Review article

Surgical techniques for lumbo-sacral fusion

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ARTICLE INFO

Article history:
Received 1st April 2016
Accepted 8 June 2016

Keywords:
Spinal fusion
Arthrodesis
Anterior lumbar interbody fusion (ALIF)
Posterior lumbar interbody fusion (PLIF)
Transforaminal lumbar interbody fusion (TLIF)
Lordosis

ABSTRACT

Lumbo-sacral (L5-S1) fusion is a widely performed procedure that has become the reference standard treatment for refractory low back pain. L5-S1 is a complex transition zone between the mobile lordotic distal lumbar spine and the fixed sacral region. The goal is to immobilize the lumbo-sacral junction in order to relieve pain originating from this site. Apart from achieving inter-vertebral fusion, the main challenge lies in the preoperative determination of the fixed L5-S1 position that will be optimal for the patient. Many lumbo-sacral fusion techniques are available. Stabilisation can be achieved using various methods. An anterior, posterior, or combined approach may be used. Recently developed minimally invasive techniques are gaining in popularity based on their good clinical outcomes and high fusion rates. The objective of this conference is to resolve the main issues faced by spinal surgeons in their everyday practice.

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1. Introduction

Lumbo-sacral fusion can be viewed as a biological process that ultimately produces a strong bony bridge between L5 and S1, at the selected site, in order to obtain complete ankylosis of the intervertebral joint. The goal is to relieve pain due either to exaggerated mobility or to an inappropriate position of the lumbo-sacral junction.

The chief objective is to permanently block one or more intervertebral joints at the lumbo-sacral junction. The architecture of the spine consists in three vertical columns [1]; an anterior column comprising the vertebral bodies and discs and two posterior columns composed of the facet joints and neighbouring structures. Fusion is induced at the intervertebral spaces, where spinal mobility occurs. The fusion site may be anterior, between two vertebral bodies; posterior, at the facet joints or inter-transverse region (posterolateral graft); or both anterior and posterior.

The lumbo-sacral junction has several unique characteristics. The lumbar spine is mobile, whereas the sacrum is lodged between the two iliac wings and therefore fixed. Thus, the lumbo-sacral junction is a zone where transitions occur in both anatomical structure and mechanical behaviour.

2. Specific characteristics of the lumbo-sacral junction

The lumbo-sacral junction is located at the distal end of the lordotic lumbar segment. Roussouly et al. [2] demonstrated that the lumbar spine can be divided into two segments, proximal and distal to the apex of the lordotic curvature. The apex is the most anterior point of the lumbar spine and is located on the vertical line tangent to the anterior lumbar convexity. Here, we will focus on the distal lordotic curvature, which normally prolongs the sacral slope (SS). Given this geometry and the strong correlation between distal lumbar lordosis and SS, L5-S1 fusion positioned in insufficient or excessive distal lumbar lordosis directly affects the SS value and, consequently, the position of the sacrum and pelvis in space when the patient assumes an erect posture.

The only radiographic parameter that predicts the optimal segmental lordosis at L5-S1 in patients with alignment abnormalities is pelvic incidence (PI). PI correlates strongly with lumbar lordosis and even more strongly with distal lumbar lordosis. Thus, the optimal amount of distal lumbar lordosis can be pragmatically estimated using two formulae: total lumbar lordosis = PI and distal (L4-S1) lordosis = 2/3 of total lordosis. This relationship is the starting point for the preoperative determination of the optimal amount of L5-S1 lordosis to be restored, since it is never modified, even in abnormal situations.

Two other unique features of the lumbo-sacral junction are considerable mobility and strong vertical forces produced by the weight of the torso. Both features may contribute to the high...
frequency at this level of disc disease, facet joint wear, and pain, which may require L5-S1 fusion.

3. Available methods for achieving L5-S1 fusion

Obtaining strong fusion in the optimal position is the main goal of fusion procedures. Regardless of the technique used, two requirements must be met if fusion is to be achieved:

- a substrate that features osteogenic, osteoinductive, or osteoconductive properties must be implanted, to contribute to the formation of the bony bridge;
- and the vertebrae must be stabilised in the optimal position by internal fixation material, to maximise the likelihood of fusion.

3.1. Substrates available for joint fusion procedures

There is no consensus regarding the best substrate. Furthermore, depending on the type of fusion, the choice of the substrate is often guided by surgeon preference and by the internal fixation material used.

Of the many available substrates, the most widely used are autologous bone harvested from the iliac crest or spinal processes and bone morphogenetic protein-2 (BMP2). Allogeneic bone and bone-marrow mesenchymatous cells are also used but have been less extensively evaluated in the literature.

3.2. Techniques available for lumbo-sacral fusion

3.2.1. Anterior lumbar inter-body fusion (ALIF)

ALIF is now performed using a minimally invasive approach. The technique is well standardised. The main challenge lies in determining that ALIF is the best option for the individual patient.

There are several prerequisites to performing an optimal surgical procedure with a simple postoperative course and outcomes that meet patient expectations. The surgeon must be conversant with the anterior approaches to the spine; if needed, the assistance of a vascular or gastro-intestinal surgeon may be obtained. Dedicated instruments and good lighting must be available. Preoperative CT angiography or magnetic resonance angiography should be performed to obtain a detailed map of the local anatomy. The risk of patient injury is greatest during mobilisation of the veins and, consequently, obtaining detailed information on the location of the left iliac vein (regardless of the side of the approach) and venous confluence is of utmost importance.

The patient is in the supine position with the lower limbs aligned on the torso. The surgeon stands on one side of the patient. Alternatively, the patient may be supine with the legs abducted (i.e., in the “French position”) and the surgeon standing between the legs and working in the axis of the spine: this position facilitates discectomy, preparation of the plates, and proper positioning of the inter-body implant. Either a midline sub-umbilical incision or a transverse Pfannenstiel incision is performed. The incision should be centred on the L5-S1 level, whose location is identified preoperatively.

3.2.1.1. There are three possible approaches (Fig. 1).

3.2.1.1.1. The left retro-peritoneal approach. The left retro-peritoneal approach is the oldest among them. The L5-S1 disc is approached in the arterial bifurcation and venous confluence. This approach is described in detail elsewhere [3,4]. It is now reserved for procedures at L4-L5 and revisions of procedures on L5-S1 performed through a right-sided approach.

3.2.1.1.2. The trans-peritoneal approach. The trans-peritoneal approach is the most direct route to the L5-S1 disc and is easy to perform in patients who are obese, have a history of abdominal surgery, or are undergoing a revision spinal procedure. A midline skin incision is performed. The linea alba must be opened. A midline incision is then performed. The abdominal contents are carefully displaced to expose the posterior parietal peritoneum, which covers the lumbo-sacral vessels and lumbo-sacral disc space. The posterior parietal peritoneum is opened, on the right side, starting 1 cm medial to the right of the common iliac artery. The pre-vertebral fat and hypogastric plexus are gently displaced from the right to the left to expose the anterior circumference of the L5-S1 disc. Blade retractors are then positioned on the vessels to retract and protect them.

Despite the many advantages of these approaches, the risk of vascular injury [5] and retrograde ejaculation [6] limits their use. Anatomical studies have established that the hypogastric plexus is located to the left of the L5-S1 disc space and that its left edge exchanges multiple Anastomoses with the sigmoid plexus, so that injury is more likely to occur during a left-sided approach [7].

3.2.1.1.3. The right retro-peritoneal approach. The right retro-peritoneal approach is therefore preferred. In our opinion, this is the method of first choice for approaching the L5-S1 disc space. A vertical or transverse skin incision centred on the L5-S1 level is performed. On the right side of the lumbo-sacral region, the hypogastric plexus is very often absent or meagre, with only scant collaterals. This fact limits the risk of nerve injury by stretching, which can cause retrograde ejaculation in males or vaginal dryness and ovulation dysfunction in females.

In clinical practice, the left-sided approach is used in 40% of patients, due to contra-indications to the right-sided approach.

3.2.1.2. Discectomy. Discectomy is the first step of ALIF. Because this step is essential, an approach extending along the entire width of the disc, i.e., over nearly 50 mm, is warranted. The disc is one of the sources of pain and must therefore be removed as completely as possible, without damaging the subchondral bone. Freshening of the plateaus should be sufficient to promote bone formation yet cautious, since any excess would impair mechanical strength, inducing a risk of cage subsidence into the vertebral bodies.

The posterior part of the annulus must be completely exposed. If mobilisation of the space proves difficult, posterior release should be achieved by excising the posterior part of the annulus. The result is exposure of the posterior longitudinal ligament, which should be removed in the event of nerve root pain and difficulties distracting the inter-vertebral space. In the event of bleeding due to epidural
vessel injury, haemostasis should be achieved by applying pressure and warm serum or haemostatic agents.

In the absence of nerve root pain, decompression is unnecessary and the posterior longitudinal ligament is therefore preserved to serve as a pivoting structure when the lumbar spine is placed in lordosis, thereby obviating the need for parallel distraction. Otherwise, the posterior longitudinal ligament should be removed from one foramen to the next.

3.2.1.3. Distraction of the disc space. Distraction of the space allows introduction of the fusion material, which may be either bone or an interbody cage. Distraction has major advantages. It indirectly relieves compression on the foramina by increasing disc height and it allows implant positioning under better mechanical conditions, with no risk of damaging the plateaus. Distraction also enables ideal positioning of the implant in the posterior part of the disc space, a factor that is crucial to the optimal adjustment of L5-S1 lordosis.

A distraction system specific of the implant is often used. This system serves to restore both disc height, thus allowing selection of the most appropriate implant dimensions (width, depth, and height), and lumbar lordosis. A trial implant is introduced into the disc space. Fluoroscopy is used to check that the implant is properly positioned. The final implant is then filled with the fusion substrate and introduced into the disc space (Fig. 2).

3.2.2. Choosing the implant and deciding whether to add fixation

A broad array of inter-body fusion cages is now available. The cages are composed of polyetherether ketones (PEEK) or titanium. No consensus exists regarding selection of cage type or fixation modality. Some cages are designed to be implanted without fixation (Fig. 3), whereas others have integrated fixation devices (Fig. 4) or are used in combination with plate fixation (Fig. 5). Studies have established that ALIF without fixation carries a risk of non-union [8]. ALIF is sometimes combined with posterior fixation. The wide variety of fixation devices used ranges from pedicle screws to trans-facet screws implanted through a minimally invasive approach.

The good outcomes of ALIF have considerably increased the popularity of this procedure. The complications of ALIF fall into two categories, those related to the approach and those specific of ALIF. As discussed above, complications related to the approach include retrograde ejaculation, vessel injury, superficial surgical-site infection, ureteral injury, and injury to the abdominal muscles. The complications specific of ALIF are implant migration, subsidence of the cage into the vertebral bodies, non-union, and collapse of a femoral ring allograft.

3.2.3. Restoring lordosis

Sagittal spinal alignment must be evaluated in each patient to determine the appropriate amount of lordosis. This evaluation is described later.

No consensus exists about the best method for restoring lordosis via the anterior approach. In most patients, the lordotic curvature of the cage and, if needed, opening the disc space by extension of the lower limbs provide the desired amount of lordosis.

3.2.4. Posterior lumbar interbody fusion (PLIF)

This discussion is confined to PLIF with instrumentation.

3.2.4.1. Types of PLIF. PLIF combines bone grafting and screw fixation using pedicle or trans-facet screws. Inter-spinous fixation devices were introduced recently but are not discussed here, as the S1 spinous process is too small to allow their use. Either a
conventional or a minimally invasive approach can be used for internal fixation.

The pedicle screw fixation technique is well established. The trans-facet screw (Fig. 6) is inserted through the L5-S1 facet joint after freshening of the joint surfaces, as described by Boucher [9]. The L5-S1 facet joint is perforated and a 50-mm screw inserted through it. When used alone, this fixation technique must be performed bilaterally and combined with posterior-lateral grafting. Trans-laminar facet screw fixation consists in introducing one screw on each side, at the base of the spinous process. The two screws cross each other on the midline. The screw trajectory is drilled using a 3.2-mm bit introduced through the lamina then through the facet joint to the base of the transverse process. Trans-facet screws induce direct compression of the joint, whereas pedicle screws immobilise the entire mobile segment.

Furthermore, trans-facet screws do not allow reduction, in contrast to pedicle screws, which are the reduction technique of first choice.

Isolated posterior fusion techniques carry a risk of non-union and poor clinical outcomes. A study of autopsy specimens reported by Rolander [10] demonstrated that rigid posterior fixation left residual intra-discal movement and compression forces, a possible source of persistent pain in patients with disc disease. Suk et al. [11] reported that adding inter-body fusion to posterior fusion increased the fusion rate and improved the clinical outcomes.

3.2.4.2. Combining inter-body fusion and posterior fusion. Two techniques are available for achieving inter-body fusion, posterior lumbar inter-body fusion (PLIF) and trans-foraminal inter-body fusion (TLIF).

3.2.4.2.1. The PLIF technique [12] (Fig. 7). Ideally, the patient should be installed on a frame or spinal surgery table to minimise pressure on the abdomen, which increases the risk of bleeding from the epidural vessels. The level to be fused is exposed and laminectomy performed. The medial part of the facet joint is resected to expose the passing nerve root and lateral portion of the disc. The dural sac and passing nerve root are mobilised and retracted towards the midline, on both sides. After exposure of the posterior annulus, the disc is removed as completely as possible, on both sides. The vertebral plateaus must be completely free of disc tissue.

Disc space height is restored by alternately using two distractors introduced into the disc space, one on the right and the other on the left. Once the appropriate height is determined, the distraction force is distributed over the residual annulus and the compressed inter-body material is then introduced. This material may consist in a cortical-cancellous bone graft or an inter-body cage made of PEEK, titanium, or tantalum. In the conventional PLIF technique, two cages with a rectangular design are used, one on each side of the disc space. Provided bone quality is sufficient, each cage can be introduced by its smallest face then rotated in situ so that it is taller than it is wide. Tools are provided with the cage to facilitate insertion. Lordotic cages are available and are particularly recommended at L5-S1. Care must be taken to ensure that the cages do not subside into the adjacent vertebral plateaus. The cages are packed with a substrate designed to promote fusion. Solid titanium cages feature a surface treatment that ensures osteoconduction, thereby promoting fusion. With all cage types, cortical and cancellous bone from
the laminectomy specimen can be added, in front of and lateral to the implants.

Once the two cages are in place, posterior fixation is achieved using pedicle screws, which are compressed along lordotic rods to reduce any kyphosis induced by the inter-body distraction. In situ rod contouring can be performed to obtain the desired amount of lordosis. A postero-lateral graft is then placed in contact with the transverse processes and sacral wings or introduced into the facet joints after removal of the joint cartilage.

PLIF without posterior fixation is not recommended, as this technique carries a risk of non-union and posterior cage displacement into the spinal canal, which result in poor clinical outcomes.

3.2.4.2.2. The TLIF technique [13] (Fig. 8). Patient installation is the same as for PLIF. A skin incision centred on the level to be fused is made and the muscles retracted to expose the lateral aspect of the spinous process, lamina, and facet joints on the side of the patient’s symptoms. Lateral laminotomy is performed and the joint facets are partially resected. Depending on the quality of inter-vertebral disc exposure and need for greater medial exposure, the lateral edge or the entire inferior articular process may be resected. Bilateral laminectomy may be required in patients with bilateral nervous structure compression.

At L5-S1, a bulky iliac crest may impede introduction of the cage. In this situation, extensive resection of the inferior L5 and superior S1 articular processes is required. Once the neurological structures are fully released, the pedicle screws are inserted using the standard technique.

The disc space is gradually distracted to the desired amount, either by applying a distractor against the screws or by using an inter-body distractor. The distraction is maintained with either a contra-lateral rod or a distractor applied to the screws. Discectomy is performed as described above. All disc tissue in contact with the vertebral plateaus must be removed. Care should be taken to protect the exiting nerve root, dural sac, and passing nerve root.

The selected implant is then packed with the substrate needed to achieve bone fusion. Bone from the laminectomy specimen and resected articular processes can be introduced into the disc space at the front and sides of the cage to promote bone fusion.

The implant is introduced either obliquely or in the straight forwards direction, depending on its shape and design, then turned until it is located as anteriorly as possible in the disc space, to ensure even distribution of the forces exerted by the implant in the disc space and to minimise the kyphosis-inducing effect. The edge of the cage should be located 5–10 mm from the anterior portion of the disc space. Fluoroscopy is then performed to check the position of the implant. The pedicle screws are compressed on a lordotic rod and locked to restore local lordosis.

TLIF has the advantage over PLIF of not requiring penetration into the spinal canal. Furthermore, TLIF can be performed without resecting the inferior articular process. In this case, the disc space is approached via the inter-transverse approach. The disc is accessed through an extra-foraminal approach, taking care to identify the exiting nerve root, the pars inter-articularis, and the pedicle of the infra-jacent vertebra. The challenge lies in obtaining sufficient disc exposure to allow discectomy and insertion of the cage, which requires partial resection of the pars inter-articularis and of the supra-pedicular portion of the superior articular process. Once the disc is adequately exposed, the technique is similar to that described above.

Changes have been made to the TLIF technique in recent years. Several technical modifications have produced highly satisfactory outcomes:

- minimally invasive techniques are now preferred by many surgeons. A meta-analysis by Phan et al. [14] showed less blood loss and lower infection rates with minimally invasive TLIF than with the conventional open technique;
- in addition to the approach techniques, fixation methods have undergone changes:  
  - fixation can be performed unilaterally using pedicle screws (Fig. 9). Wang et al. [15] found no convincing proof that unilateral or bilateral screw fixation provided better clinical outcomes, higher fusion rates, or lower complication rates. The difference was that unilateral fixation resulted in less blood loss. However, Yuan et al. [16] reported similar fusion rates and outcomes but more frequent cage migration with unilateral vs. bilateral screw fixation,
  - Zeng et al. [17] and others have used percutaneous unilateral trans-laminar facet screw fixation. They obtained good clinical and radiological outcomes but advised reserving this technique for highly selected patients.

A number of comments are in order:

- although minimally invasive TLIF with fixation by four screws tends to be gaining preference, percutaneous minimally invasive techniques usually do not include bone grafting on the side of
percutaneous fixation, leaving the inter-body implant as the sole source of fusion. A graft must therefore be added, either in the posterolateral position or at the articular processes if the facet joint was preserved;
• with minimally invasive techniques, completing lordosis restoration by in situ contouring is more difficult, since the facet joints are preserved on the contra-lateral side.

3.2.4.3. Other techniques. There are two other posterior inter-body fusion techniques: AxiaLif® or percutaneous axial S1-L5 interbody fusion, and posterior S1-L5 fusion:

• AxiaLif® allows fusion of S1-L5, and even S1-L4, using a screw introduced via the para-coccygeal approach. An incision is made on the lateral edge of the coccyx. The first step is the creation of a pre-sacral channel through a tube. Then, under fluoroscopy guidance, a pin is introduced into S1, through L5-S1, and into L5. Cutters are used to remove the centre of the disc, which is then filled with bone. A double-threaded screw is inserted. The reverse threading serves to restore disc height by allowing disc space distraction, relieve the compression, and ensure stabilisation. In addition to the anterior screw, posterior fixation is often performed. This technique is useful in patients who have anatomical characteristics that are unsuitable for ALIF or contra-indications to the anterior approach. Complications include superficial surgical-site infection, non-union, and rectal perforation [18];
• posterior S1-L5 fusion is performed via a conventional posterior approach to the lumbo-sacral region. The L5-S1 disc is exposed and sacral laminectomy is performed down to S2 to allow retraction of the dural sac. Under fluoroscopic guidance, a pin is inserted from S1 towards L5. Burr is used to create a channel for the introduction of either a peroneal fragment harvested previously from the patient and fit into the channel or a trans-sacro-lumbar screw. The L5-S1 disc is removed and bone placed in the disc space. This technique is indicated in patients with contra-indications to the anterior approach or spondylolisthesis. Another indication is insertion of anterior supportive material to widely open the disc (e.g., to achieve more than 20° of L5-S1 lordosis). Posterior screw fixation is performed routinely with this technique.

3.2.4.4. Circumferential fusion: definition. Circumferential fusion, over 360° of the disc space circumference, is achieved by combining an anterior approach for ALIF with a posterior approach for internal fixation. Fixation methods vary widely, from conventional pedicle screw fixation to minimally invasive fixation using pedicle screws, trans-facet screws, and inter-spinous fixation (Fig. 10). Alternatively, circumferential fusion can be performed using the above-described TLIF and PLIF techniques.

3.2.4.5. Indications of circumferential fusion. PLIF and TLIF are similar in terms of fusion rates, clinical outcomes, and risk of complications. Advantages of TLIF are a lower frequency of nerve root injury, a shorter operative time, and less extensive surgery. TLIF is appropriate only for patients with unilateral symptoms, whereas PLIF is suitable for disorders that affect both sides.

3.2.4.6. Complications of posterior techniques. Posterior techniques, particularly PLIF, are associated with several complications. Nerve root injury may cause endoneurial fibrosis and chronic radiculopathy. Other complications include hardware failure, non-union, and loss of correction, notably after extensive posterior decompression. Posterior techniques are also associated with a higher risk of posterior migration of the inter-body implants, which may put pressure on neurological structures.

Maruenda et al. [19] documented a deterioration in clinical outcomes 15 years after circumferential fusion. The high frequencies of adjacent segment degeneration and revision surgery led the authors to challenge the usefulness of this technique.

Lee et al. [20] reported a higher frequency of adjacent segment degeneration 10 years after PLIF vs. posterolateral fusion. Age older than 60 years was also an independent risk factor for adjacent segment degeneration. Finally, infections are classically more common after posterior fusion than after ALIF.

4. Indications of each technique

4.1. Arguments for selecting a specific technique

4.1.1. Biomechanical arguments

Circumferential techniques have a number of theoretical advantages over isolated posterior fusion. PLIF, TLIF, and ALIF offer greater mechanical stability, because the grafts are introduced under compression into the anterior column. However, with PLIF and TLIF, posterior column resection is sometimes required, possibly inducing a risk of instability and, therefore, of correction loss and non-union. With ALIF, the larger implantation surface area leads to more extensive fusion, and no bony structures need to be resected.

4.1.2. Technical arguments

The retro-peritoneal approach used for ALIF is associated with less bone resection and less surgical trauma to the nerve roots and posterior muscles. Furthermore, the absence of extensive penetration into the spinal canal minimises the development of posterior epidural fibrosis.

On the other hand, ALIF requires a technically challenging approach and is associated with several complications. Surgeon preference and proficiency also affect the choice of the technique.

4.1.3. Clinical arguments

The clinical arguments are unclear, since all techniques, if performed properly, produce similar clinical outcomes.
4.2. Best technique for restoring lordosis

Based on a retrospective comparative study, Hsieh et al. [21] concluded that ALIF was superior over TLIF in terms of restoring foramen height, restoring disc angle and lordosis, and improving sagittal alignment. Another study by Dimar et al. [22] confirmed that ALIF, PLIF, and TLIF resulted in better restoration of lumbar lordosis compared to posterolateral fusion.

Although ALIF has many advantages, the amount of lordosis to be restored may exceed the capacities of available implants. The lordotic curvature of the implant is determined by the designer. A posterior procedure such as a Smith-Petersen osteotomy or articular process resection with in situ contouring may be needed to obtain the amount of lordosis best suited to the patient’s needs. No single technique is superior over the others. The surgeon should choose the technique best suited to each individual situation and to the amount of correction needed.

4.3. Possible influence of implant design on lordosis restoration

Gödde et al. [23] retrospectively evaluated the potential influence of implant geometry on sagittal alignment after PLIF. Rectangular cages were associated with less lumbar lordosis and segmental lordosis of the fused segments compared to wedge-shaped cages. The wedge-shaped design imposes a certain amount of lordosis on the intervertebral space.

4.4. Indications of ALIF and posterior fusion techniques (PLIF, TLIF, and posterolateral fusion)

Both the posterior and the anterior techniques are ideal techniques for the treatment of degenerative disc disease with loss of disc height, loss of stability and mobility of the inter-vertebral unit, spondylolytic and degenerative spondylolisthesis, and degenerative lumbar scoliosis.

There is no evidence from class I studies that one technique is superior over the others. Fusion rates are higher with inter-body fusion techniques, but fusion does not correlate perfectly with the clinical and functional outcomes.

Selection of the technique is based on whether the patient has radicular pain, low-back pain, or both; a tight disc space; and kyphosis and/or instability. Surgeon preferences and experience with a given technique also influence the choice of the technique.

4.5. Treatment strategy for complex situations

The main complex situations involve failure of primary surgery (hardware failure, non-union, low bone mass) or specific diagnoses (discitis, recurrent disc herniation, or epidural fibrosis).

ALIF is the technique of first choice in patients with non-union after a posterior fusion procedure (PLIF, TLIF, or posterolateral fusion), recurrent disc herniation, or epidural fibrosis.

Discitis raises specific issues. When extensive destruction of the disc and vertebral bodies has occurred, ALIF is indicated to allow filling of the defect. A posterior step must be performed also. An autograft is preferable over an inert implant. In isolated discitis without bone destruction, an isolated posterior procedure ensures eradication of the infection with spontaneous fusion. Appropriate antibiotic therapy is mandatory in every case.

After a primary posterior procedure, ALIF has the advantages of being performed in a previously untouched region, allowing resection of the disc, and offering a large surface area for grafting. ALIF alone may be sufficient to stabilise the inter-vertebral unit.

In patients with a history of anterior surgery, in contrast, ALIF carries a high risk of complications, most notably vascular injury. A posterior procedure must be performed in this situation.

Each complex situation requires a detailed evaluation to ensure that optimal management is provided while minimising the risks to the patient.

5. Specific issues: should the lumbo-sacral junction be included within extensive thoraco-lumbar or lumbar procedures? Should the instrumentation end in the sacrum or in the ilium?

This specific situation requires careful attention. Numerous parameters including the condition of the L5-S1 disc, bone quality, and presence of anterior sagittal malalignment must be taken into account.

5.1. Lumbo-sacral fusion as part of an extensive fusion procedure

Including the lumbo-sacral junction within a long lumbar fusion is challenging and may increase the risk of non-union (particularly if the disk is tall) and of surgical revision. Bridwell stated that inclusion of L5-S1 is mandatory in patients with spondylolisthesis, previous laminectomy, stenosis of the spinal canal or foramina, oblique origin of L5 (> 15°), or evidence of severe osteoarthritis [24]. Including the L5-S1 junction is also advisable in the event of anterior malalignment or insufficient lumbar lordosis [25]. Bicortical fixation to the sacrum is sufficient in patients with good bone quality, whereas additional iliac fixation is advisable in patients with low bone mass. Introduction of supportive material into the disc space (ALIF, PLIF, or TLIF) may diminish the risk of non-union, although data on this point are conflicting.

Secondary extension to L5-S1 after primary fusion ending at L5 deserves specific comment. In this situation, the development of L5-S1 degenerative disease requires revision surgery. Edwards et al. reported L5-S1 degenerative disease in 67% of patients after 5 years, with a revision rate of up to 23% [26] and secondary anterior malalignment as the most common reason for revision. In these complex situations, the stability imperatives are the same as with primary fusion.

5.2. Fixation to the sacrum only or to both the sacrum and ilium

Lumbo-sacral fusion as part of a long construct requires a high level of stability. Therefore, fixation to the ilium can be added to decrease the risk of screw dislodgement, secondary mobilisation, and non-union. During primary fusion, iliac fixation is recommended in patients with low bone mass or severe malalignment. Crawford et al. stated that iliac fixation was warranted in patients older than 65 years with pre-operative malalignment [27]. However, it may be worth considering sacral fixation combined with an inter-body graft, given that iliac screws are often poorly tolerated by the patients. However, alternatives are available for iliac screw fixation. Thus, construct strength can be improved by combining S1 and S2 screws or by using expanding or cemented screws to increase the purchase on the bone.

6. Predicting the effects of fusion

Correcting disc kyphosis at the lumbo-sacral junction seems crucial to obtain an overall amount of lordosis appropriate to the specific pelvic anatomy of each individual. A decrease in L5-S1 lordosis inevitably leads to compensatory changes in lumbo-pelvic posture of variable importance:

- the segmental lordosis of the supra-jacent discs and vertebrae increases to obtain sufficient total lordosis to maintain sagittal alignment. The resulting facet-joint overloading may cause pain;
pelvic tilt may be increased to compensate for pelvic retroversion. This change may cause muscle pain in the lower limbs.

6.1. Determining the optimal amount of lordosis for the individual patient

The lordosis produced by the fusion procedure must be optimal for the individual patient. The optimal amount of lordosis depends on a number of criteria. Segmental L5-S1 lordosis is the angle formed by the superior S1 endplate and the superior L5 endplate. This angle is the sum of the lordosis due to the L5-S1 disc and of the lordosis due to the body of L5. Lumbo-sacral fusion has no effect on the shape of the L5 body and, consequently, does not change the lordosis due to this component. Lordosis at the L5-S1 disc space, in contrast can be modified. Interestingly, in the sagittal plane, the shape of the L5 body tends towards a rectangle when pelvic incidence (PI) is low, whereas high PI values are associated with a more trapezoidal shape of the L5 body that increases the natural lordosis of this vertebral segment.

The optimal degree of lordosis for the individual patient can be determined as follows. First, the optimal distal lordosis is estimated based on work by Vialle et al. [28], who showed that SS can be derived from PI as follows: $SS = 7.3 + 0.63PI$. Also according to Vialle et al., 58% of the distal lordosis is at L5-S1 (31.3° [32.5° – 30°]) and 42% at L4-L5 (27° [28° – 26.2°]). The optimal segmental L5-S1 lordosis can therefore be estimated at 0.58 SS. Finally, the optimal L5-S1 disc lordosis is obtained by subtracting the L5 body lordosis from the optimal segmental L5-S1 lordosis. L5 body lordosis is measured on a lateral radiograph of the lumbo-sacral junction. The formula is therefore as follows:

$$\text{Optimal L5-S1 disc lordosis} = 0.58 \times (7.3 + 0.63 \text{PI}) - \text{L5 body lordosis}.$$

6.1.1. Example assuming a PI value of 50°

*Optimal SS = 7.3 + 0.63 \times 50 = 38.8°.

*Optimal segmental L5-S1 lordosis = 0.58 \times 38.8 = 22.5°.

*Optimal L5-S1 disc lordosis, assuming that L5 body lordosis is 10° = 22.5° – 10° = 12.5°. When performing L5-S1 fusion in this example, 12° of lordosis must be restored at the L5-S1 disc, regardless of the surgical technique used.

When PI < 45°, there is normally little L5-S1 disc lordosis and the risk of iatrogenic hypolordosis is therefore low. For instance, if PI is 40°, the optimal SS is about 32.5° and the optimal segmental L5-S1 lordosis is therefore about 18.6°. When the initial situation is abnormal, for instance with 10° of lordosis pre-operatively, the additional 7° correction is easily achieved. Excessive correction of segmental lordosis resulting in iatrogenic hyperlordosis may cause pain due to overloading of the supra-jacent facet joints. In contrast, if PI > 60°, L5-S1 disc lordosis is marked. Consequently, restoring the required amount of lordosis may be technically challenging, and the risk of iatrogenic hypolordosis is high. Let us consider for instance a patient with spondylolotic spondylolisthesis (Fig. 11), a PI of 65°, and a pre-operative segmental L5-S1 lordosis of 15°. The optimal L5-S1 lordosis is about 28° (high SS value of 48.3°), resulting in lumbo-sacral kyphosis. The required segmental correction is therefore about 13°, which may be difficult to achieve. In this situation, it is helpful to choose a surgical technique that induces lordosis (Fig. 12).

A Smith-Petersen osteotomy combined with in situ contouring can produce about 20° of lordosis at the L5-S1 disc space. In this situation, ALIF may fail to fill the anterior gap, as highly lordotic implants are not available. Anterior support should therefore be provided by a trans-sacro-lumbar graft.

In a study of cadaver specimens, Drazin et al. [29] demonstrated that SS values greater than 40° resulted in pure shear L5-S1 motion instead of in the combination of compression and shear seen with lower SS values. This situation carries a high risk of mechanical failure and, therefore, of non-union. Consequently, the construct should be as stable as possible (circumferential fusion).

The patient’s PI value is a crucial factor. Low or moderate PI values raise no particular challenges. High PI values are associated with higher risks of iatrogenic hypolordosis and non-union and, consequently, require a construct that provides maximum stability and lordosis.

6.2. Potential contribution of fusion to adjacent segment degeneration

Many studies have sought to identify factors that contribute to degeneration of the segments adjacent to a fused segment. The results point to a multifactorial pathogenesis. Insufficient lordosis with a low SS value is a key contributor. Other important factors include naturally occurring changes in disc tissue, body mass index, pre-operative status of the disc, length of the fusion, status of the facet joints, degenerative scoliosis, condition of the para-spinal muscles, and PLIF techniques that produce only limited lordosis [30,31,32,33].

Preventing adjacent segment degeneration does not seem feasible. However, the surgical technique should be designed to create the mechanical conditions most likely to promote harmonious spinal function.
7. Conclusion

Many lumbo-sacral fusion techniques are available and surgeons can therefore choose the technique best suited to the individual patient. Minimally invasive techniques are gaining in popularity. Reported outcomes are improving steadily, although most of the numerous published studies provide only level IV evidence. Only very few level I studies have provided data of use for an objective analysis.

A successful lumbo-sacral fusion procedure relieves pain and produces good long-term outcomes by inducing strong fusion under mechanical conditions that match the patient’s needs.

Disclosure of interest

The authors declare that they have no competing interest.

References