Is Less Really More? Economic Evaluation of Minimally Invasive Surgery

Andrew S. Chung, DO1, Alexander Ballatori, MS1, Brandon Ortega, MD1, Elliot Min, MD1, Blake Formanek, BA1, John Liu, MD1, Patrick Hsieh, MD1, Raymond Hah, MD1, Jeffrey C. Wang, MD1, and Zorica Buser, PhD1

Abstract

Study Design: Review.

Objective: A comparative overview of cost-effectiveness between minimally invasive versus and equivalent open spinal surgeries.

Methods: A literature search using PubMed was performed to identify articles of interest. To maximize the capture of studies in our initial search, we combined variants of the terms “cost,” “minimally invasive,” “spine,” “spinal fusion,” “decompression” as either keywords or MeSH terms. PearlDiver database was queried for open and minimally invasive surgery (MIS; endoscopic or percutaneous) reimbursements between Q3 2015 and Q2 2018.

Results: In general, MIS techniques appeared to decrease blood loss, shorten hospital lengths of stay, mitigate complications, decrease perioperative pain, and enable quicker return to daily activities when compared to equivalent open surgical techniques. With regard to cost, primarily as a result of these latter benefits, MIS was associated with lower costs of care when compared to equivalent open techniques. However, cost reporting was sparse, and relevant methodology was inconsistent throughout the spine literature. Within the PearlDiver data sets, MIS approaches had lower reimbursements than open approaches for both lumbar posterior fusion and discectomy.

Conclusions: Current data suggests that overall cost-savings may be incurred with use of MIS techniques. However, data reporting on costs lacks in uniformity, making it difficult to formulate any firm conclusions regarding any incremental improvements in cost-effectiveness that may be incurred when utilizing MIS techniques when compared to equivalent open techniques.

Keywords
minimally invasive, cost, spine surgery, TLIF, deformity, discectomy

Introduction

Health care in the United States accounts for 18% of its gross domestic product, approximately twice as much as other high-income countries.1 A significant contributor to this economic load is spine-related health care expenditures.2 Out of necessity, implementation of bundled payments has led to the coordination of patient care among hospitals and surgeons with a greater emphasis on improving both quality of care and cost-efficiency.3

Recent advancements in techniques and instrumentation have further increased the utilization of minimally invasive surgical techniques by expanding indications to include decompression, fusion, trauma, deformity, and oncology.4 Initial reports found that minimally invasive surgery (MIS) had a higher upfront cost for implants and equipment.5 As a result of a steep associated learning curve, higher initial operative times also made MIS appear to be more expensive than equivalent open surgeries.6 However, recent literature suggests that MIS may actually offset these higher costs by lowering complications, infections, hospital length of stay (LOS), estimated blood loss (EBL), and recovery time.5,7,11

1 University of Southern California, Los Angeles, CA, USA

Corresponding Author:
Zorica Buser, Department of Orthopedic Surgery, Keck School of Medicine, University of Southern California, 1520 San Pablo St, Suite 2000, Los Angeles, CA 90033, USA.
Email: zbuser@usc.edu

Creative Commons Non Commercial No Derivs CC BY-NC-ND: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs 4.0 License (https://creativecommons.org/licenses/by-nc-nd/4.0/) which permits non-commercial use, reproduction and distribution of the work as published without adaptation or alteration, without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
In the era of the opioid epidemic, MIS can also further mitigate costs by decreasing approach-related morbidity, postoperative pain, and subsequent opioid demand. The economic burden of prescription opioid overdose, abuse, and dependence in the United States was estimated to be $78.5 billion in 2013.12 Numerous studies have demonstrated a significant decrease in postoperative pain using MIS techniques.13,14 In this context, significant advancements in postoperative pain management protocols have helped further drive down costs associated with surgical episodes of care by enabling many MIS spine procedures to be performed in an outpatient setting.15

While a fair number of studies have evaluated the cost-effectiveness of MIS, definitive conclusions regarding the economic value of MIS cannot be made given the significant variability in cost comparison methodologies.16 Therefore, the primary objective of this study is to serve as a comparative overview of cost-effectiveness between minimally invasive versus equivalent open spinal surgeries. Secondly, a brief comparative overview of clinical outcomes between minimally invasive versus open spinal surgical outcomes is offered.

Methods

A literature search using PubMed was performed to identify articles of interest. To maximize the capture of studies in our initial search, we combined variants of the terms “cost,” “minimally invasive,” “spine,” “spinal fusion,” “decompression,” “deformity,” “discectomy,” “trauma,” “tumor” as either keywords or MeSH terms. All retrieved articles were then further reviewed to match our inclusion and exclusion criteria. We included all clinical studies evaluating minimally invasive and comparative open surgical spine outcomes. We excluded all basic science and animal studies. In addition to cost analyses performed, additional attention was paid to study design, indication for surgery, surgical intervention, sample size, age, operative time, blood loss, perioperative complications, and LOS.

Additionally, we assessed reimbursement costs using commercially available data sets. Costs of open and minimally invasive (endoscopic and percutaneous) surgery were compared using the PearlDiver online health care database (www.pearldiverinc.com) to analyze Mariner all payer claims dataset. Using the Classification of Diseases, Tenth Revisions (ICD-10), procedure codes between Quarter 3 of 2015 and Quarter 1 of 2017, patients were queried and grouped based upon their surgery (open fusion, MIS fusion, open discectomy, MIS discectomy), anterior or posterior approach, and whether the surgery was single or multi-level. Within each surgical group, patients with outlier costs were excluded so that only patients comprising the range between the 25th and 75th percentiles were analyzed. Averages and standard deviations of the insurance reimbursement rates were then analyzed for each surgical group. Total reimbursements for 2016 for each surgical group were reported as well. Due to the PearlDiver policy, groups with less than 11 patients were excluded. T-test was used to calculate significant differences between open and MIS groups with \( P < .05 \) being significant.

Results

Lumbar Stenosis

Minimally invasive lumbar decompression for the treatment of symptomatic lumbar stenosis has been shown to be equivalent to, and in some aspects, superior to equivalent open approaches.17-19 In regard to cost-effectiveness, Parker et al conducted a 2-year cost utility study on open versus MIS multi-level hemilaminectomy for the treatment of symptomatic lumbar stenosis.20 Open technique involved the use of a subperiosteal dissection via a midline approach, while the MIS approach utilized tubular retractors via a paramedian approach. A total of 54 patients (27 open vs 27 MIS) were included in the study. All patients had multilevel (\( \geq 2 \)) pathology, with 42 (78%) patients undergoing a 2-level decompression and 12 (22%) patients undergoing a 3-level decompression. Clinical outcomes were measured via visual analogue scale (VAS) scores for low back pain, VAS scores for leg pain, Oswestry Disability Index (ODI) scores, Short Form (SF)-12 physical and mental component scores, and EQ-5D scores, while treatment effectiveness was measured via quality-adjusted life years (QALYs). Ultimately, patients in both cohorts improved significantly when compared to preoperative scores. Both open and MIS laminectomy were associated with a cumulative gain of 0.72 QALYs 2 years after surgery. Total 2-year mean cost for open hemilaminectomy was $25,420 (95% confidence interval: $25,389 to 25,450) versus $23,109 (95% confidence interval: $23,078 to 23,140) for the MIS approach \( (P = .21) \). Both groups had similar resource utilization (ie, outpatient visits, spine-related diagnostic tests, injections, assist devices, emergency room visits, and rehabilitation or nursing facility days). Ultimately, they concluded that MIS multilevel hemilaminectomy is associated with similar cost over 2 years when compared to a traditional open approach.

Knight et al compared outcomes and cost utilization in open versus MIS approaches to lumbar stenosis as well in a group of 104 patients.21 Thirty-eight (37%) patients underwent open decompression while 66 (63%) underwent MIS decompression. This study analyzed single-level decompression in addition to multilevel surgery, with no significant difference in number of levels decompressed in both groups. Consistent with prior studies, there was no significant difference in clinical outcomes between the 2 groups. In terms of cost analysis, this study analyzed the median cost per procedure type for Medicare patients only by looking at median operation room time cost and median LOS cost. For stenosis patients, median cost for open procedures was significantly higher compared to a tubular approach ($7305 vs $4518, \( P < .0001 \)). In this study, as a result of shorter operation room times and LOS, the direct cost of an MIS approach to lumbar stenosis appears to be significantly lower than that of an open approach.

Lumbar Discectomy

One cost-utility study from the Netherlands specifically examined open versus MIS tubular approaches to lumbar disc...
when compared to their open counterparts. Multiple studies had a significantly lower 6-month postoperative VAS score from $3569 to $9295 per patient, while direct hospital to indirect costs which account for productivity loss, ranged savings, which accounted for direct hospital costs in addition to indirect costs which account for productivity loss, ranged from $3569 to $9295 per patient, though this was not significant. The authors also compared total non–health care costs, including loss of productivity, domestic help, informal care, and out-of-pocket expenses, and found a difference of $1032 in favor of open microdiscectomy versus MIS ($11,329 vs $10,297, P = .42). Overall, the authors conclude that MIS microdiscectomy is not likely to be cost-effective when compared to an open approach.

The cost-effectiveness of percutaneous and endoscopic discectomy has also been demonstrated in the literature. In their retrospective analyses of 456 patients surgically managed for lumbar disc herniations, Choi et al found that endoscopic lumbar discectomy (regardless of technique) was associated with a cost savings of $8064 per QALY when compared to traditional microdiscectomy. A noninferiority randomized controlled trial comparing the effectiveness and cost-effectiveness of percutaneous transforaminal endoscopy versus open discectomy is also currently underway.

Transforaminal Lumbar Interbody Fusion

The most commonly published topic regarding cost-effectiveness in MIS versus open surgery is for transforaminal lumbar interbody fusion (TLIF). Five separate studies from 2012 to 2015 conducted a treatment outcomes and cost analysis of open versus MIS TLIF. All studies demonstrated cost savings for MIS TLIF when compared to open TLIF, though not all differences reached statistical significance. Total savings, which accounted for direct hospital costs in addition to indirect costs which account for productivity loss, ranged from $3569 to $9295 per patient, while direct hospital costs ranged from $1758 to $2820 per patient. In general, patient outcomes were reported to be similar, though in Singh et al, patients who had undergone MIS TLIF had a significantly lower 6-month postoperative VAS score when compared to their open counterparts. Multiple studies reported significant differences in surgical time, anesthesia time, and EBL, as well as LOS in favor of MIS TLIF versus open.

Additionally, Parker et al examined the risk of surgical site infections (SSIs) in MIS versus open TLIF and concluded that open procedures are associated with a higher risk of SSIs (0.6% vs 4.0%, P = .0005). The mean hospital cost associated with treatment of postoperative SSI following TLIF was calculated to be $29,110. The 3.4% decrease in reported incidence of SSI in MIS versus open TLIF corresponds to a direct cost savings of $98,974 per 100 MIS TLIF procedures performed.

Trauma/Fracture

We identified 10 articles comparing open and MIS approaches for treating spinal trauma/fractures. Seven of these studies found that MIS was significantly favorable with respect to operative time, and the remaining 3 studies found no significant difference between MIS and open surgical approaches. Eight studies evaluated intraoperative blood loss, and all 8 studies found that MIS techniques resulted in significantly less blood loss. Of the 6 studies that reported results on LOS, 3 studies found MIS to be the favorable technique and 3 studies did not find any significant differences between MIS and open. Only one Chinese group reported data on costs. In their retrospective cohort study comparing MIS (18 patients) vs a Wiltse approach (21 patients) to fixation of mono-segmental thoracolumbar fractures, Dong et al found that the Wiltse approach resulted in lower total costs when accounting for hospitalization charges and implants used when compared to MIS (open approach $4,23 ± 0.93 compared to MIS $5,31 ± 0.47; expressed in 10,000 Yuan).

Tumor

We identified 11 studies comparing open and MIS approaches to treating spinal tumors. Nine of these studies found that MIS and open procedures did not have significantly different operative times. The remaining 2 studies found that the MIS approach resulted in significantly shorter operative times. Ten studies evaluated intraoperative blood loss, and all but one found that MIS surgical techniques resulted in significantly less blood loss. Ten studies reported results on LOS, of which 7 studies favored MIS and 3 studies did not find a significant difference between the 2 approaches. No studies were identified that compared the costs/hospitalizations charges between MIS and open approaches.

Deformity

We identified 7 studies comparing open and MIS approaches to treating spinal deformities. In terms of operative time, 1 study favored open, 2 studies favored MIS, and the remaining 4 studies found no significant difference between the 2 approaches. All 7 studies reported significantly less blood loss associated with MIS approaches. Of the 6 studies that reported results on LOS, 2 studies favored MIS and the remaining 4 studies did not find any significant differences between the open and MIS approaches. Only 2 studies reported findings on costs and both found that MIS approaches resulted in significantly lower costs/hospitalization charges.

In the first study, Uddin et al conducted a comparative study in their 71 patients (33 open, 38 MIS; ie, TLIF or lateral lumbar interbody fusion) undergoing adult deformity correction for degenerative scoliosis. Utilizing cost data from institutional billing departments, they found that MIS techniques were
associated with significantly lower inpatient and total charges. Average inpatient charges for MIS were $269,807 compared to $391,889 (P < .01) for equivalent open procedures. When adjusting for inflation, the cost savings for inpatient charges associated with MIS was maintained ($292,329 for MIS, compared to $433,620 for open; P < .01). Specifically, an approximate $50,000 savings was observed when comparing costs related to operative time between the 2 groups, favoring MIS; P = .01. Furthermore, MIS was associated with significantly lower mean charges for the use of blood products, cardiac ancillary services, imaging, laboratory tests, pharmacy, and routine nursing costs.54

In their study of 22 patients who underwent T11-pelvis fusions (10 open, 12 transpsoas) with 12-month follow-up, Swamy et al found that use of MIS resulted in an incremental cost savings of $27,869 (CAD) and was associated with 0.06 more QALYs in patients when accounting for the costs associated with complications. In cases without complications, however, the minimally invasive approach was associated with an incremental cost increase of $28,715. Nonetheless, utilizing a probabilistic analysis, they found that the minimally invasive approach was less costly and more effective when compared to the open technique 57% of the time. They concluded that MIS was associated with cost savings and higher quality care when compared to equivalent open surgery.52

A recent study by Park et al found that patient factors influence the decision on the type of surgical approach for the treatment of adult spine deformity.59 Age, Numerical rating Scale (NRS), pelvic incidence-lumbar lordosis, T1 pelvic angle and coronal curve were significant factors contributing to the surgical choice. Increasing age was indicator of MIS approach, while higher NRS score or more severe deformity were indicators for open approach.

**Hospital Reimbursements—PearlDiver Data**

Anterior MIS approaches led to reimbursements from <11 patients and thus anterior reimbursements were not included in the analysis. Across both posterior fusion or discectomy procedures, open approach was associated with higher reimbursements when compared to the respective MIS approach (Table 1). Reimbursement for open posterior 1-level fusion was significantly higher than for corresponding MIS procedure ($40,485.62 vs $9824.83, P = .015). Similar significant trends were seen for multilevel posterior fusion. Difference in the reimbursement between open and MIS discectomy approach was $30,429.93, with open approach having significantly higher costs (P = .01; Table 1).

In 2016, open approaches were performed more frequently than MIS approaches within the Mariner claim database (Figure 1). The most common approaches in 2016 were single-level posterior fusion and discectomy, which also were associated with the highest relative total hospital reimbursements.

**Discussion**

In the last 2 decades, there has been a rapid expansion in the number of MIS surgical techniques that have become available to spine surgeons for the treatment of a myriad of spinal conditions. As surgeons have become more proficient with these techniques and technology has evolved, there is mounting evidence that MIS techniques decrease blood loss, shorten hospital lengths of stay, mitigate complications, decrease perioperative pain, and enable quicker return to daily activities when compared to equivalent open surgery.52

By maximally preserving normal anatomy, MIS techniques may theoretically mitigate the risks of iatrogenic instability and adjacent segment degeneration in the long-term, yielding further potential cost savings. However, despite an emerging body of evidence to support the cost-effectiveness of MIS when compared to equivalent open techniques, this data is plagued

| Average Patient Reimbursement for Open and MIS Fusion and Discectomy Approaches. |
|---------------------------------------------|
| **Average** | **Standard deviation** | **P value** |
| Posterior 1-level fusion | $40,485.62 | $60,717.25 | .015 |
| Posterior 1-level MIS fusion | $9824.83 | $22,829.19 | .015 |
| Posterior multilevel fusion | $39,347.14 | $56,421.36 | .023 |
| Posterior multilevel MIS fusion | $68,488.11 | $17,095.70 | .015 |
| Discectomy | $38,756.96 | $53,423.94 | .01 |
| MIS discectomy | $83,272.03 | $22,441.46 | .01 |

Abbreviation: MIS, minimally invasive surgery.

**Figure 1.** Patient number and total reimbursement for 2016.
by a lack of uniformity in cost reporting and in the comparative methodology used for cost-effectiveness analyses.

It is generally accepted that cost-effectiveness analysis is the best assessment of value. This type of analysis involves the calculation of incremental cost-effectiveness ratios (ICER), which are reported as a cost amount per QALY gained. Classically, the benchmark $50,000 per QALY had been set as the threshold for cost-effectiveness since the 1970s. However, there are significant limitations to this metric. Although unclear, it is thought that this value was calculated within the context of end-stage renal disease, which may limit its translatability to other clinical or surgical settings. Furthermore, given its dated origins, quality per cost may vary secondary to monetary inflation, market forces, and an overall increase in medical spending over the years. Inconsistencies in the definition or calculation of cost are also sources of ICER variability. Consequently, in the literature, multiple ICER thresholds have been utilized throughout the years. In spine, a benchmark of $120,000 per QALY has even been suggested. This substantial heterogeneity in respective data reporting ultimately underscores the fact that despite its acceptance as the standard in reporting cost-effectiveness, ICER is not without its own notable limitations. Ultimately, we found this type of cost analysis rare in the comparative studies we reviewed. Only one study reported their results within the context of ICER.

Unfortunately, given that tubular or mini-open procedures do not have a separate procedural code from open procedures, we were unable to make these cost comparisons in our analyses of the PearlDiver dataset. We did, however, find that percutaneous and endoscopic procedures were associated with cost-savings when compared to open surgeries. While these findings are quite preliminary, with interest in spinal endoscopy at an all-time high, especially outside of the United States, it may suggest that an additional benefit to use of spinal endoscopy is potential cost savings.

With the health care landscape becoming more patient-centric and cost conscious, the demand for minimally invasive spine surgery continues to rise. Current evidence appears to support the potential superiority of MIS-based procedures with regard to short-term outcomes when compared to equivalent open procedures. Furthermore, while initial start-up costs may in some instances be more expensive with use of MIS techniques, when considering the total cost of associated care, current data suggests that overall cost-savings may be incurred with use of MIS techniques. Further savings may be incurred with percutaneous and endoscopic surgery. However, data reporting on costs lacks in uniformity making it difficult to formulate any firm conclusions regarding any incremental improvements in cost-effectiveness that may be incurred when utilizing MIS techniques when compared to equivalent open techniques. Future research should focus on implementing a standardized approach to cost-effectiveness reporting valid, like-to-like comparisons in interventions are made.

Declaration of Conflicting Interests
The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Disclosures outside of submitted work: JCW-Royalties – Biomet, Seapine, Amedica, Synthes; Investments/Options – Bone Biologics, Peardev, Electrocere, Surgitech; Board of Directors - North America Spine Society, AO Foundation, Cervical Spine Research Society, Society for Brain Mapping and Therapeutics, American Orthopaedic Association; Editorial Boards - Spine, The Spine Journal, Clinical Spine Surgery, Global Spine Journal; Fellowship Funding (paid to institution): AO Foundation.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This supplement was supported by a grant from AO Spine North America.

ORCID iD
Andrew S. Chung, DO https://orcid.org/0000-0001-7513-3519
Blake Formanek, BA https://orcid.org/0000-0003-3557-9350
Patrick Hsieh, MD https://orcid.org/0000-0002-7206-4842
Raymond Hah, MD https://orcid.org/0000-0001-7513-3519
Zorica Buser, PhD https://orcid.org/0000-0002-5680-0643

References
1. Papanicolas I, Woskie LR, Jha AK. Health care spending in the United States and other high-income countries. JAMA. 2018;319:1024-1039.
2. Martin BI, Deyo RA, Mirza SK, et al. Expenditures and health status among adults with back and neck problems. JAMA. 2008;299:656-664.
3. Birkmeyer JD, Gust C, Baser O, et al. Medicare payments for common inpatient procedures: implications for episode-based payment bundling. Medicare payments for common inpatient procedures. Health Serv Res. 2010;45(6 pt 1):1783-1795.
4. Vaishnav AS, Othman YA, Virk SS, Gang CH, Qureshi SA. Current state of minimally invasive spine surgery. J Spine Surg. 2019;5(suppl 1):S2-S10.
5. Allen RT, Garfin SR. The economics of minimally invasive spine surgery: the value perspective. Spine (Phila Pa 1976). 2010;35(26 suppl):S375-S382.
6. Nowitzke AM. Assessment of the learning curve for lumbar microendoscopic discectomy. Neurosurgery. 2005;56:755-762.
7. Avila MJ, Walter CM, Bajaj AA. Outcomes and complications of minimally invasive surgery of the lumbar spine in the elderly. Cureus. 2016;8:e519. doi:10.7759/cureus.519
8. Alimi M, Hofstetter CP, Pyo SY, Paulo D, Härtl R. Minimally invasive laminectomy for lumbar spinal stenosis in patients with and without preoperative spondylosis: clinical outcome and reoperation rates. J Neurosurg Spine. 2015;22:339-352.

9. Al-Khouja LT, Baron EM, Johnson JP, Kim TT, Drazin D. Cost-effectiveness analysis in minimally invasive spine surgery. Neurosurg Focus. 2014;36:E4.

10. Parker SL, Adogwa O, Witham TF, Aaronson OS, Cheng J, McGirt MJ. Post-operative infection after minimally invasive versus open transforminal lumbar interbody fusion (TLIF): literature review and cost analysis. Minim Invasive Neurosurg. 2011;54:33-37.

11. Phan K, Hogan JA, Mobbs RJ. Cost-utility of minimally invasive versus open transforminal lumbar interbody fusion: systematic review and economic evaluation. Eur Spine J. 2015;24:2503-2513.

12. Florence CS, Zhou C, Luo F, Xu L. The economic burden of prescription opioid overdose, abuse, and dependence in the United States, 2013. Med Care. 2016;54:901-906.

13. Liu X, Yuan S, Tian Y. Modified unilateral laminotomy for bilateral decompression for lumbar spinal stenosis: technical note. Spine (Phila Pa 1976). 2013;38:E732-E737.

14. Mobbs RJ, Li J, Sivabalan P, Raley D, Rao PJ. Outcomes after decompressive laminectomy for lumbar spinal stenosis: comparison between minimally invasive unilateral laminectomy for bilateral decompression and open laminectomy. J Neurosurg Spine. 2014;21:179-186.

15. Basil GW, Wang MY. Trends in outpatient minimally invasive spine surgery. J Spine Surg 2019;5(suppl 1):S108-S114.

16. Hopkins B, Mazmudar A, Kesavabhotla K, Patel AA. Economic value in minimally invasive spine surgery. Curr Rev Musculoskelet Med. 2019;12:300-304.

17. Shih P, Wong AP, Smith TR, Lee AI, Fessler RG. Complications of open compared to minimally invasive lumbar spine decompression. J Clin Neurosci. 2011;18:1360-1364.

18. Rahaman M, Summers L, Richter B, Mimran RI, Jacob RP. Comparison of techniques for decompressive lumbar laminectomy: the minimally invasive versus the “classic” open approach. Minim Invasive Neurosurg. 2008;51:100-105.

19. Khoo LT, Fessler RG. Microendoscopic decompressive laminotomy for the treatment of lumbar stenosis. Neurosurgery. 2002;51(suppl 5):S146-S154.

20. Parker SL, Adogwa O, Davis BJ, et al. Cost-utility analysis of minimally invasive versus open multilevel hemilaminectomy for lumbar stenosis. J Spinal Disord Tech. 2013;26:42-47.

21. Knight RQ, Scribani M, Krupa N, et al. Lumbar decompressive laminectomy or laminotomy for degenerative conditions: “outcome comparison of traditional open versus less invasive techniques.” J Spine. 2013;S2. doi:10.4172/2165-7939.S2-006

22. van den Akker ME, Arts MP, van den Hout WB, Brand R, Koes BW, Peul WC. Tubular discectomy vs conventional microdiscectomy for the treatment of lumbar disk-related sciatica: cost utility analysis alongside a double-blind randomized controlled trial. Neurosurgery. 2011;69:829-836.

23. Choi KC, Shim HK, Kim JS, et al. Cost-effectiveness of microdiscectomy versus endoscopic discectomy for lumbar disc herniation. Spine J. 2019;19:1162-1169.

24. Wang D, Xie W, Cao W, He S, Fan G, Zhang H. A cost-utility analysis of percutaneous endoscopic lumbar discectomy for L5-S1 lumbar disc herniation: transforminal versus interlaminar. Spine (Phila Pa 1976). 2019;44:563-570.

25. Seiger A, Gadjaridi PS, Harhangi BS, et al. PTED study: design of a non-inferiority, randomised controlled trial to compare the effectiveness and cost-effectiveness of percutaneous transforminal endoscopic discectomy (PTED) versus open microdiscectomy for patients with a symptomatic lumbar disc herniation. BMJ Open 2017;7:e018230.

26. Parker SL, Adogwa O, Bydon A, Cheng J, McGirt MJ. Cost-effectiveness of minimally invasive versus open transforminal lumbar interbody fusion for degenerative spondylosis associated low-back and leg pain over two years. World Neurosurg. 2012;78:178-184.

27. Parker SL, Mendenhall SK, Shau DN, et al. Minimally invasive versus open transforminal lumbar interbody fusion for degenerative spondylosis: comparative effectiveness and cost-utility analysis. World Neurosurg. 2014;82:230-238.

28. Pelton MA, Phillips FM, Singh K. A comparison of perioperative costs and outcomes in patients with and without workers’ compensation claims treated with minimally invasive or open transforminal lumbar interbody fusion. Spine (Phila Pa 1976). 2012;37:1914-1919.

29. Singh K, Nandyala SV, Marquez-Lara A, et al. A perioperative cost analysis comparing single-level minimally invasive and open transforminal lumbar interbody fusion. Spine J. 2014;14:1694-1701.

30. Erichsen CJ, Heyde CE, Josten C, et al. Percutaneous versus open posterior stabilization in AOSpine type A3 thoracolumbar fractures. BMC Musculoskelet Disord. 2020;21:74.

31. Fitschen-Oestern S, Scheuerlein F, Weuster M, et al. Reduction and retention of thoracolumbar fractures by minimally invasive stabilisation versus open posterior instrumentation. Injury. 2015;46(suppl 4):S63-S70.

32. Afoboji A, Weir TB, Usmani MF, et al. Comparison of percutaneous minimally invasive versus open posterior spine surgery for fixation of thoracolumbar fractures: a retrospective matched cohort analysis. J Orthop. 2020;18:185-190.

33. Lee CH, Chung CK, Sohn MJ, Kim CH. Short limited fusion versus long fusion with deformity correction for spinal stenosis with balanced de novo degenerative lumbar scoliosis: a meta-analysis of direct comparative studies. Spine (Phila Pa 1976). 2017;42:E1126-E1132.

34. Grossbach AJ, Dahdalheh NS, Abel TJ, Woods GD, Dlouhy BJ, Hitchon PW. Flexion-distraction injuries of the thoracolumbar spine: open fusion versus percutaneous pedicle screw fixation. Neurosurg Focus. 2013;35:E2.

35. Vanek P, Bradac O, Konopkova R, de Lacy P, Lacman J, Benes V. Treatment of thoracolumbar trauma by short-segment percutaneous transpedicular screw instrumentation: prospective comparative study with a minimum 2-year follow-up. J Neurosurg Spine. 2014;20:150-156.
36. Wang H, Zhou Y, Li C, Liu J, Xiang L. Comparison of open versus percutaneous pedicle screw fixation using the sextant system in the treatment of traumatic thoracolumbar fractures. Clin Spine Surg. 2017;30:E239-E246.

37. Pishnamaz M, Oikonomidis S, Knobe M, Horst K, Pape HC, Kobbe P. Open versus percutaneous stabilization of thoracolumbar spine fractures: a short-term functional and radiological follow-up. Acta Chir Orthop Traumatol Cech. 2015;82:274-281.

38. Wild MH, Glee M, Plieschegge C, Wenda K. Five-year follow-up examination after purely minimally invasive posterior stabilization of thoracolumbar fractures: a comparison of minimally invasive percutaneously and conventionally open treated patients. Arch Orthop Trauma Surg. 2007;127:335-343.

39. Dong SH, Chen HN, Tian JW, et al. Effects of minimally invasive percutaneous and trans-spantum intermuscular short-segment pedicle instrumentation on thoracolumbar mono-segmental vertebral fractures without neurological compromise. Orthop Traumatol Surg Res. 2013;99:405-411.

40. Lee JK, Jang JW, Kim TW, Kim TS, Kim SH, Moon SJ. Percutaneous short-segment pedicle screw placement without fusion in the treatment of thoracolumbar burst fractures: is it effective? Comparative study with open short-segment pedicle screw fixation with posterolateral fusion. Acta Neurochir (Wien). 2013;155:2305-2312.

41. Saadeh YS, Joseph JR, Smith BW, Kirsch MJ, Sabbagh AM, Park P. Comparison of segmental lordosis and global spinopelvic alignment after single-level lateral lumbar interbody fusion or transforminal lumbar interbody fusion. World Neurosurg. 2019;126:e1374-e1378. doi:10.1016/j.wneu.2019.03.106

42. Tikata T, Iwanami A, Hosogane N, et al. High preoperative hemoglobin A1c is a risk factor for surgical site infection after posterior thoracic and lumbar spinal instrumentation surgery. J Orthop Sci. 2014;19:223-228.

43. Raygor KP, Than KD, Chou D, Mummaneni PV. Comparison of minimally invasive transspinal and open approaches for thoracolumbar intradural-extradullary spinal tumors. Neurosurg Focus. 2015;39:E12.

44. Wong AP, Lall RR, Dahdaleh NS, et al. Comparison of open and minimally invasive surgery for intradural-extradullary spine tumors. Neurosurg Focus. 2015;39:E11.

45. Kumar N, Malhotra R, Maharajan K, et al. Metastatic spine tumor surgery: a comparative study of minimally invasive approach using percutaneous pedicle screws fixation versus open approach. Clin Spine Surg. 2017;30:E1015-E1021.

46. Vergara P, Akhunbay-Fudge CY, Kotter MR, Laing RJC. Minimally invasive versus open surgery for lumbar synovial cysts. World Neurosurg. 2017;108:555-559.

47. Hansen-Algenstaedt N, Kwan MK, Algenstaedt P, et al. Comparison between minimally invasive surgery and conventional open surgery for patients with spinal metastasis: a prospective propensity score-matched study. Spine (Phila Pa 1976). 2017;42:789-797.

48. Huang TJ, Hsu RWW, Li YY, Cheng CC. Minimal access spinal surgery (MASS) in treating thoracic spine metastasis. Spine (Phila Pa 1976). 2006;31:1860-1863.

49. Lau D, Chou D. Posterior thoracic corpectomy with cage reconstruction for metastatic spinal tumors: comparing the mini-open approach to the open approach. J Neurosurg Spine. 2015;23:217-227.

50. Miscusi M, Polli FM, Forcato S, et al. Comparison of minimally invasive surgery with standard open surgery for vertebral thoracic metastases causing acute myelopathy in patients with short- or mid-term life expectancy: surgical technique and early clinical results. J Neurosurg Spine. 2015;22:518-525.

51. Fang T, Dong J, Zhou X, McGuire RA Jr, Li X. Comparison of mini-open anterior corpectomy and posterior total en bloc spondylectomy for solitary metastases of the thoracolumbar spine. J Neurosurg Spine. 2012;17:271-279.

52. Swamy G, Lopatina E, Thomas KC, Marshall DA, Johal HA. The cost effectiveness of minimally invasive spine surgery in the treatment of adult degenerative scoliosis: a comparison of transspinos and open techniques. Spine J. 2019;19:339-348.

53. Than KD, Mummaneni PV, Bridges KJ, et al. Complication rates associated with open versus percutaneous pedicle screw instrumentation among patients undergoing minimally invasive interbody fusion for adult spinal deformity. Neurosurg Focus. 2017;43:E7.

54. Uddin OM, Haque R, Sugrue PA, et al. Cost minimization in treatment of adult degenerative scoliosis. J Neurosurg Spine. 2015;23:798-806.

55. Than KD, Park P, Tran S, et al. Analysis of complications with staged surgery for less invasive treatment of adult spinal deformity. World Neurosurg. 2019;126:e1337-e1342.

56. Chou D, Mummaneni P, Anand N, et al. Treatment of the fractional curve of adult scoliosis with circumferential minimally invasive surgery versus traditional, open surgery: an analysis of surgical outcomes. Global Spine J. 2018;8:827-833.

57. Chou D, Mundis G, Wang M, et al. Minimally invasive surgery for mild-to-moderate adult spinal deformities: impact on intensive care unit and hospital stay. World Neurosurg. 2019;127:e649-e655.

58. Uribe JS, Beckman J, Mummaneni PV, et al. Does MIS surgery allow for shorter constructs in the surgical treatment of adult spinal deformity? Neurosurgery. 2017;80:489-497.

59. Park P, Than KD, Mummaneni PV, et al. Factors affecting approach selection for minimally invasive versus open surgery in the treatment of adult spinal deformity: analysis of a prospective, nonrandomized multicenter study. J Neurosurg Spine. Published June 19, 2020. doi:10.3171/2020.4.SPINE20169

60. Grosse SD. Assessing cost-effectiveness in healthcare: history of the $50,000 per QALY threshold. Expert Rev Pharmacoecon Outcomes Res 2008;8:165-178.

61. Neumann PJ, Cohen JT, Weinstein MC. Updating cost-effectiveness—the curious resilience of the $50,000-per-QALY threshold. N Engl J Med 2014;371:796-797.

62. McCarthy I, O’Brien M, Ames C, et al. Incremental cost-effectiveness of adult spinal deformity surgery: observed quality-adjusted life years with surgery compared with predicted quality-adjusted life years without surgery. Neurosurg Focus 2014;36:E3.