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EDITORIAL

Current concepts on spinal arthrodesis in degenerative disorders of the lumbar spine

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Abstract

Back pain is a common chronic disorder that represents a large burden for the health care system. There is a broad spectrum of available treatment options for patients suffering from chronic lower back pain in the setting of degenerative disorders of the lumbar spine, including both conservative and operative approaches. Lumbar arthrodesis techniques can be divided into subcategories based on the part of the vertebral column that is addressed (anterior *vs* posterior). Furthermore, one has to differentiate between approaches aiming at a solid fusion in contrast to motion-sparing techniques with the proposed advantage of a reduced risk of developing adjacent disc disease. However, the field of application and long-term outcomes of these novel motion-preserving surgical techniques, including facet arthroplasty, nucleus replacement, and lumbar disc arthroplasty, need to be more precisely evaluated in long-term prospective studies. Innovative surgical treatment strategies involving minimally invasive techniques, such as lateral lumbar interbody fusion or transforaminal lumbar interbody fusion, as well as percutaneous implantation of transpedicular or transfacet screws, have been established with the reported advantages of reduced tissue invasiveness, decreased collateral damage, reduced blood loss, and decreased risk of infection. The aim of this study was to review well-established procedures for lumbar spinal fusion with the main focus on current concepts on spinal arthrodesis and motion-sparing techniques in degenerative disorders of the lumbar spine.

Key words: Spinal arthrodesis; Lumbar spine; Motion-sparing implants; Intrebody fusion

Core tip: There is a broad spectrum of surgical techniques that can be performed in order to fuse lumbar motions segments. The aim of this study was to review well-established procedures for lumbar spinal fusion with the main focus on current concepts on spinal arthrodesis and motion-sparing techniques in degenerative disorders of the lumbar spine, including minimally invasive interbody fusion, total disc arthroplasty, nucleus replacement systems, percutaneous implantation of pedicle and facet screws, facet arthroplasty, and interspinous implants.

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INTRODUCTION

Back pain is a common chronic disorder that has been reported to affect more than a quarter of the adult population in the United States, representing a large burden for the health care system[1]. Within the last decades health care costs of back and neck pain have increased tremendously. In a recent report the increase in expenditures was estimated at 65% between 1997 (52.1 billions of US dollars) and 2005 (85.9 billions of US dollars)[2].

There is a broad spectrum of available treatment options for patients with lower back pain due to degenerative disorders of the lumbar spine, including both conservative and operative approaches. Furthermore, novel and innovative surgical treatment strategies involving minimally invasive and motion-sparing techniques have emerged within the last decade. The aim of this study was to review well-established procedures for lumbar spinal fusion with the main focus on current concepts on spinal arthrodesis and motion-sparing techniques in degenerative disorders of the lumbar spine.

ANATOMY

The lumbar vertebral column is usually made up of five vertebral bodies (L1-L5), each providing a dense apophyseal ring at the top and bottom surfaces. The pedicles are bony processes projecting dorsally to merge into the two laminae, which fuse to one spinous process at the posterior midline. At the pediculo-laminar junction, the transverse process projects laterally on each side. Vertebral bodies articulation is executed *via* the intervertebral spinal disc as well as the superior and inferior articular processes extending from the superior and inferior laminar margins bilaterally. The superior articular process of the inferior lumbar vertebra articulates with the inferior articular process of the superior vertebral body to form the facet joint, also referred to as the zygapophyseal joint (Figure 1). The superior articular process forms the anterior part of the facet joint with a concavely shaped articular surface, compared to the convex shape of the inferior facet. The bony joint surfaces are covered by hyaline cartilage and lined by a synovial membrane. The lumbar spine can be further divided into three parts: the thoraco-lumbar junction (Th12-L1), the mid-lumbar spine (L1-L5), and the lumbo-sacral junction (L5-S1). Within the thoraco-lumbar junction, there is a transition from the rigid kyphotic thoracic to the more flexible lordotic lumbar spine, representing a zone of increased shear stress to the intervertebral motion segment. After exiting through the foramen magnum at the base of the skull, the spinal cord travels within the spinal canal, made up of the dorsal vertebral body surfaces, the pedicles, as well as the laminae. The abdominal aorta and the inferior vena cava travel anterior to the vertebral column and bifurcate to supply the pelvis and the lower extremities. The lumbar spinal roots exit the intervertebral foramen beneath the pedicle of the corresponding vertebral body into the pelvis to form the lumbar plexus, which travels through the posterior third of the psoas muscle with branches exiting at its anterior or lateral surfaces[3-6].

While the lumbar plexus travels within the posterior third of the psoas in the majority of cases, recent studies have underlined its possible anatomical location posterior to the psoas muscle[7].

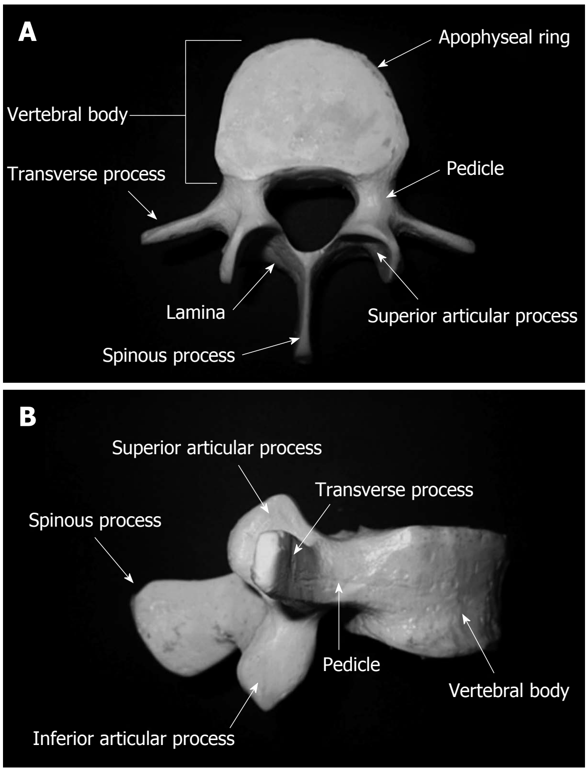

Figure 1 Schematic illustration of a typical lumbar vertebral body. A: View from above; B: View from the side.

LUMBAR ARTHRODESIS AND MOTION-SPARING TECHNIQUES

Lumbar spinal fusion is increasingly utilized to treat a broad spectrum of degenerative spine disorders, including scoliosis, spondylolisthesis, and spinal stenosis. Traditionally, fusion of a motion segment can be achieved by mechanical roughening and decortication of articular surfaces and packing the joint space with bone graft material, including iliac crest autograft, allograft material, or biologic adjuncts such as bone morphogenetic proteins (BMPs)[4,8-16].

There is a wide spectrum of lumbar spinal arthrodesis techniques addressing different parts of the vertebral column. With regard to the well-established three-column theory of the spine[17], plates, cages, and disc arthroplasty devices can be implanted with the aim to correctly align and stabilize the anterior two columns, while wiring systems, hook-based systems, pedicle screws, translaminar screws, facet replacement systems, and interspinous implants address the posterior column.

The selection of the appropriate surgical arthrodesis technique for lumbar spinal fusion is influenced by factors, such as the number of diseased motions segments, the affected number of columns per level, and the degree of instability, among others. Furthermore, to achieve

Table 1 Advantages and disadvantages of current procedures for the treatment of degenerative disorders of the lumbar spine

Surgical technique	Advantages	Disadvantages
ALIF	Direct visualization of disc space Small incisions and reduced tissue invasiveness if minimally invasive approach performed[27-30]	Intra-abdominal vascular and visceral injury[31,32]
PLIF	Avoiding intra-abdominal complications associated with anterior approach	Increased risk of surgical damage to neural structures, dural layer, and epidural veins[33-35]
LLIF	Avoiding surgical complications associated with anterior and posterior approaches Sparing of anterior longitudinal ligament (ligamentotaxis)[36] Stable implantation of device due to bilateral utilization of the dense apophyseal ring[36]	Limited surgical accessibility of L5-S1 level due to iliac crest Injury to lumbar plexus during transpsoas approach with post-operative approach-related neurological deficits[37-40]
TLIF	Minimally-invasive Reduced nerve root retraction[41] Circumferential fusion[27,41-43]	Less reduction in ROM compared to LLIF, if performed as stand-alone procedures[41]
Total disc arthroplasty	Reduced risk of adjacent segment disease due to preservation of motion[47] No fusion required[47]	Narrow spectrum of indications[48,49]
Nucleus replacement	Preservation of motion Multiple approach and revision options[53]	Risk of device migration, extrusion, and subsidence[53,54]
Sublaminar wiring	Can be implanted as an adjunct to other devices (hybrid)[4]	Risk of neurological injury[58,59]
Pedicle screws	Involvement of all three columns[4] Rigid segmental fixation[4] High fusion rates[4] Adequate deformity correction[4] Percutaneous approach possible[65-67]	High costs[4] Damage to neural and vascular structures[4] Adjacent segment disease[62]
Translaminar screws	Minimally-invasive percutaneous approach available[4,68,69]	Not indicated for multilevel arthrodesis[4,68,69]
Facet arthroplasty	Preservation of motion Reduce the risk of adjacent segment disease[71]	Complex anatomy of facet joints Narrow spectrum of indications
Interspinous implants	Preservation of motion	Narrow spectrum of indications

ALIF: Anterior lumbar interbody fusion; PLIF: Posterior lumbar interbody fusion; LLIF: Lateral lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion; ROM: Range of motion.

adequate bony fusion, factors such as local and systemic bone quality, diabetes, smoking, and corticosteroid use, among others, have to be considered[4]. The main advantages and disadvantages of current procedures for the treatment of degenerative disorders of the lumbar spine are summarized in Table 1.

In a recent systematic review on 26 articles including a total number of 3060 patients, Phillips *et al*[18] concluded that lumbar arthrodesis is a viable treatment strategy for patients with degenerative disc disease related low back pain who are refractory to non-surgical treatment, both with regard to pain reduction and functional improvement.

ANTERIOR SPINE

The implantation of anterior instrumentation systems has previously been shown to successfully restore immediate post-operative stability[19], and to correct post-traumatic deformities such as progressive kyphosis[20]. The spectrum of relative contraindications for the anterior approach includes severe osteoporosis and scaring due to previous abdominal surgery[4]. Gurwitz *et al*[21] compared three different approaches for short-segment instrumentation in a lumbar spine burst fracture model: posterior instrumentation alone (VSP plates: Acromed, Cleveland, OH) or with an anterior strut graft, and anterior instrumentation (Kaneda system: Acromed, Cleveland, OH) with an anterior strut graft. Posterior instrumentation alone indicated 76% less axial stiffness compared to the intact spine. Posterior instrumentation supplemented by anterior strut grafting revealed axial stiffness results that were not significantly different from the intact lumbar spine. Finally, anterior instrumentation with anterior strut grafting indicated 15% more axial stiffness than the intact spine. However, the three approaches showed 30%, 26%, and 24% decreased rigidity when compared to the intact spine. In their biomechanical study on anterior and posterior lumbar stabilization procedures, Flamme *et al*[22] compared three systems: anterior instrumentation alone [modular anterior construct system (MACS), Aesculap AG and Co. KG, Tuttlingen, Germany], MACS anterior instrumentation with intercorporal Pyramesh cage augmentation (Medtronic Sofamor Danek, Memphis, TN), and posterior screw-rod instrumentation alone (SOCON: SOlid CONnection, Aesculap AG and Co. KG, Tuttlingen, Germany). When compared to the physiologic lumbar motion segments all three systems demonstrated increased stability and reduced mobility. The authors concluded that anterior instrumentation with intercorporal cage augmentation results in comparable or even greater stability than posterior stabilization, with the exception of flexion/extension.

Interbody fusion

Since augmentation of the intervertebral space with bone graft alone has resulted in insufficient support of the anterior vertebral column of the lumbar spine with a resulting high rate of pseudarthrosis, intercorporal implantation of cage devices has emerged in recent years[23]. The principle of achieving intervertebral fusion with cage implantation is to expose the intervertebral disc space, to perform complete diskectomy as well as end plate preparation (*i.e.*, removal of cartilage), and to implant a synthetic device. Commercially available cages can be loaded with bone graft supplements, including vertebral body and iliac crest aspirate, iliac crest bone graft (ICBG) material, β tricalcium phosphate, stem cell allografts, demineralized bone matrix, and biologic adjuncts, such as BMPs[4].

Various techniques for intervertebral cage implantation have been described. The diverse spectrum of common interbody fusion techniques comprises anterior lumbar interbody fusion (ALIF), lateral lumbar interbody fusion (LLIF), transforaminal lumbar interbody fusion (TLIF), and posterior lumbar interbody fusion (PLIF), each characterized by a different approach to access the lumbar spine.

ALIF: Since the early 1930s, when the anterior approach for lumbar arthrodesis *via* bone grafting was first described as a surgical alternative for the management of spondylolisthesis[24,25], the spectrum of conditions being addressed by the ALIF technique has widened. Currently, ALIF can be used to treat spondylolisthesis, lumbar instability, degenerative disc disease, and pseudarthrosis[26,27]. *Via* either a retroperitoneal or a transperitoneal approach, the spine surgeon gains access to the lumbar intervertebral motions segments to excise the disk and insert a cage at the anterior part of the intervertebral space. A suggested advantage of ALIF over other interbody fusion techniques is direct visualization of the intervertebral space, potentially associated with improved post-operative outcome. In contrast to traditional invasive ALIF approaches, a minimally invasive surgical approach has been emerged recently, with the advantage of small incisions and reduced tissue invasiveness[28-31]. ALIF has been reported to be associated with an increased risk of surgical collateral damage, such as intra-abdominal vascular and visceral injury[32,33].

PLIF: The PLIF procedure, as originally described by Cloward[34] in 1953, is characterized by sparing the facet joints, and by gaining access to the lumbar motion segment *via* laminotomy/laminectomy, followed by diskectomy, decortication of vertebral body end plates, and the implantation of an interbody fusion device/graft. A suggested advantage of the posterior approach in PLIF is the avoidance of intra-abdominal vascular and visceral injury as seen in anterior approaches to the lumbar spine (*e.g.*, ALIF). However, PLIF is associated with an increased risk of damage to neural structures, epidural vein injury potentially resulting in increased peri-operative blood loss, and dural laceration, among others[34-36].

LLIF: Due to reduced risk of surgical collateral damage associated with the ALIF or PLIF approach[32,33,35,36], the minimally-invasive LLIF procedure has recently been established to address lumbar motion segments L1-L5, as described by Ozgur *et al*[37] in detail. The implantation of LLIF cages at the L5-S1 level can be difficult due to the presence of the iliac crest potentially blocking the surgical access. The LLIF approach requires blunt dissection of the psoas muscle in order to insert minimally invasive tubular retractors. Following diskectomy the procedure utilizes the dense apophyseal ring for device implantation, allowing a more stable fixation of the device and preventing subsidence. Furthermore, when compared to ALIF, the surgical approach in LLIF spares the anterior longitudinal ligament, leading to increased post-operative vertebral column stability and improved alignment *via* ligamentotaxis[37]. However, due to the proximity of the lumbar plexus, which usually travels within the posterior third of the psoas muscle[6,7], concerns regarding approach-related neurological adverse sequelae have arisen[38-41]. Analysis of our unpublished data on 919 treated levels revealed that neurological deficits following LLIF, although high in the immediate post-operative setting, steadily decrease over time, which underlines the transiency of the majority of these deficits.

TLIF: TLIF is another minimally invasive approach to achieve lumbar arthrodesis, which has been reported to reduce the extent of nerve root retraction associated with the PLIF procedure[42]. Unilateral facetectomy and/or laminectomy/laminotomy are followed by implantation of pedicle screws, diskectomy at the appropriate level, gradual distraction of the intervertebral disk space, and surgical preparation of vertebral bony endplates. By careful retraction of the thecal sac and protection of the traversing nerve root, interbody fusion cages can be implanted through the intervertebral foramen, and the pedicle screws can be connected *via* a rod. Posterolateral fusion can further be achieved by decortication of the transverse processes and augmentation with ICBG. Due to surgeon's ability to address both the anterior as well as the posterior columns of the spine, TLIF has become a favorable procedure to achieve circumferential fusion[28,42-44]. In their study on comparative effectiveness and cost-utility analysis comparing minimally invasive TLIF (MIS TLIF) *vs* the open TLIF procedure for degenerative spondylolisthesis, Parker *et al*[45] reported a similar post-operative patient-reported outcome for both techniques, but significantly less lengths of both hospital stay and return to the work force for MIS TLIF, resulting in a reduction in both societal and hospital costs.

Biomechanics of interbody cages: According to Oxland *et al*[46], the implantation of anterior lumbar interbody cages alone provides stability of the vertebral column in flexion, axial rotation, and lateral bending, when compared to the intact spine, but no stabilization in extension. Posterior implantation of a titanium interbody cage has been reported to achieve higher stiffness, when compared to both the intact spine and the augmentation with bone graft alone, and to result in similar stiffness, when compared to posterior instrumentation supplemented by bone graft[47]. In their biomechanical study, Cappuccino *et al*[48] evaluated the range of motion (ROM) after the implantation of LLIF cages. The authors compared their results with current literature and concluded that the implantation of LLIF devices without supplemental instrumentation (*i.e.*, stand-alone LLIF) results in greater segmental reduction in ROM, when compared to stand-alone ALIF or TLIF procedures. Furthermore, the authors demonstrated that supplemental bilateral posterior instrumentation with pedicle screws results in the largest decrease of ROM.

Total disc arthroplasty

The principle of total disc arthroplasty (TDA) is to replace the degenerated disc by an intervertebral prosthesis with the theoretical advantage of preservation of ROM. Due to reduced shear stresses at the adjacent level based on preserved motion, a decreased risk for adjacent segment disease has been suggested. Furthermore, since no fusion is required, arthrodesis-associated adverse sequelae such as pseudarthrosis and donor site morbidity due to bone graft harvesting can be avoided[49]. However, the surgical indications for performing TDA at the lumbar spine remain narrow. Previous studies have suggested young patients, with disc disease involving one motion segment, normal bone quality, intact facet joints, and absence of scoliosis and spinal instability (*e.g.*, spondylolisthesis, spinal fracture) as the ideal candidates to undergo lumbar TDA[50,51]. In their prospective, randomized, multicenter study, Blumenthal *et al*[52] revealed that the implantation of the CHARITÉ artificial disc (DePuy Spine, Raynham, MA) results in at least equivalent clinical outcomes, when compared to ALIF. Zigler *et al*[53] compared ProDisc-L (Synthes Spine, West Chester, PA) lumbar TDA with circumferential fusion for the treatment of single-level lumbar degenerative disc disease. The authors concluded that ProDisc-L, with careful patient selection, achieves superior clinical results compared to circumferential fusion. The efficacy of ProDisc-L implantation was supported by a recent study on the long-term postoperative outcome. Although the results support both ProDisc-L and circumferential arthrodesis as adequate approaches to treat single-level degenerative disc disease, patients who had undergone TDA demonstrated more rapid improvement, with regard to post-operative pain, disability, and neurological function[54].

Nucleus replacement

Nucleus replacement (nucleoplasty) devices can be functionally divided into two major groups: elastomeric and mechanical nucleus devices, with elastomeric devices further being divided into hydrogel and non-hydrogel devices that are either injectable or preformed. Mechanical nucleus devices can further be sub-classified as one- or two-piece systems. The proposed advantages of nucleoplasty are the variety of minimally invasive surgical approaches that can be performed, and the multiple revision options after failed nucleoplasty, including lumbar disc arthroplasty and spinal fusion[55]. Furthermore, as seen in other motion sparing techniques[49], the risk of adjacent segment disease may also be reduced due to preservation of mobility of the addressed motion segment. However, the risk of device migration or extrusion, as well as subsidence remain a source of concern[55,56]. The evaluation of post-operative outcome following NUBAC™ implantation, a novel nucleus disc device made of polyetheretherketone and two articulating pieces, revealed absence of major intra- and post-operative complications as well as significant post-operative decrease in visual analogue scale and oswestry disability index parameters in addition to symptomatic improvement in all patients, underlining both the efficacy and safety of the approach, likely attributable to the reduced invasiveness of the procedure[57]. However, further prospective studies on long-term outcomes and the influence on the adjacent motion segments are warranted.

POSTERIOR SPINE

Laminar wiring

One of the most common wiring procedures is the Luque technique, utilizing sublaminar wires for segmental spinal stabilization[4,58-60]. This procedure has been associated with an increased risk of neurological injury, especially in the thoracic spine[60,61]. Wires can also be used to attach the implanted rod to the spinous process ("Wisconsin method"[62]), thereby avoiding the risk of injury to the spinal cord associated with the Luque technique[60,61,63]. Currently, wiring systems are more commonly implanted supplemental to other fusion or stabilization devices such as pedicle screws, instead of being utilized alone (hybrid systems)[4].

Pedicle screws

Transpedicular screw fixation, a common procedure aiming at the stabilization of the vertebral column, is the only available surgical technique that addresses all three columns of the spine. It has been reported to achieve rigid segmental fixation, high fusion rates, and deformity correction. Disadvantages include the high cost and the risk of damage to the thecal sac, the nerve roots, and major vascular structures[4]. Furthermore, pedicular screw insertion has been shown to be associated with a higher risk of developing adjacent segment disease (12.2%-18.5%) compared to patients with a different instrumentation technique (posterior midline and interbody arthrodesis) or non-instrumented fusion (5.2%-5.6%)[64]. When a recent retrospective series evaluated adverse sequelae related to the implantation of transpedicular screws in 648 patients screw misplacement was evident in three cases, nerve root impingement in one case, leakage of cerebrospinal fluid in two cases, pedicular fracture in two cases, deep wound infection in four cases, screw loosening in two cases, and rod-screw disconnection in one case[65]. In a recent meta-analysis, comparing different constructs in terms of mid- to long-term outcomes following instrumented posterior spinal fusion for adolescent idiopathic scoliosis, Cotrel-Dubousset instrumentation achieved higher degree of correction in the coronal plane, as well as better restoration of thoracic kyphosis and lumbar lordosis when compared to all-pedicle screw constructs. All-pedicle screw fixation was associated with the lower risk of pseudarthrosis, infection, neurologic deficit, and revision surgery[66]. A novel technique for pedicle screw implantation is the percutaneous approach supplemental to an ALIF procedure for the treatment of spondylolisthesis. Advantages include reduced surgical time, blood loss and collateral tissue damage, high fusion rates, and low incidence of adjacent disc degeneration[67-69].

Translaminar screws

Compared to transpedicular screw fixation, the translaminar approach has been shown to be associated with reduced soft tissue damage when screws are implanted *via* a minimally invasive percutaneous approach. However, translaminar screw technique is not indicated for multilevel arthrodesis since it does not provide enough strength of fixation[4,70,71].

Facet arthroplasty

Replacement systems of the facet joint, such as the total facet arthroplasty system (TFAS) (Archus Orthopedics, Redmond, WA), can be implanted following posterior decompression in the setting of degenerative facet complex disease, and degenerative lumbar spinal stenosis[72], with the aim to avoid the need for lumbar spinal fusion[4]. By restoring the ROM at the operated motion segment to intact values and to almost physiologic kinematics at the adjacent levels, TFAS may reduce the risk of adjacent segment disease[73]. TFAS is characterized by the transpedicular implantation of two straight metal stems into the inferior vertebral bodies and two bent metal stems into the superior ones. The two superior L-shaped metal stems are connected to a cross-arm with spherically-shaped ends that articulate with the bearing surfaces at the tops of the two inferior straight metal stems during flexion and extension[72-74]. Due to financial problems the company had to discontinue distribution of the TFAS system, with a resulting lack of data regarding long-term outcomes. Other facet replacement systems, being characterized by individually sizing all articulating bony components in order to satisfactorily emulate the individual's anatomy of the facet joint, are currently under investigation. Clinical studies focusing on the long-term outcomes of these devices are warranted[4].

Interspinous implants

Interspinous spacers, including the X-STOP device (Medtronic, Minneapolis, MN), have recently been introduced as motion-preserving implants for the treatment of lumbar degenerative conditions such as spinal stenosis, due to increase of flexion and prevention of extension at the motion segment level, in addition to distraction of the spinous processes[4]. This concurs with the results of a randomized, controlled, prospective multicenter trial underlining the efficacy of the X-STOP interspinous spacer in the treatment of spinal stenosis. After 2 years of follow-up, patients treated with X-STOP showed an improvement of 45.5% in terms of disease symptom severity, compared to an improvement of only 7.4% recorded in conservatively treated patients[75]. The Wallis System (Zimmer, Warsaw, IN) is implanted into the lumbar spine without permanent bony fixation ("floating" system) with the aim to decrease the risk of device loosening. It is recommended in the setting of diskectomy for massive and/or recurrent disc herniation, adjacent segment disc degeneration, and chronic low-back pain due to mild degenerative disc disease (Modic I)[76].

CONCLUSION

There is a broad spectrum of surgical techniques that can be performed in order to fuse lumbar motions segments. Advantages and disadvantages of each arthrodesis technique have to be taken into consideration during preoperative surgical planning. The transition from open to minimally invasive surgical procedures, potentially supplemented by biologic adjuncts such as BMPs, is promising. The field of application and long-term outcomes of novel motion-sparing surgical techniques, such as facet arthroplasty, nucleus replacement, and lumbar disc arthroplasty, need to be more precisely evaluated in further, ideally prospective, studies.

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