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REVIEW ARTICLE

Current concepts of spondylosis and posterior spinal motion preservation for radiologists

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Abstract

Spinal fusion is performed to eliminate motion at a degenerated or unstable segment. However, this is associated with loss of motion at the fused levels and increased stress on adjacent levels. Motion-preserving implants have been designed in effort to mitigate the limitations of fusion. This review will focus on posterior spinal motion-preserving technologies. In the cervical spine, laminoplasty is a posterior motion-preserving procedure used in the management of myelopathy/cord compression. In the lumbar spine, motion-sparing systems include interspinous process devices (also referred to as interspinous process spacers or distraction devices), posterior dynamic stabilization devices (also referred to as pedicle screw/rod fixation-based systems), and posterior element replacement systems (also referred to as total facet replacement devices). Knowledge of the intended physiologic purpose, hardware utilized, and complications is important in the assessment of imaging in those who have undergone posterior motion preservation procedures.

Keywords Spondylosis · Fusion · Laminoplasty · Interspinous process device · Posterior dynamic stabilization device · Posterior element replacement system

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Introduction

Conventional fusion

Spinal fusion may be utilized in a number of clinical situations. With fusion, spinal deformity and instability can be corrected and stabilized, degeneration can be addressed, and iatrogenic instability that may result from spinal decompression can be avoided. Biologically, fusion is the process by which vertebrae are induced to grow together to functionally form a single unit. This is achieved through decortication of bony surfaces of neighboring levels and placing bone graft or graft substitute that can be osteogenic, osteoinductive, or osteoconductive [1]. In order to increase the process of biologic fusion, gain better control of alignment, and decrease the need for external immobilization, spinal instrumentation is frequently used and has evolved over the past few decades.

However, fusion is not without drawbacks. One potential shortcoming of fusion is that stiffening a segment can be associated with reduction in motion and an increase in stresses incurred by adjacent levels [2, 3]. The uneven distribution of these forces and loss of segmental mobility may lead to adjacent disk degeneration. Long-term clinical studies have reported the incidence of adjacent segmental

degeneration (ASD) to be between 5 and 100% after undergoing lumbar spinal fusion [4, 5]. Notably, although such ASD is seen radiographically, it may not be associated with symptoms [2, 6–8]. In addition, attempted fusion is not always achieved, and pseudoarthrosis may lead to inferior clinical outcomes [7]. This may be of particular concern in patients with factors known to inhibit biologic fusion, such as smoking [1, 9].

Motion-preserving implants

Some have surmised that the preservation of motion or load sharing at an index level may help to address pathology while reducing ASD and, in turn, reduce the need for subsequent surgery [2, 6]. In response, motion preservation treatment options have been developed [3, 10].

The concept of "dynamic stabilization" was first described by Sengupta et al. who postulated that restoring the normal motion of the spine, rather than rigidly stabilizing, would decrease the risk of ASD by avoiding the abnormal loading patterns placed on the adjacent segments surrounding the fusion [4, 11]. Biomechanically, restoration of the normal motion allows the spine to naturally redistribute the aforementioned forces. In return, this method seeks to reduce pain, prevent ASD, and allow for natural disk restoration [3, 4].

Technologies have been developed, and others are being explored, to address the anterior aspect of the spine. These technologies range from biomaterials targeting disk regeneration through principles of bioengineering [12] to disk arthroplasty devices. There is much literature and clinical experience with these interventions [12]; however, this is not the focus of the current review. Rather, we detail posterior-based spinal motion-preserving technologies. In the cervical spine, posterior motion-sparing procedures include laminoplasty, which may be considered in the management of myelopathy/cord compression. In the lumbar spine, posterior motion-sparing systems have been classified into three separate categories including interspinous process devices (also referred to as interspinous process spacers or distraction devices), posterior dynamic stabilization devices (also referred to as pedicle screw/rod fixation-based systems), and posterior element replacement systems (also referred to as total facet replacement devices) [2, 13, 14].

Cervical spine

Background

Multilevel cervical stenosis can be associated with myelopathy/cord compression. Based on the natural history of myelopathy, surgery is often recommended for this condition. Although several levels are typically addressed from an anterior approach, three or more levels, ossification of the posterior longitudinal ligament (OPLL), and patient-specific obstacles may make the posterior approach preferable. Notably, there is no definite indication for an anterior versus posterior approach, and there are many clinical situations where either may be considered [15].

Historically, cervical laminectomy was frequently performed; however, this was associated with post-laminectomy kyphosis due to deficient posterior structures [16]. Consequently, posterior cervical decompression and fusion have gained popularity but associated with the fusion limitations discussed in the conventional fusion section.

Cervical laminoplasty is a motion-preserving procedure for treatment of cervical spondylotic myelopathy in which the laminae are selectively cut and hinged open, dorsally expanding the spinal canal, and indirectly decompressing the anterior canal by allowing the cord to dorsally migrate. Preserving the laminae allows for mechanical stability as cadaveric studies have shown that significant axial load is transmitted through the cervical posterior column [17].

Laminoplasty is avoided in patients with kyphosis (greater than 13 degrees) or thick OPLL, as posterior opening of the canal does not alleviate the draping of the spinal cord over the anterior vertebrae. A virtual line, referred to as the K-line, that connects the midpoints of the anteroposterior diameter of the spinal canal at C2 and C7 on a lateral radiograph can be used as a preoperative predictor of outcome in those with kyphotic deformity or significant OPLL. Where the peak of ossification exceeds the K-line, the effects of laminoplasty are considered ineffective [18]. Significant axial neck pain is another relative contraindication for laminoplasty, as this is not well addressed by this procedure. These factors, as well as any significant segmental instability (spondylolisthesis or hypermobility) or previous posterior cervical surgery, would deter one from utilizing laminoplasty as a surgical option [19].

First described in 1973 by Oyama et al. as a treatment for OPLL, laminoplasty has since been adapted for other processes that lead to cervical stenosis, and several technique variations have been described with the shared principle of hinging open posterior elements [20].

Technique

Z-plasty

The original cervical laminoplasty, Z-plasty, was performed by Oyama et al. in 1973. In this procedure, the laminae of the myelopathic levels are attenuated with a surgical burr, and a Z-shaped laminotomy is made in each lamina. The cut laminae are partly separated at the midline, and sutured end-to-end, thereby expanding the

posterior neural arch. Given the inherent complexity of the Z-plasty, the laminoplasty was reimagined as the open-door laminoplasty [20, 21].

Open-door laminoplasty

First described by Hirabayashi et al. in 1978 [20], the open-door laminoplasty is currently the most commonly considered laminoplasty technique. This involves burring a trough on one side of the lamina through both cortices (opening side) and partially through the opposite side (hinge side). Typically, the side of greater radiculopathy is chosen for the opening side. The interspinous ligament immediately cephalad and caudal to the operative segment is released, and the laminae are "hinged" open to expand the canal [22–24].

To maintain the opening afforded by this technique, the hinged laminae are stabilized in the open position. Originally, this was described with sutures placed through the posterior spinous processes and the hinge side facet capsule, articular process, or paravertebral muscle (Fig. 1). As an alternative to sutures, mini-plates have evolved to hold the hinged lamina open. These extend from the lamina of the open side to the ipsilateral lateral mass [22, 23] (Fig. 2).

Although the posterior bony arch will typically unite through the hinge side, bone graft may be considered at the opening to facilitate further bony healing, as well as maintain the open door. These can be autograft or allograft fashioned into wedges placed within the open side, held in place by tension from the laminae [22] or the mini-plates [23] (Fig. 3).

French-door laminoplasty

A variant of the open-door laminoplasty is the French-door laminoplasty, first described by Kurokawa et al. in 1982 [20]. In this procedure, the posterior neural arch at each operative level is reconstructed by creating a midsagittal osteotomy through the spinous process and burring hinge troughs at the lamina-facet capsule junction bilaterally. The split spinous process (and thereby posterior neural arch) is splayed open and stabilized with an interposed bone graft used to hold this open (Fig. 4). Reported benefits of the French-door laminoplasty are symmetric expansion of the spinal canal and decreased bleeding from the venous plexus [22, 25].

Outcomes

The clinical outcomes of anterior approach surgery for cervical myelopathy, either anterior cervical dissectomy and fusion (ACDF) or anterior cervical corpectomy and fusion, are comparable to those of French-door laminoplasty as demonstrated by Seng et al. [26]. For both anterior and posterior approach surgery patients, functional metrics, such as the Japanese orthopedics association score (JOA), neck disability index (NDI), and visual analog score neck pain, were improved at 6 months (short term) and at 2 years (long term) when compared to preoperative baselines. A notable metric that was worse relative to preoperative baseline in both cohorts was range of motion flexion and extension, however, was stable from 6 months to 2 years. Between the anterior and posterior surgery cohorts, the long-term functional outcomes were statistically similar. The short-term outcomes statistically differed for 2 metrics: JOA and NDI. Specifically, laminoplasty resulted in improved JOA scores

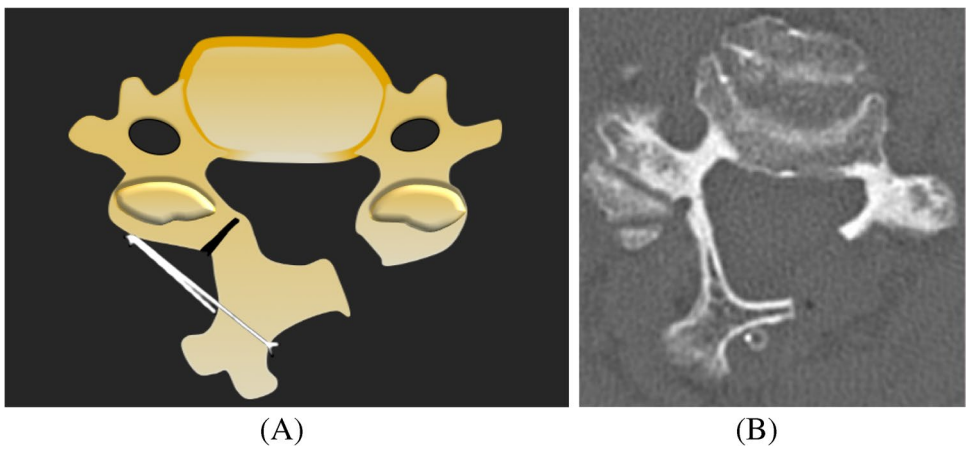

Fig. 1 Diagrammatic depiction (**A**) and accompanying axial CT image of the cervical spine (**B**) from a 63-year-old-female demonstrating a left-sided open-door laminoplasty. On the open side, a complete bony trough has been burred at the lamina-facet capsule junction. On the contralateral side, a partial bony trough has been burred at the lamina-facet capsule junction, extending from the outer cortex to the inner cancellous bone but with preservation of the inner cortex. The hinged right-sided lamina is stabilized in open position by sutures placed through the posterior spinous process and the facet capsule, as shown in diagram (**A**)

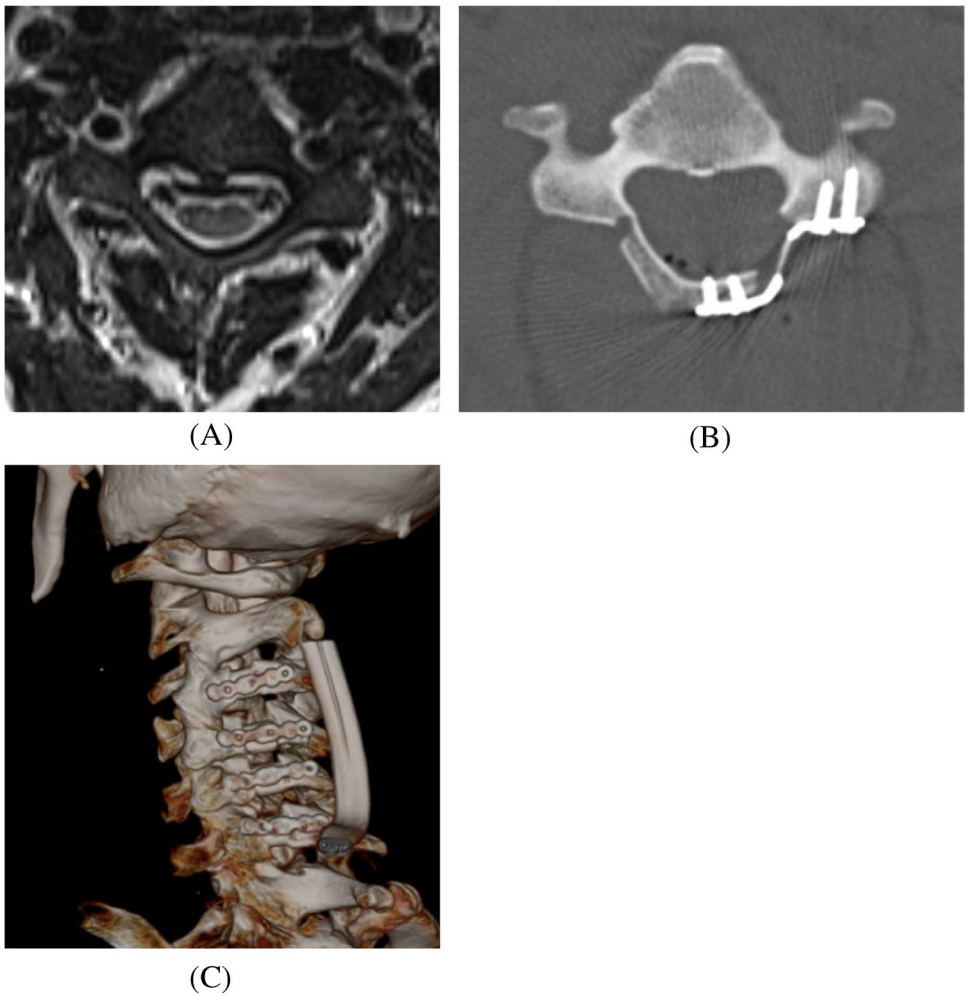

Fig. 2 60-year-old-male with augmented open-door laminoplasty utilizing a mini-plate and screw hardware construct. Axial T2-weighted image at C3 from a preoperative MRI (**A**) demonstrates an AP diameter of 12 mm. Axial CT image at C3 (**B**) with 3D-reformatted imaging in the sagittal plane (**C**) following left-sided open-door laminoplasty with mini-plate and screw hardware to prevent door closure, which extends from the lamina of the open side to the ipsilateral articular process. There has been an interval increase in AP diameter of the central canal, now 15.5 mm. There is an incomplete bony gutter on the hinge side

at 6 months, possibly due to more expansive decompression of the spinal canal. However, the extensive posterior cervical muscular dissection in laminoplasty likely resulted in worse NDI scores at 6 months.

A meta-analysis by Xu et al. further demonstrated a statistically similar recovery rate of the JOA score between ACDF and laminoplasty cohorts [27]. Perioperative metrics of blood loss and operative time were also similar between the two cohorts. One key difference between ACDF and laminoplasty was the odds of total complications, which was lower in laminoplasty. Complications for the ACDF cohort included adjacent spinal degeneration and post-operative hematoma, while those for the laminoplasty cohort included C5 palsy and posterior arch collapse.

Complications

There are potential complications inherent to any posterior cervical procedure performed for myelopathy. These include hardware dysfunction (Fig. 5), which may result in loss of the open door, neurologic risk to the compromised spinal cord, C5 nerve palsy [28] most typically attributed to drift back of the spinal cord, and wound-/pain-related issues. Additionally, there are some potential complications specific to laminoplasty.

Kyphosis post-laminoplasty is an inherent risk due to the lack of fusion (Fig. 6). Ensuring that the spine is not overly kyphotic preoperatively and maintaining the attachments of the deep extensor musculature to the posterior aspect of C2 can help limit the occurrence of this adverse outcome. Furthermore, avoiding disruption to the facet capsules can limit the occurrence [29, 30].

Axial neck pain, not only not well addressed by laminoplasty, may result from the procedure, with a reported prevalence as high as 60% [32]. In the process of deep extensor muscle detachment from the open side lamina, early pain (during the first month), usually ipsilateral to the opened side, is expected. [33].

Finally, although promoted as a motion-preserving procedure, in distinction to laminectomy, laminoplasty has been reported to restrict sagittal plane motion (flexion and extension). This is believed to be due to interlaminar

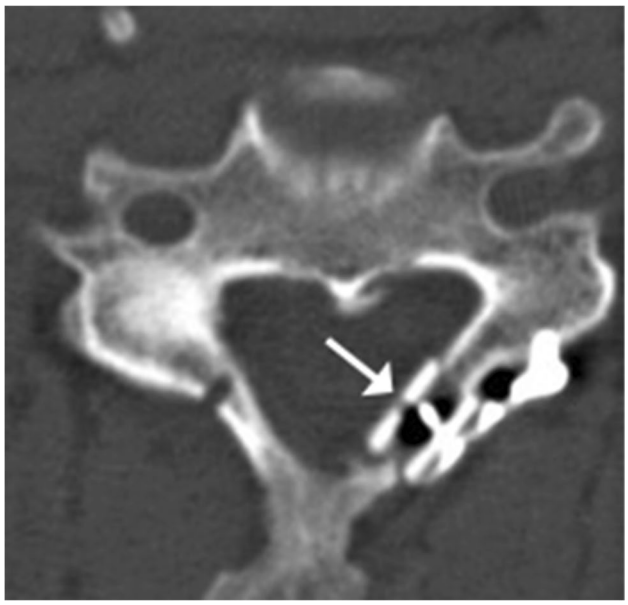

Fig. 3 67-year-old male with augmented open-door laminoplasty. Axial CT image at C4 demonstrates an augmented open-door laminoplasty with placement of an allograft spacer (arrow) that is secured by a laminoplasty mini-plate and screws to the same level, ipsilateral lamina and lateral mass

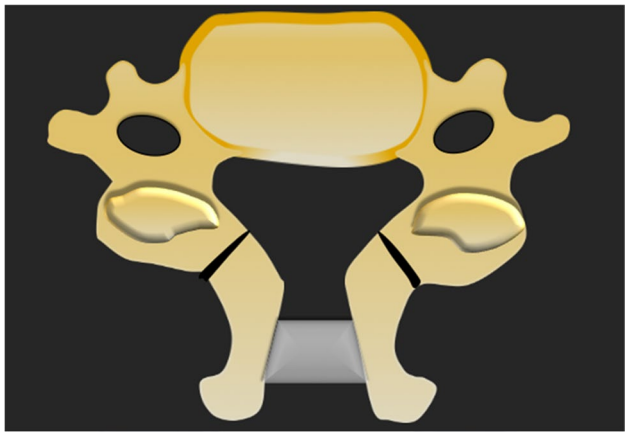

Fig. 4 Diagrammatic depiction of the French-door laminoplasty in which an osteotomy has been made through the spinous process and hinge troughs created at the lamina-facet capsule junction bilaterally. The split spinous process is splayed open and stabilized with interposed hydroxyapatite spacer, autograft, or allograft

bony fusion, which can be associated with loss of motion [34]. However, the restricted range of motion post-laminoplasty is significantly lower when compared to laminectomy and fusion [35].

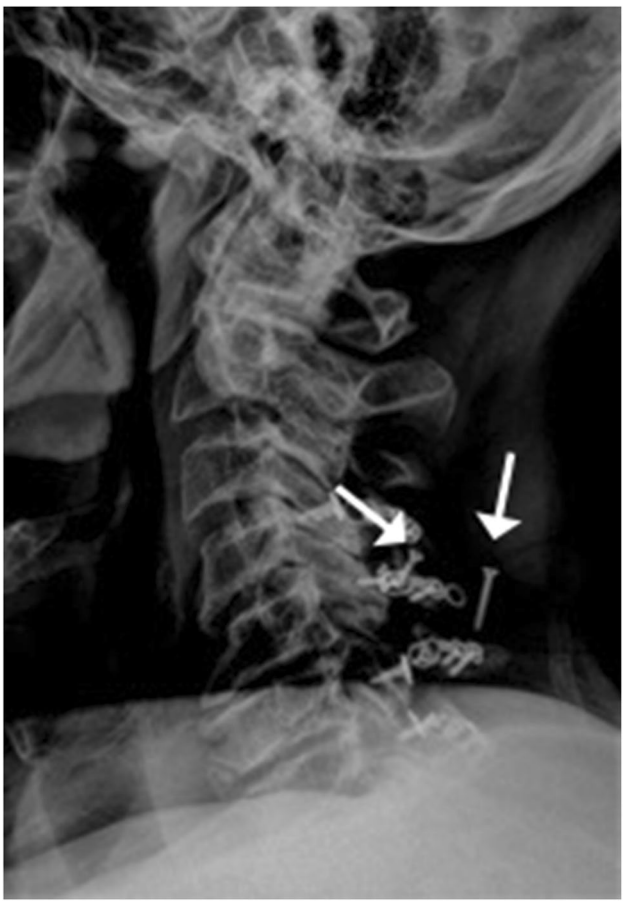

Fig. 5 Lateral radiograph of the cervical spine in a 63-year-old-male status post-C4-C7 augmented open-door laminoplasty with allograft spacers and ARCH laminoplasty system. There is loosening and migration of two of the C5 screws

Lumbar spine

Interspinous process devices (spacers or distraction devices)

Background

Posterior lumbar decompression is often used in the management of neurogenic claudication. This involves the removal of posterior bony overgrowth and associated ligamentum flavum. In cases of acceptably aligned, stable lumbar segments, this is often performed alone. However, in the setting of spondylolisthesis/instability, decompression may be performed in conjunction with fusion. In an attempt to limit the scope and drawbacks of such intervention, interspinous process devices (IPDs) were introduced.

IPDs are devices that are positioned between adjacent spinous processes at the level of stenosis in order to induce segmental flexion and indirect nerve decompression. In addition to maintaining a larger cross-sectional area of the

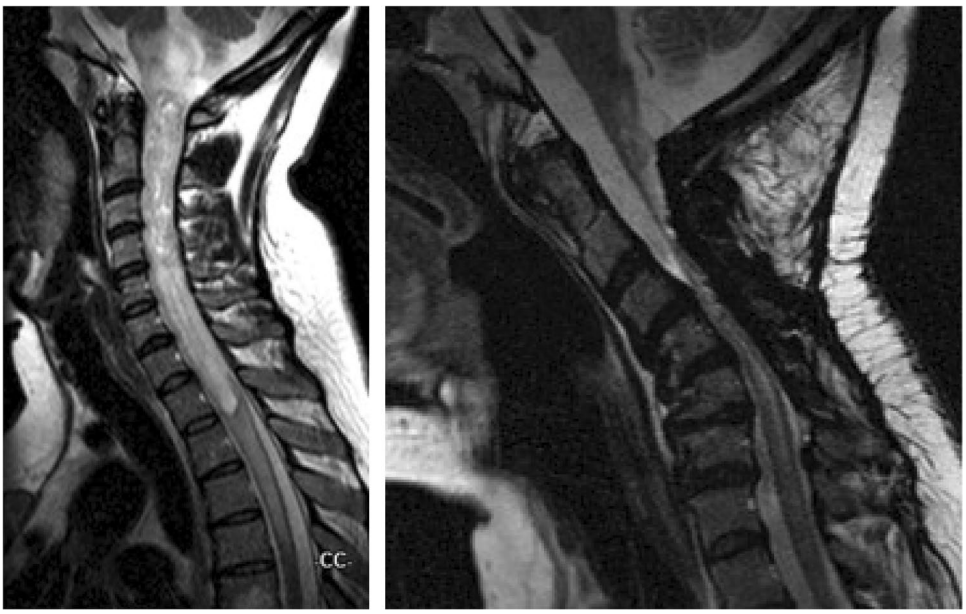

Fig. 6 Kyphosis post-laminoplasty. 35-year-old woman with a cervico-bulbar ependymoma (preoperative MRI (**A**)), status post-C1-C5 laminectomy, lesion removal, and a C2-C5 laminoplasty, with development of cervical kyphosis five months following surgery (postoperative MRI (**B**)) and intense neck and scapular girdle pain (figures used with permission from Elsevier, License number 5081411294607, from the original manuscript: Dugoni DE, Mancarella C, Landi A, Tarantino R, Ruggeri AG, Delfini R. Post laminoplasty cervical kyphosis-case report. Int J Surg Case Rep. 2014;5(11):853–7. https://doi.org/10.1016/j.ijscr.2014.09.020. Epub 2014 Oct 5. PMID: 25,462,050; PMCID: PMC4245682 [31])

central canal and neural foramen, the ligamentum flavum can potentially be tensioned and buckling decreased [36].

The first interspinous implant has been credited to Dr. Fred L. Knowles, who reportedly began implanting metal "plugs" between the spinous processes in the 1950s for the treatment of spinal stenosis. Since then, there have been a variety of different materials such as bone allograft, titanium, polyetheretherketone, and elastomeric compounds that have been used in devices with the common goal of maintaining distraction between the spinous processes [37].

IPDs are considered either static or dynamic. Static implants are made of non-compressive material and examples include the X-Stop, Wallis, and Superion Interspinous Spacer. Dynamic implants have a degree of compression, which allows for flexion and compression on extension, and provide relative distraction of the posterior elements throughout the range of motion. Some examples include the Coflex Interlaminar Stabilization and DIAM [38]. We describe two IPDs that are FDA approved and commercially available in the USA – the Coflex Interlaminar Stabilization and Superion Interspinous Spacer [38, 39].

Technique

Coflex Interlaminar Stabilization Coflex Interlaminar Stabilization is a U-shaped dynamic interlaminar device composed of a titanium alloy that fits between two adjacent spinous processes of the lumbar spine. A midline skin incision is made, and the interspinous ligament is removed. The interlaminar implant is placed tightly with gentle hammering using a mallet. The wing clamps of the U body are tightened to anchor both sides of the superior and inferior spinous processes [38] (Fig. 7).

A unique, reported benefit to Coflex Interlaminar Stabilization is the "topping-off technique" [40]. Patients with multilevel lumbar stenosis can undergo decompression and fusion in the inferior levels with decompression and Coflex device placement at the superior most stenotic level, referred to as the transition segment. The theoretical advantage of this approach is that it can reduce the incidence of stenosis in the adjacent upper level since Coflex is not as rigid as instrumented fusion [41, 42] (Fig. 8).

Indications/contraindications

According to the US FDA 2012, indications for use include one- or two-level lumbar stenosis from L1 to L5 that produces at least moderate impairment in skeletally mature patients. Patients should experience relief of symptoms of leg/buttock/groin pain, with or without back pain, in flexion and have undergone at least 6 months of non-operative treatment. Interlaminar stabilization is performed after decompressive surgery at the level(s) of stenosis [43].

Contraindications include prior fusion or decompression at the index level, radiographically compromised vertebral bodies at any lumbar level caused by current or past trauma or tumor (e.g., compression fracture), severe facet hypertrophy requiring bone excision that would result in instability, grade 2 or greater spondylolithesis, isthmic spondylolisthesis or spondylolysis, degenerative lumbar scoliosis with a Cobb angle greater than 25 degrees, osteoporosis, back or leg pain of unknown etiology, axial back pain only with no leg, buttock, or groin pain, morbid obesity defined as a body mass index greater than 40, active or chronic infection

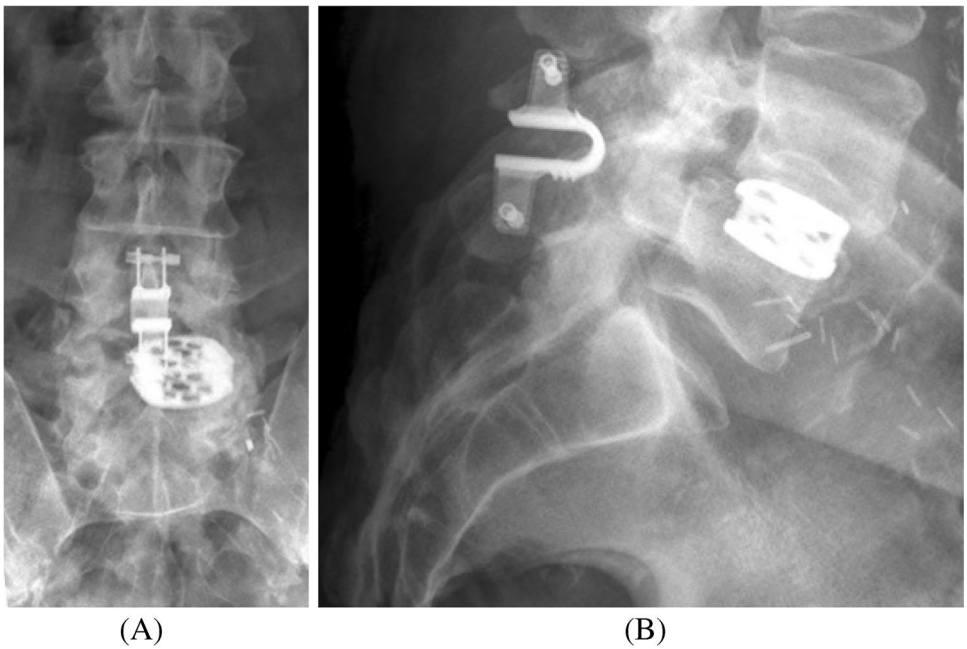

Fig. 7 62-year-old-male with a Coflex U-shaped Interlaminar Stabilization at the L4-L5 level on frontal (**A**) and lateral (**B**) radiographs of the lumbar spine. An interbody spacer is also present with numerous surgical clips along the ventral lower lumbar spine

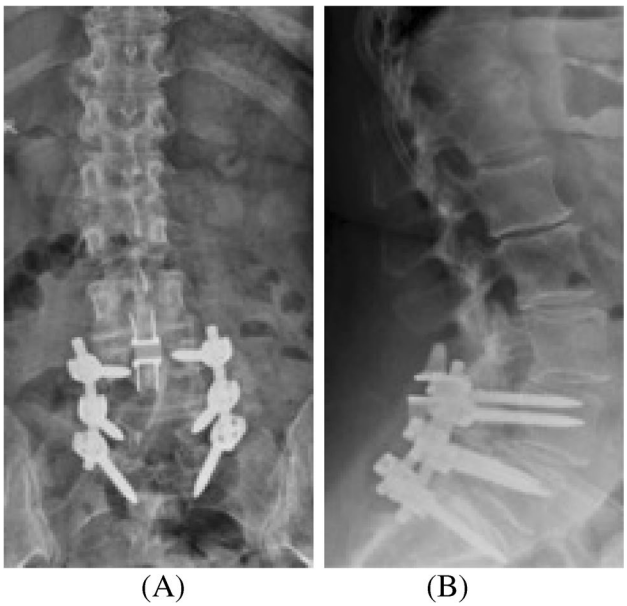

Fig. 8 Topping-off technique with Coflex Interlaminar Stabilization in a 67-year-old-male. Frontal (**A**) and lateral (**B**) radiographs of the lumbar spine demonstrating L3-L4 laminectomy with Coflex Interlaminar Stabilization, as well as L4-S1 laminectomies with instrumented posterior fusion

– systemic or local, known allergy to titanium alloys or MRI contrast agents, and cauda equina syndrome defined as neural compression causing neurogenic bowel or bladder dysfunction [43].

Outcomes

There have been numerous studies indicating a favorable outcome with use of the Coflex Interlaminar Stabilization device as an adjunct to decompressive surgery. For instance, a recent prospective study demonstrated use of the Coflex Interlaminar Stabilization implant following spinal decompression had superior clinical outcomes compared to decompression alone for symptomatic lumbar spinal stenosis up to two years post-operatively. Decompression included partial laminotomy, excision of hypertrophic ligamentum flavum, and undercutting facetectomy [44].

Similarly, a trial conducted across 21 clinical sites in the USA demonstrated Coflex subjects following laminectomy with moderate to severe stenosis and up to grade 1 spondylolisthesis had equivalent to superior functional outcome compared to posterolateral instrumented spinal fusion with laminectomy at 3-year post-operative follow-up [45].

Additionally, a retrospective study evaluating the clinical outcome of those with Coflex Interlaminar Stabilization following decompression versus posterior lumbar interbody fusion demonstrated those with the Coflex device had significantly better clinical outcomes during the early post-operative follow-up period of 6 and 12 months. Both groups showed improved clinical outcomes at 5 years post-operatively. The Coflex group experienced less blood loss, shorter hospital stays, and shorter operative time compared to the posterior fusion cohort [46].

Conversely, Dong et al. found that Coflex implantation and fusion after spinal decompression had the same clinical outcomes and satisfaction in treatment of symptomatic lumbar spinal stenosis at 7-year follow-up [47]. Additionally, a prospective study by Richter et al. demonstrated no clinical benefit of Coflex implantation following decompressive surgery compared to decompressive surgery alone at 1-year follow-up [48].

Superion Interspinous Spacer Superion Interspinous Spacer is a H-shaped static interspinous spacer composed of a titanium alloy with wings that extend cranially and caudally to prevent lateral displacement (Fig. 9). In contrast to the earlier version of the static interspinous device X-Stop (Fig. 10), the reported advantage of Superion is that it can be delivered percutaneously and minimize tissue disruption of the spinal anatomy [49].

The Superion Interspinous Spacer is delivered percutaneously through a cannula after multiple dilators have opened the interspinous space. Once the proper device size is determined, it is deployed between adjacent spinous processes at the level of stenosis [50].

Indications/contraindications

According to the instructions for use of the Superion Interspinous Spacer accessible from the US FDA 2015, the device is indicated to treat skeletally mature patients suffering from pain, numbness, and/or cramping in the legs (neurogenic intermittent claudication) secondary to a diagnosis of moderate lumbar spinal stenosis, with or without grade 1 spondylolisthesis, confirmed by X-ray, MRI, and/or CT evidence of thickened ligamentum flavum, narrowed lateral recess, and/or central canal narrowing. The Superion Interspinous Spacer is indicated for those patients with impaired physical function who experience relief in flexion from symptoms of leg/buttock/groin pain, with or without back pain, who have undergone at least 6 months of non-operative treatment. The device may be implanted at one or two adjacent lumbar levels in patients in whom operative treatment is indicated at no more than two levels, from L1 to L5. For this intended use, moderate degenerative lumbar spinal stenosis was defined as follows:

- 25 to 50% reduction in the central canal and/or nerve root canal (subarticular, neuroforaminal) compared to the adjacent levels on radiographic studies, with radiographic confirmation of any one of the following:
  - Evidence of thecal sac and/or cauda equina compression
  - Evidence of nerve root impingement (displacement or compression) by either osseous or non-osseous elements
  - Evidence of hypertrophic facets with canal encroachment

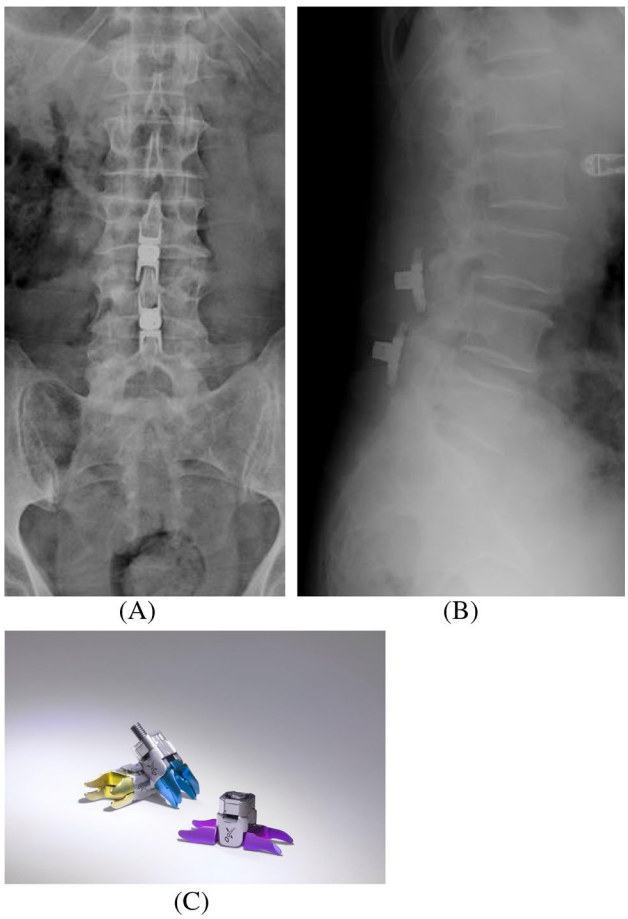

Fig. 9 64-year-old-male following Superion Interspinous Spacer. Frontal (**A**) and lateral (**B**) radiographs of the lumbar spine with the Superion Interspinous Spacer H-shaped titanium alloy implant at L3-L4 and L4-L5. A photograph of the Superion device is shown in part (**C**)

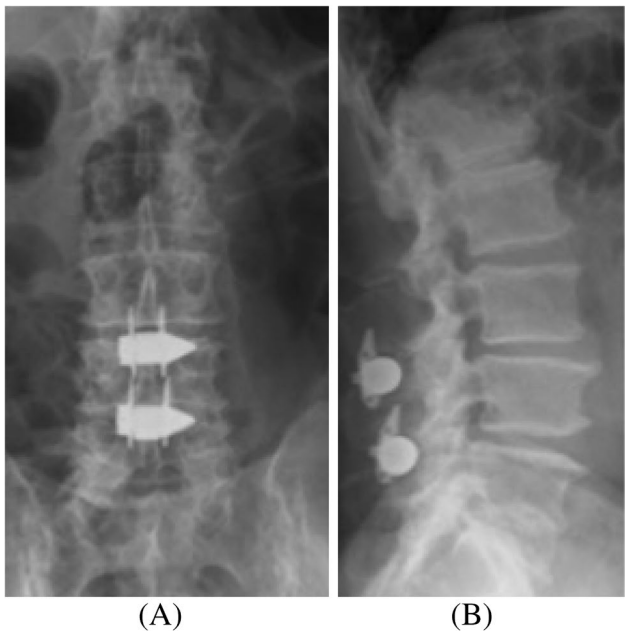

Fig. 10 77-year-old-male with X-Stop device at L3-L4 and L4-L5 demonstrated on frontal (**A**) and lateral (**B**) radiographs of the lumbar spine

- And associated with the following clinical signs:
  - Presents with moderately impaired physical function (PF) defined as a score of ≥ 2.0 of the Zurich Claudication Questionnaire (ZCQ)
  - Ability to sit for 50 min without pain and to walk 50 feet or more [51]

The Superion Interspinous Spacer is contraindicated in patients with an allergy to titanium or titanium alloy, spinal anatomy or disease that would prevent implantation of the device or cause the device to be unstable in situ (such as instability of the lumbar spine, e.g., isthmic spondylolisthesis or degenerative spondylolisthesis greater than grade 1 (on a scale of 1 to 4), an ankylosed segment at the affected level(s), fracture of the spinous process, pars interarticularis, or laminae (unilateral or bilateral), scoliosis (Cobb angle > 10 degrees)), cauda equina syndrome defined as neural compression causing neurogenic bladder or bowel dysfunction, diagnosis of severe osteoporosis defined as bone mineral density (from DEXA scan or equivalent method) in the spine or hip that is more than 2.5 S.D. below the mean of adult normal, active systemic infection, or infection localized to the site of implantation, prior fusion or decompression procedure at the index level, and morbid obesity defined as a body mass index (BMI) greater than 40 [51].

Outcomes

There have been numerous studies indicating a favorable outcome with use of the Superion Interspinous Spacer. For instance, a recent prospective, randomized clinical trial by Patel et al. showed Superion had superior clinical outcomes when compared to the X-Stop device at the 3-year postoperative period [52].

Similarly, a retrospective study by Lauryssen et al. demonstrated that the Superion cohort exhibited superior clinical symptoms, specifically improved back and leg pain severity at 12 and 24 months, compared with a decompressive laminectomy group [53].

In addition, a randomized controlled FDA trial by Nunley et al. evaluating the 5-year clinical outcomes for Superion Interspinous Spacer concluded that at 5-year follow-up, Superion provided sustained clinical benefit, most notably of leg pain symptom relief, and the majority of patients who received the device were free from reoperation, revision, or supplemental fixation [54].

Complications

The complications of IPDs include spinous process fracture, device dislocation or malposition, dura mater tears with cerebrospinal fluid leakage, infection, hematoma, erosion of the spinous process, heterotopic ossification, deep venous thrombosis, and neurologic sequelae [55].

Spinous process fracture may be a result of a background of osteoporosis, over-distraction of the interspinous space with a large interspinous device, and stress-related/fatigue changes. In a retrospective study by Gazzeri et al. consisting of 1108 patients and 8 different IPDs, 27 had a spinous process fracture (18 in the early post-operative stage and 9 one year after surgery). Twenty two of these patients were symptomatic, and the interspinous device had to be subsequently removed [55]. The authors also found that 20 patients experienced device dislocation with supraspinous ligament rupture [55]. Barbagallo et al. reported that 4 out of 69 patients treated with X-Stop had device dislocation, all of them requiring revision surgery and repair of the supraspinous ligament [56]. Lee et al. demonstrated that 14 of 30 patients with the Coflex Interlaminar Stabilization developed erosion of the bone immediately in contact with the device (Fig. 11), placing the spinous process at risk for fracture, predisposing to device malposition, and possibly leading to segmental instability [57].

Posterior dynamic stabilization devices or pedicle screw/rod fixation-based systems

Background

Several posterior dynamic stabilization (PDS) systems have received FDA 510(k) clearance as an adjunct to spinal

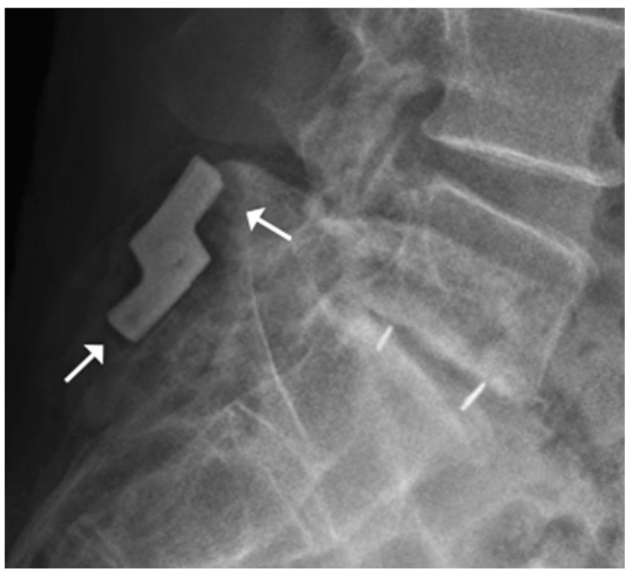

Fig. 11 55-year-old-female with L5-S1 osseous resorption (arrows) at the interspinous spacer and spinous process/fusion mass interface, as shown on the lateral view of the lumbar spine. There is an interbody spacer at L5-S1

interbody fusion [3, 4, 10]. This class of devices attempts to allow controlled motion of the spine in an effort to achieve more normal movement, analogous to an internal brace, in the treatment of spondylolisthesis and degenerative disk disease [58]. As opposed to relying upon rigid screws and stiff metallic rods, this group incorporates cords, spacers, flexible screws, flexible rods, inflatable rods, and movable parts [58].

The most common PDS device used around the world is Dynesys. This device is a popular non-fusion pedicle-based system that utilizes dynamic rods to allow for more mobile motion compared to conventional spine fusions [3, 4, 59, 60].

Technique

Dynesys

In 1994, the Dynesys system was designed to preserve or restore intersegmental kinematics and alleviate loading at the diseased disk and facet joints in an effort to reduce ASD. The system was designed to maintain greater movement and function when compared to conventional fusion [6].

The Dynesys system utilizes pedicle screws, flexible spacers, and cords [61]. Specifically, the standard closed-head conical pedicle screws used in the procedure are made of Ti–Al-Nb forge alloy Protasul 100 and are attached by a polyethylene terephthalate cord (Sulene PET) that is enveloped in a polycarbonate urethane (Sulene PCU) cylindrical sheath spacer [6, 62]. The function of the PET cord is to maintain a high tensile force in order to resist excessive flexion of the spine [4]. The PCU spacer opposes compressive forces placed on the disk during spinal extension [4]. The spacer also prevents foraminal narrowing while simultaneously decreasing the loading stress on the posterior annulus [4, 61] (Fig. 12).

Indications/contraindications

According to the US FDA 510(k) summary 2009, when used as a pedicle screw fixation system in skeletally mature patients, the Dynesys is intended to provide immobilization and stabilization of spinal segments as an adjunct to fusion in the treatment of degenerative spondylolisthesis with objective evidence of neurologic impairment and failed previous fusion (pseudoarthrosis). It is also indicated for use in patients receiving fusions with autogenous graft only, who are having the device fixed or attached to the lumbar or sacral spine, and who are having the device removed after the development of a solid fusion mass [63].

Reported contraindications for the system as an adjunct to spinal fusion include elderly patients with osteoporotic bone, primary and secondary spinal bone tumors, severe segmental instability combined with degenerative spondylolisthesis, severe degenerative spondylolisthesis, advanced degenerative disease, pregnancy, and allergy to the device [6, 59].

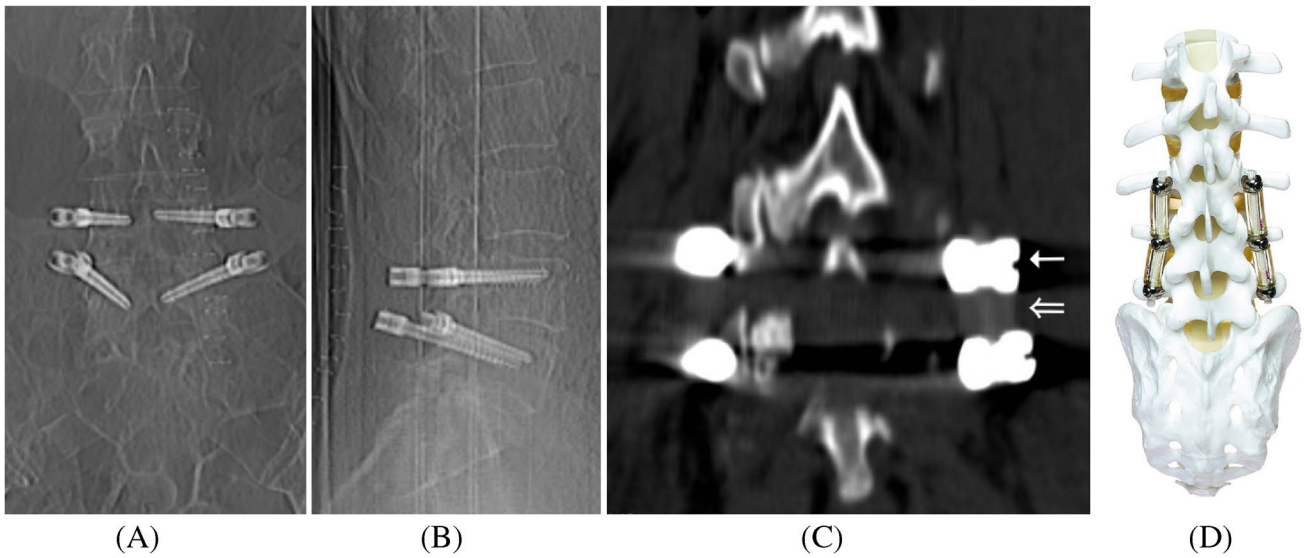

Fig. 12 70-year-old-female with right sided radiculopathy and severe central canal stenosis at L4-L5 resulting in placement of the Dynesys implant. The Dynesys utilizes pedicle screws, flexible spacers, and cords. Frontal (**A**) and lateral (**B**) intraoperative images demonstrate the titanium screws that anchor the system to the spine. Coronal CT (**C**) demonstrates the polymer cord (arrow) which connects the screws and limits flexion, acting as a tension band, and the polycarbonate urethane spacer (open arrow) surrounding the cord and limiting extension. A photograph of the Dynesys implant is shown in part (**D**) (part (D) used with permission from Hindawi, from the original publication: Gomleksiz C, Sasani M, Oktenoglu T, Ozer AF. A short history of posterior dynamic stabilization. Adv Orthop. 2012;2012:629,698. https://doi.org/10.1155/2012/629698. Epub 2012 Dec 26. PMID: 23,326,674; PMCID: PMC3541638 [4])

Outcomes

A recent meta-analysis by Wang et al. evaluated prospective and retrospective comparative studies on the clinical efficacy and safety of Dynesys as a standalone system compared to posterior decompression and fusion. The analysis included 17 studies, with findings suggesting that the Dynesys system achieves comparable clinical outcomes versus fusion in the treatment of lumbar degenerative diseases. Additionally, the system could maintain range of motion of surgical segments, and with less operative time, blood loss, length of stay, ASD, and lower complications relative to fusion [60].

Conversely, a retrospective study performed by Grob et al., which evaluated 50 patients with at least 2-year follow-up from surgical treatment with Dynesys system alone, demonstrated that 19% of patients either required reoperation or were undergoing tests with a view to reoperate in the near future. Forty percent of patients reported an improvement in their ability to perform physical activities, and close to half reported an improvement in quality of life. These results were inferior to historical controls that had undergone fusion for similar indications [62].

Additionally, Bothmann et al. conducted a prospective study of 54 patients who had undergone treatment with the Dynesys device without fusion. While post-operative pain symptoms improved in 73% of the patient population, the outcomes were not considered superior to traditional fusion surgery, with a complication rate requiring revision surgery of 27.5% [64].

Complications

Although the goal of Dynesys is to prevent the development of ASD [3, 65], clinical trials have demonstrated that Dynesys only slightly decreases the incidence of ASD relative to conventional fusion. Additional complications include wound infection, screw loosening and fractures, and reoperation [65]. In general, the incidence of pedicle screw fractures has been reported to be lower than those reported for lumbar spinal fusion procedures [65]. However, when compared to lumbar fusion, Dynesys has higher rates of pedicle screw loosening, which may be related to the added mobility that Dynesys offers as compared to conventional fusion [65] (Fig. 13).

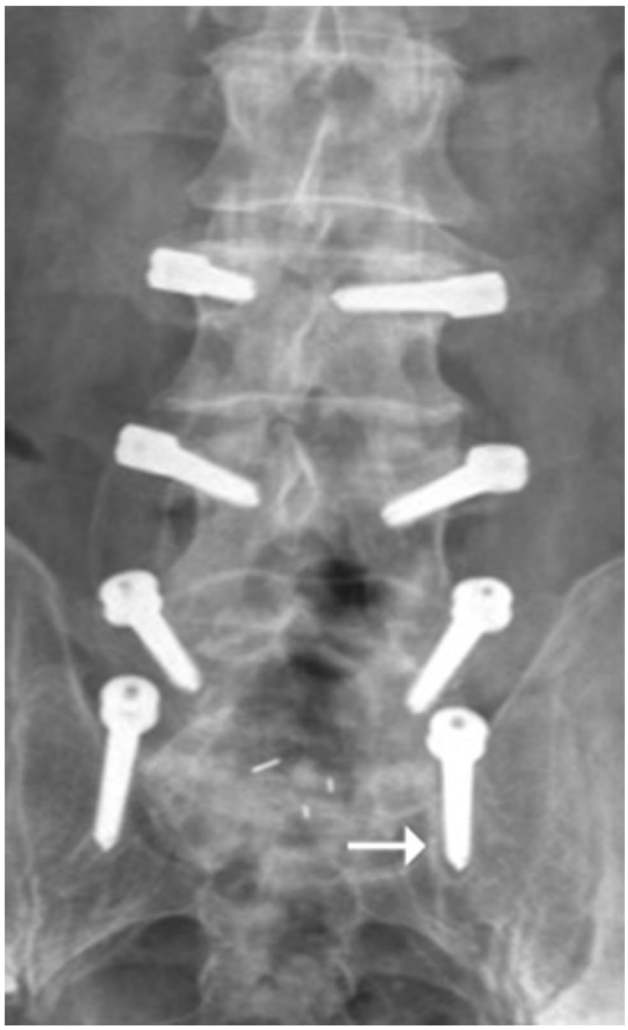

Figure 13 68-year-old-female with Dynesys pedicle screw loosening demonstrated at the lower most left pedicle screw, where paralleling lucency (arrow) is present, on a frontal radiograph of the lumbar spine

Posterior element replacement systems/ total facet replacement devices

Background

Posterior element replacement systems have been devised to treat not only posterior spinal disease/facet arthropathy and spinal stenosis, but also to address the iatrogenic instability that occurs as a result of surgical decompression [6]. The procedure is relatively invasive, whereby a laminectomy and bilateral facetectomy are performed and a prosthetic facet device placed, in an effort to relieve canal and foraminal stenosis while maintaining some degree of motion at the affected level [2]. As with other posterior motion preservation interventions, posterior element replacement systems are intended to serve as an alternative to fusion, restoring stability but while preserving motion at the stabilized level, with the goal of preventing degeneration of the adjacent segment. Additionally, traditional fusion results may deteriorate with time due to factors that reduce fusion rates, such as smoking or non-steroidal anti-inflammatory use [7, 8]. Devices in this class include the TOPS System, ACADIA Facet Replacement System, and Total Facet Arthroplasty

System, none of which are FDA approved. The TOPS System is discussed in further detail below.

Technique

TOPS System

The TOPS System is a dynamic total facet replacement device featuring a motion preservation solution for patients undergoing surgery for degenerative spondylolisthesis and lumbar spinal stenosis. The device is a mobile total posterior arthroplasty designed to provide segmental stability, but not fusion, of the affected lumbar stenotic level while preserving near-anatomical motion characteristics. The device is placed following total laminectomy and facetectomy. There is resistance to excessive posterior and anterior sagittal translation and shear force while recreating physiological motion [6–8].

Traditional fusion unites vertical rods with 2 pedicle screws of adjacent vertebrae. The TOPS System utilizes a dual horizontal metal crossbar configuration that attaches 2 polyaxial pedicle screws at the same vertebra (Fig. 14). The design reportedly decreases peak moments by more equally distributing loads across all 4 pedicle screws, which decreases the chance of loosening at the bone-screw interface and screw pullout before osteointegration occurs. Additionally, by permitting a wide range of motion in all planes, (flexion, extension, lateral bending, and axial rotation), loads are reportedly shared with the intervertebral disk and ligaments [6–8].

The TOPS System is a unitary device that consists of two titanium plates, each with a mating spherical protrusion, which creates an articulating function that is similar to the native facet joints. The articulating surfaces are covered with a polycarbonate urethane (PCU) component, and the moving parts of the implant are sealed with a polycarbonate urethane boot. The boot resists motion which simulates the elastic properties of the facet capsule and posterior ligaments. The PCU boot incorporates a PEEK ribbon which acts as a restraint for excessive flexion of the motion segment, preventing dislocation of the articulating surfaces under extreme loads. Metal arms project laterally from the titanium plates in effort to anchor the implant to the spine through polyaxial pedicle screws [6, 7] (Fig. 14). Additional devices in this class that have garnered attention include the ACADIA Facet Replacement System and Total Facet Arthroplasty System (Fig. 15).

Indications/contraindications

As part of a US FDA investigational device exemption, indications for use of the TOPS System within the clinical trial setting include patients between the ages of 35 and 80 years old with neurogenic claudication resulting from

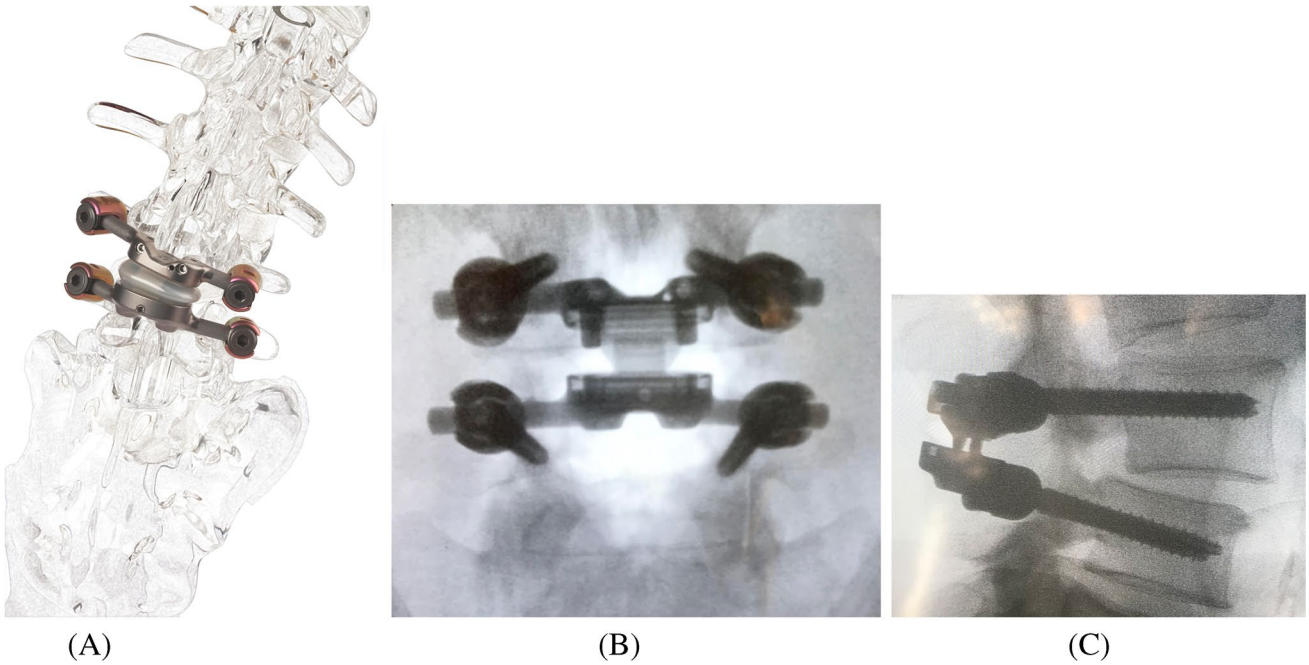

Fig. 14 Model (**A**) and frontal (**B**) and lateral (**C**) intraoperative images of the TOPS System, a unitary device that consists of two titanium plates, each with a mating spherical protrusion creating an articulating function similar to the native facet joints. Metal arms project laterally from the titanium plates in effort to anchor the implant to the spine through polyaxial pedicle screws (figure used with permission from Premia Spine, December 26, 2020)

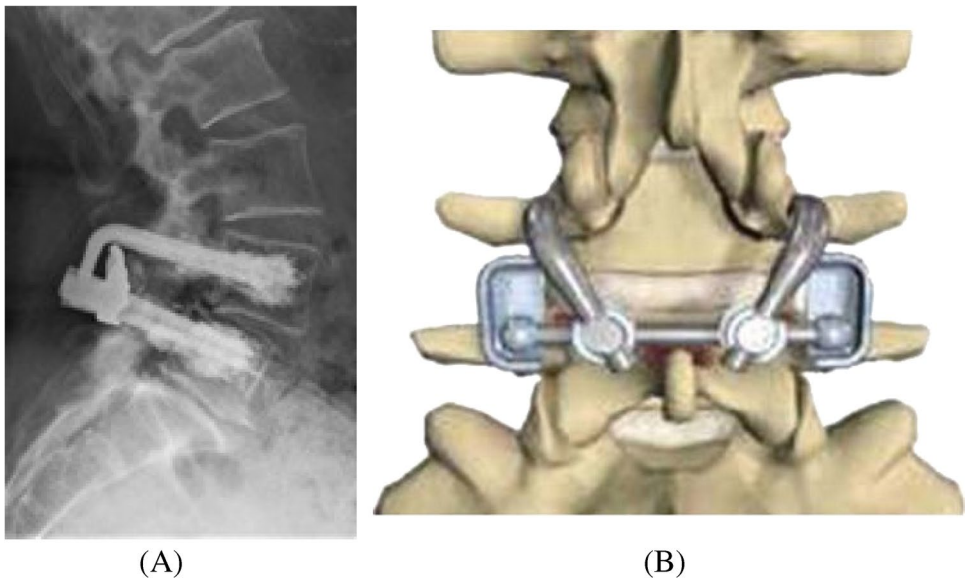

Fig. 15 62-year-old-female with Total Facet Arthroplasty System. Lateral radiograph of the lumbar spine (**A**) demonstrating the Total Facet Arthroplasty System at L4-L5. A drawing of the Total Facet Arthroplasty System is shown in part (**B**) (part (B) used with permission from Hindawi, from the original publication: Gomleksiz C, Sasani M, Oktenoglu T, Ozer AF. A short history of posterior dynamic stabilization. Adv Orthop. 2012;2012:629,698. https://doi.org/10.1155/2012/629698. Epub 2012 Dec 26. PMID: 23,326,674; PMCID: PMC3541638 [4])

degenerative spondylolisthesis up to grade 1 with moderate to severe lumbar spinal stenosis and either thickening of the ligamentum flavum or scaring of the facet joint capsule. The TOPS System is intended to provide stabilization following decompression in skeletally mature patients with disease at one level from L2 to L5 who have not achieved sufficient symptom relief with prior conservative care. Contraindications include prior lumbar surgery (fusion, laminectomy, discectomy, etc.) [66].

Outcomes

Positive outcomes with the use of the TOPS System have been reported. For instance, a recent prospective cohort study of 10 patients with lumbar spinal stenosis and degenerative spondylolisthesis who underwent decompression and posterior arthroplasty with the TOPS System followed patients for 11 years after surgery. The authors found significant clinical improvement which was maintained over the 11-year follow-up time frame. There was no screw loosening, and the TOPS System could reduce the rate of ASD when compared to conventional fusion [8].

Briefly, posterior element replacement systems/total facet replacement devices are not to be confused with the emerging class of devices known as minimally disruptive facet fusion systems, utilized at both the cervical and lumbar spine, and also referred to as cervical interfacet spacers or cages at the cervical spine [67]. In this category, intervention is directed at the facet joints utilizing hardware or, in some instances, allograft bone dowel without hardware. The approach intends to increase foraminal height and volume through distraction of the facet joint, thereby indirectly decompressing the nerve root [67]. Minimally disruptive facet fusion systems placed percutaneously aim to limit the expected morbidity of open techniques, such as extensive subperiosteal muscular dissection that may result in muscle denervation, delayed wound healing, unfavorable cosmesis, and infection [67]. The DTRAX Expandable Cage is a titanium cervical cage placed between both facet joints at the symptomatic level through a posterior approach, used to treat select patients with cervical radiculopathy [67, 68] (Fig. 16). The zLOCK Facet Fusion System is a miniature, screwless, flexible design titanium implant placed percutaneously into the facet joints of the affected level, intended for use at both the cervical and

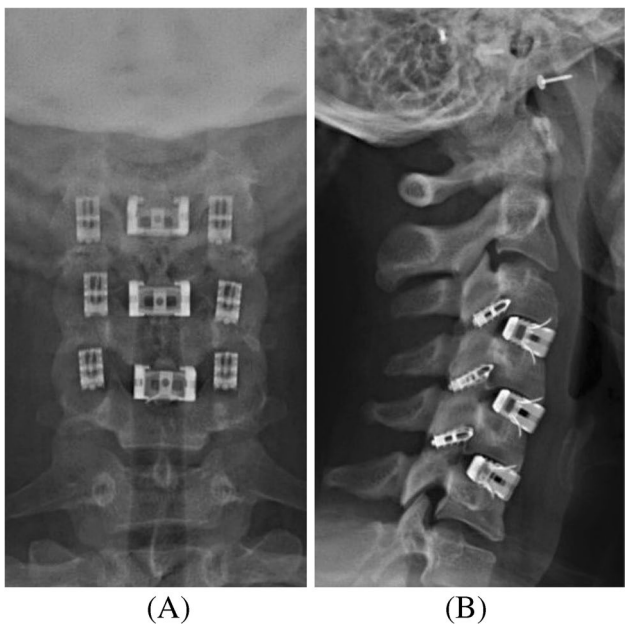

Fig. 16 43-year-old-female with DTRAX Expandable Cage hardware at the bilateral C3-C5 facet joints, along with interbody spacers, as demonstrated on frontal (**A**) and lateral (**B**) radiographs

lumbar spine for single-level stabilization in the treatment of facet arthrosis and spinal stenosis [69, 70].

Complications

As noted, the primary concern for posterior arthroplasty systems is screw loosening. With fusion surgery, screws withstand loads and peak moments for a short time period until fusion occurs, at which time the healed bone handles the majority of the dynamic load. With posterior arthroplasty systems, the pedicle screws are subject to loads and peak moments indefinitely, which can result in screw loosening [7, 8].

Conclusion

Motion preservation surgery seeks to maintain normal or near-normal motion of the affected spinal segment in order to avoid the adverse outcome of conventional posterior spinal fusion ASD. The principles of motion preservation surgery remain relatively constant, while the devices being used evolve. In the cervical spine, laminoplasty is a posterior motion-preserving procedure utilized for myelopathy with variable techniques. In the lumbar spine, posteriorly, motion-sparing systems have been classified into three separate categories including interspinous process devices (also referred to as interspinous process spacers or distraction devices), posterior dynamic stabilization devices (also referred to as pedicle screw/rod fixation-based systems), and posterior element replacement systems (also referred to as total facet replacement devices). Knowledge of the intended physiologic purpose, hardware utilized, and complications is important in the assessment of imaging in those who have undergone posterior motion preservation procedures.

Declarations

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Conflict of interest Author Andrew Haims, MD, discloses a financial relationship with Pfizer. Author Jonathan Grauer, MD, discloses a financial publishing role with North American Spine Society. Other authors declare no competing interests.

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