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EDITORIAL

Breaking Through the "Glass Ceiling" of Minimally Invasive Spine Surgery

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Minimally invasive spine (MIS) surgery has rapidly evolved over the past decade and is increasingly being applied in the treatment of complex spinal pathologies. This journal last published a focus issue on MIS surgery in late 2010 and, in that issue, set forth the following, "We propose a definition [of MIS surgery] based on identifying the common goals and principles of MIS surgery—'An MIS procedure is one that by virtue of the extent and means of surgical technique results in less collateral tissue damage, results in [a] measureable decrease in morbidity and more rapid functional recovery than traditional exposures, without differentiation in the intended surgical goal.'"[1] At the time of the last focus issue, MIS surgery could well be described as having been in its adolescence, as was reflected in the table of contents that was dedicated primarily to describing foundational components to performing MIS surgery (*e.g.*, MIS anesthetic and analgesic requirements,[2] the role of intraoperative neuromonitoring in MIS surgery,[3] muscle splitting *versus* muscle sacrificing techniques,[4] and an editorial on the potential economics of MIS approaches[5]). Other reports from the issue focused on technical advancements with some early confirmatory evidence, especially for more advanced applications such as adult deformity correction[6] and corpectomy,[7,8] and included review articles with limited scope (due to the lack of published evidence at that time).[9,10]

What has changed in the last five and a half years in MIS surgery? In 2010, approximately one of six instrumented spine procedures in the United States was performed with a minimally invasive exposure. In 2016, that number is nearing one in three, with estimates that more than half of all spine procedures will be performed with minimally invasive techniques by 2020. In short, twice as much MIS surgery is being performed today compared to five and a half years ago. Many procedures, such as discectomy, have for some time and continue to be performed with MIS exposures but fusion techniques, in particular, have seen relatively larger shifts to smaller exposures. However, there remain rate-limiting factors to wider spread adoption of certain MIS techniques such as extended learning curves and the technical challenges of addressing more complex spinal disease. It has been suggested these factors impose a ceiling effect on the capabilities, especially with respect to indications, for MIS surgery.[11] The current focus issue sets out to begin to assess this assumption to determine whether we have reached a true ceiling in MIS surgery or if with new evidence and techniques we are able to break through the glass ceiling.

With the increasing adoption of MIS techniques, there has been a concomitant increase in the volume and quality of evidence available to guide evidence- and experience-based decision making. In 2010, a literature review of available MIS lateral approach outcomes studies was performed and listed 14 articles.[12] In 2015, a lateral approach systematic review identified nearly 250 published articles.[13] Karikari and Isaacs[10] reviewed comparative studies of MIS and

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open transforaminal or posterior lumbar interbody fusion (T/PLIF) in 2010 as part of the first MIS focus issue and found seven articles. A similar systematic review was undertaken in 2012 by Goldstein *et al*[14] and 26 original studies meeting their inclusion criteria were found. That same literature review performed less than 3 years later by Goldstein *et al* reported 45 articles, and is included in this issue.[15] With the expansion of the breadth and depth of available literature, our understanding of the techniques, indications, outcomes, and limitations has grown substantially.

In parallel, MIS techniques continue to be applied in new and/or more advanced settings and in patients with comorbidities that would make open surgeries challenging.[16,17] In 2010, MIS procedures were largely performed for simple degenerative pathologies, with the lateral approach gaining some traction in the treatment of spinal infections, tumors, and trauma.[7,8] MIS techniques today now play an important role in the treatment of adult deformity, an area of significant continued growth and potential. In 2010, MIS lateral interbody fusion was first being reported in the treatment of degenerative scoliosis, with an analysis of complications and perioperative results,[6] as well as with technical considerations as part of ''experience-based medicine'' articles from the first MIS focus issue.[18] In 2016, there are dozens of reports of MIS approaches being used to treat simple as well as moderate-to-severe deformity,[19–47] and many of the prominent spine institutions around the country are performing MIS surgery and teaching these techniques and approaches in their training programs.[25,32,33,48–55] Applications of MIS approaches in adult deformity have received considerable scrutiny in the recent literature. Studies have confirmed that MIS deformity procedures result in substantial decreases in approach-related morbidity compared to similar procedures performed with open exposures,[13–16,56–61] longer-term outcomes in MIS spine surgery are at least equivalent to conventional exposure procedures,[14,15,58,59,61–63] and that the early benefits in morbidity reduction and more efficient care during the surgical period may bend the cost curve and result in significant cost-effectiveness over open spine surgery for many indications.[13,36,56–58,61]

Recently, a suggestion of a ceiling effect in the capability of MIS approaches to treat more advanced deformity has been published,[11] although there are legitimate concerns about whether or not this retrospective observational series is simply reporting selection bias where MIS approaches were chosen to treat less severe deformity rather than those techniques not technically being able to treat advanced deformity. With the advent of more advanced MIS technologies, particularly those designed to treated more advanced deformity,[64] the ceiling has been dramatically raised and will continue to rise over the next 5 years. Modern MIS techniques in deformity include ''hybrid'' surgery with MIS interbody fusion and open posterior fusion, the use of percutaneous posterior instrumentation with MIS osteotomies, or the application of anterior column realignment (ACR) techniques performed through MIS lateral or anterior approaches.[31,33,64–69] Other MIS techniques that continue to progress are the use of percutaneous instrumentation in the thoracic spine and ilium, the expansion of retropleural approaches in the thoracic spine, and expandable implants that can be placed through smaller approach corridors and expanded to improve spinal alignment and provide indirect decompression.

Despite all this, the question remains—have we reached or are we nearing the limits of applications of MIS technology? This issue is intended to provide evidence to begin to solidify and crack through current understanding of the limitations and applications of MIS techniques.

Within this issue, you will find a substantial amount of both new and confirmatory evidence on modern MIS techniques and procedures. New techniques for less invasive posterior interbody and posterolateral fusion have been developed and are dependent upon cortical bone trajectory pedicle screw and rod fixation. Khanna *et al* in this issue present technical considerations for a medialized, muscle-splitting PLIF approach, whereas Bae *et al* report on 2-year outcomes of a medialized posterior fusion. As direct posterior approaches remain the most commonly performed exposures in spine surgery, there is considerable interest in utilizing muscle-preserving approaches as a way of reducing morbidity and complications.

This edition also includes an important 2-year, prospective, multicenter comparative study of two MIS approaches for degenerative spondylolisthesis: MIS lateral interbody fusion and MIS TLIF. These reports find largely similar 2-year clinical and radiographic outcomes, despite different mechanisms of action—indirect *versus* direct decompression—and provide further comparative outcomes of modern MIS approaches. As has been previously mentioned, Goldstein, Phillips, and Rampersaud in this issue present a systematic literature review of the complications, outcomes, and economics of MIS *versus* open T/PLIF with near universal benefits seen in all clinical and economic parameters studied for MIS compared to open exposures.

This issue also contains several examples of new frontiers in MIS surgery. First, there continue to be significant efforts to minimize cost while improving the patient experience and outcome. It is apparent that hospitals are not always the most efficient venues for providing elective surgery in relatively healthy patients. Smith, Rodgers, and Wohns present a large-scale predictive analysis of patient factors associated with the ability to perform lumbar fusion in an outpatient setting, as well as a multicohort series of ambulatory MIS lumbar fusion patients presented as confirmatory evidence of the predictive analysis. This will allow for greater evidence-based decision making in selecting the appropriate venue for the appropriate patients based on patient pathology and the procedure to be performed. If even a fraction of spine surgery currently being performed at an inpatient facility could be responsibly and reproducibly converted to an outpatient setting, significant cost savings could be realized by society and more efficient care would be delivered to patients.

The biggest area we, as a group, feel has the potential for continued rapid growth in MIS procedural adoption and technological advancement is in advanced deformity correction. Historically, several articles have reported insufficient sagittal correction following lateral and MIS interbody fusion for scoliosis[19] or even degenerative conditions.[37] Arguably the most important advancement in the ability of MIS techniques to improve sagittal alignment was the development of ACR techniques that utilize anterior longitudinal ligament release with placement of hyperlordotic cages in mini-open lateral and anterior interbody fusions. Akbarnia *et al*[64] and Turner *et al*[68] have examined multicentric mid-term outcomes of the ACR approach and have found the ability to correct segmental alignment with ACR equivalent to that gained with a Smith-Petersen osteotomy, although with blood loss just more than 100 mL. In this issue, Akbarnia *et al* as well as Kanter *et al* review the literature to present technical considerations and outcomes following ACR and also a broader analysis of MIS techniques for the treatment of adult deformity.

With greater understanding of the consequences of sagittal malalignment in spine surgery, an inability to correct sagittal plane deformity with MIS procedures would be a major limitation. In this issue, Uribe and Youssef report findings from a literature review of alignment outcomes and predictors of alignment in MIS interbody fusion techniques for short-segment degenerative pathology. Their results suggest that appropriately selected MIS approaches are able to significantly increase segmental and lumbar lordosis. Articles in this issue also tackle contemporary issues being used to qualify MIS techniques, including what is the evidence-based role of neuromonitoring in lateral transpsoas approaches (Cheng and Acosta) as well as the introduction of a "take-off" checklist in performing extreme lateral interbody fusion (XLIF), to help systematize and encourage reproducibility of a detail-oriented exposure.

Despite the new and confirmatory evidence presented in this issue, there remain several areas for continued MIS advancements including in new diagnostics and prognostics, cervical applications, the treatment of rigid deformities, the expanded use of navigated technologies, and in the reduction of radiation for the surgical team and patient.

In summary, we do not believe that we have hit a true ceiling with respect to the capabilities of MIS techniques. As with nearly all other surgical specialties, minimally invasive approaches have incrementally replaced open exposures and this similar progression in spine surgery has become undeniable. The cumulative and consistent evidence in this field confirms we are near or at the tipping point of MIS procedures to be increasingly, and at some point solely, used in responsible applications with appropriate techniques in properly selected patients at the most efficient surgical venues.

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