JOURNAL OF JPOSNA®

Volume 4, Number 4, November 2022

Master's Surgical Technique

Surgical Techniques for Adolescent Lumbar Spondylolisthesis

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Received: July 19, 2022; Accepted: September 12, 2022; Published: November 1, 2022

DOI: 10.55275/JPOSNA-2022-545

Abstract

Lumbar spondylolisthesis in adolescents is a common cause of back pain. Low-grade spondylolisthesis usually responds to non-surgical treatment. High-grade spondylolisthesis often requires surgery for the relief of symptoms. The primary goals in the surgical treatment of adolescent lumbar spondylolisthesis (L5-S1) are relief of back and radicular pain, relief of any motor weakness from nerve compression, and to achieve a stable spinal fusion. Optimal surgical strategy is debated with questions regarding the need for reduction of deformity, choice of spinal instrumentation, use of interbody fusion, and choice of bone graft. This technique paper reviews commonly used surgical techniques with a focus on the pearls and pitfalls of each. Recommended postoperative care and management of common complications are included.

Key Concepts

- There are a variety of techniques described for surgical treatment of adolescent lumbar spondylolisthesis with no one identified as superior to the rest.
- If doing a reduction of L5-S1, wide decompression of the dural sac and bilateral L5 nerve roots is advised along with use of neuromonitoring.
- Lumbar interbody fusion (posterior, transforaminal, or anterior) may aid in fusion at the L5-S1 segment.
- Understanding the preoperative and target postoperative sagittal plane alignment of the spine and pelvis is important to achieve appropriate sagittal balance postoperatively.

Introduction

The primary goals in the surgical treatment of adolescent lumbar spondylolisthesis (L5-S1) are relief of back and radicular pain, relief of any motor weakness from nerve compression, and to achieve a stable spinal fusion. Surgery is rarely indicated for low-grade spondylolisthesis due to excellent results with nonoperative care and low risk of progression to high-grade spondylolisthesis;[1] however, when rarely indicated, low-grade spondylolisthesis is treated with uninstrumented or instrumented posterolateral fusion from the transverse processes of L5 to the sacral ala.

High-grade spondylolisthesis more often requires surgical treatment due to failed nonoperative treatment. There is no universally identified "best" surgical treatment option for high-grade spondylolisthesis in adolescents. Treatment options range from in situ uninstrumented posterolateral fusion L5-sacrum to full reduction of L5 on the sacrum via posterior or combined anterior and posterior approach.[1] Addition of instrumentation to fusion for lumbar spondylolisthesis has been thought to improve fusion rates. If reduction of the deformity in isthmic or dysplastic spondylolisthesis is to be attempted, then instrumentation is mandatory. Whether to do a reduction and if so how much of a reduction to do remains debated.[1]

Classification

Mac-Thiong et al. proposed a classification system that incorporates slip grade, sacropelvic balance, and global spinopelvic balance.[2] The system has been shown to have high intraobserver and inter-observer reliability.[3] The six types, which demonstrate a progression of likelihood for surgical indication, are as follows:

- Type I – low-grade spondylolisthesis, low pelvic incidence
- Type II – low-grade spondylolisthesis, normal pelvic incidence
- Type III – low-grade spondylolisthesis, high pelvic incidence
- Type IV – high-grade spondylolisthesis, balanced sacropelvis
- Type V – high-grade spondylolisthesis, unbalanced sacropelvis with a balanced spine
- Type VI – high-grade spondylolisthesis, unbalanced sacropelvis with an unbalanced spine

Low-grade spondylolisthesis is defined as less than 50% anterior displacement of L5 on S1 and high-grade spondylolisthesis is defined as greater than 50% anterior displacement of L5 on S1. Pelvic incidence (PI) is a fixed parameter that describes lumbo-pelvic alignment by combining the values of sacral slope and pelvic tilt (Figure 1A and 1B). It has been suggested that patients with spondylolisthesis are more likely to have elevated pelvic incidence compared to control patients and elevated PI may be a risk factor for progression of spondylolisthesis.[4] Patients with a balanced sacropelvis have a high sacral slope and low pelvic tilt (more horizontal sacrum), whereas those with an unbalanced sacropelvis have a more vertically oriented retroverted sacrum with low sacral slope and high pelvic tilt.[5]

Treatment Indications

Operative treatment is indicated for patients with symptomatic low-grade isthmic spondylolisthesis who fail to respond to nonoperative management (continued back or radicular pain after a minimum 3-6 months of treatment) and for patients with dysplastic spondylolisthesis that is progressive. Presence of neurologic symptoms in particular is a generally accepted indication for surgical treatment. High-grade spondylolisthesis of any type also usually requires surgical treatment since symptoms are invariably present and nonoperative treatment may be ineffective.

Preoperative Preparation

- Assessment of coronal and sagittal balance is required preoperatively. This is best studied with standing frontal and lateral radiographs that include the skull and proximal femora. These images allow assessment of global sagittal alignment, slip grade, slip angle, and pelvic incidence.

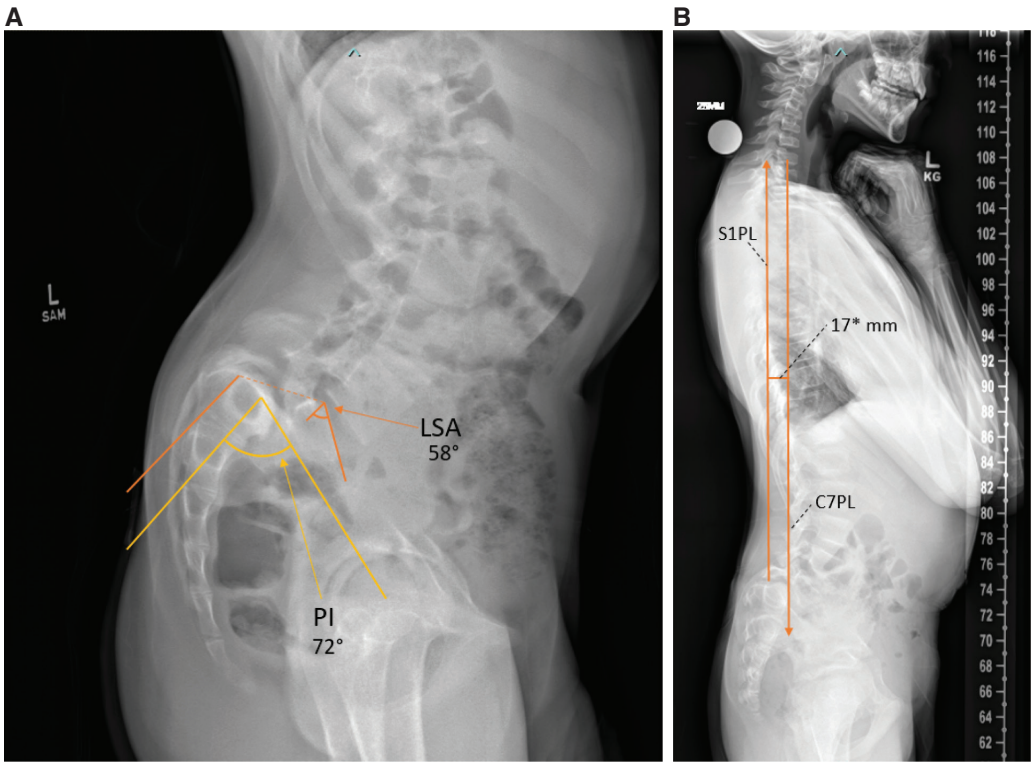

Figure 1A. *Lumbosacral angle (slip angle) is the angle made between a line perpendicular to the S1 upper endplate and a line along the L5 upper or lower endplate (if lower endplate is deformed, use upper endplate). Pelvic incidence is patient-specific fixed angle created by a line perpendicular to the center of the S1 upper endplate and a line from this point to the center of the femoral heads.* ***Figure 1B.*** *Sagittal vertical axis is a measure of global sagittal balance. It is defined as the horizontal distance between a C7 plumb line and a vertical drawn from the posterior aspect of the S1 upper endplate. C7 plumb line (C7PL) is the vertical line going down from mid-point of C7. S1 line is going up from back of S1—horizontal distance. Retroversion of the pelvis here has led to a nearly vertical sacrum and global sagittal imbalance.*

- Computed tomography (CT) allows for assessment of pedicle and sacral morphology. It is recommended for planning intervertebral fixation options and sizing of implants, as well as to evaluate for a posterior distal L5 bone spur that may need to be addressed prior to a reduction attempt.
- Magnetic resonance imaging (MRI) evaluation is useful for assessment of neural elements in the presence of neurologic symptoms, spinal and foraminal stenosis, and for evaluation of disease of adjacent disc levels.

Positioning

- Standard prone positioning on an open frame table with care to extend hips to aid in reduction and flex knees to relax nerve roots.
- Multi-modal neuromonitoring including SSEP, MEP, and EMG monitoring.
- Fluoroscopy and/or intraoperative 3D imaging for navigation and evaluation of implant position.

Operative Technique

Exposure of L5 to S1 may be performed through a standard posterior midline incision with subperiosteal exposure to the tips of the transverse processes of L5, L5/S1 joint, and sacral ala. A Wiltse approach may also be used to minimize soft tissue disruption for in situ fixation for low-grade deformity yet will not allow central decompression often required in higher grade cases. In high-grade spondylolisthesis with radicular symptoms, it is recommended to decompress the L5

nerve roots bilaterally to the foramen, especially if planning reduction of the deformity. If reduction is to be attempted, decompression of the dural sac with laminectomy and visualization of the nerve roots are mandatory to avoid iatrogenic compression with reduction. A posterior sacral dome osteotomy is often needed to allow mobility and to shorten the distance at the L5-S1 disc space for a safer reduction.

Fixation of L5–S1 can be either via segmental pedicle screws, or if not reducing a high-grade slip, transdiscal screws or Bohlman bone dowel directed superoposterior from the S1 pedicle into the L5 vertebral body (Figures 2 and 3).[6] Try to maximize screw diameter and length to obtain strong fixation especially if planning reduction. Because of the wide lateral-to-medial trajectory of pedicle screws at these levels, including a tricortical S1 pedicle screw, a longer than expected approach is often needed to facilitate implant placement. Consider iliac, sacral ala, and/or sacral-alar-iliac screws if additional fixation is desired for stability for attempted reduction. Be cognizant of implant prominence, especially with sacral and iliac fixation in a retroverted pelvis.

If reduction is attempted, anterior support in the L5–S1 disc is beneficial for supporting the corrected sagittal plane and for improving fusion rates. This can be done via anterior interbody fusion (ALIF), posterior (PLIF), or transforaminal lumbar interbody fusion (TLIF) based on the surgeon's preference.

Reduction Technique

The decision to reduce, and how much to reduce, a spondylolisthesis deformity in children and adolescents is controversial. Typically, reduction is not done when using transdiscal screws or Bohlman dowel for intervertebral fixation. Adequate overlap of L5 and S1 endplates is required if planning ALIF, PLIF, or TLIF and this usually requires at least a partial reduction in high-grade spondylolisthesis. Proponents believe correction of the deformity, especially the slip angle, will improve long-term functional outcomes by correction of the abnormal sagittal plane caused by the spondylolisthesis.[7] Furthermore, some believe fusion rates are higher with instrumented versus uninstrumented in situ fusion. High-quality data is lacking for both of these assumptions. Those against reduction point to the lack of evidence supporting reduction along with presence of data showing increased rates of neurologic deficits following attempts at reduction. Increasingly, the push from experts in the field has been to a middle ground in high-grade spondylolisthesis with decompression of the neural elements, and partial reduction, with a primary goal of slip angle improvement as a way to restore sagittal plane alignment without the neurologic risks of a full reduction.[8]

Reduction is done by gentle distraction between the L5 screws and sacral screws followed by posteriorly reducing the L5 vertebral body locking a rod at S1 and reducing the L5 (and L4 if included) pedicle screws to the fixed rod. Extended tab (reduction) pedicle screws are useful in L4 and L5 to allow for posterior force on these levels during attempted reduction. Prior to application of reduction forces, it is important to have done the following steps to allow safe mobilization of L5: decompressive laminectomy at L5, wide foraminal decompression of L5 nerve roots bilaterally, consider disc release and/or discectomy at L5/S1, consider sacral dome osteotomy. A small amount of compression between L5 and S1 after distraction-driven reduction can then help facilitate restoration of lumbosacral angle and ensure no over-distraction placing undue tension of L5 roots but must be done with careful attention to not to compromise the L5 foraminal spaces. This can be done over an anteriorly placed interbody graft or implant to further assist improved alignment.

In Situ Techniques

Bohlman Dowel Technique

In high-grade cases without a reduced L5, including spondyloptosis, fusion and fixation can be supplemented with a fibular auto or allograft from the sacrum into the body of L5 between the S1 and L5 screws. If fibula is not available, one can also use radius or ulna allograft. Preoperative CT scan

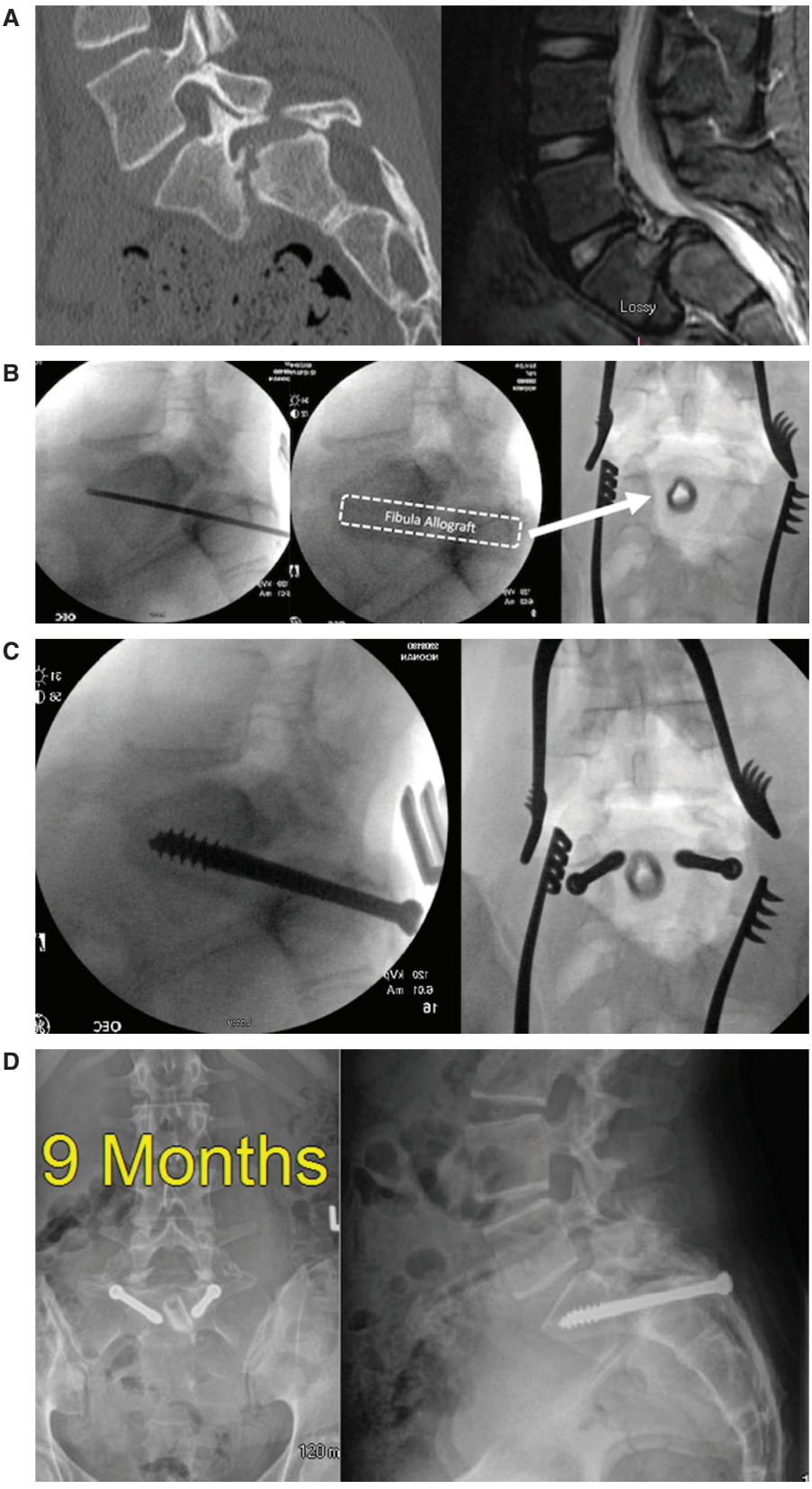

Figure 2A. *A 13-year-old girl with Grade IV Spondylolisthesis will undergo the Bohlman technique.* ***Figure 2B.*** *A posteriorly directed guide pin is placed and will be over-reamed with a 10 mm ACL reamer. A fibular allograft has been placed and is seen on the lateral and AP fluoroscopic image.* ***Figure 2C.*** *Fibula strut graft is further stabilized by two, 6.5 mm solid stainless-steel screws placed from the lateral aspect of the S1 superior articular facet directed anterior medially into L5. Posterior lateral fusion from the ala of the sacrum to the transverse process of L5 is also performed with local iliac crest autograft.* ***Figure 2D.*** *Nine months later, the 5th lumbar vertebra is solidly fused to the sacrum.*

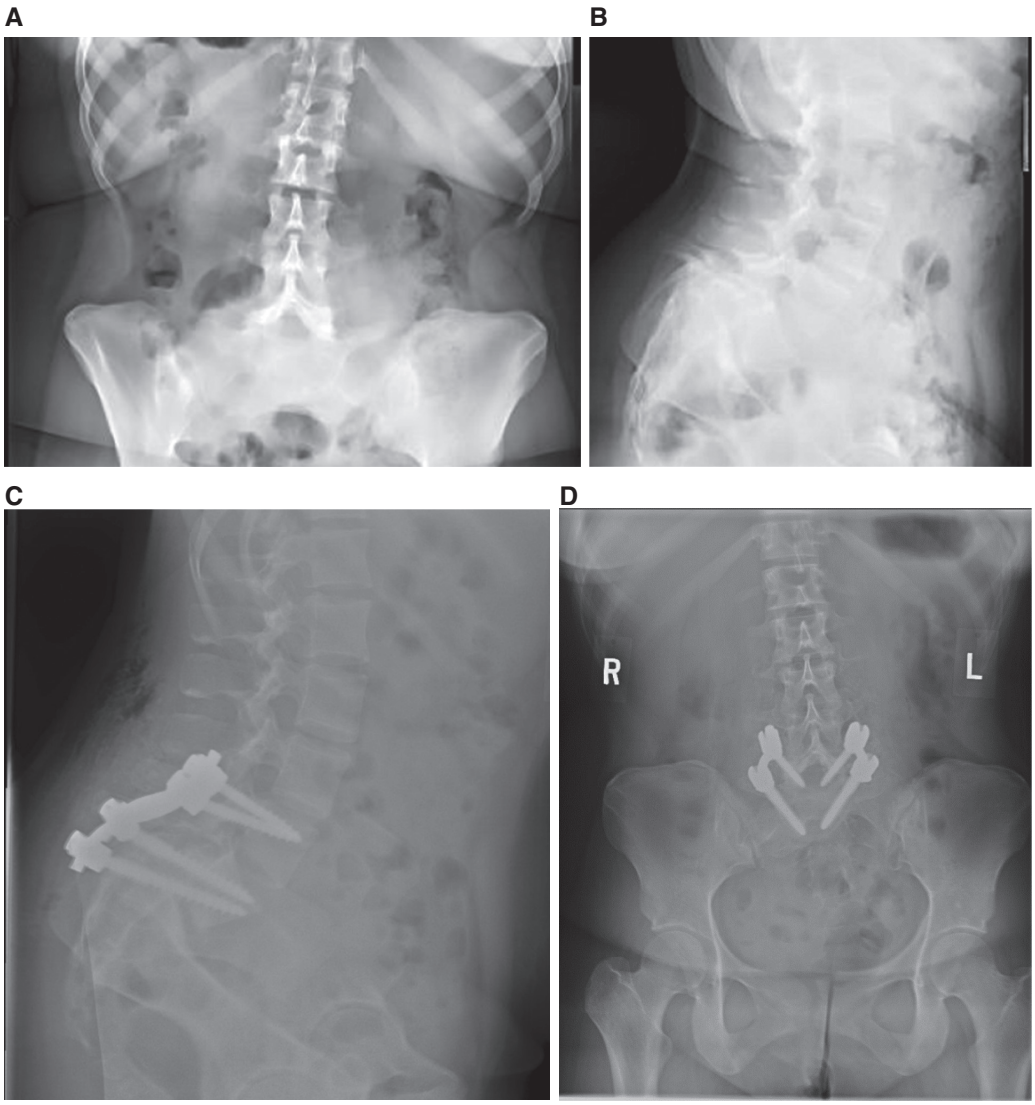

Figure 3 A-D. *A 16-year-old with grade 4 L5-S1 isthmic spondylolisthesis treated with decompression, PSF L4-S1 with transdiscal screws L5-S1.*

is helpful in planning length and diameter of the needed graft. This technique was popularized by Bohlman and affords excellent fusion rates in high-grade spondylolisthesis with relief of symptoms.[9-11] Bohlman's published series reported no postoperative neurologic deficits, but other authors have described neurologic deficit postoperatively with this technique.[11] Use of an ACL reamer through the sacrum into L5 is a helpful technique for bony tunnel preparation for the fibular allograft. The graft can be placed either from the posterior approach as described by Bohlman or anteriorly as described by Sasso et al.[12]

To complete this technique, laminectomy of S1 is done to visualize the dural sac and sacral nerve roots. After gently retracting the dural sac medially, identify a start point in the posterior vertebral body of S1 about a 1 cm off midline. Place a 2 mm guidewire and advance it antero-superior across the L5-S1 disc and into the L5 vertebral body. Take care not to penetrate the anterior cortex of L5. Placement and advancement of the guidewire should be done with fluoroscopy or intraoperative navigation. Prepare dowel graft to the appropriate length and confirm diameter using ACL graft sizer. Sequentially ream over the guidewire using

ACL reamers to 1 mm more than the planned graft. Remove the guidewire. Tamp the prepared graft through the tunnel. Repeat the process on the opposite side for a second fibular graft. Place final rods bilaterally into the previously placed pedicle screws.

Alternatively, one can use a singular strut graft in the center of the sacrum into L5. In this instance, the interval between the nerve root and thecal sac is developed and protected with a reamer guide; it may be helpful to perform an S2 laminectomy for greater visualization and mobilization of neural elements. A mesh titanium cage can also be used as the dowel and placed with packed morselized graft which has the benefit of uniform diameter to fit the reamed path.

Instead of posterior pedicle screw and rod fixation, two standard 6.5 mm screws can be placed starting from the lateral aspect of the superior articular facet of S1 directed anterior medially into L5 body on either side of the central strut Figure 2.

Transdiscal Screws

These are placed through a standard entry site for S1 screws with an anteromedial trajectory, traversing the sacral promontory, superior end plate of S1, and L5-S1 disc, and into the L5 body, ending in the midline of the displaced L5 inferior end plate. These should be placed either using fluoroscopy or spinal navigation technologies to optimize the trajectory and fixation. Final rods can be placed into the pedicle screws. Typically, reduction is not done when using transdiscal screws for intervertebral fixation (Figure 3). It is important to note that posterior lateral fusion is still an important part of this technique and all others. Fully clearing the sacral ala and the transverse process of L5 and placing autograft is very important to increase fusion. Simply counting on anterior fusion or intradiscal screws is not prudent.

PLIF (Posterior Lumbar Interbody Fusion) / TLIF (Transforaminal Lumbar Interbody Fusion)

Interbody fusion cages are widely used in an effort to improve fusion rates and correct sagittal plane imbalance. Use of expandable cages can further enhance the surgeon's ability to achieve the sagittal correction needed. Intraoperative navigation can make cage placement more accurate and minimize the risk of mal-positioning. Both PLIF and TLIF can be done through a posterior approach.

Pedicle screws are placed at the indicated levels with usual technique. A facetectomy is performed, resecting the inferior articular facet of the cephalad vertebrae and superior articular facet of the caudal vertebrae. In the instance of a large slip, often a partial reduction will be needed before obtaining good access to the disc. The inferior aspect of the lamina and ligamentum flavum is resected to allow visualization and decompression of the exiting nerve root. A discectomy is then performed, taking care to avoid injury to the dural sac or nerve roots. Using a trap door technique, an 11-blade scalpel can release a "trap door" of the annulus, then work can be done through this opening with instruments just superior to the pedicle of S1 to reduce the risk of injury to the L5 nerve root which passes just inferior to the L5 pedicle. Interbody spacer trials are then sequentially trialed, and the height of the implant(s) is chosen when a snug fit is achieved. Discectomy must be meticulous for fusion, ensuring that the superior and inferior end plates are curetted to expose bleeding subchondral bone. In young patients, the disc may be most easily removed by first releasing the apophysis from each endplate using a Cobb within the plane adjacent to this bone. The TLIF cage or PLIF cages are then inserted under fluoroscopic guidance with graft material placed within the cage(s) based on surgeon and patient preference. Typically, a single TLIF cage is placed unilaterally or two PLIF cages are bilaterally. Navigation may be used to optimize cage placement. Expandable cages may be used to optimize correction of sagittal alignment. Rods are then placed and compression is applied across the interbody graft via the previously placed pedicle screws.

ALIF (Anterior Lumbar Interbody Fusion)

If the surgeon chooses to utilize ALIF, the authors' preference is to complete the posterior portion of the

surgery first—exposure, decompression, instrumentation, and reduction. After closure of the posterior wound, the patient is flipped supine on a radiolucent flat top table. An anterior approach is made by an access surgeon. Once retractors are placed and level is confirmed with fluoroscopy, discectomy is undertaken and the end plates are decorticated. The implant of appropriate lordosis and size is selected based on preoperative planning and trialing. The cage is packed with autologous graft or allograft and then seated appropriately with fluoroscopy confirmation of placement (Figure 4).

Graft Choices to Consider

Osseous union may be promoted with the use of autograft or graft substitutes to create an osseous bridge and promote fusion.[13-15] Graft options include the use of local autograft, iliac crest bone autografting, or synthetic graft substitutes which may include use of recombinant human bone morphogenic proteins. Recombinant human bone morphogenic proteins (rhBMP2 and 7) has been advocated by some as an addition or alternative to allograft, although their use has not been shown to improve fusion rate or clinical outcomes and is not approved for use in skeletally immature patients.[11] Graft placement in the posterolateral gutters should be considered prior to placing pedicle screws, as access lateral to the screws will be more challenging then.

Tips and Pearls

- Intraoperative navigation can make placement of spinal implants and intervertebral fixation more accurate.
- Pre-plan sizing of interbody cages to ensure you have appropriate sizes available for pediatric patients.
- Consider low profile screw systems in thin patients to minimize implant prominence of sacral and iliac fixation.
- If planning reduction of L5 on S1, decompress the L5 roots bilaterally out to the neural foramina to decrease risk of nerve palsy with reduction and excessive nerve stretch. Meticulous decortication and grafting, no matter the surgical option chosen, is vital for fusion.

Postoperative Care

After surgery, it is recommended to initially keep the hips and knees flexed with pillows under the knees. This reduces neural tension. The pillows are slowly removed over the postoperative course as the patient tolerates. Currently, most surgeons do not use any immobilization following surgical treatment of high-grade spondylolisthesis treated with spinal instrumentation. An off-the-shelf lumbar brace may be used for pain relief with early mobilization, which should be encouraged as soon as postoperative day 1.

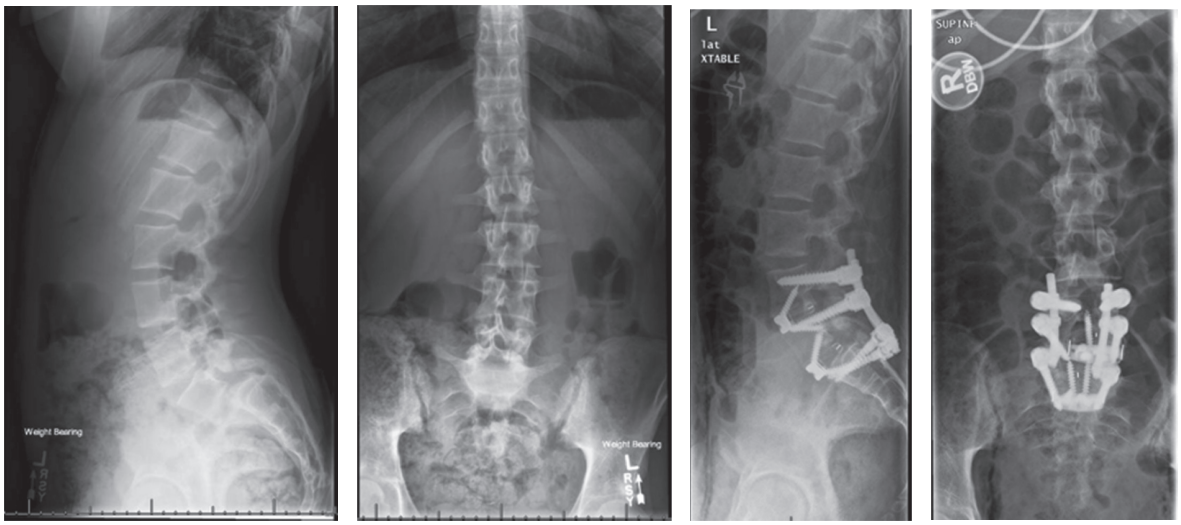

Figure 4. *A 15-year-old female with Marfanoid hypermobility syndrome and grade 4 L5-S1 isthmic spondylolisthesis who underwent Gill laminectomy, ALIF L4-L5 and L5-S1, PSF L4-S1.*

Neuropathic pain is common, in particular when there has been dural retraction as part of the surgical procedure. Medications such as gabapentin and tricyclic antidepressants can be useful in the management of acute neuropathic pain postoperatively.[1] These can usually be weaned off within 1-2 months following surgery. Non-steroidal anti-inflammatory medication will help decrease both neural and postoperative inflammation without evidence of negative effect on fusion in pediatric spines.

Follow-up appointment in 1-2 months for wound check and upright AP/lateral views of the entire spine. Consider using upright low dose biplanar slot scanning to reduce radiation exposure. Consider CT scan lumbar spine at 6-12 months to evaluate fusion. Patients can generally resume light activities such as swimming, running, and bicycling after 1-2 months when the soft tissue is healed. Patients may resume all other non-contact sports at 3-4 months. Contact sports are discouraged until at least 6 months, ideally until radiographic evidence of arthrodesis is appreciated.

Complications

- L5 nerve palsy

  Neurologic deficit occurs in up to 25 % of cases; however, this is most often transient with a permanent deficit incidence less than 5%.[37,38] A recent large review of the SRS morbidity and mortality database for pediatric spondylolisthesis surgery reported a 5% rate of neurologic injury, of which 94 % of patients had improvement (half of who had full resolution).[37] Some important things we have learned over time include:

  - Neurologic injury can result from direct trauma during instrumentation or decompression or traction injury during reduction.
  - Decreased incidence of injury is possible with early detection through EMG monitoring.
  - Consider removing or adjusting instrumentation when nerve deficit detected by monitoring.
  - When palsy is produced by traction during reduction, consider decreasing reduction.
  - The majority recover full muscle strength within 3 to 6 months of surgery.
- Dural tear
  - Watertight dural repair with suture. With larger defects, augment closure with fibrin glue, collagen matrix, hydrogel, or interposition of muscle or fat graft.
  - Test strength of repair with Valsalva prior to skin closure.
  - Usually no long-term sequelae.
- Misplaced implants
  - Remove or adjust misplaced implants.
  - Can lead to early or late neurologic complications, especially if not detected intraoperatively or early postoperatively.
- Pseudarthrosis / Fractured implants

  Results of instrumented fusion with some degree of reduction have been published recently, demonstrating high fusion rates, improved clinical status, and low rates of neurologic injury.[8,16-19] Re-operation rates, however, remain high with the most common indication for revision being implant failure.[20] No direct trials comparing uninstrumented and instrumented fusion with reduction have been done to compare the two techniques. Pseudarthrosis is a complication of instrumented fusion with reduction; however, the rates seem to be less than with uninstrumented fusion in the small series reported.[3,8-11]

  - Pseudarthrosis/implant failure typically will require revision surgery as patients are usually symptomatic if they develop a pseudarthrosis and/or implant fracture. Approach will be dictated by what option was used for the index surgery.
  - Failure of fusion at or after 1 year from index surgery may be detected with loss of fixation, fractured implants, or progression of deformity. CT scan may be needed to evaluate implants and fusion mass.
  - Revision surgery (anterior or combined anterior/posterior approaches) with removal of implants,

debridement of fibrous tissue, decortication, bone grafting, and instrumentation with compression across fusion area is indicated if patient is symptomatic.

Additional Links

- Bauer, J., Cho, R., Lebel, D., & Hresko, T. (2020). High-Grade Pediatric Lumbar Spondylolisthesis: Expert Panel Approach: Panel Discussion. *Journal of the Pediatric Orthopaedic Society of North America*, *2*(3).

Disclaimer

No funding was received for this study. The authors have no conflicts of interest to report.

References

1. Garg S, Erickson M. Spondylolysis and isthmic spondylolisthesis. In: Patel V, Patel A, Harrop J, Burger E, eds. *Spine Surgery Basics.* Berlin, Heidelberg: Springer; 2014:311-324.
2. Mac-Thiong JM, Labelle H, Parent S, et al. Reliability and development of a new classification of lumbosacral spondylolisthesis. *Scoliosis.* 2008;3:19.
3. Mac-Thiong JM, Duong L, Parent S, et al. Reliability of the spinal deformity study group classification of lumbosacral spondylolisthesis. *Spine (Phila Pa 1976).* 2012;37(2):E95-102.
4. Labelle H, Roussouly P, Berthonnaud E, et al. Spondylolisthesis, pelvic incidence, and spinopelvic balance: a correlation study. *Spine (Phila Pa 1976).* 2004;29(18):2049-2054.
5. Hresko MT, Labelle H, Roussouly P, et al. Classification of high-grade spondylolistheses based on pelvic version and spine balance: possible rationale for reduction. *Spine (Phila Pa 1976)*. 2007;32(20):2208-2213.
6. Abdu WA, Wilber RG, Emery SE. Pedicular transvertebral screw fixation of the lumbosacral spine in spondylolisthesis. A new technique for stabilization. *Spine (Phila Pa 1976).* 1994;19(6):710-715.
7. Labelle H, Roussouly P, Chopin D, et al. Spino-pelvic alignment after surgical correction for developmental spondylolisthesis. *Eur Spine J.* 2008;17(9):1170-1176.
8. Boachie-Adjei O, Do T, Rawlins BA. Partial lumbosacral kyphosis reduction, decompression, and posterior lumbosacral transfixation in high-grade isthmic spondylolisthesis: clinical and radiographic results in six patients. *Spine (Phila Pa 1976).* 2002;27(6):E161-168.
9. Bohlman HH, Cook SS. One-stage decompression and posterolateral and interbody fusion for lumbosacral spondyloptosis through a posterior approach. Report of two cases. *J Bone Joint Surg Am.* 1982;64(3):415-418.
10. Smith MD, Bohlman HH. Spondylolisthesis treated by a single-stage operation combining decompression with in situ posterolateral and anterior fusion. An analysis of eleven patients who had long-term follow-up. *J Bone Joint Surg Am.* 1990;72(3):415-421.
11. Roca J, Ubierna MT, Cáceres E, et al. One-stage decompression and posterolateral and interbody fusion for severe spondylolisthesis. An analysis of 14 patients. *Spine (Phila Pa 1976).* 1999;24(7):709-714.
12. Sasso RC, Shively KD, Reilly TM. Transvertebral Transsacral strut grafting for high-grade isthmic spondylolisthesis L5-S1 with fibular allograft. *J Spinal Disord Tech.* 2008;21(5):328-333.
13. Delawi D, Jacobs W, van Susante JL, et al. OP-1 compared with iliac crest autograft in instrumented posterolateral fusion: a randomized, multicenter non-inferiority trial. *J Bone Joint Surg Am.* 2016;98(6):441-448.
14. Abou-Madawi AM, Ali SH, Abdelmonem AM. Local autograft versus iliac crest bone graft PSF-augmented TLIF in low-grade isthmic and degenerative lumbar spondylolisthesis. *Global Spine J.* 2022;12(1):70-78.
15. Ito Z, Matsuyama Y, Sakai Y, et al. Bone union rate with autologous iliac bone versus local bone graft in posterior lumbar interbody fusion. *Spine (Phila Pa 1976).* 2010;35(21):E1101-1105.
16. Goyal N, Wimberley DW, Hyatt A, et al. Radiographic and clinical outcomes after instrumented reduction and transforaminal lumbar interbody fusion of mid and high-grade isthmic spondylolisthesis. *J Spinal Disord Tech.* 2009;22(5):321-327.
17. Laursen M, Thomsen K, Eiskjaer SP, et al. Functional outcome after partial reduction and 360 degree fusion in grade III-V spondylolisthesis in adolescent and adult patients. *J Spinal Disord.* 1999;12(4):300-306.
18. Hu SS, Bradford DS, Transfeldt EE, et al. Reduction of high-grade spondylolisthesis using Edwards instrumentation. *Spine (Phila Pa 1976).* 1996;21(3):367-371.
19. Ruf M, Koch H, Melcher RP, et al. Anatomic reduction and monosegmental fusion in high-grade developmental spondylolisthesis. *Spine (Phila Pa 1976).* 2006;31(3):269-274.
20. Nielsen E, Andras LM, Siddiqui AA, et al. 40% reoperation rate in adolescents with spondylolisthesis. *Spine Deform.* 2020;8(5):1059-1067.