, Broggi G. Complications of degenerative lumbar spondylolisthesis and stenosis surgery in patients over 80 s: comparative study with over 60 s and 70 s. Experience with 678 cases. Acta Neurochir. 2022;164:923–31. https://doi.org/10.1007/s00701-022-05118-9.
9. Sharma M, Dietz N, Ugiliweneza B, Wang D, Drazin D, Boakye M. Differences in clinical outcomes and health care utilization between octogenarians and nonagenarians following decompression for lumbar spinal stenosis. A market scan analysis. Clin Neurol Neurosurg. 2019;182:63–9. https://doi.org/10.1016/j.clineuro.2019.04.031.
10. Telfeian AE, Sastry R, Oyelese A, Fridley J, Camara-Quintana JQ, Niu T, Sampath P, Lewandrowski K-U, Mueller K, Gokaslan ZL. Awake, Transforaminal endoscopic lumbar spine surgery in octogenarians: case series. Pain Physician. 2022;25:E255–62.
11. Hussain I, Hartley BR, McLaughlin L, Reiner AS, Laufer I, Bilsky MH, Barzilai O. Surgery for metastatic spinal disease in octogenarians and above: analysis of 78 patients. Glob Spine J. 2023;13:1481–9. https://doi.org/10.1177/21925682211037936.
12. Puvanesarajah V, Jain A, Shimer AL, Li X, Singla A, Shen F, Hassanzadeh H. Complications and mortality following 1 to 2 level lumbar fusion surgery in patients above 80 years of age. Spine. 2017;42:437–41. https://doi.org/10.1097/BRS.0000000000001759.
13. Rajpal S, Lee Nelson E, Villavicencio AT, Telang J, Kantha R, Beasley K, Burneikiene S. Medical complications and mortality in octogenarians undergoing elective spinal fusion surgeries. Acta Neurochir. 2018;160:171–9. https://doi.org/10.1007/s00701-017-3384-9.
14. Hayashi K, Matsumura A, Konishi S, Kato M, Namikawa T, Nakamura H. Clinical outcomes of posterior lumbar interbody fusion for patients 80 years of age and older with lumbar degenerative disease: minimum 2 years' follow-up. Glob Spine J. 2016;6:665–72. https://doi.org/10.1055/s-0036-1578806.
15. Elsamadicy AA, Koo AB, Reeves BC, Freedman IG, David WB, Ehresman J, Pennington Z, Laurans M, Kolb

L, Sciubba DM. Octogenarians are independently associated with extended los and non-routine discharge after elective ACDF for CSM. Glob Spine J. 2022;12:1792–803. https://doi.org/10.1177/21925682221989293.
16. Kha ST, Ilyas H, Tanenbaum JE, Benzel EC, Steinmetz MP, Mroz TE. Trends in lumbar fusion surgery among octogenarians: a nationwide inpatient sample study from 2004 to 2013. Glob Spine J. 2018;8:593–9. https://doi.org/10.1177/2192568218756878.
17. Hikata T, Ishii K, Matsumoto M, Kobayashi K, Imagama S, Ando K, Ishiguro N, Yamashita M, Seki S, Terai H, Suzuki A, Tamai K, Aramomi M, Ishikawa T, Kimura A, Inoue H, Inoue G, Miyagi M, Saito W, Yamada K, Hongo M, Endo K, Suzuki H, Nakano A, Watanabe K, Ohya J, Chikuda H, Aoki Y, Shimizu M, Futatsugi T, Mukaiyama K, Hasegawa M, Kiyasu K, Iizuka H, Kobayashi R, Iizuka Y, Nishida K, Kakutani K, Nakajima H, Murakami H, Demura S, Kato S, Yoshioka K, Namikawa T, Watanabe K, Nakanishi K, Nakagawa Y, Yoshimoto M, Fujiwara H, Nishida N, Imajo Y, Yamazaki M, Abe T, Fujii K, Kaito T, Eguchi Y, Furuya T, Orita S, Ohtori S. Risk factor for poor patient satisfaction after lumbar spine surgery in elderly patients aged over 80 years. Clin Spine Surg. 2021;34:E223–8. https://doi.org/10.1097/BSD.0000000000001101.
18. Epstein NE. Unnecessary cervical epidural injection in an octogenarian. Surg Neurol Int. 2019;10:108. https://doi.org/10.25259/SNI-197-2019.
19. Liang H, Lu S, Jiang D, Fei Q. Clinical outcomes of lumbar spinal surgery in patients 80 years or older with lumbar stenosis or spondylolisthesis: a systematic review and meta-analysis. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sec Cerv Spine Res Soc. 2020;29:2129–42. https://doi.org/10.1007/s00586-019-06261-1.
20. Hajibandeh S, Hajibandeh S, Antoniou GA, Antoniou SA. Meta-analysis of mortality risk in octoagenarians undergoing emergency general surgery operations. Surgery. 2021;169:1407–16. https://doi.org/10.1016/j.surg.2020.11.027.
21. Kitridis D, Tsikopoulos K, Givissis P, Chalidis B. Mortality and complication rates in nonagenarians and octogenarians undergoing total hip and knee arthroplasty: a systematic review and meta-analysis. Eur Geriatr Med. 2022;13:725–33. https://doi.org/10.1007/s41999-022-00610-y.
22. Stovell MG, Jenkinson MD. Neurosurgery in octogenarians. Br J Neurosurg. 2014;28:611–5. https://doi.org/10.3109/02688697.2014.889809.
23. Maldaner N, Sarnthein J, Bozinov O, Regli L, Neidert MC. Neurosurgery in octogenarians: a prospective study of perioperative morbidity, mortality, and complications in elderly patients. World Neurosurg. 2018;110:e287–95. https://doi.org/10.1016/j.wneu.2017.10.154.
24. Kim DU, Park HK, Lee GH, Chang JC, Park HR, Park SQ, Cho SJ. Central sarcopenia, frailty and comorbidity as predictor of surgical outcome in elderly patients with degenerative spine disease. J Korean Neurosurg Soc. 2021;64:995–1003. https://doi.org/10.3340/jkns.2021.0074.
25. Kim TW, Oh JK, Lee JY, Cho SK, An SB, Jeon HS, Kim HC, Kim KJ, Shin DA, Yi S, Kim KN, Yoon DH, Kim CO, Ha Y. Association of frailty and self-care activity with sagittal spinopelvic alignment in the elderly. World Neurosurg. 2020;138:e759–66. https://doi.org/10.1016/j.wneu.2020.03.071.
26. Youngerman BE, Neugut AI, Yang J, Hershman DL, Wright JD, Bruce JN. The modified frailty index and 30-day adverse events in oncologic neurosurgery. J Neurooncol. 2018;136:197–206. https://doi.org/10.1007/s11060-017-2644-0.
27. Jung J-M, Chung CK, Kim CH, Yang SH, Ko YS. The modified 11-item frailty index and postoperative outcomes in patients undergoing lateral lumbar interbody fusion. Spine. 2022;47:396–404. https://doi.org/10.1097/BRS.0000000000004260.
28. Hersh AM, Pennington Z, Hung B, Patel J, Goldsborough E, Schilling A, Feghali J, Antar A, Srivastava S, Botros D, Elsamadicy AA, Lo S-FL, Sciubba DM. Comparison of frailty metrics and the Charlson comorbidity index for predicting adverse outcomes in patients undergoing surgery for spine metastases. J Neurosurg Spine. 2022;36:849–57. https://doi.org/10.3171/2021.8.SPINE21559.
29. Leven DM, Lee NJ, Kothari P, Steinberger J, Guzman J, Skovrlj B, Shin JI, Caridi JM, Cho SK. Frailty index is a significant predictor of complications and mortality after surgery for adult spinal deformity. Spine. 2016;41:E1394–401. https://doi.org/10.1097/BRS.0000000000001886.
30. Yuan S, Larsson SC. Epidemiology of sarcopenia: prevalence, risk factors, and consequences. Metabolism. 2023;144:155533. https://doi.org/10.1016/j.metabol.2023.155533.
31. Chotai S, Gupta R, Pennings JS, Hymel AM, Archer KR, Zuckerman SL, Stephens BF, Abtahi AM. Frailty and sarcopenia: impact on outcomes following elective degenerative lumbar spine surgery. Spine. 2022;47:1410–7. https://doi.org/10.1097/BRS.0000000000004384.
32. Charest-Morin R, Street J, Zhang H, Roughead T, Ailon T, Boyd M, Dvorak M, Kwon B, Paquette S, Dea N, Fisher CG, Flexman AM. Frailty and sarcopenia do not predict adverse events in an elderly population undergoing non-complex primary elective surgery for degenerative conditions of the lumbar spine. Spine J Off J North Am Spine Soc. 2018;18:245–54. https://doi.org/10.1016/j.spinee.2017.07.003.
33. Pinter ZW, Salmons HI, Townsley S, Omar A, Freedman BA, Currier BL, Elder BD, Nassr AN, Bydon M, Wagner SC, Sebastian AS. Multifidus sarcopenia is associated with worse patient-reported outcomes following posterior cervical decompression and fusion. Spine. 2022;47:1426–34. https://doi.org/10.1097/BRS.0000000000004386.
34. Chua M, Hochberg U, Regev G, Ophir D, Salame K, Lidar Z, Khashan M. Gender differences in multifidus fatty infiltration, sarcopenia and association with preoperative pain and functional disability in patients with lumbar spinal stenosis. Spine J. 2022;22:58–63. https://doi.org/10.1016/j.spinee.2021.06.007.
35. Salari N, Darvishi N, Bartina Y, Larti M, Kiaei A, Hemmati M, Shohaimi S, Mohammadi M. Global prevalence of osteoporosis among the world older adults: a comprehensive systematic review and meta-analysis. J Orthop Surg. 2021;16:669. https://doi.org/10.1186/s13018-021-02821-8.
36. Carlson BB, Salzmann SN, Shirahata T, Ortiz Miller C, Carrino JA, Yang J, Reisener M-J, Sama AA, Cammisa FP, Girardi FP, Hughes AP. Prevalence of osteoporosis and osteopenia diagnosed using quantitative CT in 296 consecutive lumbar fusion patients. Neurosurg Focus. 2020;49:E5. https://doi.org/10.3171/2020.5.FOCUS20241.
37. Arceo-Mendoza RM, Camacho PM. Postmenopausal osteoporosis. Endocrinol Metab Clin North Am. 2021;50:167–78. https://doi.org/10.1016/j.ecl.2021.03.009.

38. Kanis JA, Johansson H, Harvey NC, McCloskey EV. A brief history of FRAX. Arch Osteoporos. 2018;13:118. https://doi.org/10.1007/s11657-018-0510-0.
39. Chaudhary N, Lee JS, Wu JY, Tharin S. Evidence for use of teriparatide in spinal fusion surgery in osteoporotic patients. World Neurosurg. 2017;100:551–6. https://doi.org/10.1016/j.wneu.2016.11.135.
40. Machino M, Nakashima H, Ito K, Katayama Y, Matsumoto T, Tsushima M, Ando K, Kobayashi K, Imagama S. Age-related degenerative changes and sex-specific differences in osseous anatomy and intervertebral disc height of the thoracolumbar spine. J Clin Neurosci Off J Neurosurg Soc Australas. 2021;90:317–24. https://doi.org/10.1016/j.jocn.2021.06.020.
41. Baliga S, Treon K, Craig NJA. Low back pain: current surgical approaches, Asian. Spine J. 2015;9:645–57. https://doi.org/10.4184/asj.2015.9.4.645.
42. Lurie J, Tomkins-Lane C. Management of lumbar spinal stenosis. BMJ. 2016;352:h6234. https://doi.org/10.1136/bmj.h6234.
43. Kohno M, Iwamura Y, Inasaka R, Akiyama G, Higashihira S, Kawai T, Niimura T, Inaba Y. Influence of comorbid knee osteoarthritis on surgical outcome and sagittal spinopelvic/lower-extremity alignment in elderly patients with degenerative lumbar spondylolisthesis undergoing transforaminal lumbar interbody fusion. Journal of neurosurgery. Spine. 2020;1–9. Advance online publication. https://doi.org/10.3171/2019.11.SPINE19978.
44. Patel PD, Canseco JA, Houlihan N, Gabay A, Grasso G, Vaccaro AR. Overview of minimally invasive spine surgery. World Neurosurg. 2020;142:43–56. https://doi.org/10.1016/j.wneu.2020.06.043.
45. Epstein NE. A review of complication rates for anterior cervical diskectomy and fusion (ACDF). Surg Neurol Int. 2019;10:100. https://doi.org/10.25259/SNI-191-2019.
46. Yeshoua BJ, Singh S, Liu H, Assad N, Dominy CL, Pasik SD, Tang JE, Patel A, Shah KC, Ranson W, Kim JS, Cho SK. Association between age-stratified cohorts and perioperative complications and 30-day and 90-day readmission in patients undergoing single-level anterior cervical discectomy and fusion. Clin Spine Surg Spine Publ. 2023. https://doi.org/10.1097/BSD.0000000000001509.
47. Skovrlj B, Qureshi SA. Minimally invasive cervical spine surgery. J Neurosurg Sci. 2017;61:325–34. https://doi.org/10.23736/S0390-5616.16.03906-0.
48. Lee CH, Son DW, Lee SH, Lee JS, Sung SK, Lee SW, Song GS. Radiological and clinical outcomes of anterior cervical discectomy and fusion in older patients: a comparative analysis of young-old patients (ages 65–74 years) and middle-old patients (over 75 years). Neurospine. 2020;17:156–63. https://doi.org/10.14245/ns.1836072.036.
49. Tavares S, Costa GG, Galego O, Pereira R. Can morphometric analysis of cervical spondylotic myelopathy be a tool for surgical outcome prediction? Int J Spine Surg. 2021;15:718–23. https://doi.org/10.14444/8094.
50. Yue JK, Ordaz A, Winkler EA, Deng H, Suen CG, Burke JF, Chan AK, Manley GT, Dhall SS, Tarapore PE. Predictors of 30-day outcomes in octogenarians with traumatic C2 fractures undergoing surgery. World Neurosurg. 2018;116:e1214–22. https://doi.org/10.1016/j.wneu.2018.05.237.
51. Tenny S, Munakomi S, Varacallo M. Odontoid fractures, in: StatPearls, StatPearls Publishing, Treasure Island (FL). 2023. http://www.ncbi.nlm.nih.gov/books/NBK441956/. Accessed 23 Oct 2023.
52. Joaquim AF, Patel AA. Surgical treatment of type II odontoid fractures: anterior odontoid screw fixation or posterior cervical instrumented fusion? Neurosurg Focus. 2015;38:E11. https://doi.org/10.3171/2015.1.FOCUS14781.
53. Luo C-A, Lim AS, Lu M-L, Chiu P-Y, Lai P-L, Niu C-C. The surgical outcome of multilevel anterior cervical discectomy and fusion in myelopathic elderly and younger patients. Sci Rep. 2022;12:4495. https://doi.org/10.1038/s41598-022-08243-8.
54. Davies BM, Mowforth OD, Smith EK, Kotter MR. Degenerative cervical myelopathy. BMJ. 2018;360:k186. https://doi.org/10.1136/bmj.k186.
55. Li N, Scofield J, Mangham P, Cooper J, Sherman W, Kaye A. Spondylolisthesis. Orthop Rev (Pavia). 2022;14(4):36917. https://doi.org/10.52965/001c.36917.
56. Koreckij TD, Fischgrund JS. Degenerative spondylolisthesis. J Spinal Disord Tech. 2015;28:236–41. https://doi.org/10.1097/BSD.0000000000000298.
57. Zhang J, Liu T-F, Shan H, Wan Z-Y, Wang Z, Viswanath O, Paladini A, Varrassi G, Wang H-Q. Decompression using minimally invasive surgery for lumbar spinal stenosis associated with degenerative spondylolisthesis: a review. Pain Ther. 2021;10:941–59. https://doi.org/10.1007/s40122-021-00293-6.
58. Kang SY, Cho HS, Yi J, Kim HS, Jang IT, Kim D-H. The comparison of fluoroscopy-guided epidural anesthesia with conscious sedation and general anesthesia for endoscopic lumbar decompression surgery: a retrospective analysis. World Neurosurg. 2022;159:e103–12. https://doi.org/10.1016/j.wneu.2021.12.019.
59. Xu L, Sun H, Li Z, Liu X, Xu G. Anterior cervical discectomy and fusion versus posterior laminoplasty for multilevel cervical myelopathy: a meta-analysis. Int J Surg. 2017;48:247–53. https://doi.org/10.1016/j.ijsu.2017.06.030.
60. Momin AA, Steinmetz MP. Evolution of minimally invasive lumbar spine surgery. World Neurosurg. 2020;140:622–6. https://doi.org/10.1016/j.wneu.2020.05.071.
61. Vergara P, Timofeev I. Minimally invasive anterior cervical discectomy and fusion: a valid alternative to open techniques. Acta Neurochir (Wien). 2018;160:2467–71. https://doi.org/10.1007/s00701-018-3719-1.
62. Porter M, Schmitz MA. ACDF and posterior spinal fusion revision for posterior nonunion with deformity, myelopathy, and osteoporosis in an 87-year-old: a case report and literature review. Int J Surg Case Rep. 2022;90:106650. https://doi.org/10.1016/j.ijscr.2021.106650.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.