Review Article

Recent Advances in Technique and Clinical Outcomes of Minimally Invasive Spine Surgery in Adult Scoliosis

Gang Liu[1], Sen Liu[1,2], Yu-Zhi Zuo[1], Qi-Yi Li[1], Zhi-Hong Wu[2,3], Nan Wu[1,2], Ke-Yi Yu[1], Gui-Xing Qiu[1,2]

[1]Department of Orthopaedic Surgery, Peking Union Medical College Hospital, Peking Union Medical College and Chinese Academy of Medical Sciences, Beijing 100730, China

[2]Beijing Key Laboratory for Genetic Research of Skeletal Deformity, Beijing 100730, China

[3]Department of Central Laboratory, Peking Union Medical College Hospital, Peking Union Medical College and Chinese Academy of Medical Sciences, Beijing 100730, China

Abstract

Objective: Conventional open spinal surgery of adult scoliosis can be performed from anterior, posterior, or combined approach. Minimally invasive spine surgery (MISS) was developed for the purpose of reducing the undesirable effects and complications. This review aimed to make a brief summary of recent studies of the approach and clinical outcomes of MISS in adult scoliosis.

Data Sources: We conducted a systematic search from PubMed, Medline, EMBASE, and other literature databases to collect reports of surgical methods and clinical outcomes of MISS in treatment of adult scoliosis. Those reports were published up to March 2017 with the following key terms: "minimally invasive," "spine," "surgery," and "scoliosis."

Study Selection: The inclusion criteria of the articles were as followings: diagnosed with adult degenerative scoliosis (DS) or adult idiopathic scoliosis; underwent MISS or open surgery; with follow-up data. The articles involving patients with congenital scoliosis or unknown type were excluded and those without any follow-up data were also excluded from the study. The initial search yielded 233 articles. After title and abstract extraction, 29 English articles were selected for full-text review. Of those, 20 studies with 831 patients diagnosed with adult DS or adult idiopathic scoliosis were reviewed. Seventeen were retrospective studies, and three were prospective studies.

Results: The surgical technique reported in these articles was direct or extreme lateral interbody fusion, axial lumbar interbody fusion, and transforaminal lumbar interbody fusion. Among the clinical outcomes of these studies, the operated levels was 3–7, operative time was 2.3–8.5 h. Both the Cobb angle of coronal major curve and evaluation of Oswestry Disability Index and Visual Analog Scale decreased after surgery. There were 323 complications reported in the 831 (38.9%) patients, including 150 (18.1%) motor or sensory deficits, and 111 (13.4%) implant-related complications.

Conclusions: MISS can provide good radiological and self-evaluation improvement in treatment of adult scoliosis. More prospective studies will be needed before it is widely used.

Key words: Adult Scoliosis; Complications; Minimally Invasive Spine Surgery; Outcomes; Surgical Methods

Introduction

Adult scoliosis is defined as a coronal deformity with a Cobb angle >10° in a skeletally mature patient. It can be divided into two broad types: degenerative scoliosis (DS) and adult idiopathic scoliosis.[1,2] The aims of surgical treatment of adult scoliosis are to obtain coronal and sagittal alignment, pain relief, and solid fusion.[3] Conventional open spinal surgery, which could improve Oswestry Disability Index (ODI)[4] and achieve pain relief, functional restoration, and satisfaction,[5] is widely used in the operative decompression and correction of the deformity. To decompress and reconstruct the alignment of the spine, multilevel surgery is usually

Access this article online

Quick Response Code:

Website: www.cmj.org

DOI: 10.4103/0366-6999.212688

Address for correspondence: Prof. Gui-Xing Qiu, Department of Orthopaedic Surgery, Peking Union Medical College Hospital, Peking Union Medical College and Chinese Academy of Medical Sciences, No. 1 Shuaifuyuan, Beijing 100730, China
E-Mail: qiuguixingpumch@126.com

Received: 10-05-2017 **Edited by:** Xin Chen

How to cite this article: Liu G, Liu S, Zuo YZ, Li QY, Wu ZH, Wu N, Yu KY, Qiu GX. Recent Advances in Technique and Clinical Outcomes of Minimally Invasive Spine Surgery in Adult Scoliosis. Chin Med J 2017;130:2608-15.

needed, and this is often associated with large quantity of blood loss and longer time for anesthesia which are harmful to elderly people, especially who are suffered from complications.[6] Meanwhile, large operative scars may bring high psychological and physiological burden to patients.[4-8] The incidence of complications for conventional surgery was reported from 20% to 80% in recent studies.[6,9,10] For the purpose of reducing these undesirable effects and complications caused by traditional open spinal surgeries, the minimally invasive spine surgery (MISS) was developed.[11]

After the conception of MISS was proposed in the 1990s,[12,13] the use of MISS in the treatment of adult scoliosis has been widely reported. Compared with traditional open surgery which may have a series of perioperative complications such as excessive blood loss, infection, neurological injury, incisional pain, vascular injury, retrograde ejaculation, and ureteral and bladder injury,[8,14,15] MISS has the advantages of less pain, shorter hospital stay, earlier mobilization, and less infection.[16-19] However, the correlation between this new surgery and favorable outcomes has not been fully established.[20] This review aimed to make a brief summary of recent studies of the approach and clinical outcomes of MISS in adult scoliosis.

Surgical Technique and Clinical Outcomes

Since the introduction of minimally invasive transforaminal lumbar interbody fusion (MI-TLIF), the technical feasibility and safety have been well established both in primary and revision surgery.[17,21,22] This is a technique of MISS with several advantages over traditional open procedure such as less postoperative back pain, less adjacent tissue damage, less blood loss, shorter hospital stay, and rapid recovery.[23-25] However, it is not widely used or even regarded as a relative contraindication in patients with fixed coronal and/or sagittal deformities, especially in those who need to be operated in more than three segments.[20,26]

To overcome the disadvantages of traditional open and posterior approach, the MI axial lumbar interbody fusion (AxiaLIF), which is a presacral retroperitoneal approach, was introduced.[27] It is not only an alternative with the potential to expand the narrowed disc space and restore normal disc height with decreased blood loss, operative time, and hospital stay but also a good choice for overweight patients.[28,29] To our knowledge, single use of AxiaLIF in treatment of scoliosis was seldom reported. Limited reports were of AxiaLIF associated with additional anterior or posterior pedicle screw instrumentation.[28,30]

A recent advancement in the field of MISS is the lateral transpsoas approach for lumbar interbody fusion that is extreme lateral interbody fusion (XLIF) or direct lateral interbody fusion (DLIF); there have been some reports of their uses in surgical treatment of lumbar DS. This approach is a lateral retroperitoneal, transpsoas approach to the anterior disc space allowing for complete discectomy, distraction, and interbody fusion. Because it does not penetrate into abdominal cavity as traditional laparoscopic surgery, and the cage can be located into the intervertebral disc without the incision of anterior and posterior longitudinal ligament, less damage to the adjacent tissues can be achieved.[31-39]

In this series of patients, 831 patients of twenty studies of MISS in adult DS and adult idiopathic scoliosis were collected. The surgical techniques reported were DLIF or XLIF, AxialLIF, and TLIF. Among the clinical outcomes of these studies, the operated levels was from 3 to 7, and operative time was from 2.3 to 8.5 h. Both the Cobb angle of coronal major curve and evaluation of ODI and Visual Analog Scale were decreased after surgery.[16,30,35-52] The results of recent studies of MISS for adult scoliosis and their outcomes are shown in Table 1 and Table 2, respectively.

Complications of Minimally Invasive Spine Surgery in Adult Scoliosis

MISS or MISS plus other instrumentation approaches can have several complications compared to conventional open spinal surgery. Traditional open surgery had high complication incidence rate from 20% to 80%, such as pain, swelling of incision, large amount of blood loss, and even death.[8,14,53-55] Several factors were correlated strongly with the incidence of complications, such as age, number of levels operated, and time of operation.[20,56] MISS could avoid some disadvantages of traditional procedure; it also had certain complications compared to open surgery. MISS plus other instrumentation approaches experienced a higher incidence rate of complications than MI procedure alone. In one report, the rate was 37.9% compared to 19.2% ($P = 0.045$).[38] In this section, the complications of MISS in adult scoliosis treatment are summarized into three parts.

Systemic complications

Systemic complications include motor or sensory deficits, cardiovascular system (CVS), digestive system, respiratory system, central nerve system (CNS), and urinary system.

Motor or sensory deficits are the most common disadvantages of MISS, especially in lateral transpsoas approach, because the femoral nerve and the lumbar plexus nerve roots may be damaged during the operation. Among twenty studies, the occurrence of motor or sensory deficits was 150 (18.1%) in all 831 patients.[16,30,35-52]

The incidence of complications of CVS among these studies was 1.1% (9 cases in all 831 patients), such as atrial fibrillation, myocardial infarction, deep vein thrombosis,[38] congestive heart failure,[38] and pulmonary embolism.[35]

The incidence of complications of the digestive system was 1.1% (9 in all 831 patients), including intraoperative bowel injury, abdominal viscera, postoperative ileus, and gastrointestinal bleed.[38]

Eight patients (1.0% in all 831 cases) had respiratory system complications such as pneumothorax, pleural effusion,[35,38,41] pulmonary hypertension, and pneumonia.[38]

The incidence rate of CNS complication in all 831 patients reported was 0.7% (6 cases), including idiopathic

Table 1: Summary of recent studies of MISS in adult scoliosis

Author	Year	Patients number	Average age (years)	Type of scoliosis	Surgical technique	Follow-up (months)
Tormenti *et al*.[35]	2010	8	60.0	Thoracolumbar DS	XLIF + open posterior TLIF	10.5
Dakwar *et al*.[16]	2010	25	62.5	Thoracolumbar DS	Lateral retroperitoneal transpsoas	11.0
Wang and Mummaneni[37]	2010	23	64.4	17 LDS and 8 others	Anterior transpsoas MISS + posterior instrumentaion	13.4
Isaacs *et al*.[38]	2010	107	68.4	DS	XLIF + anterior/posterior instumentation	1.5
Anand *et al*.[30]	2010	28	67.7	Adult idiopathic scoliosis + DS	XLIF/DLIF/AxiaLIF + posterior instrumentation	22.0
Kelleher *et al*.[40]	2010	16	–	Stenosis with scoliosis	MISS lumbar laminoplasty (bilateral decompression from a unilateral approach)	32.0
		12	–	Stenosis combined with spondylolisthesis and scoliosis		30.0
Acosta *et al*.[36]	2011	8	–	DS	DLIF + PSF	21.0
Akbarnia *et al*.[41]	2011	16	56.0	Adult idiopathic scoliosis + DS	Lateral retroperitoneal transpsoas LIF	24.0
Karikari *et al*.[42]	2011	30	–	DS	XLIF, TLIF or XLIF + posterior instrumentation	–
Anand *et al*.[39]	2013	71	64.0	DS + idiopathic scoliosis + iatrogenic scoliosis	DLIF + AxiaLIF + posterior instrumentation	39.0
Phillips *et al*.[43]	2013	107	68.0	DS	XLIF, or XLIF + posterior instrumentation	24.0
Deukmedjian *et al*.[44]	2013	27	61.0	DS	LIF + posterior instrumentation	17.0
Caputo *et al*.[45]	2013	30	65.9	DS	XLIF + posterior instrumentation	14.3
Anand *et al*.[46]	2014	90	63.5	ASD	DLIF, or DLIF + AxiaLIF, + posterior instrumentation	40.0
Haque *et al*.[47]	2014	42	61.7	ASD	LIF + TLIF + anteriorinterbody fusion	25.7
Castro *et al*.[48]	2014	35	68.2	DS	LIF	24.0
Anand *et al*.[49]	2014	46	67.0	DS + adult idiopathic scoliosis + iatrogenic scoliosis	Segmental multilevel percutaneous pedicle screw fixation, correction, and fusion; lateral transpsoas discectomy and interbody fusion; and transsacral fixation and fusion	24.0
Khajavi and Shen[50]	2014	24	70.1	DS	LIF, or LIF + posterior instrumentation	24.0
Manwaring *et al*.[51]	2014	36	64.3	DS	LIF + posterior instrumentation	22.9 (non-ACR) 11.3 (ACR)
Anand *et al*.[52]	2014	50	61.0	Adult idiopathic scoliosis	DLIF, or DLIF + posterior instrumentation	48.0

DS: Degenerative scoliosis; ASD: Adult spinal deformity; LDS: Lumbar degenerative scoliosis; PSF: Posterior spinal fusion; LIF: Lateral interbody fusion; DLIF: Direct lateral interbody fusion; XLIF: Extreme lateral interbody fusion; AxiaLIF: Axial lumbar interbody fusion; TLIF: Transforaminal lumbar interbody fusion; –: Not available; ACR: Anterior column release; MISS: Minimally invasive spine surgery.

cerebellar hemorrhage,[39,52] cerebral spinal fluid leakage,[37] meningitis,[35] and cerebellar hemorrhage.[30]

Only four (0.5%) cases of urinary system damage were described in all 831 patients, one intraoperative renal capsular hematoma and one patient had ureteropelvic injury,[41] one urinary tract infection,[38] and one retrocapsular renal hematoma.[30]

Generalized complications

Twenty-six (3.1%) generalized complications have also been described in all 831 patients including superficial wound dehiscence,[52] wound infection[44] or sepsis,[35] postanesthesia delirium and hyponatremia[38] and rhabdomyolysis.[16]

Implant-associated complications

The complications of instrumentation among twenty studies occurred in 111 cases (13.4% in all 831 patients), including misplaced hardware,[52] pseudarthrosis related with screw implantation and hardware revision,[46,49] cage subsidence or micromotion,[48] nonunion,[45] hardware revision,[43] screw prominence,[39] implant failure,[16] cage dislodgment,[41] and asymptomatic proximal screw fracture.[30]

There were 323 complications reported in the 831 patients (38%), including 150 motor or sensory deficits (18.1%) and 111 implant-related complications (13.4%). The complications of these studies are shown in Table 3. Not all open surgery complications could be avoided in MISS. The complications may restrict it from routine use in the surgical treatment of scoliosis.[57-59] Furthermore, a learning curve lies in it and appropriate training is needed before practicing this new approach.[23,60]

Conclusions

The MISS provides the surgeon with an alternative option when dealing with adult scoliosis. The primary clinical results showed that, MISS can be effective in both

Table 2: Summary of clinical outcomes of MISS in adult scoliosis

Author	MOL	Operative time (h)	AEBL (ml)	AVT (cm)		Major curve changed (cobb angle)			
						Coronal		Sagittal	
				Preoperation	Postoperation	Preoperation	Postoperation	Preoperation	Postoperation
Tormenti *et al.*[35]	3.9	–	–	3.6	1.8	38.5	10.0	–	–
Wang and Mummaneni[37]	3.7	6.7	477	–	–	31.4	11.5	37.4	45.5
Isaacs *et al.*[38]	4.4	3.0	62.5% <100 8.4% >300	–	–	24.3	–	–	–
Anand *et al.*[30]	>3.0	3.9	241 (anterior) 231 (posterior)	–	–	22.0	7.0	–	–
Dakwar *et al.*[16]	4.8	8.5	150	–	–	–	20.3	7.8	–
Akbarnia *et al.*[41]	–	–	–	–	–	47.0	17	–	–
Kelleher *et al.*[40]	–	–	–	–	–	–	–	–	–
Acosta *et al.*[36]	–	–	–	–	–	21.4	9.7	–	–
Anand *et al.*[39]	4.4	4.9* 3.0† 4.1‡	412* 314† 357‡	24.0	12.0	24.7	9.5	–	–
Phillips *et al.*[43]	3.0	3.0	–	–	–	20.9	15.2	27.7	33.6
Deukmedjian *et al.*[44]	–	–	–	–	–	26.9	12.8	–	–
Caputo *et al.*[45]	4.2	–	–	23.6	9.5	20.2	5.6	43.5	48.5
Anand *et al.*[46]	6.3	–	–	–	–	35.8	13.9	45.4	48.6
Haque *et al.*[47]	–	7.7	507	–	–	32.0	13.1	33.8	39.4
Castro *et al.*[48]	3	2.3	54	–	–	21.0	12.0	33.0	41.0
Anand *et al.*[49]	–	–	–	–	–	–	–	–	–
Khajavi and Shen[50]	3.3	3.6	68	–	–	27.7	16.6	31.8	44.0
Manwaring *et al.*[51]	3.8	–	–	–	–	28.9 (non-ACR) 24.8 (ACR)	12.9 (non-ACR) 9.7 (ACR)	–	–
Anand *et al.*[52]	7.0	5.6* 8.0§	613* 763§	–	–	42	16	–	–

Author	Evaluation improved			
	ODI		VAS	
	Preoperation	Postoperation	Preoperation	Postoperation
Tormenti *et al.*[35]	–	–	8.8	3.5
Wang and Mummaneni[37]	–	–	7.3	3.4
Isaacs *et al.*[38]	–	–	–	–
Anand *et al.*[30]	39.1	7.0	7.1	3.1
Dakwar *et al.*[16]	53.6	29.9	8.1	2.4
Akbarnia *et al.*[41]	60.0	24.0	6.5	2.5
Kelleher *et al.*[40]	50.7 53.0	31.5 22.0	–	–
Acosta *et al.*[36]	–	–	–	–
Anand *et al.*[39]	50.3	49.7	6.4	4.3
Phillips *et al.*[43]	–	–	–	–
Deukmedjian *et al.*[44]	53.5	34.7	7.5	4.6
Caputo *et al.*[45]	–	–	–	–
Anand *et al.*[46]	–	–	–	–
Haque *et al.*[47]	41.6	23.3	6.2	3.1
Castro *et al.*[48]	51.0	29.0	8.5	2.7
Anand *et al.*[49]	47.6	21.8	6.6	2.8
Khajavi and Shen[50]	48.4	24.4	7.0	2.9
Manwaring *et al.*[51]	–	–	–	–
Anand *et al.*[52]	44.0	22.0	5.7	2.9

*One stage; †Two stage-DLIF; ‡Two stage AxiaLIF; §Two stage. MOL: Mean operated level; AEBL: Average estimated blood loss; AVT: Apical vertebral translation; ODI: Oswestry Disability Index; VAS: Visual analog scale; ACR: Anterior column release; –: Not available; MISS: Minimally invasive spine surgery.

Table 3: The reported complication types of MISS in adult scoliosis

Author	Systemic complications						Generalized complications	Implant-associated complications
	Motor or sensory deficits	Urinary system	Digestive system	Respiratory system	CNS	CVS		
Akbarnia *et al*.[41]	3 abdominal weakness 3 quadriceps weakness 9 thigh numbness 8 thigh pain	–	–	1 pleural effusion	–	–	–	1 cage dislodgment
Anand *et al*.[30]	17 thigh dysesthesias 2 quadriceps palsy	1 renal hematoma	1 ileus	–	1 cerebellar hemorrhage	–	–	1 screw prominent 1 screw fracture
Tormenti *et al*.[35]	2 motor radiculopathy 6 thigh paresthesias or dysesthesias	–	1 bowel injury 1 ileus	2 pleural effusion	1 incidental durotomy 1 meningitis	1 PE	1 wound infection 1 intraoperative hemodynamic instability	–
Wang and Mummaneni[37]	7 thigh numbness, pain, dysesthesias	–	–	2 pneumothorax	1 CSF leakage	1 AF	–	1 screw pullout
Dakwar *et al*.[16]	3 thigh numbness	–	–	–	–	–	1 rhabdomyolysis 1 subsidence	1 implant failure
Isaacs *et al*.[38]	29 lower extremity weakness	1 kidney laceration	4 ileus 1 GI bleed	1 pleural effusion 1 pneumonia 1 pulmonary hypertension	–	1 DVT 3 AF 1 CHF 1 MI	1 postanesthesia delirium 1 hyponatremia 3 wound infection	–
Anand *et al*.[39]	4 radiculopathy	–	–	–	1 idiopathic cerebellar hemorrhage	–	2 wound dehiscence 1 wound infection 1 osteomyelitis 1 discitis 1 proximal junctional kyphosis	4 pseudarthrosis 1 screw prominence
Phillips *et al*.[43]	36 lower extremity weakness	–	–	–	–	–	–	3 hardware revision 14 pseudarthrosis 46 supplemental fixation
Deukmedjian *et al*.[44]	2 thigh numbness 1 groin pain	–	–	–	–	–	1 wound infection	–
Caputo *et al*.[45]	–	–	1 lateral incisional hernia	–	–	1 AF	2 wound breakdown 1 pedicle fracture 2 rupture of the anterior longitudinal ligament	1 nonunion requiring revision
Anand *et al*.[46]	–	–	–	–	–	–	–	3 hardware revision 7 pseudarthroses

Contd...

Table 3: Contd...

Author	Systemic complications						Generalized complications	Implant -associated complications
	Motor or sensory deficits	Urinary system	Digestive system	Respiratory system	CNS	CVS		
Castro *et al*.[48]	2 radiculopathy	–	–	–	–	–	–	10 cage subsidence 1 cage micromotion
Anand *et al*.[49]	–	–	–	–	–	–	3 superficial wound dehiscence	5 pseudarthroses
Khajavi and Shen[50]	1 foot drop 5 hip flexion weakness 3 thigh or groin discomfort	–	–	–	–	–	–	–
Anand *et al*.[52]	3 radiculopathy 3 quadriceps palsy 1 foot drop	1 renal capsular hematoma 1 ureteropelvic junction injury	–	–	1 idiopathic cerebellar hemorrhage	–	2 superficial wound dehiscence	3 misplaced hardware 2 proximal junction kyphosis 6 pseudarthrosis

CNS: Central nervous system; GI: Gastrointestinal; CVS: Cardiovascular system; CSF: Cerebrospinal fluid; PE: Pulmonary embolism; DVT: Deep venous thrombosis; AF: Atrial fibrillation; CHF: Congestive heart failure; MI: Myocardial infarction; –: Not reported.

radiological and self-evaluation outcomes, but it also has several complications. More studies are needed to provide further favorable results before it is widely used to compare with traditional open surgery.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Ha KY, Jang WH, Kim YH, Park DC. Clinical Relevance of the SRS-Schwab Classification for Degenerative Lumbar Scoliosis. Spine (Phila Pa 1976). 2016;41:E282-E288. doi: 10.1097/BRS.0000000000001229.
2. Aebi M. The adult scoliosis. Eur Spine J 2005;14:925-48. doi: 10.1007/s00586-005-1053-9.
3. Birknes JK, White AP, Albert TJ, Shaffrey CI, Harrop JS. Adult degenerative scoliosis: A review. Neurosurgery 2008;63 3 Suppl: 94-103. doi: 10.1227/01.NEU.0000325485.49323.B2.
4. Kinkpe CV, Onimus M, Sarr L, Niane MM, Traore MM, Daffe M, *et al*. Surgical Treatment of Angular Pott's Kyphosis with Posterior Approach, Pedicular Wedge Osteotomy and Canal Widening. Open Orthop J. 2017;11:274-80. doi: 10.2174/1874325001711010274.
5. Shapiro GS, Taira G, Boachie-Adjei O. Results of surgical treatment of adult idiopathic scoliosis with low back pain and spinal stenosis: A study of long-term clinical radiographic outcomes. Spine (Phila Pa 1976) 2003;28:358-63. doi: 10.1097/01.BRS.0000048502.62793.0C.
6. Cho KJ, Suk SI, Park SR, Kim JH, Kim SS, Choi WK, *et al.* Complications in posterior fusion and instrumentation for degenerative lumbar scoliosis. Spine (Phila Pa 1976) 2007;32:2232-7. doi: 10.1097/BRS.0b013e31814b2d3c.
7. Noonan KJ, Dolan LA, Jacobson WC, Weinstein SL. Long-term psychosocial characteristics of patients treated for idiopathic scoliosis. J Pediatr Orthop 1997;17:712-7. doi: 10.1097/01241398-199711000-00004.
8. Kim YB, Lenke LG, Kim YJ, Kim YW, Blanke K, Stobbs G, *et al.* The morbidity of an anterior thoracolumbar approach: Adult spinal deformity patients with greater than five-year follow-up. Spine (Phila Pa 1976) 2009;34:822-6. doi: 10.1097/BRS.0b013e31818e3157.
9. Passias PG, Poorman GW, Jalai CM, Line B, Diebo B, Park P, *et al*. Outcomes of open staged corrective surgery in the setting of adult spinal deformity. Spine Journal 2017. doi: 10.1016/j.spinee.2017.03.012.
10. Zurbriggen C, Markwalder TM, Wyss S. Long-term results in patients treated with posterior instrumentation and fusion for degenerative scoliosis of the lumbar spine. Acta Neurochir (Wien) 1999;141:21-6. doi: 10.1007/s007010050261.
11. Guiot BH, Khoo LT, Fessler RG. A minimally invasive technique for decompression of the lumbar spine. Spine (Phila Pa 1976) 2002;27:432-8. doi: 10.1097/00007632-200202150-00021.
12. Leu H, Schreiber A. Percutaneous nucleotomy with disk endoscopy – A minimally invasive therapy in non-sequestrated intervertebral disk hernia. Schweiz Rundsch Med Prax 1991;80:364-8.
13. Findlay GF. Minimally invasive lumbar disc surgery. Br J Neurosurg 1992;6:405-8. doi: 10.3109/02688699208995028.
14. Kreinest M, Rillig J, Grutzner PA, Kuffer M, Tinelli M, Matschke S. Analysis of complications and perioperative data after open or percutaneous dorsal instrumentation following traumatic spinal fracture of the thoracic and lumbar spine: a retrospective cohort study including 491 patients. European Spine Journal 2017;26:1535-40. doi: 10.1007/s00586-016-4911-8.
15. Lee MJ, Konodi MA, Cizik AM, Bransford RJ, Bellabarba C, Chapman JR. Risk factors for medical complication after spine surgery: A multivariate analysis of 1,591 patients. Spine J 2012;12:197-206. doi: 10.1016/j.spinee.2011.11.008.
16. Dakwar E, Cardona RF, Smith DA, Uribe JS. Early outcomes and safety of the minimally invasive, lateral retroperitoneal transpsoas approach for adult degenerative scoliosis. Neurosurg Focus 2010;28:E8. doi: 10.3171/2010.1.FOCUS09282.
17. Selznick LA, Shamji MF, Isaacs RE. Minimally invasive interbody fusion for revision lumbar surgery: Technical feasibility and safety. J Spinal Disord Tech 2009;22:207-13. doi: 10.1097/BSD.0b013e318169026f.
18. Uribe JS, Beckman J, Mummaneni PV, Okonkwo D, Nunley P, Wang MY, *et al*. Does MIS Surgery Allow for Shorter Constructs in the Surgical Treatment of Adult Spinal Deformity? Neurosurgery. 2017;80:489-97. doi: 10.1093/neuros/nyw072.

19. Zhu W, Sun W, Xu L, Sun X, Liu Z, Qiu Y, *et al*. Minimally invasive scoliosis surgery assisted by O-arm navigation for Lenke Type 5C adolescent idiopathic scoliosis: a comparison with standard open approach spinal instrumentation. J Neurosurg Pediatr 2017;19:472-8. doi: 10.3171/2016.11.PEDS16412.
20. Park Y, Ha JW, Lee YT, Sung NY. The effect of a radiographic solid fusion on clinical outcomes after minimally invasive transforaminal lumbar interbody fusion. Spine J 2011;11:205-12. doi: 10.1016/j.spinee.2011.01.023.
21. Foley KT, Holly LT, Schwender JD. Minimally invasive lumbar fusion. Spine 2003;28:S26-35. doi: 10.1097/01.BRS.0000076895.52418.5E.
22. Isaacs RE, Podichetty VK, Santiago P, Sandhu FA, Spears J, Kelly K, *et al*. Minimally invasive microendoscopy-assisted transforaminal lumbar interbody fusion with instrumentation. J Neurosurg Spine 2005;3:98-105. doi: 10.3171/spi.2005.3.2.0098.
23. Lau D, Lee JG, Han SJ, Lu DC, Chou D. Complications and perioperative factors associated with learning the technique of minimally invasive transforaminal lumbar interbody fusion (TLIF). J Clin Neurosci 2011;18:624-7. doi: 10.1016/j.jocn.2010.09.004.
24. Schwender JD, Holly LT, Rouben DP, Foley KT. Minimally invasive transforaminal lumbar interbody fusion (TLIF): Technical feasibility and initial results. J Spinal Disord Tech 2005;18 Suppl:S1-6. doi: 10.1097/01.bsd.0000132291.50455.d0.
25. Dhall SS, Wang MY, Mummaneni PV. Clinical and radiographic comparison of mini-open transforaminal lumbar interbody fusion with open transforaminal lumbar interbody fusion in 42 patients with long-term follow-up. J Neurosurg Spine 2008;9:560-5. doi: 10.3171/SPI.2008.9.08142.
26. Meyer SA, Wu JC, Mummaneni PV. Mini-open and minimally invasive transforaminal lumbar interbody fusion: Technique review. Semin Spine Surg 2011;23:45-50. doi: 10.1053/j.semss.2010.12.004.
27. Cragg A, Carl A, Casteneda F, Dickman C, Guterman L, Oliveira C. New percutaneous access method for minimally invasive anterior lumbosacral surgery. J Spinal Disord Tech 2004;17:21-8. doi: 10.1097/00024720-200402000-00006.
28. Patil SS, Lindley EM, Patel VV, Burger EL. Clinical and radiological outcomes of axial lumbar interbody fusion. Orthopedics 2010;33:883. doi: 10.3928/01477447-20101021-05.
29. Park P, Wang MY, Nguyen S, Mundis GJ, La Marca F, Uribe JS, *et al*. Comparison of Complications and Clinical and Radiographic Outcomes Between Nonobese and Obese Patients with Adult Spinal Deformity Undergoing Minimally Invasive Surgery. World Neurosurgery 2016;87:55-60. doi: 10.1016/j.wneu.2015.12.024.
30. Anand N, Rosemann R, Khalsa B, Baron EM. Mid-term to long-term clinical and functional outcomes of minimally invasive correction and fusion for adults with scoliosis. Neurosurg Focus 2010;28:E6. doi: 10.3171/2010.1.FOCUS09278.
31. Ozgur BM, Aryan HE, Pimenta L, Taylor WR. Extreme Lateral Interbody Fusion (XLIF): A novel surgical technique for anterior lumbar interbody fusion. Spine J 2006;6:435-43. doi: 10.1016/j.spinee.2005.08.012.
32. Benglis DM, Elhammady MS, Levi AD, Vanni S. Minimally invasive anterolateral approaches for the treatment of back pain and adult degenerative deformity. Neurosurgery 2008;63 3 Suppl:191-6. doi: 10.1227/01.NEU.0000325487.49020.91.
33. Knight RQ, Schwaegler P, Hanscom D, Roh J. Direct lateral lumbar interbody fusion for degenerative conditions: Early complication profile. J Spinal Disord Tech 2009;22:34-7. doi: 10.1097/BSD.0b013e3181679b8a.
34. Sharma AK, Kepler CK, Girardi FP, Cammisa FP, Huang RC, Sama AA. Lateral lumbar interbody fusion: Clinical and radiographic outcomes at 1 year: A preliminary report. J Spinal Disord Tech 2011;24:242-50. doi: 10.1097/BSD.0b013e3181ecf995.
35. Tormenti MJ, Maserati MB, Bonfield CM, Okonkwo DO, Kanter AS. Complications and radiographic correction in adult scoliosis following combined transpsoas extreme lateral interbody fusion and posterior pedicle screw instrumentation. Neurosurg Focus 2010;28:E7. doi: 10.3171/2010.1.FOCUS09263.
36. Acosta FL, Liu J, Slimack N, Moller D, Fessler R, Koski T. Changes in coronal and sagittal plane alignment following minimally invasive direct lateral interbody fusion for the treatment of degenerative lumbar disease in adults: A radiographic study. J Neurosurg Spine 2011;15:92-6. doi: 10.3171/2011.3.SPINE10425.
37. Wang MY, Mummaneni PV. Minimally invasive surgery for thoracolumbar spinal deformity: Initial clinical experience with clinical and radiographic outcomes. Neurosurg Focus 2010;28:E9. doi: 10.3171/2010.1.FOCUS09286.
38. Isaacs RE, Hyde J, Goodrich JA, Rodgers WB, Phillips FM. A prospective, nonrandomized, multicenter evaluation of extreme lateral interbody fusion for the treatment of adult degenerative scoliosis: Perioperative outcomes and complications. Spine (Phila Pa 1976) 2010;35 26 Suppl:S322-30. doi: 10.1097/BRS.0b013e3182022e04.
39. Anand N, Baron EM, Khandehroo B, Kahwaty S. Long-term 2- to 5-year clinical and functional outcomes of minimally invasive surgery for adult scoliosis. Spine (Phila Pa 1976) 2013;38:1566-75. doi: 10.1097/BRS.0b013e31829cb67a.
40. Kelleher MO, Timlin M, Persaud O, Rampersaud YR. Success and failure of minimally invasive decompression for focal lumbar spinal stenosis in patients with and without deformity. Spine (Phila Pa 1976) 2010;35:E981-7. doi: 10.1097/BRS.0b013e3181c46fb4.
41. Akbarnia BA, Mundis GM, Bagheri R, Kabirian N, Salari P, Pawelek J. Lateral Approach for Interbody Fusion (LIF) is a Safe and Effective Technique to Reconstruct the Anterior Spinal Column in Complex Adult Spinal Deformity: A Minimum Two-Year Follow-Up Study: POSTER #306. Spine Journal Meeting Abstracts; 2011.
42. Karikari IO, Grossi PM, Nimjee SM, Hardin C, Hodges TR, Hughes BD, *et al.* Minimally invasive lumbar interbody fusion in patients older than 70 years of age: Analysis of peri- and postoperative complications. Neurosurgery 2011;68:897-902. doi: 10.1227/NEU.0b013e3182098bfa.
43. Phillips FM, Isaacs RE, Rodgers WB, Khajavi K, Tohmeh AG, Deviren V, *et al.* Adult degenerative scoliosis treated with XLIF: Clinical and radiographical results of a prospective multicenter study with 24-month follow-up. Spine (Phila Pa 1976) 2013;38:1853-61. doi: 10.1097/BRS.0b013e3182a43f0b.
44. Deukmedjian AR, Ahmadian A, Bach K, Zouzias A, Uribe JS. Minimally invasive lateral approach for adult degenerative scoliosis: Lessons learned. Neurosurg Focus 2013;35:E4. doi: 10.3171/2013.5.FOCUS13173.
45. Caputo AM, Michael KW, Chapman TM, Jennings JM, Hubbard EW, Isaacs RE, *et al.* Extreme lateral interbody fusion for the treatment of adult degenerative scoliosis. J Clin Neurosci 2013;20:1558-63. doi: 10.1016/j.jocn.2012.12.024.
46. Anand N, Baron EM, Khandehroo B. Limitations and ceiling effects with circumferential minimally invasive correction techniques for adult scoliosis: Analysis of radiological outcomes over a 7-year experience. Neurosurg Focus 2014;36:E14. doi: 10.3171/2014.3.FOCUS13585.
47. Haque RM, Mundis GM Jr., Ahmed Y, El Ahmadieh TY, Wang MY, Mummaneni PV, *et al.* Comparison of radiographic results after minimally invasive, hybrid, and open surgery for adult spinal deformity: A multicenter study of 184 patients. Neurosurg Focus 2014;36:E13. doi: 10.3171/2014.3.FOCUS1424.
48. Castro C, Oliveira L, Amaral R, Marchi L, Pimenta L. Is the lateral transpsoas approach feasible for the treatment of adult degenerative scoliosis? Clin Orthop Relat Res 2014;472:1776-83. doi: 10.1007/s11999-013-3263-5.
49. Anand N, Baron EM, Khandehroo B. Does minimally invasive transsacral fixation provide anterior column support in adult scoliosis? Clin Orthop Relat Res 2014;472:1769-75. doi: 10.1007/s11999-013-3335-6.
50. Khajavi K, Shen AY. Two-year radiographic and clinical outcomes of a minimally invasive, lateral, transpsoas approach for anterior lumbar interbody fusion in the treatment of adult degenerative scoliosis. Eur Spine J 2014;23:1215-23. doi: 10.1007/s00586-014-3246-6.
51. Manwaring JC, Bach K, Ahmadian AA, Deukmedjian AR, Smith DA, Uribe JS. Management of sagittal balance in adult spinal deformity with minimally invasive anterolateral lumbar interbody fusion: A preliminary radiographic study. J Neurosurg Spine 2014;20:515-22. doi: 10.3171/2014.2.SPINE1347.
52. Anand N, Baron EM, Khandehroo B. Is circumferential minimally invasive surgery effective in the treatment of moderate adult

idiopathic scoliosis? Clin Orthop Relat Res 2014;472:1762-8. doi: 10.1007/s11999-014-3565-2.
53. Houten JK, Alexandre LC, Nasser R, Wollowick AL. Nerve injury during the transpsoas approach for lumbar fusion. J Neurosurg Spine 2011;15:280-4. doi: 10.3171/2011.4.SPINE1127.
54. Carl A, Kaufman E, Lawrence J. Complications in spinal deformity surgery: Issues unrelated directly to intraoperative technical skills. Spine (Phila Pa 1976) 2010;35:2215-23. doi: 10.1097/BRS.0b013e3181fd591f.
55. Hamilton DK, Kanter AS, Bolinger BD, Mundis GJ, Nguyen S, Mummaneni PV, *et al*. Reoperation rates in minimally invasive, hybrid and open surgical treatment for adult spinal deformity with minimum 2-year follow-up. European Spine Journal 2016;25:2605-11.doi:10.1007/s00586-016-4443-2.
56. Gruskay J, Kepler C, Smith J, Radcliff K, Vaccaro A. Is surgical case order associated with increased infection rate after spine surgery? Spine (Phila Pa 1976) 2012;37:1170-4. doi: 10.1097/BRS.0b013e3182407859.
57. Galan TV, Mohan V, Klineberg EO, Gupta MC, Roberto RF, Ellwitz JP. Case report: Incisional hernia as a complication of extreme lateral interbody fusion. Spine J 2012;12:e1-6. doi: 10.1016/j.spinee.2012.02.012.
58. Dakwar E, Le TV, Baaj AA, Le AX, Smith WD, Akbarnia BA, *et al.* Abdominal wall paresis as a complication of minimally invasive lateral transpsoas interbody fusion. Neurosurg Focus 2011;31:E18. doi: 10.3171/2011.7.FOCUS11164.
59. Dakwar E, Rifkin SI, Volcan IJ, Goodrich JA, Uribe JS. Rhabdomyolysis and acute renal failure following minimally invasive spine surgery: Report of 5 cases. J Neurosurg Spine 2011;14:785-8. doi: 10.3171/2011.2.SPINE10369.
60. Lee JC, Jang HD, Shin BJ. Learning curve and clinical outcomes of minimally invasive transforaminal lumbar interbody fusion: Our experience in 86 consecutive cases. Spine (Phila Pa 1976) 2012;37:1548-57. doi: 10.1097/BRS.0b013e318252d44b.