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Defining the MIS-TLIF: A Systematic Review of Techniques and Technologies Used by Surgeons Worldwide

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Abstract

Study Design: Systematic review.

Objective: To date there is no consensus among surgeons as to what defines an MIS-TLIF (transforaminal lumbar interbody fusion using minimally invasive spine surgery) compared to an open or mini-open TLIF. This systematic review aimed to examine the MIS-TLIF techniques reported in the recent body of literature to help provide a definition of what constitutes the MIS-TLIF, based on the consensus of the majority of surgeons.

Methods: We created a database of articles published about MIS-TLIF between 2010 and 2018. We evaluated the technical components of the MIS-TLIF including instruments and incisions used as well the order in which key steps are performed.

Results: We could identify several patterns for MIS-TLIF performance that seemed agreed upon by the majority of MIS surgeons: use of paramedian incisions; use of a tubular retractor to perform a total facetectomy, decompression, and interbody cage implantation; and percutaneous insertion of the pedicle-screw rod constructs with intraoperative imaging.

Conclusion: Based on this review of the literature, the key features used by surgeons performing MIS TLIF include the use of nonexpandable or expandable tubular retractors, a paramedian or lateral incision, and the use of a microscope or endoscope for visualization. Approaches using expandable nontubular retractors, those that require extensive subperiosteal dissection from the midline laterally, or specular-based retractors with wide pedicle to pedicle exposure are far less likely to be promoted as an MIS-based approach. A definition is necessary to improve the communication among spine surgeons in research as well as patient education.

Keywords

minimally invasive spine surgery, transforaminal lumbar interbody fusion, MIS-TLIF, systematic review

Background

Posterior lumbar interbody fusion has evolved tremendously since Cloward first described the procedure in 1952.[1] In 1982, Harms and Rolinger introduced the open transforaminal lumbar interbody fusion (TLIF),[2] which has since become one of the most effective procedures for lumbar spinal fusion. Although open TLIF is a well-established procedure, it is highly invasive and is reported to have complication rates of up to 25%.[3] With the advent of minimally invasive spine surgery (MISS), Foley and Lefkowitz introduced the minimally

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invasive variation (MIS-TLIF) in the early 2000s.[4] Since its introduction, the MIS-TLIF has demonstrated fewer complications, less intraoperative blood loss, shorter hospital stay and recovery time, and less postoperative narcotic use with similar clinical outcomes and fusion rates compared with conventional open TLIF.[5-23] Furthermore, MIS-TLIF has been associated with advantageous outcomes in obese patients.[24-28] The benefits of MIS-TLIF relative to open TLIF can be attributed to the key principles that define MISS, specifically the following: (1) minimizing soft tissue disruption and minimizing destabilization of the spinal segment(s), thus leaving the smallest operative footprint possible while achieving the operative goal; (2) achieving bilateral decompression via a unilateral approach when necessary; and (3) achieving indirect neural decompression.

In general, the key steps of the MIS-TLIF are well defined and include decompression, with central/bilateral decompression if clinically indicated, discectomy and interbody graft insertion, and pedicle screw and rod placement. However, there are a number of technical nuances to each step that have resulted in significant heterogeneity in how surgeons perform MIS-TLIF. To our knowledge, there are no publications that examine the various MIS-TLIF techniques reported in the literature in a systematic manner. The aim of the present systematic review is to provide an overview of the published techniques labeled as "MIS-TLIF" over the past 10 years. Since there is no accepted definition of MIS-TLIF, this overview hopes to provide a detailed examination of the reported MIS-TLIF techniques and to help inform clinicians on what exactly constitutes the MIS-TLIF. Ultimately, we hope this review will facilitate an agreement on a definition of MIS-TLIF and, importantly, identify techniques that disqualify the MIS label.

Material and Methods

Systematic Review and Study Inclusion

Our systematic review was performed following the guidelines proposed by the Meta-analysis of Observational Studies in Epidemiology (MOOSE) Group[29] and the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement.[30] We included articles published between 2008 and 2018. Identification of relevant studies began with an electronic search of MEDLINE. Terms included derivatives of "minimally invasive" and "lumbar spine" or "fusion." Citations were limited to those published in English. Potential articles were then imported into the online reference management program Mendeley (Mendeley Desktop, 1.17.13, Mendeley Ltd, Elsevier, Amsterdam, Netherlands) to remove duplicate citations and organize the studies before reviewing them for study inclusion. Three independent reviewers (SL, RNH, CW) then screened study titles, abstracts, and full-text articles to identify studies reporting on MIS-TLIF. Included articles contained a detailed technical description of the MIS-TLIF and at least one of the following: (1) description of the surgical approach, (2) description of the retractor, (3) description of the interbody graft. Reviewers were not blinded in terms of the authors, journals, and/or any other data regarding the papers. A study was included in the systematic review only if all 3 screeners agreed that the study met the inclusion criteria. In cases of disagreement, the senior author (RH) was consulted regarding suitability for study inclusion. Twenty-three papers reported on the same patient cohort and used the same technique as already reported in previous publications. These papers were eliminated as they were redundant and therefore did not provide additional information. Ultimately, 75 papers were selected for inclusion (Figure 1).[7,9-17,20-23,27,31-90]

Data Extraction

The MIS-TLIF procedure was divided into several major components to allow a step-by-step overview and comparison of the applied techniques. The first component described was the operating room setup and equipment used, including information about intraoperative imaging and the use of computer-assisted navigation (CAN), use of the operative microscope or endoscope, and use of intraoperative neuromonitoring (IOM). This section was followed by the description of the surgical approach, including the size and location of the incision(s), the approach to the target region, and the type of retractor used. The next described component was the decompression, including the approach and details of how the decompression was performed, followed by the interbody fusion, including the type of interbody cage and types of graft and/or biologic materials used. The final component was pedicle screw and rod implantation, including the manner of insertion, unilateral or bilateral constructs, and use of Kirschner (K)-wires.

In order to perform the above-described detailed examination, data on the following features was extracted for each study: (1) name of the authors; (2) year of publication; (3) type of study; (4) total number of patients/number of MIS-TLIF treated patients; (5) diagnoses/indication for fusion; (6) levels of fusion; (7) patient positioning; (8) type of intraoperative imaging used, including use of CAN; (9) use of microscope; (10) use of IOM; (11) number of incisions; (12) location of incision(s); (13) size of incision(s); (14) type of surgical approach; (15) type and manufacturer of the retractor; (16) size of the retractor; (17) side of decompression; (18) type of decompression; (19) instruments used for the decompression; (20) timing of decompression during the procedure; (21) type of graft and/or biologics used for interbody fusion; (22) type and manufacturer of interbody cages; (23) timing of interbody fusion during the procedure; (24) use of K-wires for screw placement; (25) technique for rod placement; (26) number of screws; (27) system and manufacturer of screws/rods; and (28) timing of pedicle screw placement during procedure.

Results

Study Inclusion

A total of 75 studies with 7808 patients (4920 treated with MIS-TLIF) were included in the analysis (Tables 1 and 2). Indications

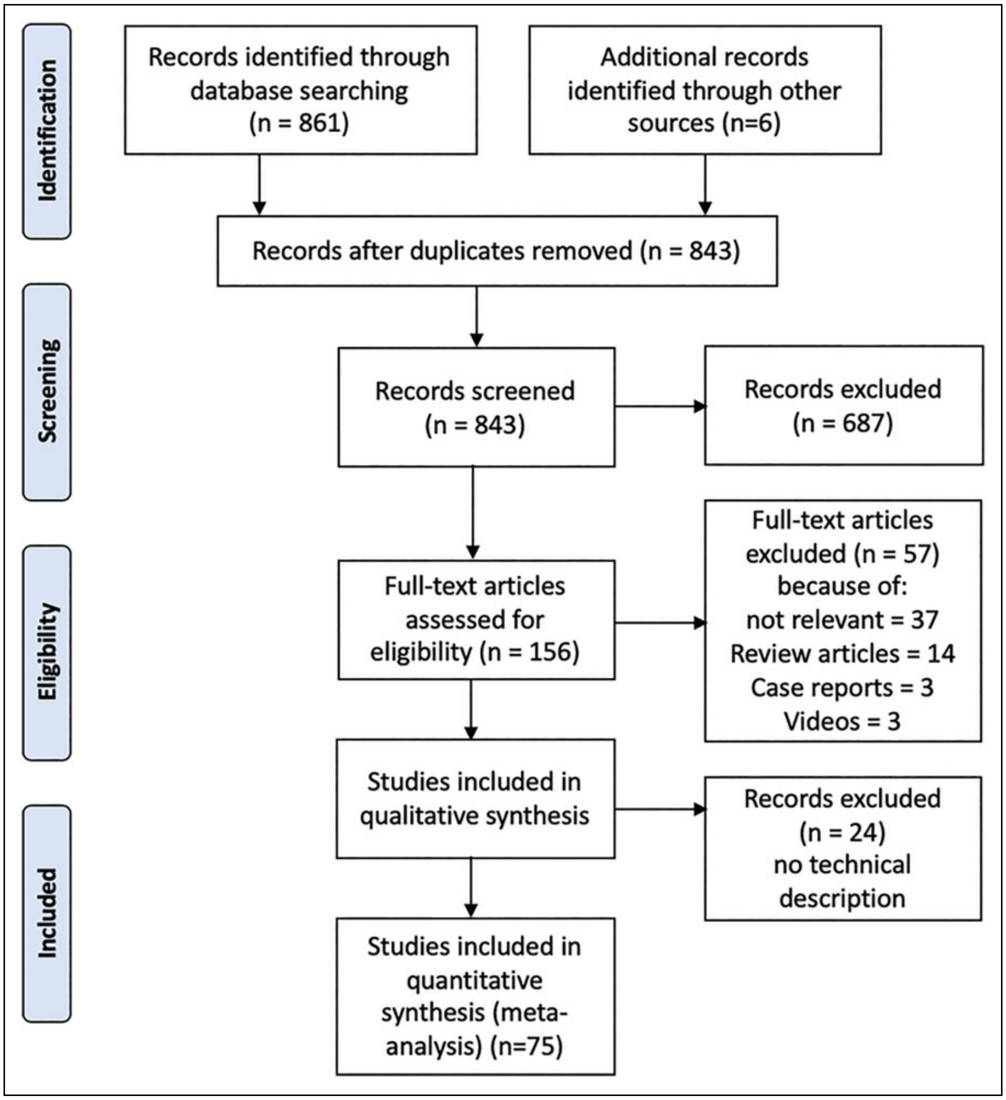

Figure 1. Inclusion algorithm.

for MIS-TLIF included isthmic/degenerative spondylolisthesis, spondylolysis, spinal and/or foraminal stenosis, recurrent disc herniations, and undefined degenerative disc disease.

Operating Room Setup and Equipment

The majority of patients were positioned prone on a Jackson table. With the exception of one paper, all surgeries were performed under general anesthesia. Wang and Grossman applied sedation without general anesthesia.[80] Fifty-nine studies (79%) used standard fluoroscopy for intraoperative imaging, 8 studies (11%) utilized 3D fluoroscopy, and 2 studies (3%) used intraoperative computed tomography (CT); this resulted in a total of 10 publications (13%) reporting the use of CAN (Figure 2). Six studies (8%) did not mention the type of intraoperative imaging used. For visualization purposes, 25 studies (33%) specifically mentioned the use of the surgical microscope; 3 studies (4%) used an endoscope of which 2 used the endoscope through a tubular retractor and 1 study performed a percutaneous endoscopic approach; 1 study used a microscope or surgical loupes; and 1 study reported direct visualization without the use of any visualization aid. Forty-six studies (61%) did not include information about the use of the microscope or other means for enhanced visualization. With regard to IOM, 7 studies (9%) specifically reported the use of IOM, whereas the remaining 68 (91%) of studies did not mention the use of IOM.

Incision(s)

The location of the incision(s) used for inserting the retractor was categorized into 3 groups: (1) midline requiring subperiosteal dissection, (2) close paraspinal/paramedian, and (3) a determined distance further lateral from the midline, which was further divided into (3a) in relation to a specific anatomical structure according to fluoroscopy or navigation or (3b) a measured distance from the midline (Figure 3). A single midline incision (1) was used by only 2 studies (3%), and an unspecified paramedian or paraspinal incision (2) was performed in 5

Table 1. Literature Overview of Instruments' Technical Details in MIS-TLIF.

Study	Imaging	IOM	Incisions	Incision Lz.	Incision Loc	Workflow	Scope	K-wire	Screw BL vs UL	Retractor Type	Tube Size	Deco	Screws Insertion	Rod Insertion
Adogwa 2011[7]	F	N/A	N/A	AL	3b	d>c>s	N/A	y	BL	T	N/A	ULBD	PC	PC
Ahn 2015[31]	F	N/A	2	F	3a	Kw>d>c>s	y	y	BL	T	21 mm	ULBD	PC	PC
Brodano 2015[32]	F	N/A	5	N/A	N/A	d>c>s	N/A	N/A	BL	N/A	N/A	N/A	PC	PC
Chen 2015[34]	F	N/A	N/A	N/A	N/A	d>c>s	N/A	N/A	UL vs BL	T	N/A	ULBD	PC	PC
Choi 2013[35]	F	N/A	2 vs 3	F	3a	d>c>s	N/A	N/A	UL vs BL	T	22 mm	ULBD	PC	PC
Choi 2018[36]	F	N/A	N/A	AL	2	d>c>s	y	N/A	BL	T	24 mm	ULBD	PC	PC
Eliades 2015[37]	F	y	1 or 2	AL	3b	d>c>s	N/A	N/A	UL or BL	NT/E	N/A	ULBD	MO	MO
Emami 2016[38]	F	y	N/A	AL	3b	Kw>d>c>s	y	y	BL	T	N/A	ULBD	PC	PC
Fan 2016[39]	F	N/A	2	AL	3b	d>c>s	N/A	y	BL	T/E	N/A	BL	PC	PC
Fomekong 2017[40]	3D-F	N/A	2	N	3a	d>c>s	N/A	y	BL	T	N/A	ULBD	PC	PC
Giorgi 2015[41]	F	N/A	N/A	N/A	N/A	s>d>c	N/A	N/A	UL or BL	T	N/A	N/A	N/A	N/A
Guan 2016[9]	3D-F/F	N/A	2	N	3a	d>c>s	N/A	y	BL	N/A	N/A	N/A	PC	PC
Hansen 2016[42]	F	N/A	N/A	F	3a	Kw>d>c>s	y	y	BL	NT/E	N/A	ULBD	PC	PC
Hawasli 2017[43]	F	N/A	N/A	AL	3a	s>d>c	y	y	BL	T	N/A	BL	PC	PC
Hey 2015[10]	F	N/A	3	AL	3a	d>c>s	N/A	y	BL	T	N/A	ULBD	PC	PC
Hijji 2017[44]	F	N/A	N/A	N/A	N/A	d>c>s	N/A	N/A	BL	T	21 mm	N/A	PC	PC
Hsiang 2013[45]	3D-F	N/A	2	AL	1 and 3a	d>c>s	N/A	y	BL	N/A	N/A	ULBD	MO	MO
Huang 2017[46]	F	N/A	1	AL	3b	d>c>s	N/A	N/A	BL	T	N/A	N/A	N/A	N/A
Hung 2017[47]	N/A	N/A	N/A	AL	1	N/A	N/A	N/A	N/A	N/A	N/A	ULBD	PC	PC
Isaacs 2016[99]	F	N/A	N/A	AL	3a	s>d>c	N/A	N/A	BL	NT/E	N/A	ULBD	PC	MO/PC
Kang 2014[48]	F	N/A	2	F	3a	d>c>s	N/A	N/A	UL	T	22 mm	ULBD	PC	PC
Kasliwal 2012[49]	N/A	N/A	2	N/A	N/A	d>c>s	N/A	N/A	BL	T/E	26 mm	N/A	N/A	N/A
Kim 2015[50]	F	N/A	2	AL	3a	d>c>s	N/A	N/A	BL	T	22 mm	ULBD	PC	PC
Klingler 2015[51]	3D-F/F	N/A	4	F	3a	Kw>d>c>s	y	y	BL	T	NR	N/A	PC	PC
Kulkarni 2016[11]	F	N/A	3	F	3a	d>c>s	y	y	BL	T	22 mm	N/A	PC	PC
Kuo 2016[52]	F	N/A	N/A	N/A	N/A	d>c>s	N/A	N/A	BL	T or T/E	N/A	ULBD	PC	PC
Lee 2010[53]	F	N/A	3	F	3a	d>c>s	y	N/A	BL	T	22 mm	ULBD	PC	PC
Lee 2012[54]	F	N/A	N/A	F	3a	d>c>s	y	y	BL	T	22 mm	ULBD	PC	PC
Lee 2016[55]	F	N/A	N/A	F	3a	d>c>s	y	N/A	N/A	T	22 mm	ULBD	PC	PC
Li 2017[56]	F	N/A	2	AL	3a	N/A	N/A	N/A	BL	T/E	N/A	N/A	MO	MO
Lian 2016[57]	N	y	N/A	N	3a	s>d>c	y	N	BL	T	N/A	N/A	PC	PC
Lim 2013[12]	F	N/A	2	AL	3b	d>c>s	N/A	N/A	BL	T/E	22 mm	ULBD	PC	PC
Lin 2017[58]	F	N/A	N/A	AL	2	d>c>s	N/A	N/A	N/A	T	N/A	ULBD	PC	PC
Liu 2017[59]	F	N/A	N/A	F	3a	d>c>s	N	y	BL	T/E	N/A	N/A	PC	PC
Lo 2015[60]	F	N/A	N/A	AL	3b	N/A	y	y	UL	T/E	N/A	N/A	PC	PC
Massie 2018[61]	F	N/A	2	AL	3b	Kw>d>c>s	y	y	BL	T/E	N/A	N/A	PC	MO/PC
McAnany 2016[62]	F	N/A	1	F	3a	Kw>d>c>s	N/A	y	UL	T	21 mm	ULBD	PC	PC
Millimaggi 2018[63]	F	N/A	N/A	AL	3a	Kw>d>c>s	y	y	BL	T/E	N/A	ULBD	PC	PC
Min 2014[64]	N/A	N/A	N/A	AL	3b	d>c>s	y	N/A	BL	T	N/A	ULBD	PC	PC
Park 2008[65]	F	N/A	2	AL	3b	d>cs>c>is	y	y	BL	T	22 mm	ULBD	PC	PC
Park 2015[66]	F	N/A	N/A	N/A	N/A	cs>c>is	N/A	N/A	BL	T	22 mm	N/A	PC	PC
Peng 2009[13]	F	N/A	2	F	3a	d>c>s	N/A	y	BL	T	24-26 mm	ULBD	PC	PC
Putzier 2016[67]	F	N/A	2	AL	3a	s>d>c	N/A	y	BL	T/E	N/A	N/A	MO	MO

(continued)

Table 1. (continued)

Study	Imaging	IOM	Incisions	Incision Lz.	Incision Loc	Workflow	Scope	K-wire	Screw BL vs UL	Retractor Type	Tube Size	Deco	Screws Insertion	Rod Insertion
Reinshagen 2015[68]	3D-F	N/A	3	AL	1 and 3b	d>c>s	y	y	BL	N/A	N/A	ULBD	PC	PC
Schizas 2009[14]	F	N/A	N/A	AL	3a	s>d>c	N/A	y	BL	T	N/A	N/A	PC	PC
Seng 2013[15]	F	N/A	2	AL	3b	d>c>s	N/A	N/A	BL	T	N/A	ULBD	PC	PC
Serban 2017[16]	F	N/A	2	AL	3b	d>c>s	y	y	BL	T	N/A	N/A	PC	PC
Shen 2014[70]	F	N/A	N/A	F	3a	d>c>s	y	N/A	UL vs BL	T	N/A	ULBD	PC	PC
Shunwu 2010[71]	F	N/A	2	AL	3a	s>d>c	N/A	N/A	BL	T/E	25-40 mm	N/A	MO	MO
Siemionow 2012[72]	F	N/A	N/A	F	3a	s>d>c	N/A	y	UL	T	21 mm	N/A	PC	PC
Sonmez 2013[73]	N/A	N/A	N/A	AL	2	d>c>s	N/A	N/A	UL vs BL	T/E	N/A	N/A	PC	PC
Soriano-Sánchez 2017[74]	F	y	N/A	N/A	N/A	d>c>s	N/	N/A	UL vs BL	T	18 mm	N/A	N/A	N/A
Sulaiman 2014[17]	F	N/A	2	F	3a	d>c>s	N/A	N/A	BL	N/A	N/A	ULBD	PC	PC
Tay 2016[75]	F	N/A	2	F	3a	d>c>s	N/A	y	BL	T	24-26 mm	ULBD	PC	PC
Tender 2014[76]	F	y	1 or 2	AL	3b	d>c>s	y	y	UL or BL	T	26 mm or 22 mm	ULBD	MO	N/A
Tian 2016[77]	F	N/A	N/A	F	3a	Kw>d>c>s	N/A	y	BL	T/E	N/A	ULBD	PC	PC
Tian 2017[20]	3D-F	N/A	2	N	3a	Kw>d>c>s	N/A	y	BL	T	24-26 mm	N/A	PC	PC
Torres 2012[78]	3D-F	N/A	N/A	N	3a	d>c>s	y	y	BL	T or T/E	22 mm	ULBD	PC	PC
Tsahtsarlis 2012[79]	3D-F	y	N/A	AL	3a	s>d>c	y	y	BL	T	20 mm	N/A	PC	PC
Vemula 2018[33]	F	N/A	N/A	F	3a	cs>c>is	N/A	y	BL	T	N/A	N/A	PC	PC
Virdee 2017[21]	F	N/A	2	AL	2	d>c>s	y	y	BL	N/A	N/A	N/A	PC	N/A
Wang 2010[22]	F	N/A	4	AL	2	d>c>s	N/A	y	BL	T/E	N/A	N/A	PC	PC
Wang 2016[80]	F	N/A	5	F	3a	d>c>s	End	y	BL	n	N/A	N/A	PC	PC
Wang 2017[27]	F	N/A	2	AL	3a	d>c>s	N/A	N/A	BL	N/A	N/A	N/A	N/A	N/A
Wong 2014[23]	F	y	2	AL	3a	s>d>c	N/A	y	BL	T or T/E	N/A	ULBD	PC	PC
Wong 2015[81]	F or N	N/A	2	AL	3b	d>c>s	Sc/Lo	y	BL	T/E	N/A	N/A	PC	PC
Wu 2013[82]	N/A	N/A	N/A	AL	1 and 2	d>c>s	N/A	N/A	BL	T/E	N/A	N/A	N/A	MO
Xia 2015[83]	F	N/A	1 vs 2	AL	1 vs 3b	d>c>s	N/A	N/A	BL	T/E	N/A	N/A	MO	MO
Yang 2017[84]	F	N/A	4	F	3a	Kw>d>c>s	y	y	BL	T	20 mm	ULBD	PC	PC
Yao 2017[85]	F	N/A	1	AL	3a	d>c>s	N/A	y	UL	T	N/A	ULBD	PC	PC
Yoo 2015[86]	N/A	N/A	N/A	AL	3b	d>c>s	y	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zeng 2015[87]	F	N/A	N/A	AL	3b	d>c>s	N/A	N/A	BL	T or T/E	N/A	N/A	PC	PC
Zhang 2015[88]	F	N/A	1	AL	1	s>d>c	y	N/A	BL	N/A	N/A	N/A	N/A	N/A
Zhang 2017[89]	F	N/A	2	F	3a	d>s>c	N/A	N/A	BL	T	22mm	BL	PC	PC
Zhang 2017[90]	3D-F	N/A	2	AL	3a	Kw>d>c>s	y	y	BL	T	N/A	ULBD	PC	PC

Abbreviations: MIS, minimally invasive surgery; TLIF, transforaminal lumbar interbody fusion; F, fluoroscopy; 3D-F, 3D fluoroscopy; N/A, not available; N, navigation; IOM, intraoperative monitoring; y, yes; n, no; Lz., localization; AL, anatomical landmark; Loc, location ([1] Midline, [2] close paramedian, [3a] in relation to a specific anatomical structure according to fluoroscopy or navigation, [3b] a measured distance from the midline); d, decompression; c, cage; s, screws; Kw, K-wire; BL, bilateral; UL, unilateral; T, tubular; NT/E, nontubular-expandable; T/E, tubular-expandable; Deco, decompression; ULBD, unilateral laminotomy for bilateral decompression; PC, percutaneous; MO, mini-open.

publications (7%). Three studies (4%) used a combination of a single midline incision with a paraspinal or defined distance from midline, and 1 study used either a midline or 2 paraspinal incisions. Sixteen studies (21%) made the incision(s) a specific distance from midline and the remaining 8 studies (11%) did not describe the technique for incision localization. The majority of studies (n = 40/75; 53%) used intraoperative imaging to localize the incision(s) relative to anatomic structures (3a; eg,

Table 2. Literature Overview of Interbody Fusion Methods, Devices, and Techniques Used in MIS-TLIF.

Study	Cage Material	Cage Shape	E	Disc Space Packed	Graft Ant. Disc Space	Cage Packed	Autograft Cage	Allograft Cage
	N/A	N/A	N/A	N/A	N	N/A	n	N/A
Adogwa 2011[7]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Ahn 2015[31]	PEEK	N/A	N/A	N	N	y	L-auto	N/A
Brodano 2015[32]	PEEK	Straight	NE	y	y	N/A	N/A	N/A
Chen 2015[34]	PEEK	Bullet	NE	N/A	N/A	y	L-auto	N/A
Choi 2013[35]	PEEK	Banana/ straight	NE	y	y	y	L-auto	N/A
Choi 2018[36]	PEEK	Straight	NE	y	y	y	BMA	Allograft
Eliades 2015[37]	no cage	N/A	N/A	y	y	No cage	No cage	No cage
Emami 2016[38]	PEEK	Straight	NE	y	y	y	L-auto	N/A
Fan 2016[39]	Titanium	Straight	NE	y	AMSC	y	AMSC	N/A
Fomekong 2017[40]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Giorgi 2015[41]	N/A	N/A	N/A	N/A	N/A	y	L-auto	N/A
Guan 201[69]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Hansen 2016[42]	N/A	Banana/ straight	NE or E	y	y	y	L-auto + BMNCC	N/A
Hawasli 2017[43]	N/A	N/A	N/A	y	y	y	L-auto	N/A
Hey 2015[10]	N/A	N/A	N/A	N/A	N/A	y	L-auto	DBM + BMP
Hijji 2017[44]	PEEK	N/A	N/A	y	y	y	L-auto + BMA	Allograft
Hsiang 2013[45]	PEEK	Bullet	NE	y	y	y	L-auto	N/A
Huang 2017[46]	PEEK	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hung 2017[47]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Isaacs 2016[99]	PEEK	Bullet	NE	N/A	N/A	y	L-auto	N/A
Kang 2014[48]	PEEK/ Titanium	Straight	NE	N/A	N/A	y	L-auto	n
Kasliwal 2012[49]	PEEK	Bullet	NE	N/A	N/A	y	L-auto	n
Kim 2015[50]	Titanium	Banana	NE	N/A	N/A	N/A	N/A	N/A
Klingler 2015[51]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Kulkarni 2016[11]	PEEK	N/A	N/A	N/A	N/A	y	L-auto	DBM
Kuo 2016[52]	PEEK	Straight	NE	y	y	y	L-auto	n
Lee 2010[53]	PEEK	Banana/ straight	NE	y	y	y	L-auto	n
Lee 2012[54]	N/A	Banana/ straight	N/A	N/A	N/A	y	L-auto	Allograft
Lee 2016[55]	PEEK	Straight	NE	N/A	N/A	y	L-auto	N/A
Li 2017[56]	N/A	N/A	N/A	N/A	N/A	y	Iliac crest	N/A
Lian 2016[57]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Lim 2013[12]	N/A	Banana/ straight	N/A	N/A	N/A	y	L-auto	DBM or BMP
Lin 2017[58]	PEEK	Banana	NE	y	y	y	L-auto	N/A
Liu 2017[59]	PEEK	Straight	NE	N/A	N/A	N/A	N/A	N/A
Lo 2015[60]	Titanium	Banana	E	y	N/A	y	N/A	N/A
Massie 2018[61]	PEEK	N/A	N/A	y	y	N/A	N/A	N/A
McAnany 2016[62]	PEEK	Banana	NE	N/A	N/A	N/A	N/A	N/A
Millimaggi 2018[63]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Min 2014[64]	PEEK	N/A	N/A	y	y	y	L-auto	BMP
Park 2008[65]	PEEK	Straight	NE	y	y	N/A	N/A	N/A
Park 2015[66]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Peng 2009[13]	N/A	N/A	N/A	y	y	y	L-auto	N/A
Putzier 2016[67]	PEEK	Foldable	NE	y	y	y	L-auto	N/A
Reinshagen 2015[68]	PEEK	N/A	N/A	y	y	y	L-auto + Iliac crest	N/A
Schizas 2009[14]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Seng 2013[15]	PEEK	N/A	N/A	y	y	N/A	N/A	N/A
Serban 2017[16]	PEEK	Straight	NE	y	y	N/A	N/A	N/A
Shen 2014[70]	Titanium	N/A	N/A	y	y	y	Iliac crest	N/A
Shunwu 2010[71]	N/A	N/A	N/A	N/A	N/A	y	L-auto	EM

(continued)

Table 2. (continued)

Study	Cage Material	Cage Shape	E	Disc Space Packed	Graft Ant. Disc Space	Cage Packed	Autograft Cage	Allograft Cage
Siemionow 2012 [72]	PEEK	N/A	N/A	y	y	y	Auto	N/A
Sonmez 2013 [73]	N/A	Bullet	N/A	y	y	N/A	N/A	N/A
Soriano-Sánchez 2017 [74]	PEEK	N/A	N/A	y	y	y	Auto	N/A
Sulaiman 2014 [17]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Tay 2016 [75]	N/A	N/A	N/A	N/A	N/A	y	L-auto	N/A
Tender 2014 [76]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tian 2016 [77]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Tian 2017 [20]	PEEK	N/A	E	N/A	N/A	y	L-auto	Allograft/DBM/BMP
Torres 2012 [78]	PEEK	Straight	NE	N/A	N/A	y	L-auto	BMP
Tsahtsarlis 2012 [79]	PEEK	Straight	NE	N/A	N/A	N/A	N/A	N/A
Vemula 2018 [33]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Virdee 2017 [21]	PEEK	Banana	NE	y	y	N/A	N/A	N/A
Wang 2010 [22]	Optimesh	Optimesh	E	y	N/A	y	N/A	Allograft
Wang 2016 [80]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Wang 2017 [27]	N/A	N/A	N/A	y	y	y	Auto + BMA	EM
Wong 2014 [23]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Wong 2015 [81]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Wu 2013 [82]	PEEK	Straight	NE	y	y	y	L-auto	N/A
Xia 2015 [83]	N/A	Bullet	N/A	y	y	y	L-auto	N/A
Yang 2017 [84]	PEEK	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Yao 2017 [85]	PEEK	Straight	NE	y	y	y	L-auto	N/A
Yoo 2015 [86]	N/A	N/A	N/A	y	y	N/A	N/A	N/A
Zeng 2015 [87]	Titanium	Straight	NE	y	y	N/A	N/A	N/A
Zhang 2015 [88]	PEEK	Straight	NE	N	N/A	y	L-auto	N/A
Zhang 2017 [89]	N/A	N/A	N/A	y	y	y	L-auto	N/A
Zhang 2017 [90]	N/A	N/A	N/A	y	y	y	L-auto	N/A

Abbreviations: MIS, minimally invasive surgery; TLIF, transforaminal lumbar interbody fusion; N/A, not available; PEEK, polyetheretherketone; AMSC, adipose-derived mesenchymal stem cells; NE, nonexpandable; E, expandable; y, yes; n, no; L-auto, local autograft; BMNCC, bone marrow nucleated cell concentrate; BMA, bone marrow aspirate; Auto, autograft; DBM, demineralized bone matrix; BMP, bone morphogenic protein; EM, extender matrix.

lateral to pedicles, at the level of the facet complex). The median number of incisions was 2 (range 1-5). Almost half of the studies did not specifically mention the number or location of incisions (n = 32/75; 43%). Four publications (5%) described using a single incision, 25 (33%) used 2 incisions, 4 (5%) used 3 incisions, 3 (4%) used 4 incisions, 2 (3%) used 5 incisions, and 5 (7%) used a varying number of incisions.

Retractor

The vast majority of studies utilized a type of tubular retractor to perform the decompression and interbody cage insertion (n = 61/75; 81%). Specifically, 26 publications (35%) used a nonexpandable tubular retractor, 16 (21%) used an expandable tubular retractor, 4 (5%) reported the use of either a non-expendable or an expandable tubular retractor in their studies, while 15 (20%) reported the use of a tubular retractor but did not distinguish between nonexpendable versus expandable. Three studies (4%) used an expandable nontubular retractor, 1 study (1%) used an endoscope percutaneously without the need for a retractor, and 10 studies (13%) either did not specify or did not report the use of a retractor. The retractor size involving endoscopic cannulas, tubular, tubular expandable, as well as specular retractors varied from 8 mm to 40 mm. However, the most frequently used retractor was a 22 mm nonexpendable tubular retractor (n = 8/75; 11%). Most of the studies chose a transmuscular (n = 27/75; 36%) or Wiltse approach (n = 17/75; 23%) to reach the level of interest, and 31 studies (41%) did not specify the approach. The types of retractors used are summarized in Figure 4.

Workflow

Forty-five studies (60%) performed the decompression and interbody cage insertion first (Figure 5), prior to pedicle screw placement. This decompression first group included facetectomy, nerve root decompression, discectomy, and interbody cage insertion with or without laminotomy/laminectomy prior to pedicle screw insertion. Eleven studies (15%) cannulated the pedicles and inserted K-wires as the initial step, followed by decompression and interbody cage insertion, and subsequent placement of the pedicle screw-rod constructs. Eight studies (11%) placed all the pedicle screws first. Six publications (8%) placed the contralateral screws first. Three of these studies (4%) next placed ipsilateral K-wires followed by decompression and cage insertion and lastly ipsilateral screw

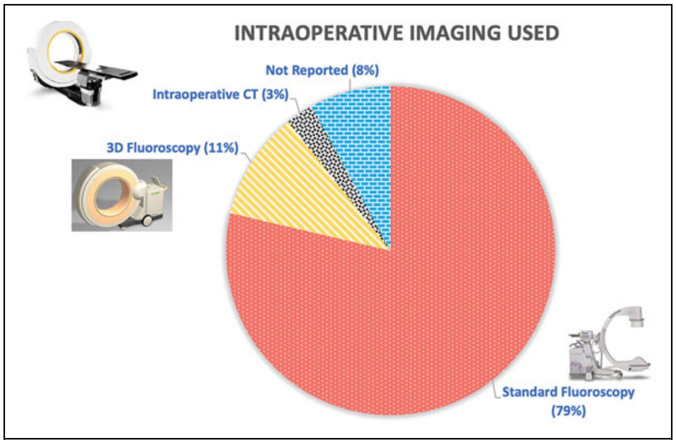

Figure 2. The use of intraoperative described in the included articles.

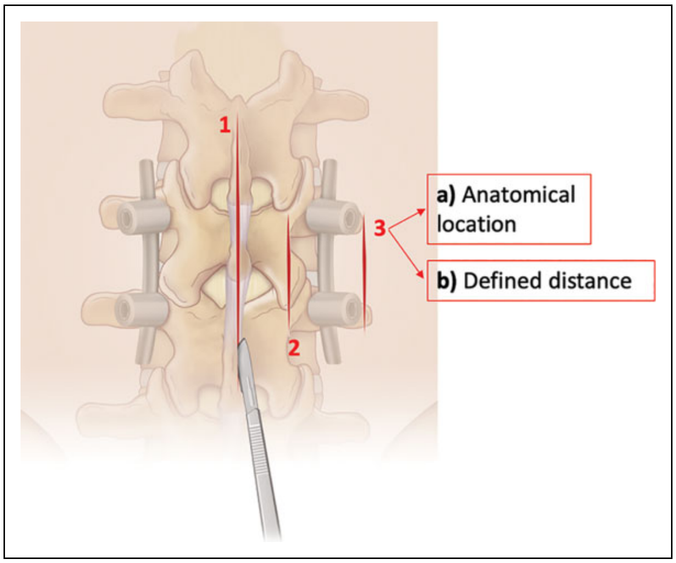

Figure 3. Incision locations for retractor insertion: (1) Midline, (2) close paramedian, and (3) a defined distance to the midline, which was further divided into (3a) in relation to a specific anatomical structure according to fluoroscopy or navigation or (3b) a measured distance from the midline.

placement. The other three (4%) next performed the decompression and cage insertion followed by ipsilateral screw placement. One study (1%) performed the decompression first followed by, in order, contralateral screw placement, cage insertion, and ipsilateral screw placement. Last, 1 study (1%) performed the decompression first followed by bilateral screw placement and lastly the interbody cage. Only 3 studies (4%) did not report the order of steps.

Decompression

When reported, the facetectomy was always performed on the symptomatic side. The majority of studies (n = 64/75; 85%) described a complete or total facetectomy, whereas 2 studies (3%) performed a partial facetectomy. The high-speed drill was used in 29 studies (39%) to perform the facetectomy and decompression with or without a pituitary rongeur, Kerrison punch, or osteotome. Twelve studies (16%) used an osteotome alone or in combination with the high-speed drill, pituitary rongeur, and/or Kerrison punches. Forty publications (53%) did not mention the instruments used for the facetectomy and decompression. When a bilateral decompression of the spinal canal was clinically indicated, 38 studies (51%) utilized a unilateral laminotomy for bilateral decompression (ULBD), 3 studies (4%) placed tubular retractors bilaterally to perform bilateral decompression, and the remaining 34 studies (45%) did not specify how bilateral decompression was performed.

Interbody Cage

Seventy-three studies (97%) reported the use of an interbody cage. One study reported the use of an "interbody graft" but did not specify exactly what was implanted and 1 study used a combination of morselized autograft, corticocancellous allograft, and demineralized bone matrix for interbody fusion. Of the 73 studies that reported the use of an interbody cage, 35 studies (48%) used a polyetheretherketone (PEEK) cage, 4 (5%) used a titanium cage, 1 (1%) used a mesh cage, 1 (1%) used either a PEEK or titanium cage, 1 (1%) used a titanium cage with a structural graft made from autologous adipose-derived stem cells, and the remaining 31 studies (42%) did not report the cage material (Figure 6). Twenty-two (30%) utilized a straight or bullet-shaped cage, 5 (7%) used a banana-shaped cage, 5 (7%) used either a straight or banana-shaped cage, 1 (1%) used a foldable cage, 1 (1%) used a mesh cage, and 39 (53%) did not mention the cage shape (Figure 7). Twenty-seven publications (37%) reported the use of a nonexpandable cage, 3 (4%) reported the use of an expandable cage, 1 (1%) used either nonexpandable or expandable, and 42 (58%) did not specify whether the cage was nonexpendable versus expandable (Figure 8). The most commonly used interbody cage was a nonexpendable, straight or bullet-shaped, PEEK cage (n = 18/73; 25%).

Graft Material

Again, 73 studies reported the use of an interbody cage. Of these 73 studies, 41 (56%) reported packing the interbody cage with graft material and 32 (44%) either did not pack or did not mention packing the interbody cage with graft material. Of the 41 studies that reported packing the interbody cage, 28 (68%) used autograft alone (either local autograft or iliac crest autograft) and 11 (27%) used autograft in combination with allograft, bone graft substitute, or other synthetic bone graft extender or biologic, which included 5 studies (12%) that used bone morphogenic protein (BMP) and 4 studies (10%) that used demineralized bone matrix (DBM). One study (2%) used allograft alone and 1 used autologous adipose-derived mesenchymal stem cells.

Forty-four studies (59%) reporting packing the anterior disc space with graft material and the remaining 31 (41%) studies

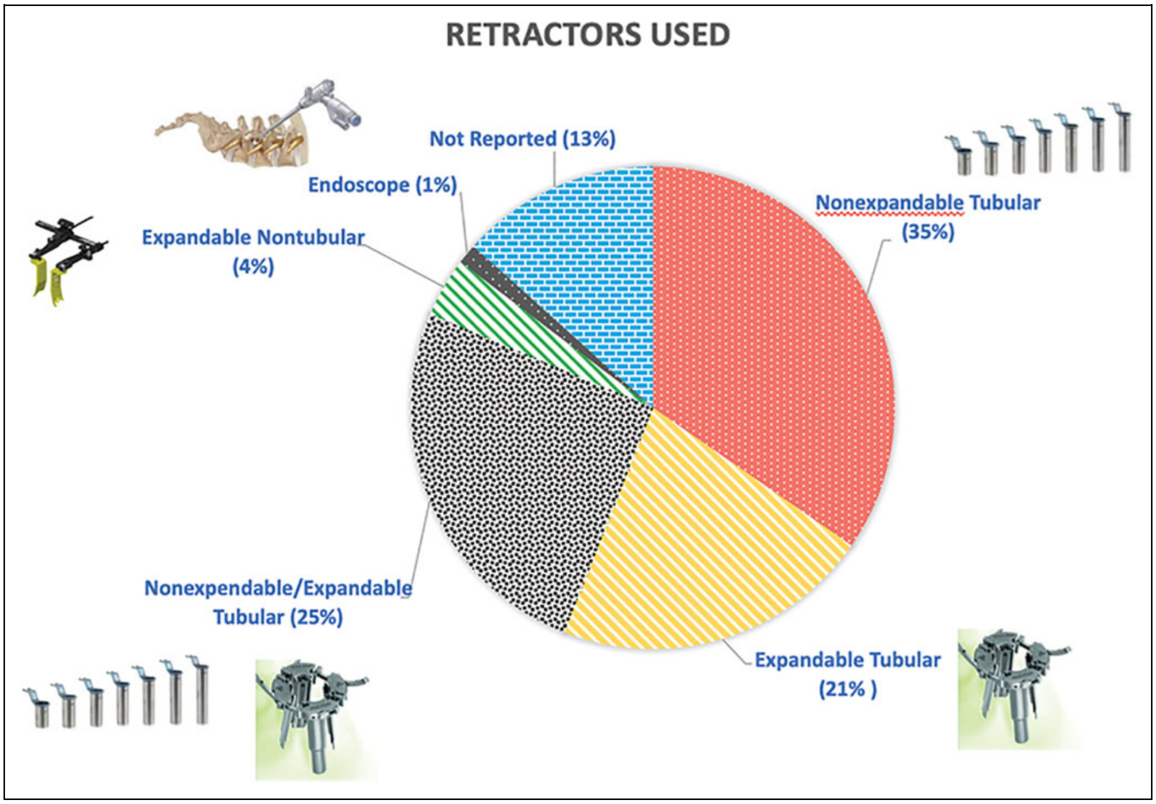

Figure 4. Different types of retractors used in the included articles.

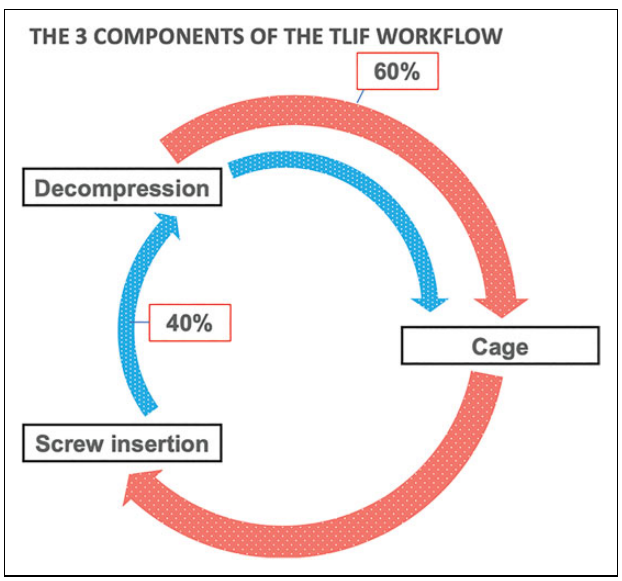

Figure 5. The components of the TLIF workflow—60% of the included articles described starting with decompression while 40% reported that starting with pedicle screw placement.

either did not pack or did not mention packing graft into the anterior disc space. Of the 44 studies that packed the anterior disc space, the most commonly used graft material was autologous bone graft alone, either local bone or iliac crest (n = 24/44; 55%). Sixteen studies (36%) combined autograft with allograft, bone graft substitute, or other synthetic bone graft extender or biologic, which included 4 studies (9%) that used BMP, 4 studies (9%) that used DBM, 4 studies (9%) that used bone graft substitute, and 2 studies (4%) that used allograft. One study used BMP alone, 1 study used autograft or bone graft substitute, 1 study used autologous adipose-derived mesenchymal stem cells to enhance fusion, and 1 study reported the use of "bone graft" but did not specify exactly what was used. An overall summary of the graft materials utilized to enhance fusion is provided in Figures 9 and 10.

Pedicle Screw and Rod Placement

The vast majority of publications (n = 59/75; 79%) inserted pedicle screws in a percutaneous manner. Five studies (7%) used a mini-open approach utilizing expandable retractors, 2 studies (3%) directly visualized the pedicle screw entry point through an unspecified retractor, and 1 study directly visualized the entry points through a nonexpendable tubular retractor. The remaining 8 studies (11%) did not specifically mention the manner of screw placement. Forty studies (53%) performed pedicle screw placement with the use of K-wires or guide wires. The majority of studies placed rods in a percutaneous manner (n = 57/75; 76%). Seven studies (9%) placed the rods in a mini-open fashion, 2 (3%) placed the ipsilateral rod mini-open and the contralateral rod percutaneously, and the remaining 9 studies (12%) did not specify how the rods were placed. Fifty-six studies (75%) placed bilateral pedicle-screw rod constructs, 5 (7%) placed unilateral screws alone, 8 (10%) placed

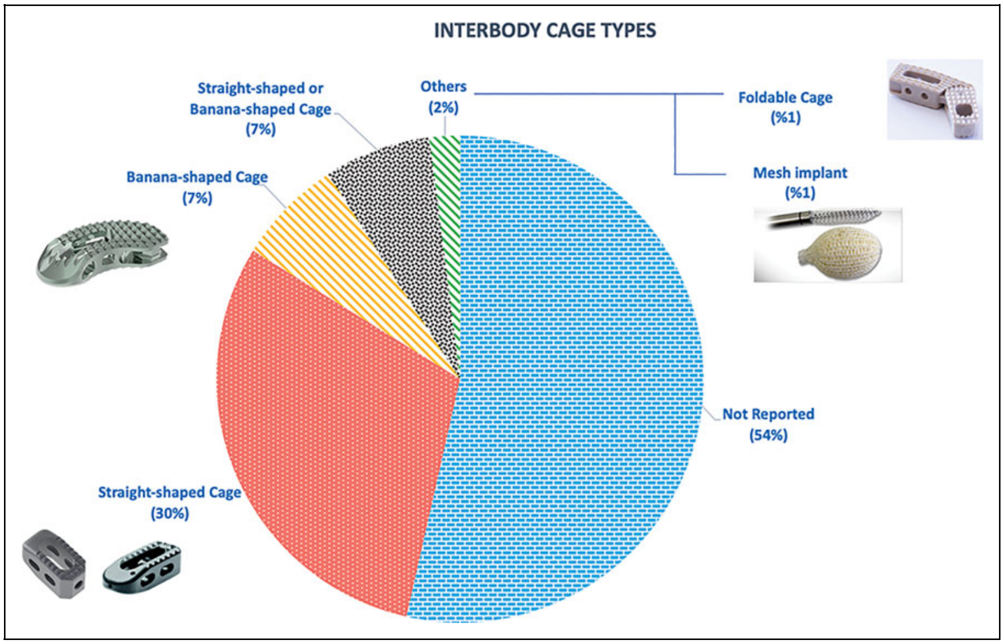

Figure 6. Interbody cage material used in the included articles.

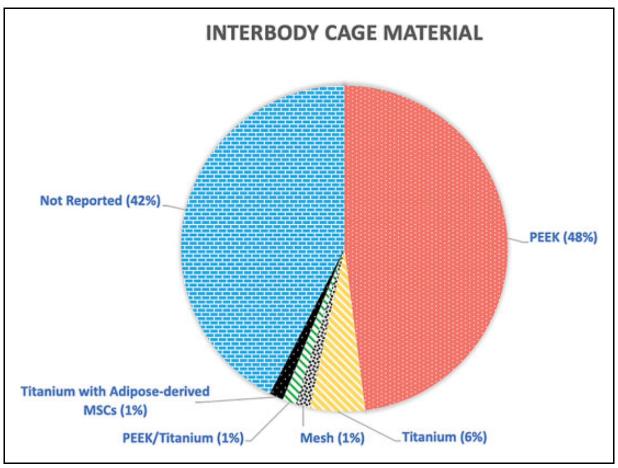

Figure 7. Shape of interbody cage used in the included articles.

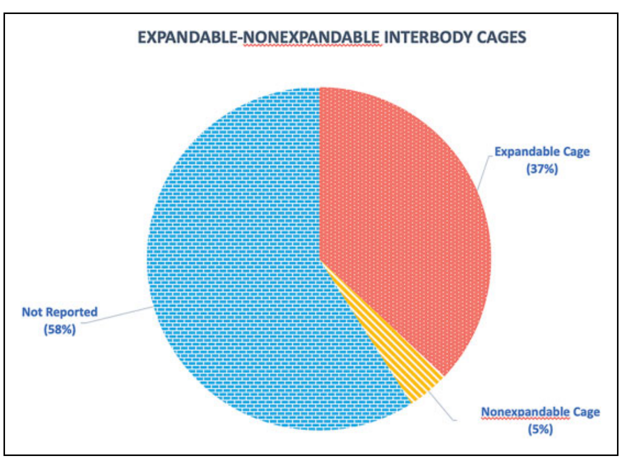

Figure 8. Type of interbody cage used in the included articles.

either unilateral or bilateral screws in their studies, 2 (3%) placed the ipsilateral rod mini-open and the contralateral rod percutaneously, and the remaining 4 (5%) did not mention placement of unilateral versus bilateral constructs. A summary of the pedicle screw insertion techniques is provided in Figures 11 and 12.

Discussion

Compared with the open TLIF, the MIS-TLIF has been shown to have less intraoperative blood loss, fewer complications, shorter hospital stay and faster recovery, and less postoperative narcotic use with similar clinical outcomes and rates of bony fusion.[5-28] Many of the benefits of the MIS-TLIF are due to the key principles of MISS: to minimize tissue disruption and trauma, to achieve bilateral decompression via a unilateral approach when indicated, and to achieve indirect neural decompression.[91]

Definition of MIS

While the general steps for MIS-TLIF (decompression, discectomy and interbody cage insertion, and pedicle screw and rod insertion) are agreed upon, there is a great degree of variability in exactly how these steps are performed. To our knowledge, there is no existing review that examines the techniques reported for the performance of the MIS-TLIF, and as such, there is no accepted definition of what constitutes the MIS-TLIF. As we have demonstrated in the present review, there is great heterogeneity not only in how MIS-TLIF is performed among surgeons but also in the definition of MIS-TLIF. While many surgeons refer to the "MIS-TLIF," it is important to realize that not all iterations of the MIS-TLIF described in the

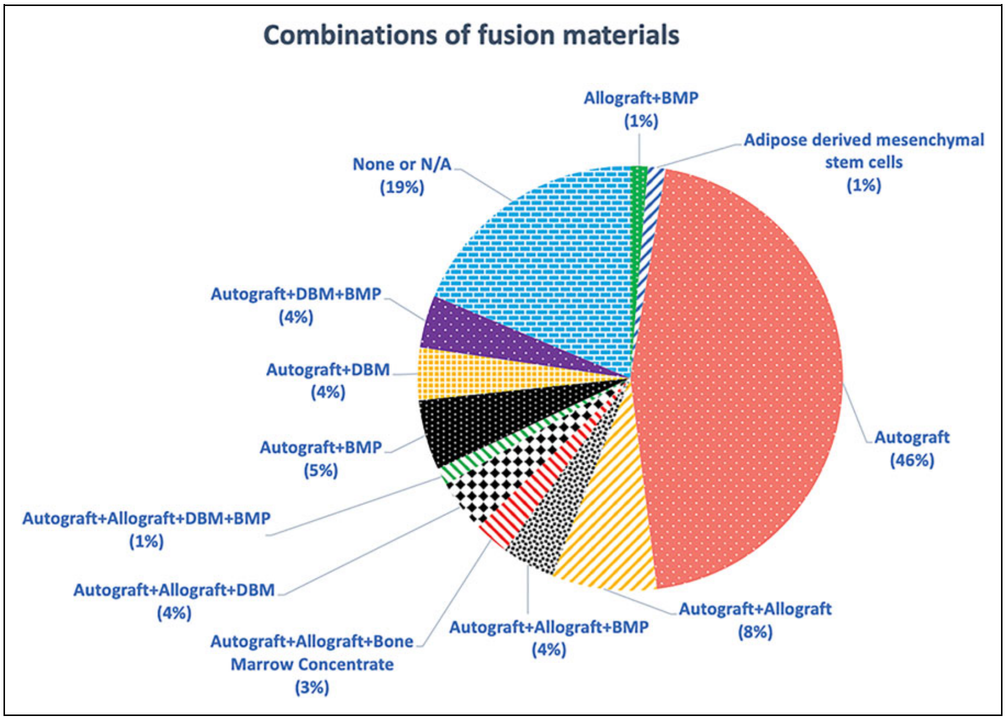

Figure 9. Different combinations of materials used to enhance interbody fusion as described in the included articles.

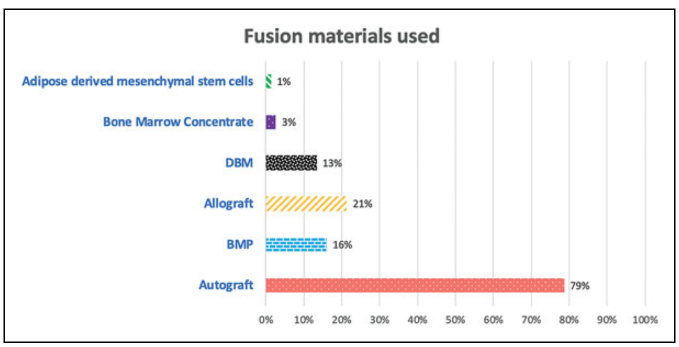

Figure 10. Overall overview of the graft materials utilized to enhance fusion as described in the included articles.

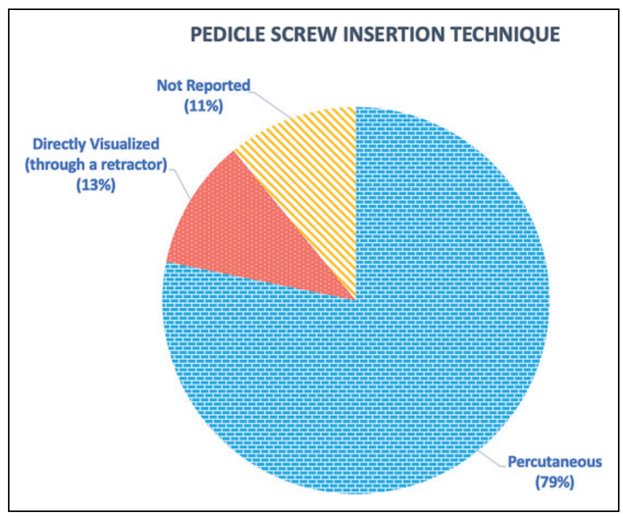

Figure 11. Technique used for pedicle screw insertion as described in the included articles.

literature are truly MIS. A clear definition of the MIS-TLIF that is agreed upon by MIS surgeons is therefore needed. Such a definition would help improve clinical research as well as patient education by separating true MIS-TLIF from mini-open approaches. The benefits of the MIS-TLIF have been well reported in the literature, and one may expect these outcomes to be even better if the mini-open TLIF is removed from such studies, resulting in the comparison of true MIS-TLIF to open TLIF. Furthermore, MIS-TLIF and mini-open TLIF should be distinguished from one another so that the two can be directly compared. Is there any benefit of a true MIS-TLIF over a mini-open TLIF? Or is there a degree of invasiveness below which there is no additional benefit? Additionally, a clear definition of MIS-TLIF is required to better inform patients. The "MIS-TLIFs" offered to patients by different surgeons, as we have demonstrated in this systematic review, have a great degree of variability in the degree of invasiveness. One surgeon's "MIS-TLIF" may rather represent a mini-open approach compared with another surgeon's true MIS-TLIF. The aim of the present systematic review was to examine the various MIS-TLIF techniques reported in the existing body of literature and to identify patterns that represent accepted techniques among spine surgeons to aid in defining the MIS-TLIF. We also aimed to identify the techniques that require a higher degree of exposure and thus increased tissue damage that should disqualify a TLIF from being labeled as MIS, and in doing so identify several components or techniques of the MIS-TLIF that contribute to

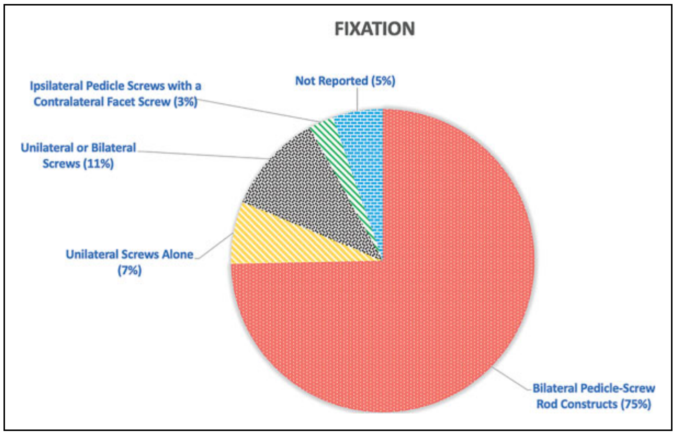

Figure 12. Technique used for pedicle screw insertion.

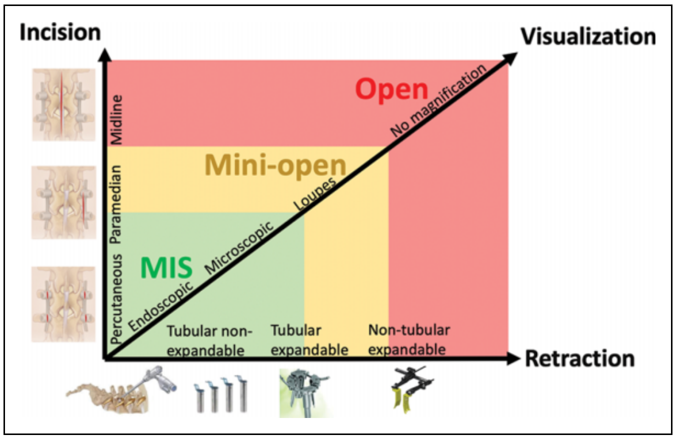

Figure 13. The 3 main criteria of MIS-TLIF and their more invasive variants.

the degree of invasiveness (Figure 13). Our review has illuminated several such patterns.

Intraoperative Imaging and Navigation

With regard to the agreed upon components of the MIS-TLIF, the majority of studies (79%) used standard fluoroscopy as the means of intraoperative imaging, with only a small minority using advanced imaging such as 3D fluoroscopy or intraoperative CT with CAN. This was an interesting finding as in our practice we almost exclusively use intraoperative CT with CAN,[57] and the field of MISS, as well as patient interest, seems to be moving toward more emphasis on navigation. Additionally, multiple studies have demonstrated the increased accuracy of pedicle screw placement with CAN relative to fluoroscopy,[92-96] and a meta-analysis demonstrated less blood loss and fewer complications with the use of CAN.[97] The cost of purchasing such equipment is certainly a burden, particularly in smaller or community hospitals. Perhaps as the technology continues to improve and become more available and affordable, its utilization may increase in practice with more surgeons adopting these advanced intraoperative imaging systems.

Screw Placement

As may be expected for an MIS procedure that requires percutaneous pedicle screw placement, over 90% of studies reported the use of incisions off midline, most commonly in relation to a specific anatomic structure (eg, the pedicle or facet joint). The incision location also allowed the vast majority of surgeons to apply either a muscle sparing Wiltse approach or a less specific transmuscular approach to reach the level of surgical interest. Both approaches fit the key principle of MISS of minimizing muscle and soft tissue disruption. The majority (79%) of studies reported the placement of pedicle screws in a percutaneous manner and 75% placed bilateral pedicle-screw rod constructs.

Retractors and Decompression Technique

Over 80% of publications used a tubular retractor, either expandable or nonexpandable. A small minority reported the use of an expandable nontubular retractor such as a blade retractor that requires extensive superiosteal dissection. Fourth, when reported, almost all studies performed a total facetectomy on the symptomatic side, and when a bilateral decompression was deemed necessary, 93% of publications that described the details of achieving bilateral decompression did so via ULBD.

Interbody Cage and Graft Material

Last, all studies except two reported the use of an interbody cage. When graft material was used, 95% and 91% used autograft with or without allograft or bone graft substitute to pack the anterior disc space and interbody cage, respectively. The use of different materials for performing the interbody fusion has been previously described by our group, and overall, fusion rates for MIS-TLIF are high regardless of the graft materials used.[57] In our study, only 16% of the authors reported the use of BMP alone or in combination with any other materials to enhance fusion. In previous studies focused on fusion materials for MIS TLIF procedures, higher prevalence of BMP use reported has been reported.[98] However, our inclusion criteria were focused on technical nuances rather than details about fusion grafts. Therefore, it is possible that the prevalence of surgeons using BMP is underestimated in our article.

To summarize, the existing body of literature describes the MIS-TLIF to entail the use of paramedian incisions to perform decompression, total facetectomy, and interbody cage placement via a tubular retractor. When graft material is used, autograft is the gold standard. If bilateral decompression is indicated, ULBD is utilized. Finally, the pedicle screw-rod constructs are placed in a percutaneous manner with the use of intraoperative imaging, most commonly standard fluoroscopy.

Workflow

With regard to workflow, most surgeons performed the decompression and interbody cage insertion prior to pedicle screw placement. When pedicle screws were placed first, many authors reported temporarily distracting on the screws in order to open the disc space, followed by compression once the interbody graft was placed. Of note, some of the mini-open retractor systems use the pedicle screw heads and towers for retraction. When using CAN, the pedicle screws or K-wires should be inserted first as insertion of an interbody cage can change the location of the pedicle in anatomical space and result in screw misplacement if an intraoperative scan is not obtained after interbody placement. For this reason, in our practice, we obtain a CT at the start of the procedure and place the pedicle screws first, followed by decompression and interbody cage insertion so as to expose the patient to a single radiation dose at the start of the procedure. Therefore, the order in which the basic steps of the TLIF are performed is not necessarily an indicator of the degree of invasiveness. Other factors that did not contribute to the level of invasiveness included the type of intraoperative imaging used, the use of IOM, the type of interbody cage used, and the type of graft material used.

Criteria for MIS-TLIF

Examination of our systematic review also yielded components of the TLIF that contributed to the degree of invasiveness and certain components that had no effect on the degree of invasiveness. Importantly, we have identified several techniques that we believe should disqualify a TLIF from being considered truly MIS due to wider exposure and subsequently increased tissue trauma. While there are multiple factors contributing to invasiveness, we managed to narrow criteria for MIS-TLIF down to 3 main criteria.

First, perhaps the most critical factor to the MIS-TLIF definition elucidated in the present review is the type of retractor used. As the vast majority of publications reported the use of tubular retractors (81%), the use of a nontubular expandable retractor should disqualify a TLIF from being defined as MIS. Expandable nontubular retractors with subperiosteal dissection rather represent a mini-open approach, and while this technique remains less invasive than the traditional open TLIF, it represents a more invasive TLIF than that obtained with a nonexpendable tubular retractor. Along the same lines, the use of an expandable tubular retractor represents a TLIF that may be more invasive than that achieved with a nonexpandable tubular retractor. If a "pedicle-to-pedicle" exposure is achieved via an expandable tubular retractor, one must not consider this an MIS-TLIF, but rather, again, a mini-open variant. Based upon the type of retractor used, we have identified 5 tiers of invasiveness: (1) most invasive traditional open TLIF; (2) mini-open approach with the use of an expandable nontubular retractor; (3) use of an expandable tubular retractor; (4) use of a nonexpendable tubular retractor; and (5) least invasive with the use of a percutaneous endoscopic approach (Figure 13).

Second, the use of a midline incision should disqualify a TLIF from being described as MIS. Assuming the midline incision is used to perform a subperiosteal dissection and to achieve lateral exposure for the correct bilateral pedicle screw trajectory, it would require a large incision not true to the spirit of MIS.

Moreover, the use of some kind of visualization aid such as surgical loupes, a surgical microscope or endoscope is required for the MIS-TLIF (Figure 13). The access corridors granted by the tubular retractors used in MIS-TLIF are narrow and visualization without magnification or additional illumination is poor. If a microscope or endoscope is not utilized, one must question the MIS nature of the procedure. Within the included articles, only 61% explicitly reported the use of a visualization device. However, since the majority of authors reported the use of a tubular retractor, we believe it is safe to assume that these procedures were performed with some sort of magnification aid. Overall, these criteria for MIS-TLIF were met by 81% of the included articles while 12% were identified as mini-open approach and 7% rather described an open approach per our above-mentioned criteria. Furthermore, we could not identify any specific geographical preferences or differences among the articles reporting about MIS-TLIF.

Limitations

There are several limitations to this review of the literature: (1) the review was conducted retrospectively and mostly reflects state of the art practice of the past 8 years; (2) we included studies independent of their quality and level of evidence; and (3) inclusion criteria were broad. Nevertheless, these limitations may not have much impact on our findings and conclusion, as the aim was to identify some degree of consensus described in the literature for the performance of MIS-TLIF and not to report the outcomes of such techniques. We also relied on detailed descriptions of the MIS-TLIF by the authors to synthesize our data. There were many aspects of the MIS-TLIF that were not specifically described or overlooked by the authors. For example, 61% of studies did not mention the use of the microscope, endoscope, or other means for enhanced visualization. However, it is unlikely that these studies did not use any equipment to improve magnification and illumination. An additional limitation relates to the perpetual advancement of MISS. With the improvements and advancements in TLIF techniques and equipment, the manner in which the procedure is performed must adapt. This is clearly demonstrated if one compares the evolution and adoption of the MIS-TLIF over the past 2 decades. Therefore, one may expect that newer publications represent less invasive techniques than older publications. We have attempted to limit this bias by examining studies published only within the past 10 years. Nevertheless, a surgeon who published on his or her series 5 years ago utilizing a mini-open approach may now have transitioned to a truly MIS approach but has not published on his or her new series; this change in practice would not be captured in the present review. As surgeons are exposed to MIS techniques earlier in their training as residents or fellows and therefore more comfortable with MIS approaches upon completion of training, the number of surgeons performing MIS techniques can be expected to increase in the coming years. This is yet another reason why a clear definition of MIS-TLIF is needed among minimally invasive spine surgeons.

Conclusion

Based on extensive review of MIS-TLIF in the literature, the following conclusions can be made: (1) the use of nonexpandable and expandable tubular retractors are the most commonly used system for minimally invasive access to the facet joint and for cage implantation; (2) paramedian incisions are utilized in the vast majority of MIS-TLIF for pedicle screw insertion; and (3) the use of a microscope or endoscope is required for adequate visualization and illumination given the narrow work corridor for this procedure. Approaches using expandable non-tubular retractors, those that require extensive subperiosteal dissection from the midline laterally, or specular-based retractors with wide pedicle to pedicle exposure, are far less likely to be promoted as an MIS-based approach, and are generally considered to be "mini-open" variants. Midline approaches with wide exposure from facet joint to facet joint and approaches that allow direct visualization without requiring microscopic or endoscopic adjuncts are primarily considered "open" surgeries. While the majority of authors describing MIS-TLIF met the above-mentioned criteria, there is still heterogeneity in the current literature. Further refinement of strict criteria for MIS-TLIF is necessary in order to standardize data reporting and outcomes of future clinical studies.

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References

1. Cloward RB.The treatment of ruptured lumbar intervertebral discs by vertebral body fusion. I. Indications, operative technique, after care. *J Neurosurg*. 1953;10:154-168.
2. Harms J, Rolinger H. A one-stager procedure in operative treatment of spondylolistheses: dorsal traction-reposition and anterior fusion [in German]. *Z Orthop Ihre Grenzgeb*. 1982;120:343-347.
3. Tormenti MJ, Maserati MB, Bonfield CM, et al. Perioperative surgical complications of transforaminal lumbar interbody fusion: a single-center experience. *J Neurosurg*. 2012;16:44-50.
4. Foley KT, Lefkowitz MA. Advances in minimally invasive spine surgery. *Clin Neurosurg*. 2002;49:499-517.
5. Jin-Tao Q, Yu T, Mei W, et al. Comparison of MIS vs. open PLIF/TLIF with regard to clinical improvement, fusion rate, and incidence of major complication: a meta-analysis. *Eur Spine J*. 2015;24:1058-1065.
6. Khan NR, Clark AJ, Lee SL, Venable GT, Rossi NB, Foley KT. Surgical outcomes for minimally invasive vs open transforaminal lumbar interbody fusion: an updated systematic review and meta-analysis. *Neurosurgery*. 2015;77:847-874.
7. Adogwa O, Parker SL, Bydon A, Cheng J, McGirt MJ. Comparative effectiveness of minimally invasive versus open transforaminal lumbar interbody fusion: 2-year assessment of narcotic use, return to work, disability, and quality of life. *J Spinal Disord Tech*. 2011;24:479-484.
8. Gu G, Zhang H, Fan G, et al. Comparison of minimally invasive versus open transforaminal lumbar interbody fusion in two-level degenerative lumbar disease. *Int Orthop*. 2014;38:817-824.
9. Guan J, Bisson EF, Dailey AT, Hood RS, Schmidt MH. Comparison of clinical outcomes in the National Neurosurgery Quality and Outcomes database for open versus minimally invasive transforaminal lumbar interbody fusion. *Spine (Phila Pa 1976)*. 2016;41:E416-E421.
10. Hey HW, Hee HT. Open and minimally invasive transforaminal lumbar interbody fusion: comparison of intermediate results and complications. *Asian Spine J*. 2015;9:185-193.
11. Kulkarni AG, Patel RS, Dutta S. Does minimally invasive spine surgery minimize surgical site infections? *Asian Spine J*. 2016;10:1000-1006.
12. Lim JK, Kim SM. Radiographic results of minimally invasive (MIS) lumbar interbody fusion (LIF) compared with conventional lumbar interbody fusion. *Korean J Spine*. 2013;10:65-71.
13. Peng CW, Yue WM, Poh SY, Yeo W, Tan SB. Clinical and radiological outcomes of minimally invasive versus open transforaminal lumbar interbody fusion. *Spine (Phila Pa 1976)*. 2009;34:1385-1389.
14. Schizas C, Tzinieris N, Tsiridis E, Kosmopoulos V. Minimally invasive versus open transforaminal lumbar interbody fusion: evaluating initial experience. *Int Orthop*. 2009;33:1683-1688.
15. Seng C, Siddiqui MA, Wong KP, et al. Five-year outcomes of minimally invasive versus open transforaminal lumbar interbody fusion: a matched-pair comparison study. *Spine (Phila Pa 1976)*. 2013;38:2049-2055.
16. Serban D, Calina N, Tender G. Standard versus minimally invasive transforaminal lumbar interbody fusion: a prospective randomized study. *Biomed Res Int*. 2017;2017:7236970.
17. Sulaiman WAR, Singh M. Minimally invasive versus open transforaminal lumbar interbody fusion for degenerative spondylolisthesis: comparative effectiveness and cost-utility analysis. *Ochsner J*. 2014;14:32-37.
18. Sun ZJ, Li WJ, Zhao Y, Qiu GX. Comparing minimally invasive and open transforaminal lumbar interbody fusion for treatment of degenerative lumbar disease: a meta-analysis. *Chin Med J (Engl)*. 2013;126:3962-3971.
19. Tian NF, Wu YS, Zhang XL, Xu HZ, Chi YL, Mao FM. Minimally invasive versus open transforaminal lumbar interbody

fusion: a meta-analysis based on the current evidence. *Eur Spine J*. 2013;22:1741-1749.
20. Tian W, Xu YF, Liu B, et al. Computer-assisted minimally invasive transforaminal lumbar interbody fusion may be better than open surgery for treating degenerative lumbar disease. *Clin Spine Surg*. 2017;30:237-242.
21. Virdee JS, Nadig A, Anagnostopoulos G, George KJ. Comparison of peri-operative and 12-month lifestyle outcomes in minimally invasive transforaminal lumbar interbody fusion versus conventional lumbar fusion. *Br J Neurosurg*. 2017;31:167-171.
22. Wang J, Zhou Y, Zhang ZF, Li CQ, Zheng WJ, Liu J. Comparison of one-level minimally invasive and open transforaminal lumbar interbody fusion in degenerative and isthmic spondylolisthesis grades 1 and 2. *Eur Spine J*. 2010;19:1780-1784.
23. Wong AP, Smith ZA, Stadler JA 3rd, et al. Minimally invasive transforaminal lumbar interbody fusion (MI-TLIF): surgical technique, long-term 4-year prospective outcomes, and complications compared with an open TLIF cohort. *Neurosurg Clin N Am*. 2014; 25:279-304.
24. Adogwa O, Carr K, Thompson P, et al. A prospective, multi-institutional comparative effectiveness study of lumbar spine surgery in morbidly obese patients: does minimally invasive transforaminal lumbar interbody fusion result in superior outcomes? *World Neurosurg*. 2015;83:860-866.
25. Terman SW, Yee TJ, Lau D, Khan AA, La Marca F, Park P. Minimally invasive versus open transforaminal lumbar interbody fusion: comparison of clinical outcomes among obese patients. *J Neurosurg Spine*. 2014;20:644-652.
26. Wang J, Zhou Y, Zhang ZF, Li CQ, Zheng WJ, Liu J. Comparison of the clinical outcome in overweight or obese patients after minimally invasive versus open transforaminal lumbar interbody fusion. *J Spinal Disord Tech*. 2014;27:202-206.
27. Wang YP, An JL, Sun YP, Ding WY, Shen Y, Zhang W. Comparison of outcomes between minimally invasive transforaminal lumbar interbody fusion and traditional posterior lumbar intervertebral fusion in obese patients with lumbar disk prolapse. *Ther Clin Risk Manag*. 2017;13:87-94.
28. Xie Q, Zhang J, Lu F, Wu H, Chen Z, Jian F. Minimally invasive versus open transforaminal lumbar interbody fusion in obese patients: a meta-analysis. *BMC Musculoskelet Disord*. 2018;19: 15.
29. Stroup DF, Berlin JA, Morton SC, et al. Meta-analysis of observational studies in epidemiology: a proposal for reporting. Meta-analysis of Observational Studies in Epidemiology (MOOSE) group. *JAMA*. 2000;283:2008-2012.
30. Moher D, Shamseer L, Clarke M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev*. 2015;4:1.
31. Ahn J, Tabaree E, Singh K. Minimally invasive transforaminal lumbar interbody fusion. *J Spinal Disord Tech*. 2015;28:222-225.
32. Brodano GB, Martikos K, Lolli F, et al. Transforaminal lumbar interbody fusion in degenerative disk disease and spondylolisthesis grade I: minimally invasive versus open surgery. *J Spinal Disord Tech*. 2015;28:E559-E564.
33. Vemula VC, Prasad BC, Jagadeesh MA, Vuttarkar J, Akula SK. Minimally invasive transforaminal lumbar interbody fusion using bone cement-augmented pedicle screws for lumbar spondylolisthesis in patients with osteoporosis. Case series and review of literature. *Neurol India*. 2018;66:118-125.
34. Chen C, Cao X, Zou L, Hao G, Zhou Z, Zhang G. Minimally invasive unilateral versus bilateral technique in performing single-segment pedicle screw fixation and lumbar interbody fusion. *J Orthop Surg Res*. 2015;10:112.
35. Choi UY, Park JY, Kim KH, et al. Unilateral versus bilateral percutaneous pedicle screw fixation in minimally invasive transforaminal lumbar interbody fusion. *Neurosurg Focus*. 2013;35: E11.
36. Choi WS, Kim JS, Hur JW, Seong JH. Minimally invasive transforaminal lumbar interbody fusion using banana-shaped and straight cages: radiological and clinical results from a prospective randomized clinical trial. *Neurosurgery*. 2017;82:289-298.
37. Eliades P, Rahal JP, Herrick DB, et al. Unilateral pedicle screw fixation is associated with reduced cost and similar outcomes in selected patients undergoing minimally invasive transforaminal lumbar interbody fusion for L4-5 degenerative spondylolisthesis. *Cureus*. 2015;7:e249.
38. Emami A, Faloon M, Issa K, et al. Minimally invasive transforaminal lumbar interbody fusion in the outpatient setting. *Orthopedics*. 2016;39:e1218-e1222.
39. Fan G, Gu G, Zhu Y, et al. Minimally invasive transforaminal lumbar interbody fusion for isthmic spondylolisthesis: in situ versus reduction. *World Neurosurg*. 2016;90:580-587.e1.
40. Fomekong E, Dufrane D, Berg BV, et al. Application of a three-dimensional graft of autologous osteodifferentiated adipose stem cells in patients undergoing minimally invasive transforaminal lumbar interbody fusion: clinical proof of concept. *Acta Neurochir (Wein)*. 2017;159:527-536.
41. Giorgi H, Prébet R, Delhaye M, et al. Minimally invasive posterior transforaminal lumbar interbody fusion: one-year postoperative morbidity, clinical and radiological results of a prospective multicenter study of 182 cases. *Orthop Traumatol Surg Res*. 2015; 101(6 suppl):S241-S245.
42. Hansen-Algenstaedt N, Liem M, Khalifah SAO, Ilg A, Giese A. Minimal-invasive TLIF. *Eur Spine J*. 2016;25(suppl 4):473-475.
43. Hawasli AH, Khalifeh JM, Chatrath A, Yarbrough CK, Ray WZ. Minimally invasive transforaminal lumbar interbody fusion with expandable versus static interbody devices: radiographic assessment of sagittal segmental and pelvic parameters. *Neurosurg Focus*. 2017;43:E10.
44. Hijji FY, Narain AS, Bohl DD, et al. Risk factors associated with failure to reach minimal clinically important difference in patient-reported outcomes following minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis. *Clin Spine Surg*. 2018;31:E92-E97.
45. Hsiang J, Yu K, He Y. Minimally invasive one-level lumbar decompression and fusion surgery with posterior instrumentation using a combination of pedicle screw fixation and transpedicular facet screw construct. *Surg Neurol Int*. 2013;4:125.
46. Huang P, Wang Y, Xu J, et al. Minimally invasive unilateral pedicle screws and a translaminar facet screw fixation and interbody fusion for treatment of single-segment lower lumbar

vertebral disease: surgical technique and preliminary clinical results. *J Orthop Surg Res*. 2017;12:117.

47. Hung PI, Chang MC, Chou PH, Lin HH, Wang ST, Liu CL. Is a drain tube necessary for minimally invasive lumbar spine fusion surgery? *Eur Spine J*. 2017;26:733-737.
48. Kang MS, Park JY, Kim KH, et al. Minimally invasive transforaminal lumbar interbody fusion with unilateral pedicle screw fixation: comparison between primary and revision surgery. *Biomed Res Int*. 2014;2014:919248.
49. Kasliwal MK, Deutsch H. Clinical and radiographic outcomes using local bone shavings as autograft in minimally invasive transforaminal lumbar interbody fusion. *World Neurosurg*. 2012;78:185-190.
50. Kim JY, Park JY, Kim KH, et al. Minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis: comparison between isthmic and degenerative spondylolisthesis. *World Neurosurg*. 2015;84:1284-1293.
51. Klingler JH, Volz F, Krüger MT, et al. Accidental durotomy in minimally invasive transforaminal lumbar interbody fusion: frequency, risk factors, and management. *ScientificWorldJournal*. 2015;2015:532628.
52. Kuo CH, Chang PY, Wu JC, et al. Dynamic stabilization for L4-5 spondylolisthesis: comparison with minimally invasive transforaminal lumbar interbody fusion with more than 2 years of follow-up. *Neurosurg Focus*. 2016;40:E3.
53. Lee CK, Park JY, Zhang HY. Minimally invasive transforaminal lumbar interbody fusion using a single interbody cage and a tubular retraction system: technical tips, and perioperative, radiologic and clinical outcomes. *J Korean Neurosurg Soc*. 2010;48:219-224.
54. 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;37:1548-1557.
55. Lee HJ, Kim JS, Ryu KS. Minimally invasive TLIF using unilateral approach and single cage at single level in patients over 65. *Biomed Res Int*. 2016;2016:4679865.
56. Li YB, Wang XD, Yan HW, Hao DJ, Liu ZH. The long-term clinical effect of minimal-invasive TLIF technique in 1-segment lumbar disease. *Clin Spine Surg*. 2017;30:E713-E719.
57. Lian X, Navarro-Ramirez R, Berlin C, et al. Total 3D Airo(R) Navigation for minimally invasive transforaminal lumbar interbody fusion. *Biomed Res Int*. 2016;2016:5027340.
58. Lin GX, Quillo-Olvera J, Jo HJ, et al. Minimally invasive transforaminal lumbar interbody fusion: a comparison study based on end plate subsidence and cystic change in individuals older and younger than 65 years. *World Neurosurg*. 2017;106:174-184.
59. Liu C, Zhou Y. Percutaneous endoscopic lumbar diskectomy and minimally invasive transforaminal lumbar interbody fusion for recurrent lumbar disk herniation. *World Neurosurg*. 2017;98:14-20.
60. Lo WL, Lin CM, Yeh YS, et al. Comparing miniopen and minimally invasive transforaminal interbody fusion in single-level lumbar degeneration. *Biomed Res Int*. 2015;2015:168384.
61. Massie LW, Zakaria HM, Schultz LR, Basheer A, Buraimoh MA, Chang V. Assessment of radiographic and clinical outcomes of an articulating expandable interbody cage in minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis. *Neurosurg Focus*. 2018;44:E8.
62. McAnany SJ, Patterson DC, Overley S, Alicea D, Guzman J, Qureshi SA. The effect of obesity on the improvement in health state outcomes following minimally invasive transforaminal interbody fusion. *Global Spine J*. 2016;6:744-748.
63. Millimaggi DF, Di Norcia V, Luzzi S, Alfiero T, Galzio RJ, Ricci A. Minimally invasive transforaminal lumbar interbody fusion with percutaneous bilateral pedicle screw fixation for lumbosacral spine degenerative diseases. A retrospective database of 40 consecutive treated cases and literature review. *Turk Neurosurg*. 2018;28:1-8.
64. Min SH, Yoo JS, Lee JY. Usefulness of contralateral indirect decompression through minimally invasive unilateral transforaminal lumbar interbody fusion. *Asian Spine J*. 2014;8:453-461.
65. Park P, Foley KT. Minimally invasive transforaminal lumbar interbody fusion with reduction of spondylolisthesis: technique and outcomes after a minimum of 2 years' follow-up. *Neurosurg Focus*. 2008;25:E16.
66. Park Y, Lee SB, Seok SO, Jo BW, Ha JW. Perioperative surgical complications and learning curve associated with minimally invasive transforaminal lumbar interbody fusion: a single-institute experience. *Clin Orthop Surg*. 2015;7:91-96.
67. Putzier M, Hartwig T, Hoff EK, Streitparth F, Strube P. Minimally invasive TLIF leads to increased muscle sparing of the multifidus muscle but not the longissimus muscle compared with conventional PLIF—a prospective randomized clinical trial. *Spine J*. 2016;16:811-819.
68. Reinshagen C, Ruess D, Walcott BP, Molcanyi M, Goldbrunner R, Rieger B. A novel minimally invasive technique for lumbar decompression, realignment, and navigated interbody fusion. *J Clin Neurosci*. 2015;22:1484-1490.
69. Sembrano JN, Tohmeh A, Isaacs R; SOLAS Degenerative Study Group. Two-year comparative outcomes of MIS lateral and MIS transforaminal interbody fusion in the treatment of degenerative spondylolisthesis: part I: clinical findings. *Spine (Phila Pa 1976)*. 2016;41(suppl 8):S123-S132.
70. Shen X, Zhang H, Gu X, Gu G, Zhou X, He S. Unilateral versus bilateral pedicle screw instrumentation for single-level minimally invasive transforaminal lumbar interbody fusion. *J Clin Neurosci*. 2014;21:1612-1616.
71. Shunwu F, Xing Z, Fengdong Z, Xiangqian F. Minimally invasive transforaminal lumbar interbody fusion for the treatment of degenerative lumbar diseases. *Spine (Phila Pa 1976)*. 2010;35:1615-1620.
72. Siemionow K, Pelton MA, Hoskins JA, Singh K. Predictive factors of hospital stay in patients undergoing minimally invasive transforaminal lumbar interbody fusion and instrumentation. *Spine (Phila Pa 1976)*. 2012;37:2046-2054.
73. Sonmez E, Coven I, Sahinturk F, Yilmaz C, Caner H. Unilateral percutaneous pedicle screw instrumentation with minimally invasive TLIF for the treatment of recurrent lumbar disk disease: 2 years follow-up. *Turk Neurosurg*. 2013;23:372-378.
74. Soriano-Sánchez JA, Quillo-Olvera J, Soriano-Solis S, et al. A prospective clinical study comparing MI-TLIF with unilateral

versus bilateral transpedicular fixation in low grade lumbar spondylolisthesis. *J Spine Surg*. 2017;3:16-22.
75. Tay KS, Bassi A, Yeo W, Yue WM. Intraoperative reduction does not result in better outcomes in low-grade lumbar spondylolisthesis with neurogenic symptoms after minimally invasive transforaminal lumbar interbody fusion—a 5-year follow-up study. *Spine J*. 2016;16:182-190.
76. Tender GC, Serban D. Minimally invasive transforaminal lumbar interbody fusion: comparison of two techniques. *Chirurgia (Bucur)*. 2014;109:812-821.
77. Tian Y, Liu X. Clinical outcomes of two minimally invasive transforaminal lumbar interbody fusion (TLIF) for lumbar degenerative diseases. *Eur J Orthop Surg Traumatol*. 2016;26:745-751.
78. Torres J, James AR, Alimi M, Tsiouris AJ, Geannette C, Härtl R. Screw placement accuracy for minimally invasive transforaminal lumbar interbody fusion surgery: a study on 3-D neuronavigation-guided surgery. *Global Spine J*. 2012;2:143-152.
79. Tsahtsarlis A, Wood M. Minimally invasive transforaminal lumber interbody fusion and degenerative lumbar spine disease. *Eur Spine J*. 2012;21:2300-2305.
80. Wang MY, Grossman J. Endoscopic minimally invasive transforaminal interbody fusion without general anesthesia: initial clinical experience with 1-year follow-up. *Neurosurg Focus*. 2016;40:E13.
81. Wong AP, Smith ZA, Nixon AT, et al. Intraoperative and perioperative complications in minimally invasive transforaminal lumbar interbody fusion: a review of 513 patients. *J Neurosurg Spine*. 2015;22:487-495.
82. Wu H, Yu WD, Jiang R, Gao ZL. Treatment of multilevel degenerative lumbar spinal stenosis with spondylolisthesis using a combination of microendoscopic discectomy and minimally invasive transforaminal lumbar interbody fusion. *Exp Ther Med*. 2013;5:567-571.
83. Xia XL, Wang HL, Lyu FZ, Wang LX, Ma XS, Jiang JY. Mast quadrant-assisted minimally invasive modified transforaminal lumbar interbody fusion: single incision versus double incision. *Chin Med J (Engl)*. 2015;128:871-876.
84. Yang Y, Liu ZY, Zhang LM, et al. Risk factor of contralateral radiculopathy following microendoscopy-assisted minimally invasive transforaminal lumbar interbody fusion. *Eur Spine J*. 2018;27:1925-1932.
85. Yao Y, Zhang H, Wu J, et al. Minimally invasive transforaminal lumbar interbody fusion versus percutaneous endoscopic lumbar discectomy: revision surgery for recurrent herniation after microendoscopic discectomy. *World Neurosurg*. 2017;99:89-95.
86. Yoo JS, Min SH, Yoon SH. Fusion rate according to mixture ratio and volumes of bone graft in minimally invasive transforaminal lumbar interbody fusion: minimum 2-year follow-up. *Eur J Orthop Surg Traumatol*. 2015;25(suppl 1):S183-S189.
87. Zeng ZL, Jia L, Xu W, et al. Analysis of risk factors for adjacent superior vertebral pedicle-induced facet joint violation during the minimally invasive surgery transforaminal lumbar interbody fusion: a retrospective study. *Eur J Med Res*. 2015;20:80.
88. Zhang W, Li X, Shang X, et al. Modified minimally invasive transforaminal lumbar interbody fusion using a trans-multifidus approach: a safe and effective alternative to open-TLIF. *J Orthop Surg Res*. 2015;10:93.
89. Zhang D, Mao K, Qiang X. Comparing minimally invasive transforaminal lumbar interbody fusion and posterior lumbar interbody fusion for spondylolisthesis: a STROBE-compliant observational study. *Medicine (Baltimore)*. 2017;96:e8011.
90. Zhang Y, Xu C, Zhou Y, Huang B. Minimally invasive computer navigation-assisted endoscopic transforaminal interbody fusion with bilateral decompression via a unilateral approach: initial clinical experience at one-year follow-up. *World Neurosurg*. 2017;106:291-299.
91. Alimi M, Hofstetter CP, Torres-Campa JM, et al. Unilateral tubular approach for bilateral laminotomy: effect on ipsilateral and contralateral buttock and leg pain. *Eur Spine J*. 2017;26:389-396.
92. Mason A, Paulsen R, Babuska JM, et al. The accuracy of pedicle screw placement using intraoperative image guidance systems. *J Neurosurg Spine*. 2014;20:196-203.
93. Rajasekaran S, Vidyadhara S, Ramesh P, Shetty AP. Randomized clinical study to compare the accuracy of navigated and non-navigated thoracic pedicle screws in deformity correction surgeries. *Spine (Phila Pa 1976)*. 2007;32:E56-E64.
94. Shin BJ, James AR, Njoku IU, Hartl R. Pedicle screw navigation: a systematic review and meta-analysis of perforation risk for computer-navigated versus freehand insertion. *J Neurosurg Spine*. 2012;17:113-122.
95. Tajsic T, Patel K, Farmer R, Mannion RJ, Trivedi RA. Spinal navigation for minimally invasive thoracic and lumbosacral spine fixation: implications for radiation exposure, operative time, and accuracy of pedicle screw placement. *Eur Spine J*. 2018;27:1918-1924.
96. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. *Eur Spine J*. 2011;20:846-859.
97. Meng XT, Guan XF, Zhang HL, He SS. Computer navigation versus fluoroscopy-guided navigation for thoracic pedicle screw placement: a meta-analysis. *Neurosurg Rev*. 2016;39:385-391.
98. Parajón A, Alimi M, Navarro-Ramirez R, et al. Minimally invasive transforaminal lumbar interbody fusion: meta-analysis of the fusion rates. What is the optimal graft aterial? *Neurosurgery*. 2017;81:958-971.
99. Isaacs RE, Sembrano JN, Tohmeh AG; SOLAS Degenerative Study Group. Two-year comparative outcomes of MIS lateral and MIS transforaminal interbody fusion in the treatment of degenerative spondylolisthesis: part II: radiographic findings. *Spine (Phila Pa 1976)*. 2016;41(8 suppl):S133-S144.