Ten-Step Minimally Invasive Spine Lumbar Decompression and Dural Repair Through Tubular Retractors

Mohamed Abdelatif Boukebir, MD[‡,§,*]
Connor David Berlin, BS[‡,*]
Rodrigo Navarro-Ramirez, MD, MSc[‡,*]
Tim Heiland, MD[‡]
Karsten Schöller, MD[¶]
Cameron Rawanduzy, BA[‡]
Sertaç Kırnaz, MD[‡]
Ajit Jada, MD[‡]
Roger Härtl, MD[‡]

[‡]Weill Cornell Brain and Spine Center, Department of Neurological Surgery, Weill Cornell Medical College, New York-Presbyterian Hospital, New York, New York; [§]Department of Neurosurgery, Blida University Hospital, Faculty of Medicine, University Saad Dahlab de Bilda, Blida, Algeria; [¶]Department of Neurosurgery, Justus-Liebig-University Giessen, Giessen, Germany

*These authors contributed equally to this work.

Correspondence:
Roger Härtl, MD,
Weill Cornell Brain and Spine Center,
Department of Neurological Surgery,
Weill Cornell Medical College,
New York-Presbyterian Hospital,
525 E, 68th St, Box 99,
New York, NY 10065.
E-mail: roger@hartlmd.net

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BACKGROUND: Minimally invasive spine (MIS) surgery utilizing tubular retractors has become an increasingly popular approach for decompression in the lumbar spine. However, a better understanding of appropriate indications, efficacious surgical techniques, limitations, and complication management is required to effectively teach the procedure and to facilitate the learning curve.

OBJECTIVE: To describe our experience and recommendations regarding tubular surgery for lumbar disc herniations, foraminal compression with unilateral radiculopathy, lumbar spinal stenosis, synovial cysts, and dural repair.

METHODS: We reviewed our experience between 2008 and 2014 to develop a step-by-step description of the surgical techniques and complication management, including dural repair through tubes, for the 4 lumbar pathologies of highest frequency. We provide additional supplementary videos for dural tear repair, laminotomy for bilateral decompression, and synovial cyst resection.

RESULTS: Our overview and complementary materials document the key technical details to maximize the success of the 4 MIS surgical techniques. The review of our experience in 331 patients reveals technical feasibility as well as satisfying clinical results, with no postoperative complications associated with cerebrospinal fluid leaks, 1 infection, and 17 instances (5.1%) of delayed fusion.

CONCLUSION: MIS surgery through tubular retractors is a safe and effective alternative to traditional open or microsurgical techniques for the treatment of lumbar degenerative disease. Adherence to strict microsurgical techniques will allow the surgeon to effectively address bilateral pathology while preserving stability and minimizing complications.

KEY WORDS: Dural tear, Foraminotomy, Laminotomy, Microdiscectomy, Minimally invasive spine surgery, Spine decompression, Synovial cyst

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Minimally invasive spine (MIS) surgery has become increasingly common over the past 2 decades, as the usage of new surgical devices and techniques has evolved.[1,2] In 1997, Spetzger et al[3,4] first described unilateral laminotomy for bilateral decompression of the lumbar spine in a study detailing both surgical anatomy and clinical experiences, followed by McCulloch and Young a year later.[5] These studies showed that bilateral decompression of the lumbar spinal canal is practical via a unilateral laminotomy. Smith and Foley concurrently introduced the microendoscopic tubular discectomy system, which allowed spinal surgeons to decompress symptomatic lumbar nerve roots using a tubular, minimally invasive approach.[2] Subsequently, this approach has been adopted for the treatment of lumbar spinal stenosis, foraminal stenosis, disc herniation, and

ABBREVIATIONS: LF, ligamentum flavum; **MIS,** minimally invasive spine; **MTD,** microsurgical tubular discectomy; **MTF,** microsurgical tubular foraminotomy; **MTL,** microsurgical tubular laminotomy; **VAS,** visual analog scale

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synovial cysts, with the modification of using a microscope instead of an endoscope.[6-10]

In this study, we sought to provide a detailed description of the step-by-step techniques of MIS surgery with tubular retractors for microdiscectomy, foraminotomy, laminotomy for bilateral decompression, and synovial cyst resection in the lumbar spine, as these procedures are currently performed and taught at our institution. MIS surgery can potentially avoid more invasive fusion surgery and will allow treatment of patients, especially the elderly, who were previously not considered surgical candidates.[11]

METHODS

We synthesized our experience with tubular retractor decompression in the lumbar spine, based on our previously published studies from 2008 to 2015, to help assess the indications, techniques, limitations, and complication management for the 4 microsurgical tubular procedures: discectomy, contralateral approach for "over-the-top" foraminotomy, "over-the-top" laminotomy for bilateral decompression of lumbar spinal stenosis, and contralateral approach for synovial cyst resection in the lumbar spine. The data collected were based on patient data and operative results, including length of stay, blood loss, operative time, and surgical complications. Clinical outcomes were assessed based on pre- and postoperative visual analog scale (VAS) scores.[11-14] We developed instructional videos **(Videos, Supplemental Digital Content 1, 2**, and **3**) for synovial cyst resection, modified dural repair using an endoscopic dural repair set, and microsurgical tubular laminotomy.

Indications

In our institution, decompression through tubular retraction is the preferred approach for the treatment of a variety of degenerative spinal disorders including lumbar spinal stenosis, disc herniation, foraminal narrowing, and facet joint cysts. It offers particular advantages especially for high-risk patients, such as the obese and elderly.[15]

Microsurgical Tubular Discectomy

The indications for microsurgical tubular discectomy (MTD) fulfill the classical symptoms of nerve root compression, demonstrable signs of nerve root tension, and comparable magnetic resonance imaging (MRI) findings.[14] We also approach recurrent disc herniations through tubular retractors. A relative contraindication for MTD may be complex revision cases in which extensive scarring may make tubular surgery difficult.

Microsurgical Tubular Foraminotomy

In the case of foraminal narrowing that causes unilateral lower extremity radiculopathy, microsurgical tubular foraminotomy (MTF) may be indicated. The ideal candidate is a patient in whom the compression is caused by a soft foraminal disc herniation. Contraindications are bilateral foraminal stenosis with bilateral symptoms, bony compression of the exiting nerve root with severe disc collapse, and potential instability due to spondylolisthesis or lateral listhesis.

Microsurgical Tubular Laminotomy

Microsurgical tubular laminotomy (MTL) can be performed in patients who have lumbar stenosis presenting primarily with leg or buttock symptoms with neurogenic claudication.[14] Indications include acquired lumbar central and/or lateral recess spinal stenosis, epidural lipomatosis, independent of the number of segments affected or the extent of narrowing and regardless of the severity of the lumbar stenosis and thecal sac compression.[14] Contraindications to MTL include patients with grade I spondylolisthesis and significant movement on flexion/extension films and mechanical back pain, grade II spondylolisthesis and worse, significant lateral listhesis, and significant scoliosis.[10]

Relative contraindications include congenital narrow lumbar spinal canal with shortened pedicles in which the thecal sac compression is due to bony impingement, and previous spinal decompression procedures that involved removal of the lamina. This will make the contralateral "over-the-top" decompression very difficult because of the presence of scar tissue and the absence of bony landmarks when navigating contralaterally.[14]

Microsurgical Resection of Lumbar Synovial Cysts

Indications for surgical intervention include lumbar radiculopathy, neurogenic claudication, and neurological deficits. The minimally

FIGURE 1. *Alternate skin incisions following use of the "slalom technique" for multisegmental lumbar spinal stenosis. The alternating incisions are useful for balancing muscle dissection as well as lamina preservation on alternating sides of the spine to reduce biomechanical instability.*

invasive tubular approach is particularly effective when cysts are associated with stable spondylolisthesis, because it minimizes facet joint removal and the risk of progressive instability or the requirement of fusion.[16] Previous laminectomy is a relative contraindication for the tubular approach, because the contralateral "over-the-top" decompression cannot be safely performed because of scar tissue on the dura. In this case, an ipsilateral approach may be better. Other contraindications are similar to MTL.

Techniques

There are 3 main principles of the tubular surgical technique that should be understood: (1) A unilateral, tubular "over-the-top" MIS approach can be used for a bilateral decompression; (2) MIS decompression minimizes the instability associated with similar open procedures by reducing iatrogenic destabilization; (3) for multisegmental lumbar procedures (usually for stenosis), we suggest using a crossover "Slalom Technique" through multiple skin incisions, as previously described by Mayer and Heider,[17] to potentially minimize iatrogenic instability associated with multilevel decompression (Figure 1).

All procedures are performed with the patient under general anesthesia and in the prone position, by using the operating microscope to optimize visualization and illumination. Lateral fluoroscopy is used for localization. Microscope and fluoroscope should always be positioned on opposite sides, which will allow the fluoroscope to be brought into the operative area when the surgeon is under the microscope (Figure 2). The standard surgical instruments used for these procedures include (Figures 3-5):

- A surgical power drill with a 15-cm curved drill shaft with a 3-mm fluted matchstick drill bit, typically used for undercut drilling (see MTL Technique) (Figure 3). Diamond drill bits or round drill bits are not recommended.
- 45° 2-, 3-, and 4-mm bayoneted Kerrison rongeur (Figure 4).
- 2- and 3-mm 90° rongeur will allow optimal undercutting of the lamina and resection of ligamentum flavum (Figure 4).
- Size 9 and 12 metal sucker (Figure 4).
- Bayoneted ball-tip nerve hook (Figure 4).
- Regular bayoneted nerve hook (Figure 4).
- Bayoneted knife and angled 90° down-angled curette for MTD (Figure 4).
- Tubular retracting system consisting of multiple dilators of increasing diameter, a table clamp, and a rigid holding arm. We use 15- or 16-mm tubes for discectomies and 18- or 19-mm tubes for the laminotomies. It is not recommended to use a K-wire, to avoid the risk of dural and nerve injury. Once the tubes have been placed, the surgeon should be familiar with the "wanding" technique that enables inspection of a wider area of the surgical field by tilting of the tubular retractor into the desired direction.

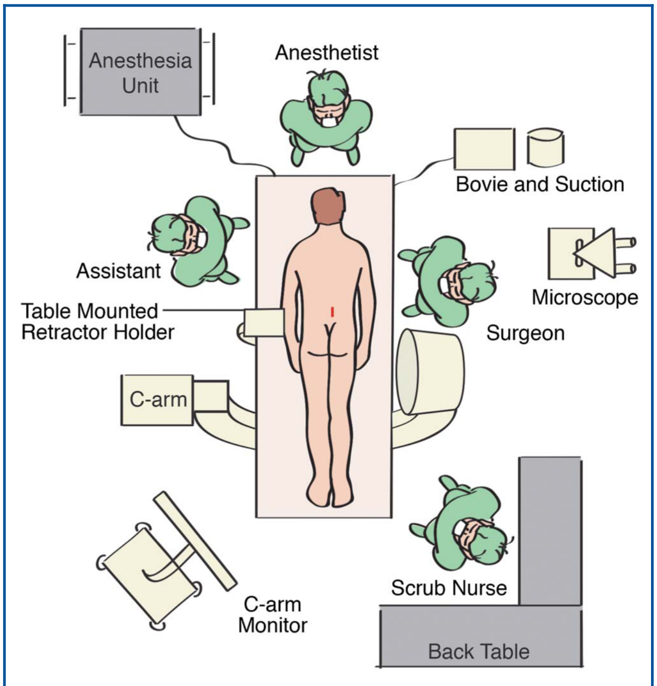

FIGURE 2. *Optimal operating room setup for MIS surgery. In cases with equal bilateral stenosis and symptoms, a right-handed surgeon should stand on the right side of the patient (who is placed in the prone position) along with the scrub nurse. The assistant stands on the opposite side. The operating microscope and the C-arm are positioned on opposite sides; this allows for no interference between these structures during surgery. After draping the patient, the table-mounted retractor unit is fixed at the opposite side of the skin incision. MIS, minimally invasive spine.*

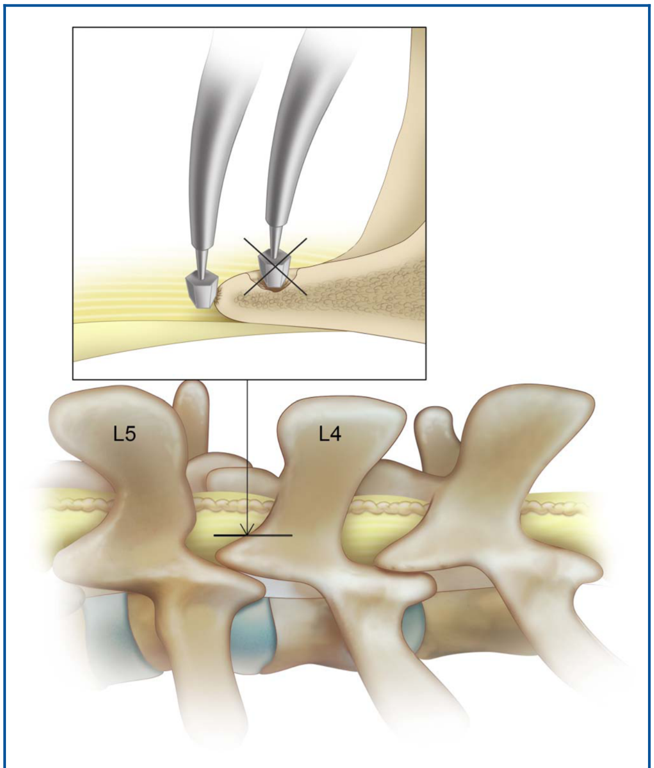

FIGURE 3. *Drilling technique with 15-cm curved drill shaft with a 3-mm fluted matchstick drill bit. The side-cutting burr is placed at the inferior edge of the lamina with the side of the drill bit depending on the type of exposure needed, with the blunt tip always sitting on the ligamentum flavum. Vertical drilling is not recommended (crossed out).*

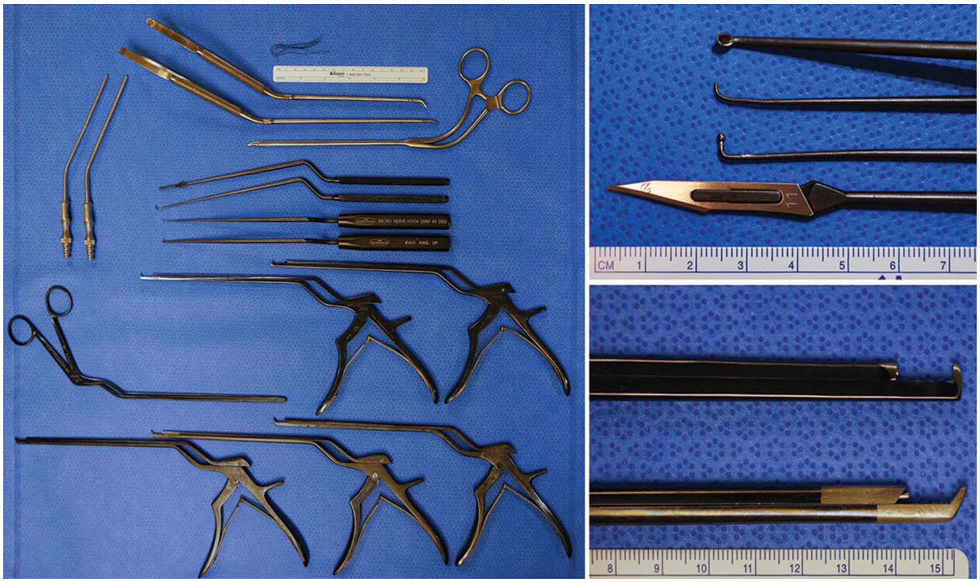

FIGURE 4. *Microsurgical tubular equipment.* **Left**, *full set of instruments including rongeurs, suckers, conventional and ball-tip nerve hook, curette, blade holder, and endoscopic dural repair kit.* **Upper right**, *close-up of blade holder with an 11 blade, nerve-hooks, and curette.* **Lower right**, *close-up of a 45° and 90° 3-mm Kerrison rongeur for different applications.*

- Endoscopic dural repair set for management of dural tears (Figure 5).

At the end of each procedure, the tubular retractor is removed and the operative site is closed in standard fashion.[12] The fascia should be closed with a separate stitch, and the muscle is typically infiltrated with local anesthetic. Meticulous hemostasis is important, because postoperative hematomas can cause significant pain and muscle spasms. We prefer to use hemostatic agents such as Floseal (Baxter International Inc, Deerfield, Illinois) before closing.

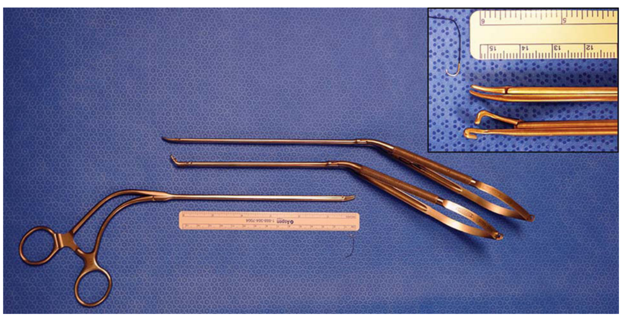

FIGURE 5. *We adapted the usage of a Scanlan endoscopic dural repair set (Scanlan International, St. Paul, Minnesota) for microscopic dural repair through a tubular retractor. The figure shows the needle holders, knot pusher, and 4-0 Nurolon TF-5 "fishhook" (Ethicon Inc, Somerville, New Jersey).*

Drilling Technique Using the Matchstick Drill Bit

When using the matchstick drill bit, the surgeon should understand that this is a side-cutting burr with a relatively blunt tip. The drilling therefore starts at the inferior edge of the lamina with the side of the drill bit and is performed cranially and laterally and medially depending on the type of exposure needed. The side-drilling technique essentially entails removal of the bone that is covering the ligamentum flavum (LF), with the blunt tip of the drill bit always sitting on the LF (Figure 3).

MTD Technique

MTD in the lumbar spine is a modification of the standard microsurgical lumbar discectomy open surgery technique. For a unilateral disc herniation, the approach should be ipsilateral.

The surgeon should stand on the side of the herniation to be treated, with the assistant standing on the contralateral side (Figure 2). A small incision is made approximately 1 to 1.5 cm from the midline over the corresponding herniated disc space and facet joint. A blunt dilator is then passed perpendicularly through the incision until the bony surface of the inferior edge of the lamina is encountered. A lateral fluoroscopy image should then be taken to confirm the dilator position over the lamina/medial facet joint. Once the position is satisfactory, dilators of increasing diameter are inserted with a twisting motion to avoid undue pressure and plunging. A 15- or 16-mm tubular retractor is large enough to perform a discectomy. Fluoroscopy is then used to confirm that the dilator is positioned directly on the bone, at the inferior edge of the lamina, with no or minimal intervening soft tissue. The working channel is then secured with a rigid holding arm and directed slightly medially toward the lamina and spinous process.

Under microscopic view, the soft tissues bulging through the tubular retractor are cleared to identify bony landmarks. The edges of the lamina

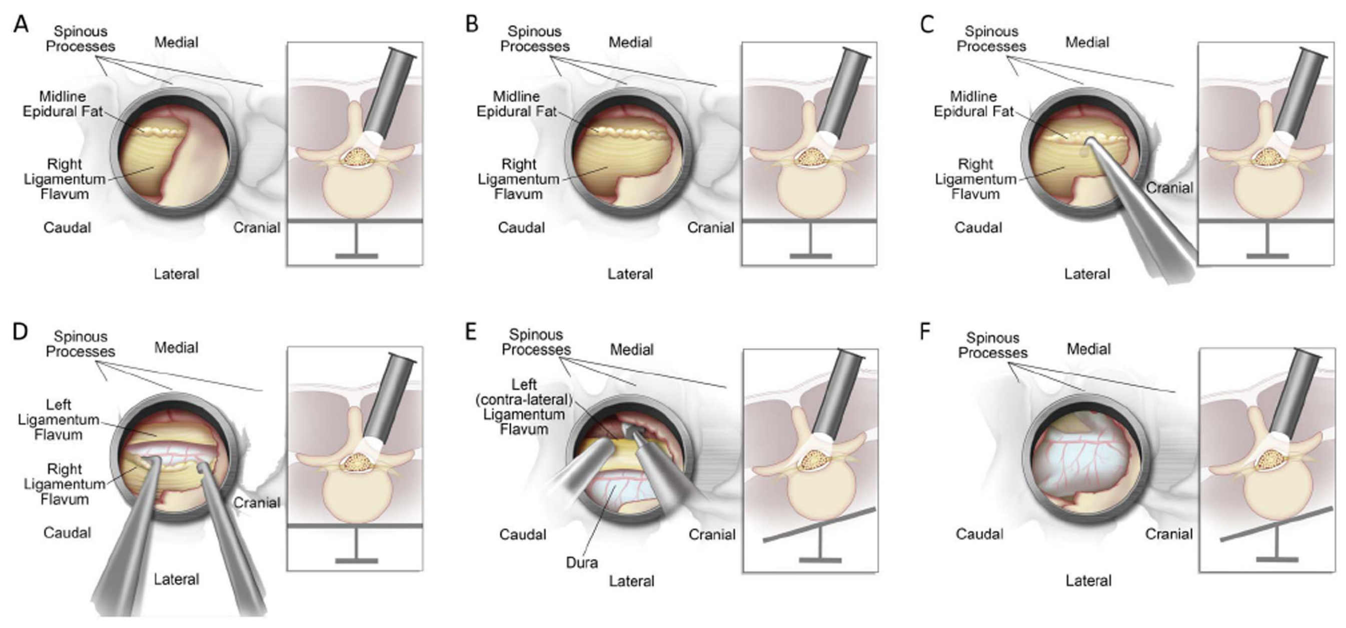

FIGURE 6. **A**, *tubular placement for a right-sided approach. Under the microscope, the inferior edge of the lamina and the inferior edge and base of the spinous process are exposed. The union of these 2 bony structures serves as a landmark for the starting point of the lumbar decompression.* **B**, *the laminotomy is conducted using a 3-mm curved drill and bayoneted 2- and 3-mm Kerrison rongeurs. The ligamentum flavum (LF) is exposed but not removed at this stage to protect the underlying dura and reduce the risk of CSF leak.* **C**, *after ipsilateral laminotomy, the typical presence of epidural fat between the 2 leaves of the LF can be identified as a landmark for safe insertion of a nerve hook to start dissection of the ligament.* **D**, *partial resection of the LF; note that the contralateral LF remains intact to be used as a protection for further undercutting of the lamina and spinous process in contralateral foraminotomies.* **E**, *drilling of the contralateral lamina; the sucker is used to protect and gently depress the LF and underlying structures, while the fluted 3-mm matchstick drill is used to undercut the contralateral lamina and other bony structures to complete the decompression. This may require further tilting of the table and/or retractor to optimize access.* **F**, *a complete removal of the LF is achieved and the dura is safely exposed. The contralateral exiting and traversing nerve roots may also be exposed if necessary.*

and the interlaminar space should be defined. A laminotomy is then performed using a drill and/or Kerrison rongeur. The medial facet may also be partially removed to extend the operating field. From this stage, the rest of this procedure is similar to the open surgery technique. For reference to the important initial steps, please see Figure 6, specifically Figures 6A and 6B.

The above-described technique is an optimal approach for first-time surgeries. In the case of recurrent discs, we recommend correlating the docking of the tube with intraoperative imaging and suggest doing the approach from the same side where the pathology is located. Under the microscope, we find the interface between remnant bone and scar tissue from the previous decompression. Initially, a few millimeters of bone at this interface are removed by using the matchstick drill until sharp dissection using an up-biting small bayoneted curette, which allows entrance to the plane between bone and dura. If the anatomy is not appropriate for an MTD approach or if too much of the facet joint has to be removed, an MIS transforaminal lumbar interbody fusion, miniopen, or open approach may be indicated.

In addition, in the case of extreme lateral or extraforaminal disc herniations, the docking point should be modified to the pars immediately caudal to the upper transverse processes of the index level. This can be accomplished with an extreme lateral ipsilateral approach, drilling the most lateral part of the facet and pars. Key structures to identify are the smooth pedicle wall and the exiting nerve root, which will lead to the pathology. For further details regarding this approach, please refer to O'Toole et al.[18]

MTF Technique

An MTF is performed from the contralateral side.[12] A small skin incision is made over the disc space of interest, approximately 1.5 cm lateral to the midline, or more lateral in obese patients. An 18- to 19-mm tubular retractor is placed over a series of tubular dilators for retraction. A summary of the 10-step approach for tubular "over-the-top" contralateral foraminotomy is outlined in Table 1.

It is important in this operation to minimize iatrogenic compression of the thecal sac and nerve structures by the crossing instruments during the contralateral decompression, especially in the presence of severe stenosis (which should be decompressed before treating the contralateral foraminal stenosis). After removal of the contralateral LF, the contralateral exiting nerve should be identified and followed out laterally with a ball-tipped nerve hook (Figures 7 and 8). In addition, note that access to the ipsilateral foramen in this MTD procedure is very limited.

MTL Technique

For the treatment of lumbar spinal stenosis, we describe a unilateral "over-the-top" minimally invasive approach to achieve a bilateral decompression of the central spinal canal and lateral recesses in 10 steps

TABLE 1. MTF Steps[a]

1. Tube placement over the inferior edge of the medial ipsilateral lamina.
2. Removal of soft tissues and identification of inferior edge of the lamina and ipsilateral base of spinous process (Figure 6A).
3. Laminotomy: Drilling of the medial portion of the lamina, just enough to access the medial LF. Bone removal using bayoneted 2- and 3-mm 45° Kerrison rongeurs (Figure 6B).
4. Exposure of the cranial insertion of the ligament, an area that may be identified by the presence of epidural fat. Epidural fat can also be identified between the 2 leaves of the LF (Figure 6C).
5. Removal of the medial portion of the ipsilateral LF either from cranially above the insertion of the LF or from the midline gap in between the leaves of the LF (Figure 6D). Note: This is for better visualization of the ipsilateral dura and underlying structures, however, keeping the LF in place until after all bony decompression is another option that some may find safer.
6. Aiming of the tube medially toward the midline and tilting of the operating table away from the surgeon, and if necessary, more medial bone drilling.
7. Contralateral drilling: undercut drilling of the bone "behind" the contralateral LF while protecting the dura with the suction (Figure 6E). The suction is downsized to a number 9, and only 2-mm rongeurs are used to minimize compression of the thecal sac and nerve roots.
8. Removal of the contralateral LF (Figure 6F). The use of 90° Kerrison rongeurs may allow more complete resection of the LF.
9. The contralateral exiting nerve is identified and followed out laterally (Figures 7 and 8). To effectively decompress this area, it may be necessary to undercut ventrally to the facet joint. This may be facilitated by additional tilting of the tube and operating room table
10. Tilting back of the tube and table and completion of the ipsilateral drilling and LF removal, if indicated. The backhanded use of 90° Kerrison rongeurs may allow more complete resection of the ipsilateral LF. Care should be taken not to violate the pars interarticularis. Meticulous hemostasis, tube removal, muscle infiltration, and closure.

[a]LF, ligamentum flavum; MTF, microsurgical tubular foraminotomy.

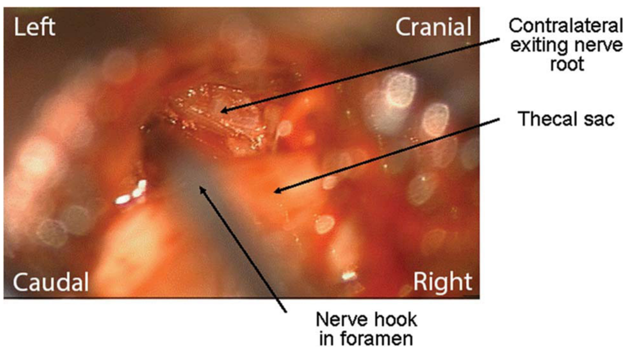

FIGURE 7. *Intraoperative microscope image of the contralateral L4/5 foramen after the exiting L4 nerve root is exposed and a ball-tipped nerve hook is inserted through the foramen.*

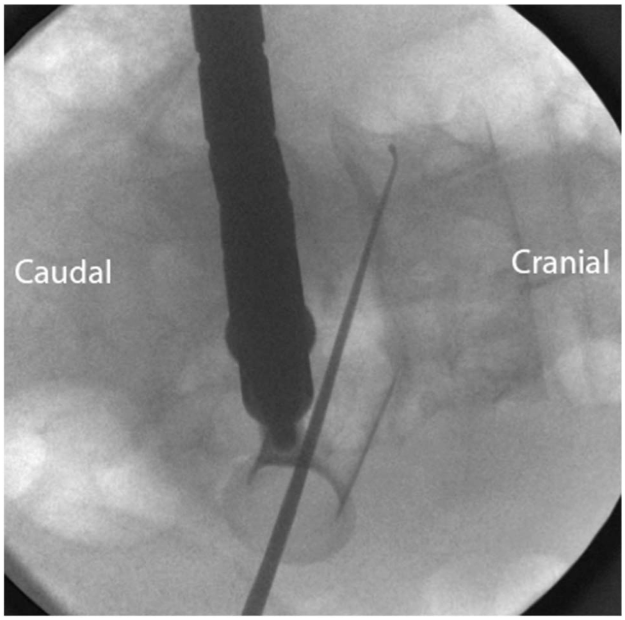

FIGURE 8. *Intraoperative X-ray showing the tubular arm holder, the tube on the right side aimed medially, and a nerve hook passing and exiting through the contralateral (left) L4/5 foramen.*

(Table 2). This is similar to the MTF technique described above but includes a more cranially and caudally directed contralateral decompression. Typically, an 18- or 19-mm tube is used. The key differences between the MTF and MTL include:

- The initial ipsilateral laminotomy includes more of the lateral ipsilateral lamina than is removed during the MTF. In some MTL cases, more of the ipsilateral facet joint may have to be removed to achieve an adequate ipsilateral decompression, although caution should be taken to avoid creating instability.
- During the contralateral decompression, we use palpation of the inferior contralateral pedicle to confirm good decompression caudally. In addition, it is important to study the sagittal T2-weighted preoperative MRI to determine the caudal extension of the ligamentous hypertrophy causing the stenosis. Especially in cases with spondylolisthesis, this can extend well below the level of the disc space and even the pedicle and will require caudal tilting of the tubular retractor and additional decompression. Given the limited visualization through tubular retractors, this can be easily missed.
- Especially in cases with severe stenosis, it is important to minimize the compression of the nerve structures during the contralateral decompression. Therefore, we downsize the size of the suction to a 9 during this part of the procedure and use only a 2-mm rongeur.
- Cranially, the complete removal of the yellow ligament is confirmed. This may require more drilling to remove the bone that is situated "behind" the LF (Figure 6E), which will free up the LF and facilitate its removal using a rongeur. The use of a ball-tip nerve hook on the contralateral superior pedicle to confirm an adequate decompression is usually not necessary, because the LF hypertrophy typically does not extend that far cranially.

TABLE 2. MTL Steps[a]

1. Tube placement over the inferior edge of the medial ipsilateral lamina.
2. Removal of soft tissues and identification of inferior edge of the lamina and base of the spinous process (Figure 6A).
3. Laminotomy: Drilling of the medial portion of the lamina to access the medial LF. Bone removal using bayoneted 2- and 3-mm 45° Kerrison rongeurs (Figure 6B).
4. Exposure of the cranial insertion of the ligament, an area that may be identified by the presence of epidural fat. Epidural fat can also be identified between the 2 leaves of the ligamentum flavum (LF) (Figure 6C).
5. Removal of the ipsilateral LF either from cranially above the insertion of the LF or from the midline gap in between the leaves of the LF (Figure 6D). Note: This is for better visualization of the ipsilateral dura and underlying structures, however, keeping the LF in place until after all bony decompression is another option that some may find safer.
6. Aiming of the tube medially toward the midline and tilting of the operating table away from the surgeon and more medial bone drilling.
7. Contralateral drilling: undercut drilling of the bone "behind" the contralateral LF while protecting the dura with the suction (Figure 6E). The suction is downsized to a number 9, and only 2-mm rongeurs are used in order to minimize compression of the thecal sac and nerve roots. For medial and inferior bony work, 90° Kerrison rongeurs can also be used to minimize risk of potential durotomy.
8. Removal of the contralateral LF (Figure 6F). The use of 90° Kerrison rongeurs may allow more complete resection of the LF.
9. The contralateral traversing nerve is identified and followed inferiorly. The contralateral inferior pedicle is palpated. The foramen can be palpated cranially and, as necessary, can be decompressed (see Table 1); this may require more drilling and additional tilting of the tube and operating room table. The goal is complete flavectomy all the way from the caudal pedicle to the insertion of the LF cranially.
10. Tilting back of the tube and table and completion of the ipsilateral drilling and LF removal. The backhanded use of 90° Kerrison rongeurs may allow more complete resection of the LF. Care should be taken not to violate the pars interarticularis. Meticulous hemostasis, tube removal, muscle infiltration, and closure.

[a]LF, ligamentum flavum; MTL, microsurgical tubular laminotomy.

- The ipsilateral decompression is typically completed at the end, and the complete removal of the LF is confirmed by clear identification of the lateral aspect of the thecal sac and inspection of the traversing nerve root. Especially in the mid and upper lumbar spine, it is important during this part of the procedure to protect the pars during the ipsilateral bone removal. The goal of the decompression is to remove the LF, and bone removal should be minimized.

The approach side and the choice of incisions for MTL is determined as follows:

- For MTL at the level of L1/2, L2/3, or L3/4, the surgeon should take into consideration that the lamina is less wide compared with lower lumbar levels. In addition, the facet joints are oriented more sagittally and the pars is thinner, which makes it more vulnerable to potential iatrogenic injury. Therefore, the tube should be positioned more medially and angled more vertically, about 1 cm from the midline (as opposed to 2 or 3 cm from the midline). This will avoid excessive ipsilateral facet removal and potential instability (Figure 9). At the levels of L4/5 or L5/S1, the tube may be docked farther from the midline and at a greater angle to achieve adequate decompression, because the anatomy is typically wider at these levels.
- In cases with equal bilateral stenosis and symptoms, a right-sided approach is preferred by a right-handed surgeon, because most of the Kerrison work is performed toward the caudal aspect with the surgeon's right hand. This may minimize the risk of intraoperative dural tears.
- Conversely, a left-sided approach is used by a left-handed surgeon.
- In cases or at levels at which, in addition to the lumbar stenosis, unilateral foraminal stenosis needs to be addressed, the surgeon should pick a contralateral approach.
- One incision is sufficient for 1 to 2 levels. In cases in which 2 levels are treated through 1 incision, we make separate fascial incisions and dilate 1 level first, remove the dilators, dilate the second level, and will start with the decompression at the second level. This eliminates the need to dilate the muscle in the presence of a laminotomy defect and will minimize accidental dural and nerve injuries from the dilators.
- For 3 to 4 levels, we suggest a crossover "slalom technique" with separate incisions from opposite sides as described by Mayer and Heider[17] (Figure 1). We have done this successfully with 2 microscopes from opposite sides with the surgeon and the assistant working simultaneously on different levels, which greatly reduces operative times. Although we prefer the "slalom technique," to the best of our knowledge, no study has been conducted to confirm if it decreases instability.

To further observe this technique please see **Video, Supplemental Digital Content 1** on MTL.

Microsurgical Tubular Resection of Lumbar Synovial Cyst Technique

The approach is similar to the decompression described under MTL. A good decompression of the LF should be achieved to create room for safe removal of the synovial cyst. The main idea of approaching the cyst from the contralateral side is to come from normal anatomy toward the pathology. This will allow for careful exposure of the cyst. If the thecal sac sticks to the cyst wall, the dura is gently dissected off by using a ball-tip nerve hook or other dissectors such as rhoton instruments. Adequate exposure is achieved cranially and caudally, and the medial edge of the synovial cyst is carefully dissected off the dural attachment (Figure 10). Sometimes the cyst cannot be cleared because of its large size, and it has to be deliberately ruptured and decompressed to prevent excessive retraction on the dura. The cyst is then removed in a piecemeal manner by using Kerrison rongeurs. This allows its marsupialization and complete removal. Resection of the facet joint is minimized by this contralateral approach; however, smaller synovial cysts can be successfully resected via an ipsilateral approach. To further observe this "over the top" technique for synovial cysts resection, please see **Video, Supplemental Digital Content 2**.

Microsurgical Tubular Repair of Dural Tears

In our experience, most durotomies occur while working caudally and contralaterally when removing thickened LF from the underlying dura. Separating the dura carefully from the LF by using a ball-tip instrument before removing LF with Kerrison rongeurs is important. The use of 90° Kerrison rongeurs will help to minimize the risk of durotomy. Another

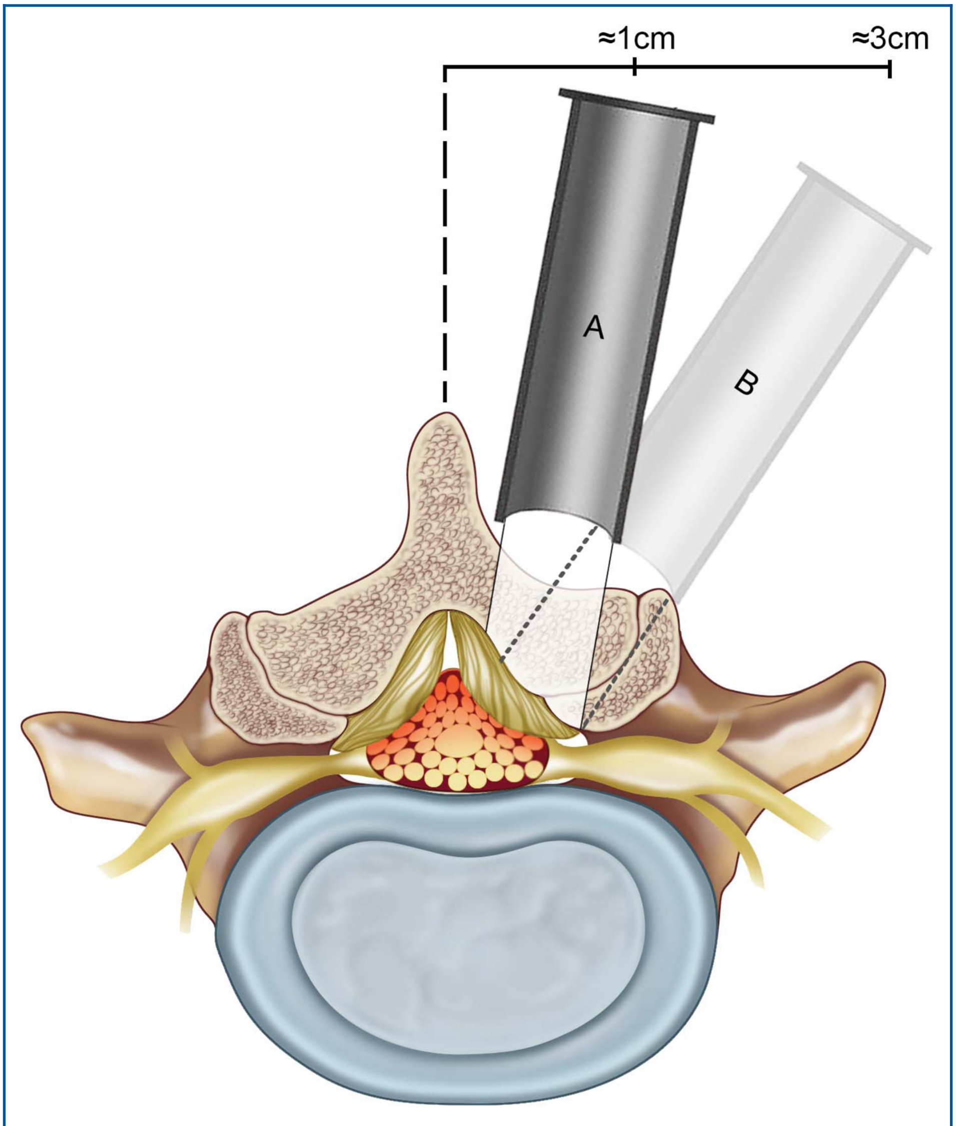

FIGURE 9. *Tube positioning for MTL at higher lumbar levels. For an MTL at L1/2, L2/3, or L3/4, the tubular retractor should be positioned more medially, about 1 cm from the midline (***A***) instead of the normal 2 to 3 cm, to avoid excessive ipsilateral facet removal (***B***). Diagram not drawn to scale. MTL, microsurgical tubular laminotomy.*

technique we use is to close the Kerrison and to move it slightly right and left before committing to a bite. If the dura has been included in the bite, it will also move significantly. This technique can avoid more significant dural tears.

If a dural tear occurs, our management depends on the size of the defect and whether or not nerve roots protrude through the defect. In the majority of cases, the dural tear is relatively small and the nerve roots will be contained in the thecal sac. In these cases, we will cover the defect with fibrin glue or DuraSeal (Confluent Surgical, Inc, Waltham, Massachusetts) after hemostasis has been achieved and before removal of the tubular retractor.

If an accidental durotomy is relatively large and there are nerve roots extruding, we will perform a primary repair. Adequate drainage of cerebrospinal fluid (CSF) will facilitate placing the nerve roots back into the thecal sac. Chou et al[19] describe their way of closing the dura using a micropituitary rongeur and a 5-0 Prolene suture (Ethicon, Inc, Somerville, New Jersey), which is an adapted technique originally described for arthroscopic surgery. This technique was modified using the Scanlan (Scanlan International, St. Paul, Minnesota) endoscopic dural repair set, as per Tan et al,[20] Ruban and O'Toole,[21] and suggested by Dr Fessler (R.G. Fessler, personal communication).

Some other tools like the U-clip, first used for coronary artery anastomosis, have also been described for dural closure in MIS surgery.[22] Because U-clips need to be applied in an interrupted manner and the clips come in different sizes, the correct choice of size will determine whether or not the dural edges are tightly approximated.[22]

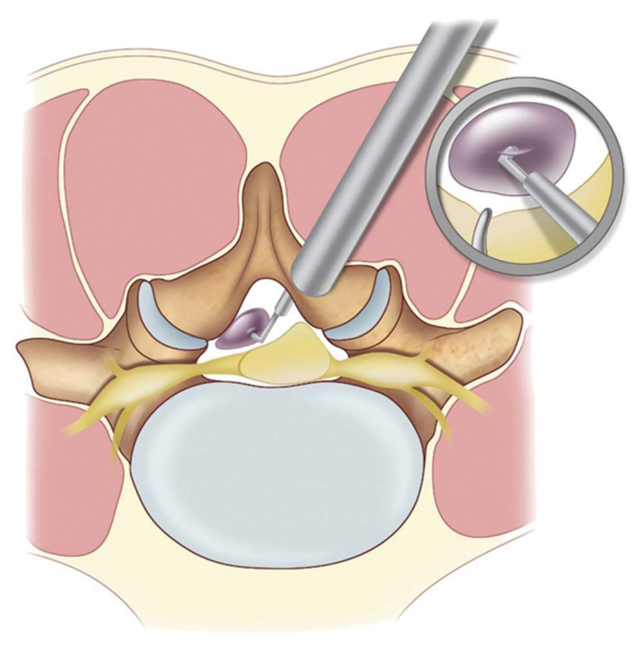

FIGURE 10. *Microtubular resection of lumbar synovial cyst. With the use of a tubular retractor, a synovial cyst should be approached from the contralateral side. The cyst is dissected off the thecal sac and a small sucker is used to protect the dura while the cyst is resected carefully to expose the facet joint.*

In our practice, we prefer using the Scanlan endoscopic dural repair set and a 4-0 Nurolon TF-5 "fishhook" (Ethicon Inc, Somerville, New Jersey) that is ideally suited for dural repair (Figure 8). This has been successfully used through tubes as small as 15 mm. A Valsalva maneuver confirms watertight closure. The repair is then covered with fibrin glue or DuraSeal (Confluent Surgical, Inc, Waltham, Massachusetts). Patients with CSF leaks will usually be placed on flat bedrest until the next morning and then mobilized early on (within the first 24 hours following surgery).[23] To further observe this technique, please see **Video, Supplemental Digital Content 3**.

Postoperative Care

Postoperatively, oral analgesia should be given to manage pain. We continue muscle relaxants in these patients for approximately a week after surgery. Depending on individual pain tolerance, patient mobilization is allowed 3 to 4 hours following surgery. Early mobilization also reduces the need for thrombosis prophylaxis. Any of these procedures can be considered for ambulatory surgery. Most of our patients are discharged on the same day of surgery. However, if surgery was in the afternoon, if the patient is elderly with significant comorbidities, if there was a CSF leak, or if the patient prefers, we will keep them overnight. Typically, we do not place drains for any of our tubular procedures unless there was unusual bleeding intraoperatively. In these cases, the drain is removed the morning after surgery. The number of levels treated does not determine whether or not we place a drain.

To avoid early recurrence, oral and written instructions should be given to the patients to avoid activities such as lifting, forced bending, or twisting. These instructions should be followed for at least 3 to 6 weeks.[14]

At 1 to 2 weeks postoperation, patients should be checked to review their surgical site and test general physical ability. After this period of time, most patients should be able to return to work, depending on the intensity of their work.

RESULTS

See Table 3 for a detailed summary of the results.

Microsurgical Tubular Discectomy

These results were taken from a case series by Parikh et al[24] which analyzed a group of 230 patients who underwent 1- or 2-level discectomy or laminotomy.

Microsurgical Tubular Foraminotomy

A study was performed by Alimi et al,[12] and the results were taken from 32 patients who underwent a minimally invasive lumbar foraminotomy through tubular retractors via a contralateral approach.

Microsurgical Tubular Laminotomy

Results for MTL were taken from a case study performed by Alimi et al[11] in which 110 patients underwent 1-, 2-, or 3-level MTL from L2 to S1. A subgroup of patients was studied who presented initially with equal bilateral buttock and leg pain; the unilateral approach for bilateral decompression showed bilaterally equal reduction in their VAS scores. This illustrates the ability of the unilateral approach to achieve bilateral decompression.[25]

Microsurgical Tubular Resection of Lumbar Synovial Cyst

A case study performed by James et al[13] reported the results of 16 patients who underwent surgery using a contralateral MIS surgical muscle splitting approach for the removal of synovial cysts.

Dural Tear Repairs

In our consideration of all 4 types of tubular procedures, of 313 total patients, there were 31 cases of incidental durotomy, a rate of 9.9%. All tears were repaired intraoperatively with either fibrin glue, DuraSeal, or by direct closure; there were no postoperative CSF leaks or infections, and there was no need to convert the surgery into an open technique. Alimi et al[11] reported a significantly higher dural injury rate in earlier MTL procedures performed by the same surgeon (27.3%) vs later procedures (1.8%), indicating a learning curve associated with tubular laminotomies and minimally invasive tubular procedures, in general.

Summary

The results for MTD revealed few complications, involving intraoperative dural tears causing CSF leaks (12 cases) and a wound infection requiring intravenous antibiotics (1 case). The data showed a statistically significant reduction in back and

TABLE 3. Summary of Our Institution's Results for Microsurgical Tubular Discectomy, Foraminotomy, Laminotomy, and Resection of Synovial Cyst[a]

Procedure	Microsurgical Tubular Discectomy	Microsurgical Tubular Foraminotomy	Microsurgical Tubular Laminotomy	Tubular Resection of Synovial Cyst
Publication	Parikh et al, 2008[24]	Alimi et al, 2014[12]	Alimi et al, 2015[11]	James et al, 2012[13]
No. of levels/patient, n (%)				
1 level	141 (91.0)	21 (65.6)	57 (51.8)	16 (100)
2 level	14 (9.0)	10 (31.3)	47 (42.7)	
3 level		1 (3.1)	6 (5.5)	
Operation time in minutes	Mean ± SD	Mean ± SD		Mean ± SD
1 level	68.7 ± 25.9	84.4 ± 4.8	N/A	105 ± 37
2 level	104.1 ± 31.4			
EBL (mL)	Mean ± SD	Median (range)	Median (range)	Mean
1 level	16.9 ± 37.0	10 (0-200)	25 (0-550)	<40
2 level	16.9 ± 24.9		50 (0-400)	
3 level			150 (100-300)	
Hospital stay in days	Mean ± SD	Median (range)	Mean ± SD	Mean ± SD
1 level	1.0 + 0.86	1 (0-2)	2.2 ± 2.63	4 ± 3.5
2 level	1.0 + 0.63			
No. complications	13[b]	2[c]	16[d]	2[e]
VAS leg pain	Mean[f]	Mean ± SE	Median (range)	Mean
	Pre: 8.26	Pre: 6.4 ± 0.7	Pre: 4.5 (0-10)	Pre: 7.6
	Post: 2.83[h]	Post: 1.9 ± 0.7[g]	Post: 0 (0-10)[h]	Post: 0.6[i]
VAS back pain	Mean[f]	Mean ± SE	Median (range)	Mean
	Pre-Op: 7.17	Pre: 4.7 ± 0.9	Pre: 8 (0-10)	Pre: 7.1
	Post-Op: 2.64[h]	Post: 1.2 ± 0.4[h]	Post: 3.5 (0-10)[h]	Post: 0.7[i]
Macnab outcome assessment	Excellent[f]: 20.8%	Excellent and good: 95.2%	Excellent and good: 71.6%	Excellent: 69%
	Good: 56%	Fair and poor: 4.8%	Fair and poor: 28.4%	Good: 31%
	Fair: 19%;			
	Poor: 14.3%			

[a]EBL, estimated blood loss; MTD, microsurgical tubular discectomy; MTL, microsurgical tubular laminotomy; VAS, Visual Analog Scale.
[b]There were 12 observed intraoperative dural tears (7.7%) and 1 infection requiring intravenous antibiotics.
[c]There was 1 dural tear (3.1%) without CSF leak and 1 case of instability requiring fusion.
[d]There were 16 observed incidental durotomies (14.5%) that were repaired intraoperatively.
[e]There were 2 small intraoperative dural tears (12.5%) without clinical CSF leak.
[f]This is a combined result taken from the outcome assessments in a cohort of 198 patients who underwent both 1- and 2-level lumbar MTD or MTL.
[g]Statistically significant improvement, $P < .05$.
[h]Statistically significant improvement, $P < .01$.
[i]No statistical analyses were performed, and 2 patients were not assessed with Macnab because of the lack of follow-up.

leg pain after surgery ($P < .01$), and the majority of patients responded with good or excellent outcome. In MTF, leg pain was considerably greater on the pathology side than the approach side preoperatively, and the data showed a statistically significant reduction in pain bilaterally after surgery ($P < .01$). Back pain also improved significantly ($P < .01$), and nearly every patient responded with good or excellent assessment. In MTL, both leg and back pain scores showed a statistically significant reduction in pain postoperatively ($P < .01$). Almost three-quarters of the series responded with good or excellent pain improvement. Patients who presented initially with equal bilateral buttock and leg pain showed bilaterally similar significant reduction in their VAS scores, which reveals the ability of a unilateral approach to achieve clinically relevant bilateral decompression.[25] For synovial cysts, leg and back pain showed excellent improvement, although these data were not analyzed for statistical significance. Intraoperative complications included 2 instances of dural tear without CSF leak that were repaired intraoperatively. Patient satisfaction was either good or excellent. Of all 4 procedures assessed in 313 patients, there were only 17 instances (5.1%) of fusion due to delayed instability.

DISCUSSION

Minimally invasive tubular approaches have less impact on the paraspinal muscle cross-sectional area compared with the open conventional surgeries[10] (Figure 11). Furthermore, in a recent biomechanical study, the minimally invasive, unilateral technique

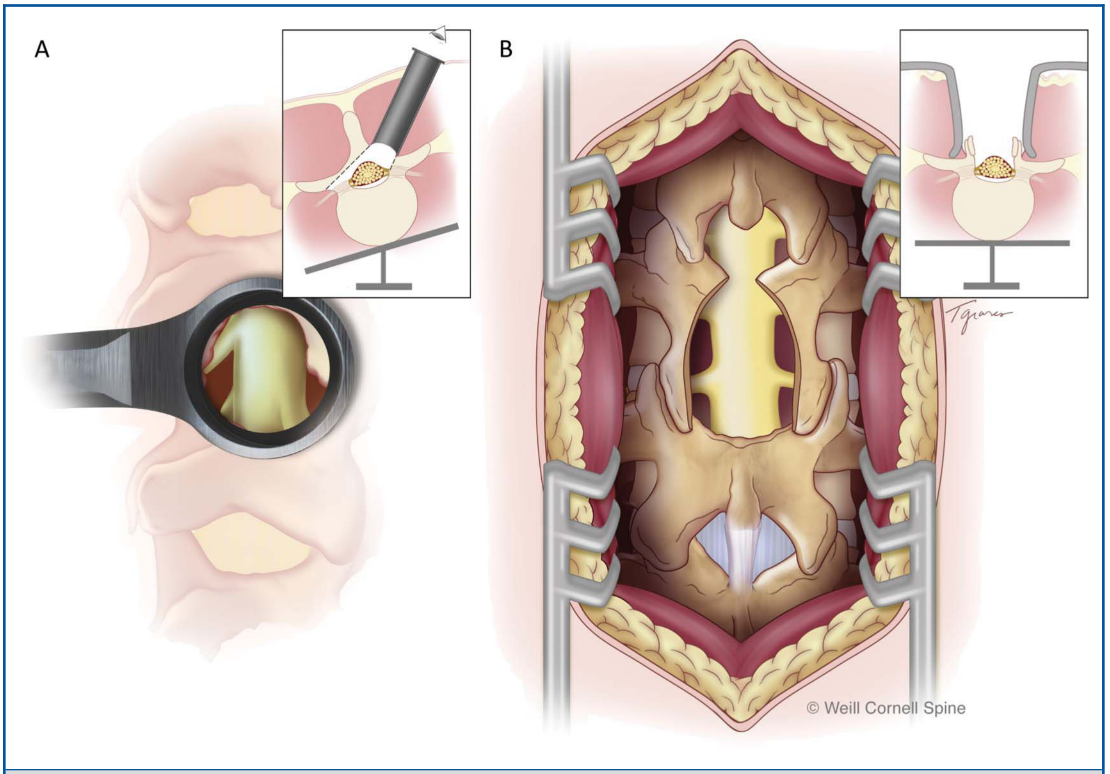

FIGURE 11. *Comparison of paraspinal muscle dissection in MTL vs open lumbar laminectomy.* **A**, *microsurgical right-sided L4/5 tubular laminotomy approach.* **B**, *open lumbar laminectomy approach.*

was shown to produce significantly less instability than a traditional midline laminectomy[26] (Figure 12). A comparison study found that minimally invasive unilateral decompression of lumbar spinal stenosis was as effective as open decompression in terms of Oswestry Disability Index reduction, but better regarding pain relief and the use of opioid analgesics.[27] This reduced need for analgesic consumption was also shown after minimally invasive tubular decompression compared with a microsurgical subperiosteal approach.[28] The results after tubular microdiscectomy are more conflicting, because the randomized control trial by Arts et al[29] found less favorable clinical results in patients receiving a tubular discectomy vs a conventional microdiscectomy. In addition, a recent Cochrane Review showed that the differences between minimally invasive vs microdiscectomy/open discectomy surgery for pain relief appear to be small and may not be clinically important.[30] However, the lower infection rate of the minimally invasive approach was supported by this review.

Versatility of Minimally Invasive Unilateral Tubular Decompression Surgery

Minimally invasive unilateral tubular approach is a versatile way to achieve a wide bilateral approach exposure of the dural sac and the nerve roots, allowing excellent decompression of bilateral spinal stenosis with clearance of the contralateral recess and neuroforamen.[11] Our results showed that secondary fusion could be avoided after minimally invasive tubular decompression in patients with lumbar spinals stenosis, with and without degenerative spondylolisthesis, for over 95% of patients.[11] These findings are also supported by Park et al,[31] who found a similar clinical outcome at a minimum of 3 years follow-up in grade I degenerative spondylolisthesis patients treated by minimally invasive unilateral decompression vs instrumented fusion. Taken together, these studies show that routine fusion is not indicated in all patients with lumbar spinal stenosis and spondylolisthesis. Furthermore, minimally invasive decompression surgery in degenerative spondylolisthesis was found to be more cost effective than instrumented fusion surgery.[32]

Microsurgical tubular decompression surgery showed a significant learning curve.[24] However, adoption of a workflow as described in our surgical technique section, as well as training in cadaver and simulation laboratories, will help the surgeon to become more comfortable with the MIS surgical approach.

CONCLUSION

The success of MIS surgery through tubular retractors depends on the experience of the surgeon and appropriate patient selection. We provide key technical details to maximize the success

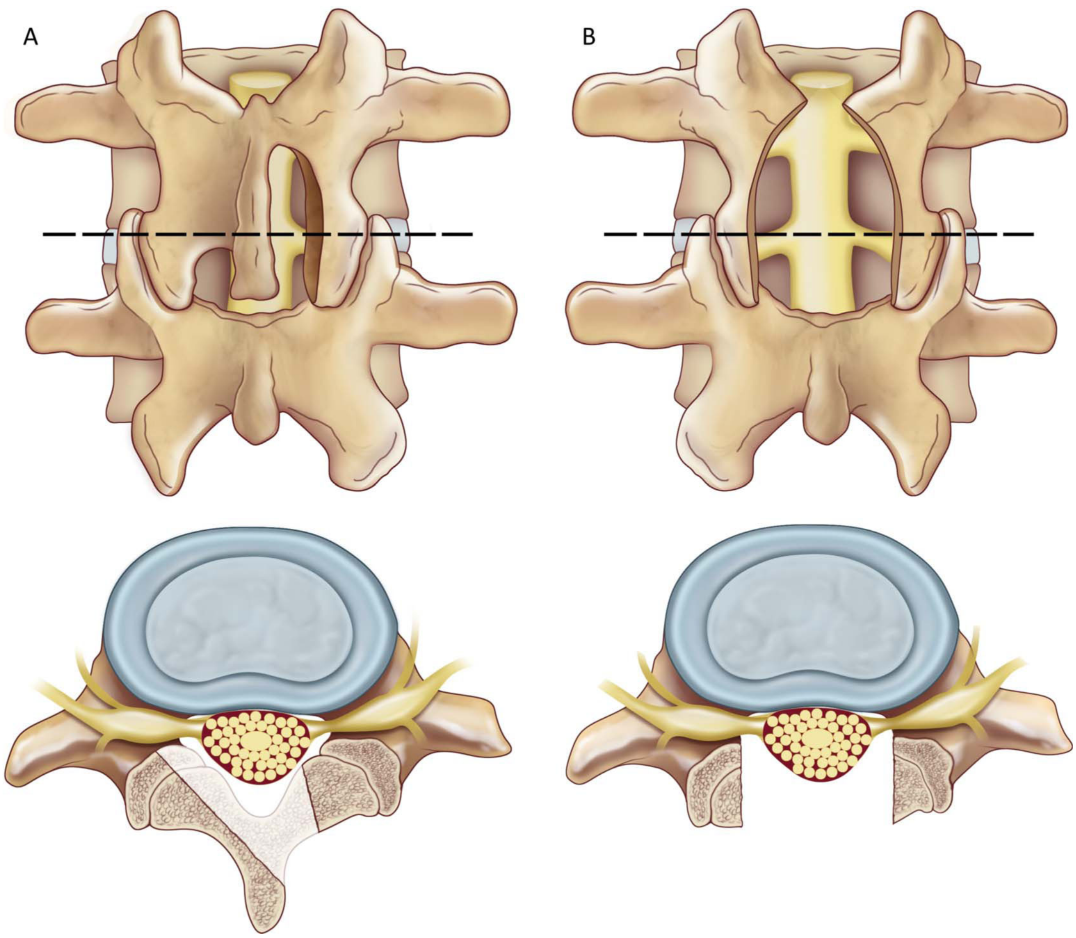

FIGURE 12. *Comparison of bone resection and relative biomechanical stability in MTL vs open lumbar laminectomy.* **A**, *microsurgical right-sided tubular laminotomy illustrating the amount of bone removal required to achieve bilateral decompression. In practice, the ipsilateral side to where the tube is docked is difficult to adequately decompress, and so more of the ipsilateral facet joint may have to be removed than is currently shown.* **B**, *traditional midline open laminectomy.*

of these operations. The 3 key principles of tubular MIS decompression surgery include: (1) A unilateral, tubular, "over-the-top" MIS approach can be used for a bilateral decompression; (2) MIS decompression minimizes the instability associated with similar open procedures by reducing iatrogenic destabilization; and (3) for multisegmental lumbar procedures for stenosis, a crossover technique with multiple skin incisions can minimize postoperative instability.

The more oblique approach angle of the described techniques compared with the subperiosteal route enables a surgeon to optimally address contralateral pathologies, leading to broad applications including contralateral resection of synovial cysts and foraminotomies, allowing optimal preservation of interspinous ligamentous structures and the facet joints.

Overall, the described MIS surgical techniques reveal similar or better clinical outcomes than classical techniques for the treatment of lumbar degenerative disease, with lower complication rates and a low incidence of CSF leakage and infection.

Disclosures

Dr Härtl is a consultant for DePuy Synthes Spine and Brainlab. Dr Boukebir's research fellowship in minimally invasive spinal surgery and navigation was sponsored by NuVasive. The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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COMMENTS

In this manuscript, the authors nicely described the minimally invasive techniques for microdiscectomy, foraminotomy, laminectomy, and synovial cyst removal along with MIS durotomy repair. I congratulate the authors on their good results with the MIS approach. A point worth mentioning is that the authors recommended removal of the ligamentum flavum prior to contralateral bony decompression in STEP 5. This practice may increase the risk of inadvertent dural tears during contralateral drilling. Keeping LF in place until all bony decompression is done may be safer since LF can protect the dura during drilling.

Lee A. Tan
Chicago, Illinois

This is a technical manuscript detailing the fundamental steps for tubular decompressive surgery by experienced MIS surgeons. There is additional guidance for treatment of durotomies. In my practice, I have used similar techniques and can attest to their efficacy. This technical guide is concisely written and would be most helpful to those new to tubular surgery although even experienced surgeons may acquire some valuable tips. The videos in general are supportive and will help to drive home the key steps for each procedure presented. The authors should be congratulated on the extensive work required in producing this manuscript.

Paul Park
Ann Arbor, Michigan

The authors have reviewed their own series of minimally invasive tubular procedures and combined that with an extensive literature review to create a resource that would serve well for anyone wishing to review or integrate minimally invasive tubular procedures into their practice. Minimally invasive techniques are increasingly being integrated into mainstream modern spine practice[1] and have been shown to have many benefits over traditional open techniques including improved local biomechanics.[2,3] Knowledge of the basic minimally invasive lumbar decompression techniques would be a great starting point for a surgeon looking to expand their spine surgery toolbox. This article does well in promoting minimally invasive spine surgery.

Christopher C. Gillis
Vancouver, Canada

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