

Lumbar interbody fusion: techniques, indications and comparison of interbody fusion options including PLIF, TLIF, MI-TLIF, OLIF/ATP, LLIF and ALIF

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Degenerative disc and facet joint disease of the lumbar spine is common in the ageing population, and is one of the most frequent causes of disability. Lumbar spondylosis may result in mechanical back pain, radicular and claudicant symptoms, reduced mobility and poor quality of life. Surgical interbody fusion of degenerative levels is an effective treatment option to stabilize the painful motion segment, and may provide indirect decompression of the neural elements, restore lordosis and correct deformity. The surgical options for interbody fusion of the lumbar spine include: posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF), minimally invasive transforaminal lumbar interbody fusion (MI-TLIF), oblique lumbar interbody fusion/anterior to psoas (OLIF/ATP), lateral lumbar interbody fusion (LLIF) and anterior lumbar interbody fusion (ALIF). The indications may include: discogenic/facetogenic low back pain, neurogenic claudication, radiculopathy due to foraminal stenosis, lumbar degenerative spinal deformity including symptomatic spondylolisthesis and degenerative scoliosis. In general, traditional posterior approaches are frequently used with acceptable fusion rates and low complication rates, however they are limited by thecal sac and nerve root retraction, along with iatrogenic injury to the paraspinal musculature and disruption of the posterior tension band. Minimally invasive (MIS) posterior approaches have evolved in an attempt to reduce approach related complications. Anterior approaches avoid the spinal canal, cauda equina and nerve roots, however have issues with approach related abdominal and vascular complications. In addition, lateral and OLIF techniques have potential risks to the lumbar plexus and psoas muscle. The present study aims firstly to comprehensively review the available literature and evidence for different lumbar interbody fusion (LIF) techniques. Secondly, we propose a set of recommendations and guidelines for the indications for interbody fusion options. Thirdly, this article provides a description of each approach, and illustrates the potential benefits and disadvantages of each technique with reference to indication and spine level performed.

Keywords: Degenerative disc disease; spine; interbody; lumbar spine fusion; posterior lumbar interbody fusion (PLIF); transforaminal lumbar interbody fusion (TLIF); minimally invasive transforaminal lumbar interbody fusion (MI-TLIF); lateral lumbar interbody fusion (LLIF); oblique lumbar interbody fusion (OLIF); anterior to psoas (ATP); anterior lumbar interbody fusion (ALIF)

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Introduction

Lumbar interbody fusion (LIF) is an established treatment for a range of spinal disorders including; degenerative pathologies, trauma, infection and neoplasia (1). LIF involves placement of an implant (cage, spacer or structural graft) within the intervertebral space after discectomy and endplate preparation. At this time LIF is performed using five main approaches; posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF or MI-TLIF), oblique lumbar interbody fusion/anterior to psoas (OLIF/ATP), anterior lumbar interbody fusion (ALIF) and lateral lumbar interbody fusion (LLIF) (*Figure 1A,B*). There is no clear definitive evidence for one approach being superior to another in terms of fusion or clinical outcomes. These operations can also be performed using mini-open or minimally invasive (MIS) approaches (2,3). Interbody fusion is preferable to postero-lateral 'on-lay' fusion techniques due to lower rates of postoperative complications and pseudoarthrosis (2).

Patient expectations and increasing demands for shorter hospital stay and early return to work has led to more innovative surgical techniques to reduce iatrogenic injury and postoperative morbidity. The growth of new techniques attempts to shorten operative times and achieve faster recovery with reduced operative complications (4). Initial descriptions of ALIF and PLIF have been challenged by the evolving alternate approaches, such as the transforaminal, lateral and more recently oblique techniques. We discuss the various zones of approach by defining anterior options as any approach that is anterior to the Transverse Process and involves a retroperitoneal corridor to the lumbar spine (ALIF/OLIF/LLIF), and posterior options being an approach posterior to the Transverse Process, involving traversing the spinal canal or foramen for access to the disc and interbody space (PLIF/TLIF/MI-TLIF).

Since the initial description of the PLIF technique by Briggs and Milligan in 1944 (5), the method of PLIF has evolved, with the development of additional options of autologous and synthetic bone grafting, advanced methods of spinal segmental fusion techniques, innovative implants including the wide variety of interbody implants we use today and the use of pedicle screw fixation for posterior instrumentation. With advances in implants and techniques, the results of spinal fusion for PLIF has improved. Harms and Rolinger reported a newer technique in 1982 via the transforaminal route to achieve the insertion of an interbody cage packed with bone graft, termed TLIF (6). This created

another option for surgeons in their armamentarium for treatment of patients with symptomatic disc disease, spondylolisthesis and degenerative lumbar scoliosis.

Technique review

PLIF

One of the original approaches for LIF is PLIF. In the PLIF technique, surgical access to the intervertebral disc is gained from a posterior direction. The patient is initially positioned in a prone position on an Andrews or Jackson table. Either an open midline approach with bilateral muscle strip dissection or MIS paramedian Wiltse muscle splitting approach can be used to access the posterior column of the vertebral body. Once the spinous process and laminae at the appropriate levels are identified (L1-S1), a laminotomy may be performed medial to the facet and the dura retracted to exposure a corridor to the disc space. The endplates and disc space can then be prepared to allow implant/spacer insertion.

The posterior approach may be suitable for degenerative indications requiring a fusion procedure. Selected patients with segmental instability, recurrent disc herniation, symptomatic spinal stenosis and pseudoarthrosis may also benefit from a PLIF procedure. Contraindications for posterior fusion surgery include extensive epidural scarring, arachnoiditis, and active infection.

There are several advantages associated with PLIF surgery. Firstly, the PLIF approach is a traditional lumbar approach that the majority of spinal surgeons are well trained and comfortable in performing. A posterior exposure allows excellent visualization of the nerve roots without compromising blood supply to the graft. PLIF allows for adequate interbody height restoration, allows for neural decompression whilst maintaining posterior support structures (7). Furthermore, posterior fusion surgery also allows for potential 360-degree fusion through a single incision. There are disadvantages that a surgeon should be wary of when performing PLIF (8). Firstly, there may be significant paraspinous iatrogenic injury associated with prolonged muscle retraction (9). This may delay recovery and mobilization due to approach-related muscle trauma. Using this technique, it may be difficult to correct coronal imbalance and restore lordosis. Endplate preparation may be difficult compared to anterior fusion approaches. Other potential risks include retraction injury of nerve roots causing fibrosis and chronic radiculopathy (10-12) (*Figure 2*).

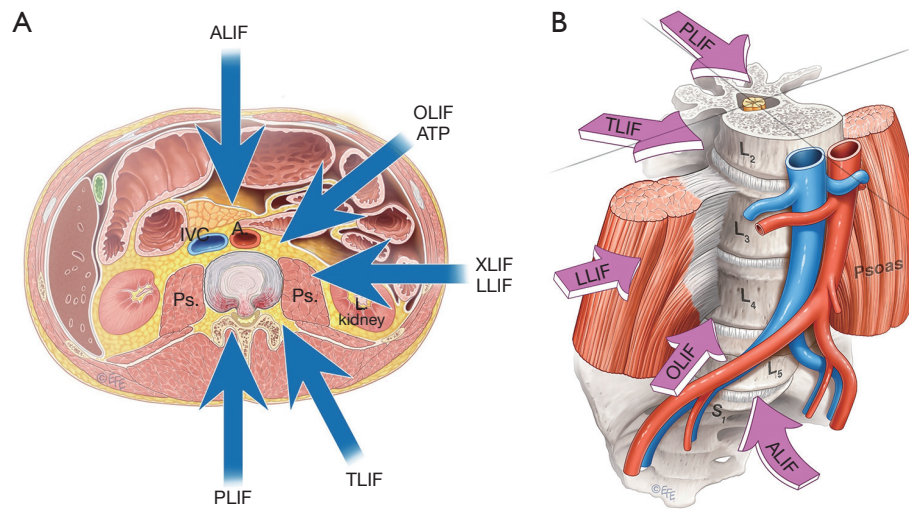


Figure 1 (A) Surgical approaches to the lumbar spine for interbody fusion techniques. The five primary interbody fusion approaches are shown here schematically: anterior (ALIF), lateral or extreme lateral interbody fusion (LLIF or XLIF), oblique lumbar interbody fusion/ anterior to psoas (OLIF/ATP), transforaminal (TLIF or MI-TLIF), and posterior (PLIF); (B) surgical approaches to the lumbar spine for interbody fusion techniques: anatomy of the psoas and anterior vasculature determines approach at various levels.

TLIF

Another posterior surgical approach for fusion is TLIF, used for stabilization and treatment of degenerative lumbar disease following failed conservative treatment. The main concerns with the posterior fusion approach was the extent of neural retraction required, with particular concerns surrounding potential nerve root injury, dural tears and epidural fibrosis. To address this limitation, the TLIF approach was proposed, involving direct, unilateral access to the intervertebral foraminal space whilst reducing direct dissection and surgical trauma to spinal muscles and structural integrity. By opening the neural foramen on one side only, damage to important anatomical structures such as nerve roots, dura and ligamentum flavum may be reduced. Like other fusion procedures, TLIF can be performed via an open procedure or MIS “mini-open” technique with smaller incision sizes and use of microscopy.

The TLIF approach involves positioning the patient prone after the patient is put under general anesthesia. A midline or bilateral paramedian mini-open incision is used, allowing access to the disc space suitable for levels L1-S1. The spinal canal is entered via a unilateral laminectomy and inferior facetectomy, which facilitates bone graft placement.

Indications of a TLIF approach include all degenerative

pathologies, including broad-based disc prolapses, degenerate disc disease, recurrent disc herniation, pseudoarthrosis, and symptomatic spondylosis. Contraindications are similar to PLIF and include extensive epidural scarring, arachnoiditis, active infection and conjoined nerve roots (that may preclude access to the disc space) and osteoporotic patients.

Advantages of the TLIF approach include relatively easier access to the posterior structures including the lamina, ligamentum flavum and facet joints. Compared to a traditional PLIF technique, the TLIF approach preserves ligamentous structures which are instrumental to restoring biomechanical stability of the segment and adjacent structures (10,13-15). In TLIF, a single unilateral incision is able to provide bilateral anterior column support. Access using a MIS mini-open incision and magnification (loupes or microscope) may further reduce access-associated muscle injury, minimize bleeding and improve postoperative recovery. The disadvantage is that TLIF, like PLIF, is associated with significant paraspinal iatrogenic injury with prolonged muscle retraction. It may be difficult to correct coronal imbalance and restore lordosis (11,16,17). Compared to anterior approaches, endplate preparation may be difficult (*Figure 3*).

ALIF

Particularly in the realm of discogenic low back pain, ALIF

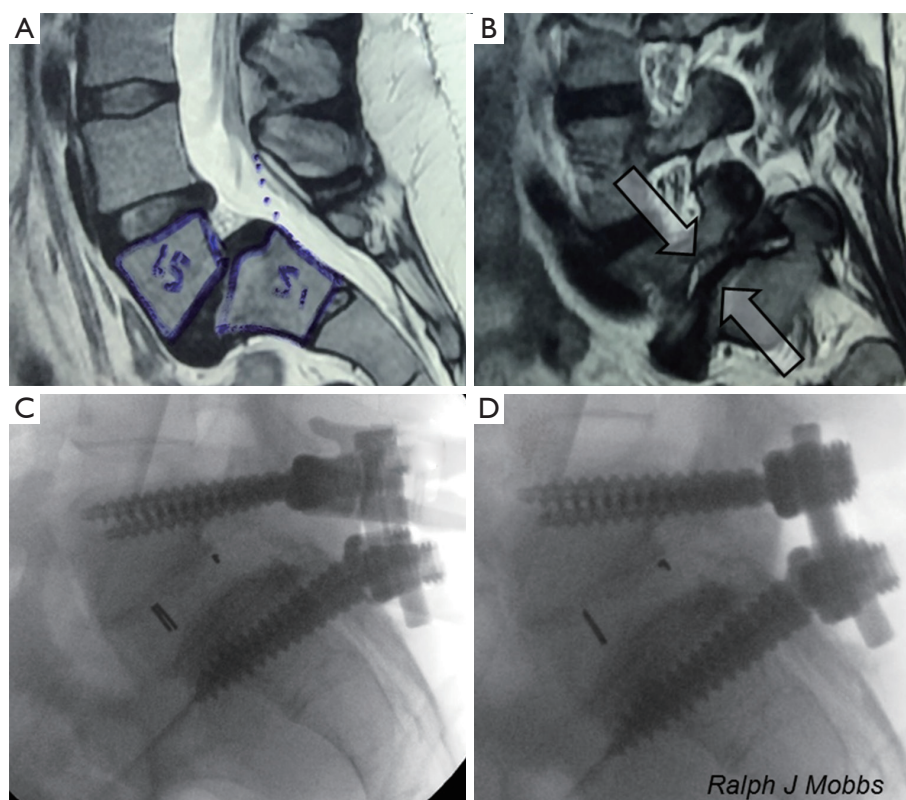


Figure 2 L5/S1 PLIF. High grade isthmic spondylolisthesis presenting with bilateral L5 radiculopathy suitable for posterior rather than anterior approach. (A) T2 weighted magnetic resonance imaging demonstrating vertical angulation of the L5/S1 articulation with Grade II spondylolisthesis; (B) severe foraminal stenosis with bilateral L5 nerve impingement (arrows); (C) bilateral pars and lamina resection with interbody cage insertion (Vigor PLIF, A-Spine ASIA, Taiwan) and pedicle screw fixation with L5 reduction screws (ES-2, Stryker, USA); (D) reduction maneuver and final result. PLIF, posterior lumbar interbody fusion.

has evolved to be an efficacious and predominant surgical technique. The anterior retroperitoneal approach facilitates adequate access to the entire ventral surface of the exposed disc, allowing comprehensive discectomy and direct implant insertion. For this technique, the patient is prepared and positioned supine. Incision and approach include midline, paramedian (all levels) or Mini-Pfannenstiel (L5/S1) incision with a retroperitoneal corridor and vascular mobilization and dissection. The ALIF approach is suitable for levels L4/L5 and L5/S1, primarily the latter due to vascular anatomy (*Figure 4*). The ALIF approach is limited for L2/3 and L3/4 secondary to extensive peritoneal and kidney (L2/3) retraction and the risk of superior mesenteric artery thrombosis, although rare.

An ALIF procedure may be suitable for degenerative disc disease, discogenic disease and revision of failed posterior fusion (18). Contraindications of ALIF include significant

prior abdominal surgery with adhesions or adverse vascular anatomy, severe peripheral vascular disease, solitary kidney on the side of exposure, spinal infection and high-grade (Grade 2+) degenerative spondylolisthesis in the absence of posterior fusion (19). Isthmic spondylolisthesis at L5/S1 is a relative contraindication (20,21) and should include posterior fixation in combination with the ALIF technique.

The ALIF approach is associated with several key advantages. Firstly, this technique allows direct midline view of the disc space and extensive lateral exposure of the vertebral bodies, which permits efficient disc space clearance with rapid endplate preparation. Furthermore, the anterior access allows maximization of the implant size and surface area, which facilitates aggressive correction of lordosis and foraminal height restoration. This may lead to high fusion rates with ample disc space preparation (13,14,19,22,23). ALIF also allows sparing of posterior spinal muscles and

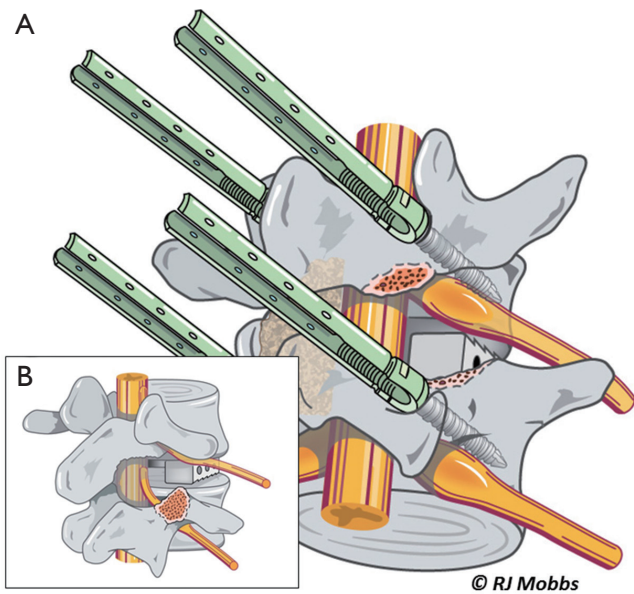


Figure 3 Transforaminal lumbar interbody fusion (TLIF). (A) TLIF with percutaneous screws offers a minimally-invasive option for interbody fusion (ES-2, Stryker, USA); (B) facetectomy followed by insertion of an interbody device can be performed via either a midline or paramedian approach.

anterolateral psoas muscles, which may reduce postoperative pain and disability. Disadvantages of the ALIF technique include approach-related complications such as retrograde ejaculation, visceral and vascular injury (14,19,24).

LLIF

The LLIF or extreme lateral interbody fusion (XLIF) technique was described by Ozgur *et al.* in 2006 (25) involves accessing the disc space via a lateral retroperitoneal, transpsoas corridor. LLIF is suitable for conditions that require access to the interbody disc space from T12/L1 to L4/5. This technique is not suitable for the L5/S1 level, due to the location of the iliac crest that obstructs lateral access. Furthermore, at more caudal levels of the lumbar spine, the lumbar plexus courses more anteriorly and the iliac vessels course more laterally, which increases risk of injury via a lateral approach. The patient is positioned laterally, either left or right side up depending on surgeon's preference and ease of access. A small lateral incision is performed based on position and angulation of the disc on image intensification when the patient is positioned. Neuromonitoring is essential for the transpsoas access to the disc space.

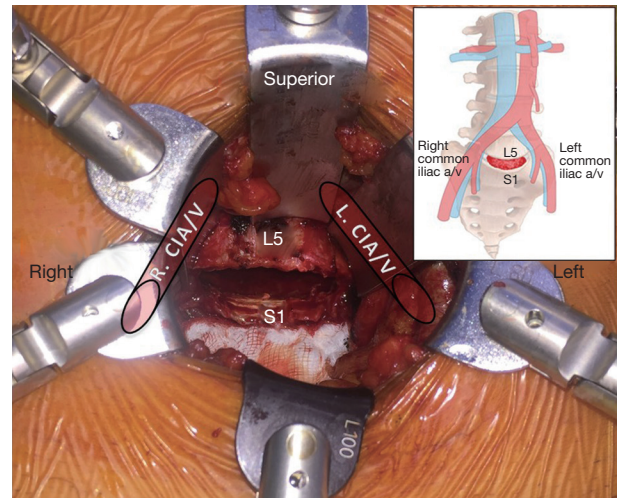


Figure 4 L5/S1 anterior lumbar interbody fusion (ALIF). Efficient vascular access to the L5/S1 disc space provides a wide visualization that assists with disc space clearance and insertion of a large footprint lordotic interbody device.

The LLIF approach is suitable for all degenerative indications. It is an excellent option for sagittal and coronal deformity correction, especially for lumbar degenerative scoliosis with laterolisthesis (26). However, the LLIF approach may not be suitable for severe central canal stenosis, bony lateral recess stenosis and high-grade spondylolisthesis (27). For operators using a standalone LLIF approach without posterior instrumentation, this should not be used under high biomechanical stress such as facet arthropathy, instability, deformity, adjacent to a previous fusion and multiple levels (28). The lateral approach is also not suitable in patients with prior retroperitoneal surgery or with retroperitoneal abscess, as well as patients with abnormal vascular anatomy. Advantages of LLIF are a MIS muscle-splitting approach that can be performed with rapid postoperative mobilization. Aggressive deformity correction can be achieved with high fusion rates and comprehensive disc space clearance (2,4). Disadvantages include potential risks of lumbar plexus, psoas muscle and bowel injury, particularly at the L4/5 level (29). Vascular injury, if it occurs, may be difficult to control and represents another risk of the lateral transpsoas approach (26,30,31) (Figure 5).

OLIF/ATP

The OLIF or ATP approach was first described by Michael

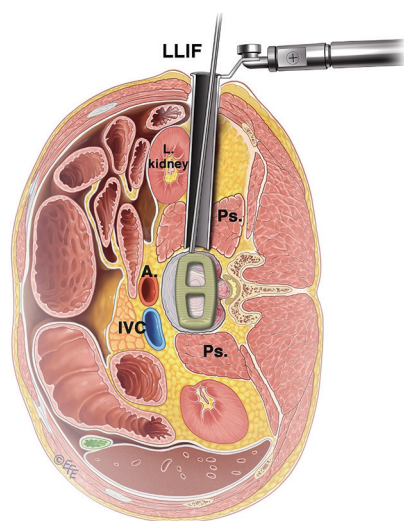


Figure 5 Lateral lumbar interbody fusion (LLIF). The transpsoas corridor is used to access the disc space via a retroperitoneal approach performed with the patient in the lateral position.

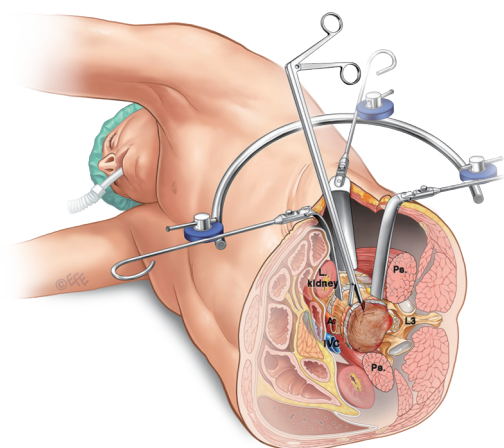


Figure 6 Oblique lumbar interbody fusion/anterior to psoas (OLIF/ATP). Lateral position for disc exposure anterior to the psoas. The exposure can be expanded via posterior retraction of the psoas to widen the corridor.

Mayer in 1977 (32) and involves an MIS access to the disc space via a corridor between the peritoneum and psoas muscle (Figure 6). Similarly to an LLIF approach, OLIF does not require posterior surgery, laminectomy, facetectomy or stripping of spinal or paraspinal musculature. However in contrast to the lateral transpsoas approach, the OLIF technique does not dissect or traverse the psoas muscle. For this technique, the patient is positioned

laterally, either left or right side up depending on the surgeon's preference and ease of access (33,34). A lateral and paramedian incision is performed based on position and angulation of the disc on image intensification when the patient is positioned (35). Neuromonitoring is not necessary as the anatomical corridor anterior to the psoas muscle is used for access. The OLIF technique is suitable for levels L1-S1.

Indications for OLIF include all degenerative indications. Similar to LLIF, OLIF is excellent for sagittal and coronal deformity correction, especially lumbar degenerative scoliosis with latero-listhesis. The OLIF approach is contraindicated in patients with severe central canal stenosis and high grade spondylolisthesis.

Advantages of the OLIF approach include that it facilitates MIS surgery with rapid postoperative mobilization. OLIF also allows aggressive deformity correction, high fusion rates with comprehensive disc space clearance (33,34,36). Lumbar plexus and psoas injury are unlikely as dissection is performed anterior to the psoas. However, potential risks involved with OLIF surgery include sympathetic dysfunction and vascular injury (36).

Part 1. Comparative evidence based on interbody fusion technique

ALIF vs. TLIF

Carefully selected patients with degenerative disc disease and spinal deformities are amenable to surgical intervention with ALIF or TLIF. While both approaches involve removal of the degenerative disc and insertion of an interbody device, the anterior and posterior approaches are both associated with their own unique benefits and challenges.

The current evidence comparing ALIF and TLIF remains mostly limited to observational retrospective evidence. To the best of our knowledge, there has been no published multi-center prospective randomized controlled trial comparing anterior and posterior fusion surgery, for either single or multilevel pathologies. One of the earliest comparative studies was reported by Hacker *et al.* (37), who compared 21 ALIF patients versus 54 TLIF patients who had 'discogenic' low back pain. Successful fusion rate was significantly higher in the TLIF group (53 out of 54 patients) compared to ALIF (16 out of 21 patients). One criticism of this study, however, was that it represents an early experience of an approach used by few groups, with higher allograft malposition rates (3 out of

53 patients) which may be attributed to a learning curve of this technique. More recent studies by Faundez *et al.* (38), Kim *et al.* (39) and Dorward *et al.* (40) did not show any significant difference in fusion rates between ALIF versus TLIF approaches.

In the context of a lack of randomized evidence, the next best level of evidence is a systematic review and meta-analysis of retrospective comparative evidence. In a recent meta-analysis (14), no significant difference in fusion rates was demonstrated between ALIF versus TLIF (88.6% *vs.* 91.9%, $P=0.23$). Dural injury was found to be significantly lower in the ALIF group (0.4% *vs.* 3.8%), blood vessel injury significantly higher in the ALIF group (2.6% *vs.* 0%), whilst no differences were detected in terms of neurological deficit (6.8% *vs.* 7.9%) and infection rates (4.9% *vs.* 4.3%).

Few of the comparative studies reported radiographic outcomes. Hsieh *et al.* reported significantly higher disc height, segmental lordosis and total lumbar lordosis in the ALIF group compared with TLIF (13). These trends were corroborated by Kim *et al.* in 2009 and 2010. In 2015, a standardized foramen measurement technique called the “pedicle-to-pedicle” technique was used to show that ALIF was associated with significant indirect foraminal decompression, with restoration of disc height and foraminal height (23).

PLIF *vs.* TLIF

PLIF and TLIF are both commonly used posterior approaches for fusion surgery, and represent the majority of cases performed worldwide in terms of LIF (41-44). First described in 1940 by Cloward, PLIF allows three-column fixation with 360° fusion and anterior support (45,46). The TLIF procedure introduced in 1982, involves placement of pedicle screws and an interbody spacer via a posterolateral route through a facetectomy corridor (6). The advantages, disadvantages and indications for these techniques are described above.

Multiple studies have attempted to compare PLIF versus TLIF in terms of clinical and fusion outcomes. Humphreys *et al.* compared 34 PLIF *vs.* 40 TLIF patients in their report in 2001 (11). There were 10 complications in the PLIF group compared to 0 events in the TLIF group. Graft malposition occurred in four patients in the PLIF group, but none were reported in the TLIF group. Park *et al.* in 2005 reported 7 patients out of 99 PLIF patients with complications, compared to 0 events out of

29 TLIF patients (10). More recent studies such as Audat *et al.* (2012) and Sakeb *et al.* (2013) have also demonstrated similar trends (15,16). Radiographic fusion rates have been reported in fewer studies. Yan *et al.* (2008) and Zhuo *et al.* (2009) both reported 100% radiographic fusion rates for PLIF and TLIF (47,48). Audat *et al.* (15) and Sakeb *et al.* (16) reported no significant differences in radiographic fusion rates between PLIF and TLIF.

To summarize the available evidence, a systematic review and meta-analysis was conducted by Zhang *et al.* (12). From seven comparative studies, PLIF was associated with a higher complication ($P<0.00001$) whilst TLIF was associated with reduced durotomy ($P=0.01$). Clinical satisfaction ($P=0.54$), blood loss ($P=0.14$), nerve root injury ($P=0.08$), graft malposition ($P=0.06$), infection ($P=0.36$) and rate of radiographic fusion ($P=0.27$) were similar between PLIF versus TLIF cohorts. PLIF however required longer operative time ($P=0.03$). As such, the evidence suggests that TLIF could reduce the complication rate and durotomy rate whilst shortening duration of procedure. Neither TLIF nor PLIF was found superior in terms of clinical satisfaction or radiographic fusion rate (12).

Recent studies have also explored MIS options for PLIF (49) and TLIF (49). An open approach may be associated with improved deformity reduction with bilateral facetectomy possible. However, MIS PLIF/TLIF may be associated with reduced blood loss and shorter hospital stay, albeit longer operative times. Evidence to date has not demonstrated any differences in patient-related outcomes when comparing open versus MIS approaches, and requires further validation in prospective randomized controlled trials (50). MIS approaches may be more suitable for single level pathologies, again with robust data lacking to confirm this statement.

LLIF *vs.* ALIF/TLIF/PSF

Given the recent introduction of LLIF and more recently OLIF approaches, there have been few comparative studies reporting clinical and radiographic outcomes of these techniques to traditional approaches. In 2015, Sembrano *et al.* compared ALIF, LLIF, TLIF and PSF (posterior spinal fusion—no interbody device inserted) in terms of 6-week radiographic outcomes (51). The primary research question of this study of 147 patients (212 levels) was: how does LLIF compare to standard fusion approaches (ALIF, TLIF and PSF) in terms of improving segmental lordosis at the operative level(s). Secondary questions examined

include how LLIF compared to standard approaches in terms of change in operative level(s) disc heights as well as regional lumbar lordosis. The operative numbers were relatively low including LLIF (35 patients; 54 levels); ALIF (36 patients; 57 levels); TLIF (50 patients; 65 levels); and PSF (26 patients; 36 levels). The authors demonstrated that the operative level lordosis change in all three interbody fusion procedures (LLIF, ALIF and TLIF) produced significantly greater segmental lordosis change compared to the traditional 'on-lay' PSF technique. These results are intuitive; however they serve to highlight the importance of interbody structural support in terms of lordosis restoration. Secondly, the authors reported no significant changes in supra-adjacent and subjacent level lordosis in all approaches except ALIF, where a decrease in supra-adjacent level lordosis was observed. Mean anterior and posterior disc heights increased in all approaches except PSF. The authors concluded that LLIF has the ability to improve sagittal contour as well as other interbody approaches and is superior to posterior approaches in disc height restoration (51). ALIF provided the greatest amount of segmental and overall lumbar lordosis correction. It must be acknowledged that this is a level III study and future comparative studies are required before any firm conclusions can be made.

ALIF vs. LLIF and TLIF

A study by Watkins *et al.* (52) of 220 consecutive patients with 309 operative levels were compared by surgery type: ALIF (184 levels), LLIF (86 levels), and TLIF (39 levels), with an average follow-up of 19.2 months in terms of sagittal correction and spondylolisthesis reduction. They concluded that improvement of lordosis was significant for both the ALIF and LLIF groups, but not the TLIF group. Intergroup analysis showed the ALIF group had significantly improved lordosis compared to both the other groups. The ALIF and LLIF groups had significantly increased disc height compared to the TLIF group. All the three groups significantly reduced spondylolisthesis, with no difference between the groups (52).

Part 2. Comparative evidence based on indication

Discogenic low back pain

There is limited comparative evidence for fusion approaches

in the context of discogenic low back pain. The comparative evidence mostly investigates surgical fusion versus nonoperative management for discogenic low back pain. Bydon *et al.* (53) performed a systematic review and meta-analysis of five randomized trials including 523 lumbar fusion patients and 134 patients managed conservatively. Despite the significant improvement in ODI in the lumbar fusion groups in three studies, pooled data revealed no significant difference when compared with the non-operative group. It is not clear whether the pooled ODI difference of 7.39 points would have any clinical significance. As such, there remains limited comparative evidence for fusion approaches when the indication is discogenic low back pain. Many surgeons, however, prefer the ALIF approach for the management of discogenic low back pain, especially at L5/S1 and L4/5 as this technique spares the paraspinal and psoas muscles from iatrogenic injury, and provides efficient disc space clearance, therefore removing the annular pain generating fibers and achieving high fusion (54). TLIF is also thought to be a safe and effective technique in patients with intractable chronic lumbar discogenic pain with an acceptable overall work resumption rate based on a study by Takahashi *et al.* (55).

Isthmic spondylolisthesis

The most appropriate approach for the surgical treatment of isthmic spondylolisthesis remains a topic of controversy and debate. The comparative literature on this topic has predominantly compared PLIF *vs.* PLF approaches for low-grade adult isthmic spondylolisthesis. A prospective study with over 7-year follow-up by Cunningham *et al.* (56) demonstrated significantly higher Low Back Outcome Scores, PCS/MCS, SF-36 scores in the PLIF group compared to PLF. However, a randomized controlled trial comparing 39 PLF and 42 PLIF patients did not show any significant differences between the groups in terms of fusion rates, postoperative pain and functional outcomes, or complication rates (57). To address conflicting literature data, a meta-analysis by Luo *et al.* (58) pooled data from nine selected studies. PLF was shown to have lower fusion rates compared to PLIF ($P=0.005$, $OR=0.29$) and shorter operation duration. However, there was no difference detected in terms of postoperative VAS leg and back scores, blood loss, complication rates or ODI scores.

Kim *et al.* (39) compared outcomes of ALIF versus TLIF for adult low-grade isthmic spondylolisthesis at L4/5 and L5/S1 levels. TLIF had significantly higher ODI

scores compared to ALIF at the L4/5 level. However, their radiographic results demonstrated that ALIF was superior in restoring disc height and whole lumbar lordosis at L5/S1 level. No differences in fusion rates were found between ALIF and TLIF. ALIF with PLF versus ALIF with percutaneous pedicle screw fixation has also been compared in elderly patients with L5/S1 isthmic spondylolisthesis (59). The authors noted a lower rate of fusion in patients with ALIF and percutaneous pedicle screw fixation compared to PLF. However, no significant differences in complication rates or VAS outcomes were noted between the groups. The retrospective nature of this study is a limitation that should be acknowledged; further well-designed studies are necessary for a more rigorous evaluation of these approaches.

Degenerative spondylolisthesis

Degenerative lumbar spondylolisthesis is characterized by facet joint degeneration, anterolisthesis and loss of disc height at affected levels, which can lead to central, lateral recess and foraminal stenosis (60,61). There has been a significant evolution in the treatment of this disease entity, with several landmark papers that have directed our treatment including the Spine Patient Outcomes Research Trial (SPORT), which offers the highest quality evidence to date (62). Although few would argue that the fusion of the diseased segment appears to offer the best and most durable results, treatment of this disease is best tailored to the individual. A study published in 2015 compared outcomes of 39 PLIF patients matched with 39 LLIF patients at levels L3/4 and L4/5 (63). This study demonstrated significantly better restoration of disc height, foraminal height and segmental lumbar lordosis in the LLIF group compared to PLIF, with similar operation times and lower average blood loss in the former approach. No differences in functional outcomes were reported. Another randomized study (64) compared TLIF versus uninstrumented PLF in 135 patients with degenerative lumbar spine disease with follow-up at 12 and 24 months. At follow-up, TLIF had a significantly higher proportion of patients who scored better in the global assessment measurement used, which the authors attributed to higher reoperation rates in the PLF group. Another study by Liu *et al.* (65) reached similar conclusions; they compared 101 TLIF *vs.* 125 PLIF cases for degenerative lumbar spondylolisthesis. PLIF was found to be associated with higher rates of complications such as nerve root injury, dural tears, blood transfusions,

and increased operative duration and reoperation rates. Likewise, Fujimori *et al.* (66) demonstrated superiority for the TLIF approach compared to PLF in reducing listhesis and restoring disc height. However, no differences in ODI or PCS were statistically obtained. Whilst the comparative evidence for various techniques for lumbar degenerative spondylolisthesis remains limited, there is some data to suggest that lateral and transforaminal fusion approaches may result in lesser complications compared to posterior fusion approaches such as PLF and PLIF.

Degenerative scoliosis/kypho-scoliosis

Degenerative spinal deformity affects a significant portion of the elderly and is increasing in prevalence. It has been suggested that sagittal plane malalignment is central to the mechanisms of pain and disability in this population and has led to a significant shift toward a more evidence-based management paradigm (67). It results from cumulative degenerative changes focused in the intervertebral discs and facet joints that occur asymmetrically to produce deformity. Operative management, in carefully selected patients, yields satisfactory outcomes that appear to be superior to non-operative strategies, however these interventions are technically demanding for the surgeon, and medically stressful for the patient. Surgery aims to restore global spinal alignment, decompress neural elements, and achieve fusion with minimal complications.

There is evidence for idiopathic scoliosis that favors the anterior approach, with Nohara *et al.* reporting surgical outcomes of anterior fusion versus posterior fusion in patients with AIS Lenke type 1 and 2 over 10-year follow-up (68), however degenerative scoliosis is a very separate pathology. In this study, correction of scoliosis was found to be significantly improved in the anterior approach cohort compared to posterior cohort immediately after operation. However, greater loss of correction was found with the anterior approach group at 10-year follow-up. A study by Etemadifar *et al.* reported outcomes of using anterior-posterior fusion versus posterior alone for correction of Scheuermann's kyphosis (69). Whilst clinical and radiology parameters including Cobb's kyphosis angle, correction rate and correction loss were similar between the groups, complication rates, operation time and blood loss were found to be higher in the hybrid anterior-posterior fusion procedure.

More recently, MIS approaches have been compared with open approaches for idiopathic and degenerative

scoliosis. Sarwahi *et al.* (70) reported in a study with 2-year follow-up that whilst MIS technique was feasible, there were no clear advances compared to open approaches in the context of idiopathic scoliosis, although this data did not translate to degenerative pathologies. For degenerative lumbar scoliosis, a recent meta-analysis of 12 studies (71) demonstrated significantly greater sagittal and coronal correction in patients receiving LLIF compared to the PLF and decompression-only cohort. Larger Cobb angles, greater sagittal balance correction, and higher reoperation rates were found in studies reporting the use of open fusion with osteotomy.

The literature remains heterogeneous in terms of techniques with a wide variety of options reported for lumbar degenerative scoliosis. Zhu *et al.* (72) reported on selective segmental transforaminal interbody fusion combined with posterior-instrumented spinal fusion, with 'reasonable' long-term clinical and radiographic outcomes. Manwaring *et al.* reported LLIF with Anterior Column Release (73), with the ability to powerfully restore lumbar lordosis and correct sagittal imbalance. This segmental MIS technique boasts equivalence to Smith Peterson Osteotomy correction of global radiographic parameters while simultaneously creating additional disc height and correcting coronal imbalance. If corrective surgery combining anterior and posterior approaches for adult degenerative scoliosis is contemplated, the timing of such interventions requires investigation. Staging the two procedures by 21 or more days apart decreases total perioperative transfusion requirements and significantly improves functional outcomes (74).

Adjacent segment degeneration

There are few papers reporting outcomes of surgery for adjacent segment degeneration. Whilst studies have been identified for treatment of adjacent segment degeneration with decompression alone, decompression and fusion, or decompression and disc arthroplasty, no comparative study has been identified to date (75). Miwa *et al.* retrospectively analyzed 18 patients who underwent repeat PLIF for adjacent segment disease, with 8 patients (44%) deteriorating again because of recurrence (76). There is some data for outcomes for cervical degenerative pathologies, with Bin *et al.* reporting the outcomes of ACDA for the treatment of adjacent segment disease in 32 patients, in which the authors suggested that ACDA was an effective treatment for post-ACDF adjacent segment

disease (77), though no similar lumbar data exists.

Lumbar non-union

There is a paucity of data that assists the surgeon in making decisions on management strategies for lumbar non-union, and whether the non-union is best managed via the same approach as the initial surgery. Recent studies (22,24) have recommended posterior surgery (PLIF or TLIF) is well managed with high fusion rates via the anterior corridor (ALIF). Intuitively this makes sense as an unencumbered corridor is used with thorough endplate preparation to prepare an ample surface area to assist with revision fusion. Re-approaching the non-union segment via the initial exposure may involve extending the operative field with further morbidity especially with nerve root injury and CSF leak to the patient. There is no data except for a case report on both LLIF and OLIF (36) on revision strategies for posterior non-union. The converse also applies that if a patient has a non-union via an anterior technique (ALIF, LLIF, OLIF), that posterior approaches may represent a reasonable strategy as re-exposure of the anterior corridor can be high risk for vascular, bowel and ureter injury and should not be performed without vascular surgeon assistance (22,24).

Discussion

There is a large volume of data in the literature detailing clinical and radiological outcomes following specific interbody surgical interventions, however little robust class 1 or 2 clinical and biomechanical data comparing the various available techniques. Surgeons who have been trained in one specific interbody technique will have a tendency to favor that technique, irrespective of the pathology being treated, or the number of operative levels performed. The literature uniformly supports the concept of interbody techniques over on-lay posterior spinal fusion for sagittal and coronal plane deformities (78), with deformity reduction correlating with positive clinical outcomes in a number of well-performed studies (79). As spine surgery evolves to become its own subspecialty as it has in many parts of the world, surgical trainees will increasingly be exposed and trained in a variety of interbody techniques so that the surgeon is empowered with multiple options to manage difficult pathologies in an evidence-based fashion.

In terms of anterior versus posterior procedures, the available literature focuses on ALIF and TLIF as

comparator techniques (14). In this systematic review, we established that blood loss and operative time in TLIF were less than in ALIF. These studies, however, described ALIF as a technique associated with an anterior and posterior combined procedure and TLIF as a single posterior procedure, and this may explain the difference in blood loss and operative time. However, there was no significant difference in the complication rate between ALIF and TLIF. No significant difference was found in the complications such as hematoma, wound infection, wound dehiscence, pedicle screw malposition, CSF leakage, and non-fusion between ALIF and TLIF. Some complications, such as incisional hernia, retrograde ejaculation, and venous injury were specific to ALIF. In addition, the risk of deep venous thrombosis and pulmonary embolus was increased after ALIF, and this may be related to the retraction of large vessels during the operation. Therefore, measures should be taken to prevent these complications, such as intraoperative anticoagulation (80) and vascular assistance with the ALIF approach and exposure (19,24). With further research comparing the stand-alone ALIF technique to TLIF, it is likely that the complication profile will alter in favor of ALIF as posterior stabilization is usually not necessary using contemporary ALIF cages with separate or integrated plate-screw fixation (14,19,22-24).

Sagittal balance and lumbar lordosis correction have become important goals as these indicators have been shown to significantly improve outcomes (81). LLIF has evolved to be a powerful MIS approach to lumbar spine fusion to achieve these goals. Recent studies now confirm that the operative level lordosis improves in all three interbody fusion procedures (LLIF, ALIF and TLIF) producing significantly greater segmental lordosis change compared to Posterior Spinal Fusion. However one study states that TLIF does not translate to measurable differences in lordosis restoration (52). As noted above, these results are intuitive and serve to highlight the importance of interbody structural support in terms of deformity reduction (51). Further studies on TLIF performed via a unilateral complete facetectomy demonstrate no significant improvement in segmental lordosis at the operative level (52). Watkins found an insignificant 0.8° change after TLIF (52). Hsieh *et al.* likewise reported no statistically significant difference in segmental lordosis after TLIF (13). They speculated that the difficulty in positioning the interbody device in the ideal anterior position, and the presence of a retained contralateral facet hinders posterior compression. The importance of positioning the cage as

anterior as possible was highlighted by Kida *et al.* who reported significant improvement in segmental lordosis after cantilever TLIF (82).

In theory, ALIF allows re-expansion of the disc space and restoration of lumbar lordosis (17,83,84). The restoration of local and regional lordosis in the lumbar spine is critical for preserving and ideally improving spinal sagittal balance. The results of Hsieh *et al.* (13) indicated that ALIF was superior to TLIF in restoring the local disc angle and lumbar lordosis. ALIF increased the local disc angle by 8.3° and lumbar lordosis by 6.2° , whereas TLIF decreased the local disc angle by 0.1° and lumbar lordosis by 2.1° . Similarly, Kim *et al.* (85) reported that the change of disc height, segmental lordosis, and lumbar lordosis before and after surgery in ALIF was greater than in TLIF. These suggest that ALIF is superior to TLIF in its capacity to restore disc height and lumbar lordosis.

Regarding clinical outcomes, most studies (85,86) showed that clinical outcomes in ALIF were similar to TLIF. However, Kim *et al.* (39) report that the ODI score in TLIF is better than that in ALIF at L4-5, but not L5-S1, and they recommend that instrumented mini-TLIF is preferable at the L4-5 level, whereas instrumented mini-ALIF may be preferable at the L5-S1 level for the treatment of unstable isthmic spondylolisthesis. Different levels and pathologies may affect clinical outcomes of ALIF and TLIF, and further studies are awaited.

Our systematic review showed that comparable fusion rates between ALIF and TLIF approaches. ALIF was associated with restoration of disc height, segmental lordosis and total lumbar lordosis, lower dural injury but higher blood vessel injury (14). Regarding financial costs, there has been conflicting evidence in the literature, with some studies reporting ALIF to be cheaper (19) and other studies reporting it to be more expensive (87) than surgical treatment with TLIF.

A further question that warrants discussion is the role of multiple approaches being performed on the same day versus staging of procedures. It is reported that the timing of surgical staging has a significant impact on the complications and functional outcomes of adult spinal deformity surgery. Hassanzadeh *et al.* (88) reported that for patients who require both anterior and posterior surgery for spinal deformity correction, staging the two procedures 21 or more days apart decreases total perioperative transfusion requirements and significantly improves functional outcomes. However, there is no available data on single level anterior/posterior interventions performed as same

Table 1 Options *vs.* level. Based on the anatomy of access, the following options are suitable depending on lumbar level performed

Option/level	L5/S1	L4/5	L3/4	L2/3	T12/L1/2
PLIF	+++	+++	+++	+++	++
TLIF	+++	+++	+++	+++	++
ALIF	+++	+++	+	-	-
LLIF	-	+++	+++	+++	++
OLIF/ATP	++	+++	+++	+++	+

+, fair option; ++, good option; +++, excellent option; -, poor option/not suitable. PLIF, posterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion; ALIF, anterior lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; OLIF, oblique lumbar interbody fusion; ATP, anterior to psoas.

-day surgery versus delayed surgeries.

There are multiple limitations in this systematic review (14). Some studies report ALIF and TLIF combined with posterolateral fusion, therefore skewing the potential fusion results and outcomes. In addition, studies reveal a heterogeneous patient population, with different levels and pathologies reported that impact radiological fusion rates and clinical outcomes. Therefore, the conclusions cannot be made about the effects of different levels and pathologies on clinical outcomes. ALIF, TLIF and PLIF remain the more commonly performed techniques for lumbar interbody fusion (LIF). LLIF has established its place as a robust technique for deformity correction and interbody fusion, with OLIF requiring further studies and data to establish its place.

Available data suggests that anterior techniques are superior to posterior in terms of disc height restoration, lumbar lordosis and deformity correction, and that clinical outcomes and fusion rates were similar to those in posterior techniques. This data, however, is based on heterogeneous studies with multiple indications and through comparison is difficult to make.

The authors provide the following recommendations for future studies based on the available literature:

- (I) Clinical and radiological outcomes on particular indications performed via specific approaches at specific levels. Is ALIF, LLIF, TLIF or PLIF the clinically superior technique for degenerative spondylolisthesis at L4/5? Assuming one technique is superior radiologically, does this translate to clinical superiority?
- (II) What is the superior option for the management of degenerative lumbar and thoracolumbar scoliosis? There are numerous options here including posterior only, lateral and anterior or a combination

of all 3 approaches. Further questions remain as to precise timing of such interventions, and if various approaches should be performed on the same day or as a staged procedure;

- (III) Revision strategies for failed lumbar fusions. Is a failed fusion/non-union best managed via the same approach as the initial surgery or via a new corridor?
- (IV) Adjacent segment degeneration. Should a revision be performed via the same approach/corridor as the index surgery, or are radiological and clinical results superior if a new corridor of approach is used?

Recommendations

Based on the available evidence in the literature, the following recommendations and guidelines are proposed, based on the level of pathology and indication (*Table 1*).

L5/S1

- (I) ALIF preferred method for discogenic LBP and lordosis restoration;
- (II) PLIF and TLIF reasonable methods especially with central canal stenosis or recurrent disc herniation (89);
- (III) PLIF preferred approach for Isthmic spondylolisthesis due to the high risk of L5 nerve injury (90);
- (IV) OLIF early data is promising; LLIF not suitable.

L4/5

- (I) PLIF and TLIF good option for degenerative spondylolisthesis;
- (II) ALIF/OLIF/LLIF all reasonable options for lordosis and deformity correction, however increased risk of lumbar plexus/psoas injury with LLIF.

L2/3 and L3/4

- (I) All techniques except for ALIF suitable;
- (II) ALIF not recommended as high risk; need experienced vascular surgical assistance;
- (III) For deformity correction, antero-lateral techniques preferred including LLIF/OLIF.

T12/L1 and L1/2

- (I) ALIF not suitable;
- (II) PLIF/TLIF difficult if cord or conus inhibits dural retraction for insertion of implant/s;
- (III) LLIF good option especially for deformity correction.

Multilevel

- (I) Multilevel usually involves deformity correction if performed for degenerative pathologies;
- (II) Combination of anterior/lateral and posterior techniques provides powerful deformity correction;
- (III) Multilevel ALIF/LLIF/OLIF provide sagittal and coronal correction but may require supplemental posterior fixation.

Conclusions

Interbody fusion remains an effective treatment option for a range of spinal disorders including degenerative pathologies, trauma, infection and neoplasia. There are various approaches available for interbody fusion including PLIF, TLIF, MI-TLIF, OLIF/ATP, ALIF and LLIF. There is limited comparative evidence demonstrating that one approach is superior to another in terms of fusion or clinical outcomes. The present study provides a broad overview of the advantages, disadvantages, indications and evidence for different LIF techniques. We propose a set of recommendations that may assist with deciding the most appropriate surgical approach for the patient.

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Footnote

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