Pathophysiology of Minimally Invasive Surgical Approaches: Current Concepts

Kris Siemionow[1] Marcin Tyrakowski[1,2] Piotr Janusz[1,3] Andrzej Maciejczak[4]

[1] Department of Orthopaedic Surgery, University of Illinois at Chicago, Chicago, Illinois, United States
[2] Department of Orthopaedics, Pediatric Orthopaedics and Traumatology, The Centre of Postgraduate Medical Education, Warsaw, Poland
[3] Spine Disorders Unit, Department of Pediatric Orthopedics and Traumatology, University of Medical Sciences in Poznan, Poznan, Poland
[4] Department of Neurosurgery, University of Rzeszow, Tarnow, Poland

Address for correspondence Kris Siemionow, MD, Department of Orthopaedic Surgery, 835 S. Wolcott Avenue, Room E-270, Chicago, Illinois 60612, United States (e-mail: siemiok@gmail.com).

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Abstract

Spine surgery is a continuously evolving field. Traditional posterior midline approaches to the lumbar spine are associated with muscle injury. Common mechanisms of injury include ischemia, denervation, and mechanical disruption of tendinous attachments of lumbar muscles. Muscle injury may be documented with chemical markers (creatinine kinase, aldolase, proinflammatory cytokines), by imaging studies, or with muscle biopsy. Minimally disruptive surgical approaches to the spine have the potential to minimize the trauma to muscular structures and thus improve the outcomes of surgery. The impact of minimally invasive spinal surgery on long-term clinical outcomes remains unknown. State-of-the-art pathophysiology of minimally invasive spine surgery is presented in this review.

Keywords
- ► minimally invasive spine surgery
- ► multifidus muscle
- ► minimally disruptive spine surgery

Introduction

Spine surgery is a continuously evolving field. The last decade has witnessed the development of less invasive surgical techniques. Advances in navigation, tissue retractors, and other specialized instruments have enabled surgeons to perform decompressions, and even fusions, through smaller incisions, with less disruption of muscle and soft tissue. It is important to note that the goals of decompression and stabilization are accomplished with minimally disruptive surgery. A growing body of literature is demonstrating the physiologic advantages of less disruptive surgery. This article reviews key biological concepts that support this surgical approach.

Anatomy

The basic concept behind all minimally disruptive approaches is the reduction of trauma to paraspinal muscle groups. The posterior paraspinal muscles are composed of two groups: the deep paramedian transversospinalis muscle group, which includes the multifidus, interspinalis, intertransversus, and short rotators, and the superficial and lateral erector spinae muscles (longissimus and iliocostalis) (►**Fig. 1**). These muscles span the thoracolumbar spine and insert distally onto the sacrum, the sacroiliac joint, and the iliac wing. In contrast to other paraspinal muscles, the multifidus muscle has a large physiologic cross-sectional area (PCSA) and short fibers. As a result of its unique structure, the multifidus muscle is designed to create large forces over relatively short distances, making it a major posterior stabilizer of the spine.[1–8]

It is important to note that the multifidus sarcomere is positioned along the ascending portion of the length-tension curve. As a result of this fiber arrangement, the multifidus muscle is able to produce more force as the spine flexes

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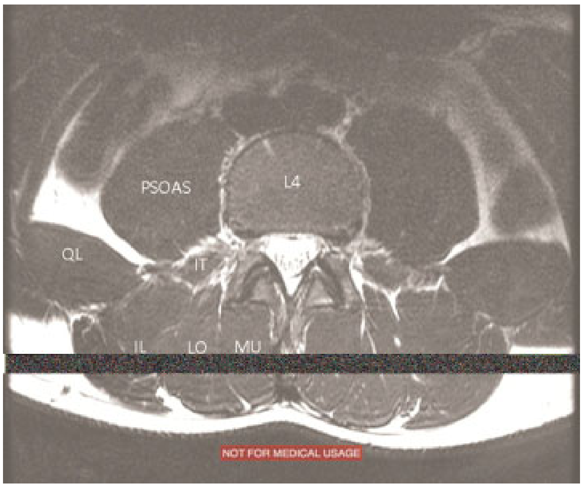

Fig. 1 Axial T-2 weighted magnetic resonance image at the L4 vertebral body level showing the psoas (PSOAS), the multifidus (MU), iliocostalis (IL), longissimus (LO), quadratus lumborum (QL), and intertransversarii (IT) muscles.

forward, protecting the spine when it is in the most vulnerable position. The morphology of the multifidus muscle is complex, and unlike other paraspinal muscles, which have specific origins and insertions, the multifidus muscle is formed by five separate bands.[9] Each band is composed of several fascicles arising from the tip of the spinous process and the lateral surface of the vertebral lamina. As one proceeds caudally, the various fascicles diverge into separate attachments on the mamillary processes of the caudal vertebrae, two to five levels below their origin. The deepest fibers of the multifidus muscle are thought to provide segmental stabilization of the lumbar spine.[10,11]

The erector spinae muscles are composed of the longissimus, the iliocostalis, and the spinalis.[5,12,13] In the lumbar spine, the longissimus muscle is positioned lateral to the multifidus muscle and originates from the transverse and accessory processes and inserts caudally into the ventral surface of the posterior superior iliac spine. The iliocostalis muscle is lateral to the longissimus muscle and originates from the tip of the transverse processes and the adjacent middle layer of the thoracolumbar fascia and inserts into the ventral edge of the iliac crest caudally.[12,14] In contrast to the multifidus muscle, microarchitectural studies reveal that the iliocostalis and longissimus muscles contain long muscle fascicles with a relatively small PCSA. This anatomical arrangement suggests that they serve to move the trunk in extension, lateral bending, and rotation. They are more likely to act as secondary stabilizers of the spinal column.[15]

Paraspinal Muscle Injury during Posterior Spinal Surgery

Traditional posterior midline approaches to the lumbar spine result in muscle atrophy.[4,7,16–24] The multifidus muscle is the most likely muscle to be injured during the standard posterior approach to the lumbar spine. Atrophy, marked by a decrease in the muscle cross-sectional area (CSA), in turn leads to decreased force production capacity of the muscle; certainly these changes are not without consequence.[25,26]

Glycerol is an important component of glycerophospholipid, the basic structural component of the cell plasma membrane. When the integrity of the cell membrane is disrupted, glycerol is released into the interstitial fluid. Ren et al demonstrated increased glycerol concentrations in the paraspinal muscles of patients undergoing instrumented posterolateral lumbar fusions when compared with glycerol concentrations in the patients' unoperated deltoid muscles, which served as a control.[27]

Kim et al studied markers of tissue injury in the blood of patients undergoing open versus minimally invasive fusions.[28] Markers of skeletal muscle injury (creatinine kinase, aldolase), proinflammatory cytokines (interleukin [IL]-6, IL-8), and anti-inflammatory cytokines (IL-10, IL-1 receptor antagonist) were found to be elevated several fold in patients undergoing open surgery. Most markers in the minimally invasive fusion group returned to baseline by 3 days, whereas patients in the open surgery group required 7 days.

Muscle biopsies obtained from patients undergoing revision spinal surgery have shown selective type II fiber atrophy, widespread fiber type grouping (a sign of reinnervation), and a moth-eaten appearance of muscle fibers.[29]

Several mechanisms are responsible for iatrogenic muscle injury. Self-retaining retractors are a common cause of muscle injury. They have a tourniquet effect on the muscle and result in local ischemia followed by reperfusion injury.[30–32] Self-retaining retractors cause elevated tissue pressures that result in decreased intramuscular perfusion.[33,34] The severity of the muscle injury is directly proportional to the degree of the intramuscular pressure and the length of retraction time.

Application of tubular retractors through a limited approach reduces crush injury observed with self-retaining retractors.[35] To our knowledge, no published studies have directly compared paraspinal muscles pressure after application of a tubular versus a self-retaining retractor. The superiority of tubular retractors may be anticipated based on better early clinical outcomes.[36–40] However, better outcomes are not only results of the difference in pressure exerted on the paraspinal muscles by the retractors, but they are also a result of their approach-related features such as avoiding detachment of the musculotendinous complex from the vertebrae and the reduced likelihood of injuring the neurovascular bundles.[35,36]

The next proposed mechanism of iatrogenic injury occurs during dissection of the multifidus muscle in conventional posterior lumbar procedures. Cutting of the tendinous origin on the spinous process may destroy the physiologic binding between muscle fibers and bone, and healing of the muscle to the bone may be affected postoperatively.[4] Destroying the internal vasculature and tissue structure of this muscle during exposure may also cause ischemic necrosis of the multifidus muscle. Resection of the dorsal vertebral bony structures (spinous process, lamina) for posterior decompression of the nerves compromises the bony insertion and separation of bilateral multifidus muscles and changes its physiologic function postoperatively.[35]

Another mechanism leading to muscle degeneration and atrophy following surgery is muscle denervation. The innervation of the multifidus muscle is monosegmental, making it especially vulnerable to injury.[9] The multifidus muscle is innervated by the medial branch nerve that originates from the dorsal rami of each of the lumbar spinal nerves.[41] Damage to the neuromuscular junction following prolonged muscle retraction can also lead to muscle denervation. Because the medial branch nerve passes near the mamillary process, it is at risk when using traditional pedicle screw insertion techniques.[42] Regev et al compared the risk of transecting the medial branch nerve after pedicle screw insertion using mini-open versus percutaneous minimally invasive techniques.[42] Medial branch nerve transection was observed in 84% of cases when the pedicles were instrumented using the mini-open technique and in 20% when the percutaneous insertion technique was used. Muscle biopsies in patients diagnosed with failed back syndrome showed signs of advanced chronic denervation consisting of group atrophy, marked fibrosis, and fatty infiltration.[43]

Application of Minimally Disruptive Techniques to Preserve Spinal Function

Strategies used during minimally disruptive surgery result in less muscle trauma, avoid disruption of tendinous attachments, and minimize damage to the neurovascular supply. Kim et al compared lumbar muscle strength between patients treated with open posterior instrumentation versus percutaneous instrumentation.[44] Patients undergoing percutaneous instrumentation displayed $> 50\%$ improvement in lumbar extension strength, whereas patients undergoing open surgery had no significant improvement in lumbar extension strength.

Stevens et al used magnetic resonance imaging (MRI) to analyze the postsurgical appearance of the multifidus muscle.[45] In patients treated with a traditional open posterior transforaminal lumbar interbody fusion (TLIF) technique, marked intermuscular edema was observed on MRI at 6 months postoperatively. In contrast, patients in the mini-open TLIF group had a normal multifidus muscle appearance on MRI at 6 months following surgery. Tsutsumimoto et al demonstrated that multifidus muscle atrophy and T2 signal intensity on MRI after mini-open PLIF were significantly lower than those observed in patients following an open PLIF. There was no difference in Japanese Orthopedic Association scores between the two groups.[46] Wang et al showed that the MRI T2 relaxation time of the multifidus muscles was significantly shorter in patients who underwent minimally invasive TLIF versus patients who had open TLIF 3 months postoperatively.[47] The electromyographic examination revealed that the average discharge amplitude and frequency of the sacrospinalis muscle were significantly higher in minimally invasive surgery (MIS). Clinical outcomes (Oswestry Disability Index [ODI] and visual analog scale [VAS] scores) were similar in both groups and better postoperatively than preoperatively.

Fan et al also found that the cross-sectional area of the multifidus muscle in MRI scanning was significantly lower in the open PLIF than in the minimally invasive PLIF group of patients.[48] The postoperative ODI and VAS scores were lower in patients who underwent minimally invasive PLIF than open surgery PLIF. However, there are reports showing no benefits of minimally invasive techniques regarding the postoperative atrophy of the multifidus muscle on MRI scans as well as the clinical outcomes.

Arts et al conducted a double-blind randomized study on patients with lumbar disk herniation, comparing tubular diskectomy and conventional microdiskectomy in aspects of creatine phosphokinase (CPK)1 and CPK2 serum concentrations, atrophy of the multifidus muscle by measuring CSA on the MRI, and clinical outcomes measured with the VAS scale.[49] There were no significant differences in the serum CPK concentration 1 day after the surgery and in atrophy grade 1 year after the surgery between the groups. Postoperative low-back pain improved in both groups; however, the improvement at 1-year follow-up was in favor of conventional microdiskectomy.

In addition to being muscle sparing, minimally disruptive techniques also strive to limit the amount of bony resection, thus limiting the chance of creating postoperative spinal instability.[50,51] Specifically, disruption of the facet joints combined with loss of the midline interspinous ligament complex, as occurs during traditional laminectomy, can contribute to flexion instability.[52–54] Efforts to limit such potentially destabilizing surgery have focused on developing ligament-sparing techniques. For instance, unilateral laminotomies in which the spinous processes and corresponding tendinous attachments of the multifidus muscle and the supraspinous/interspinous ligaments are preserved theoretically minimize the chance of developing postoperative instability. Based on finite element analysis, limiting the extent of bony resection can improve spinal stability. Limiting bone and ligament removal resulted in greater preservation of normal motion in the lumbar spine.[55]

As an example of MIS technique, we present a patient who underwent minimally invasive TLIF with an expandable cage at the L4–L5 level and subsequent percutaneous posterior spinal fixation with pedicle screws (►**Figs. 2–6**).

According to the American Association of Neurological Surgeons, MIS can be divided into percutaneous, endoscopic, and minimal access.[56] The vast majority of literature concerning injuries to muscles describe minimal access procedures or percutaneous screws insertion.

Considering MIS in the context of its less disruptive influence on paraspinal muscles, other features of MIS are worthy of mention. These include a reported reduction of postoperative pain, blood loss, and recovery time.[36,37,57]

Limited exposure and visualization frequently associated with MIS raise the question about possible incomplete decompression of neural structures. To our knowledge, no studies have directly assessed the adequacy of MIS decompression; however, clinical outcome and reoperation rates can be considered indirect markers of adequate decompression.[58] However, worse short-term clinical results in MIS diskectomy compared with microdiskectomy or open diskectomy were described by Rasouli et al in a Cochrane review.[37]

Fig. 2 Minimally invasive transforaminal lumbar interbody fusion with expandible cage with surgeon operating through a tube expander.

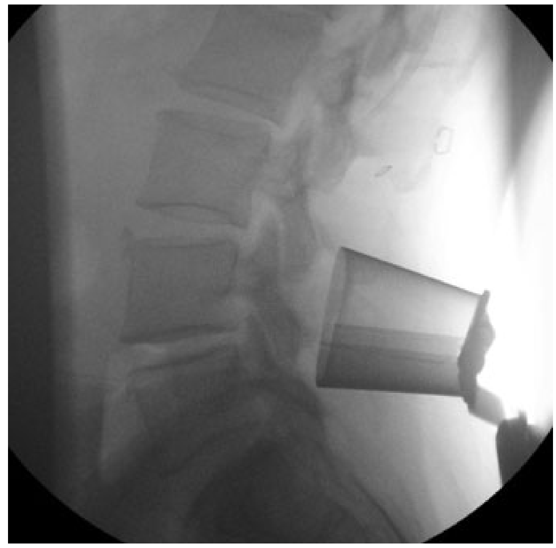

Fig. 4 Intraoperative X-ray: tube expander placed in proper position at the L4–L5 level.

However, in long-term follow-up, large sample research and meta-analysis revealed equivalent long-term outcome in both MIS and open surgery groups.[38–40,58–61]

Infection rates associated with MIS are reported to be lower than those reported for open surgery. Ee at al described a 5.77 times lower infection rate in MIS TLIF, laminectomy, and diskectomy when compared with open surgery.[62] Parker et al performed a cumulative calculation of reported infection incidence from 10 MIS-TLIF and 20 open-TLIF cohorts and described the surgical site infection rate as 0.6% for MIS versus 4.0% for open TLIF.[63]

Another concern of MIS interbody procedures related with small exposure is obtaining a successful fusion. Meta-analysis of fusion rates in MIS TLIF versus open surgery found the fusion rates to be 94.8% versus 90.9%, respectively.[64] However, bone morphogenetic protein 2 was much more commonly used in the reported MIS TLIFs.[64]

Among the typical intraoperative complications of MIS, dural tear, neural injuries, malposition of implants, guidewire fracture, or nonunion can be listed.[38,40] Incidental durotomies and nerve root injuries were more commonly reported in patients undergoing minimal invasive diskectomy with total complication rate at a similar level.[38,65] Published data regarding complications rate vary; however, in comprehensive reviews and meta-analyses they are comparable[59,66] or even lower in MIS fusion.[39] When reporting MIS

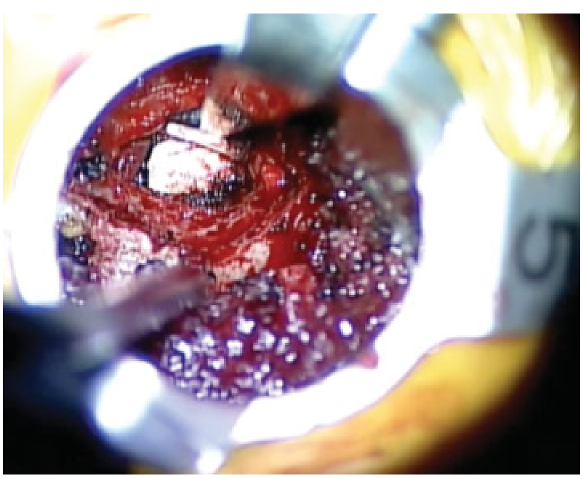

Fig. 3 View of the intervertebral disk through the tube.

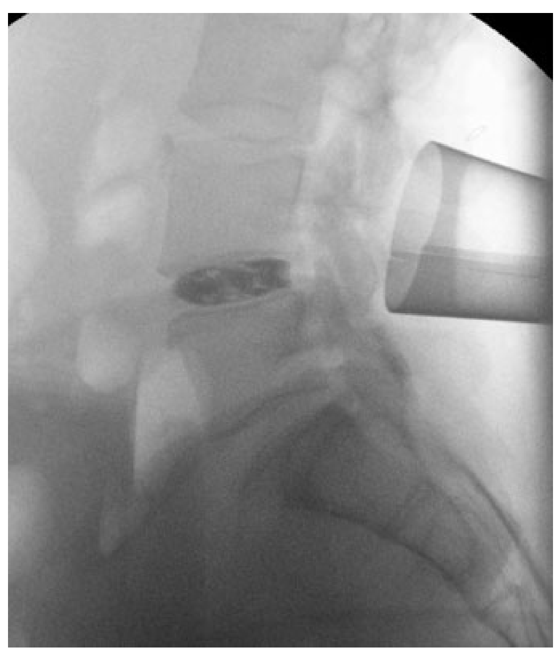

Fig. 5 Intraoperative X-ray: final cage expansion at the L4–L5 level.

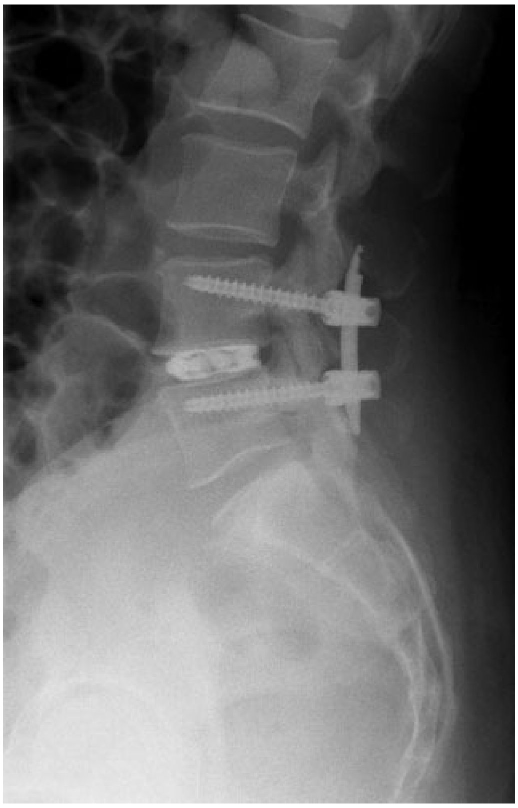

Fig. 6 Intraoperative X-ray: posterior spinal instrumentation with minimally invasive pedicle screws insertion at the L4 and L5 levels.

complications, the learning curve should be taken into consideration.[35,40]

Conclusion

Minimally disruptive spine surgery aims to minimize surgical morbidity, reduce postoperative recovery time, and improve outcomes. These techniques rely on limiting surgical dissection while safely achieving the goals of decompression and stabilization. As minimally disruptive spine surgery continues to evolve, the risks and benefits of various techniques must be evaluated. Although short-term data are encouraging, long-term prospective randomized studies are necessary to determine whether minimally disruptive approaches offer a significant clinical advantage over traditional open procedures.

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