



Computer Navigation in Minimally Invasive Spine Surgery

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Abstract

Purpose of Review The goal of the review is to discuss the common general applications of navigation in the context of minimally invasive spine surgery and assess its value in the published literature comparing against non-navigated or navigated techniques.

Recent Findings There is increasing utilization of computer navigation in minimally invasive spine surgery. There is synergy between navigation and minimally invasive technologies, such that one enhances or facilitates the other, thus leading to wider applications for both. Specifically, navigation has been shown to improve performance of percutaneous pedicle screw placement, vertebral augmentation, and minimally invasive fusion procedures. Overall, clinical studies have shown better accuracy and less radiation exposure with the use of navigation in spine surgery.

Summary The use of navigation in minimally invasive spine surgery enhances the accuracy of instrumentation and decreases radiation exposure. It is yet to be determined whether patient-reported outcomes will differ. Further research on its effect on clinical outcomes may further define the future impact of navigation in minimally invasive spine surgery.

Keywords Navigation · Minimally invasive spine surgery · Spine fusion · Percutaneous pedicle screw

Introduction

Computer navigation has allowed for more accurate and thus safer placement of spinal instrumentation. Although navigation was initially used mainly in conventional open approach spine surgery, proliferation and increasing utilization of minimally invasive surgical techniques prompted the adoption of navigation in minimally invasive surgery (MIS) as well. It can also be considered that, in some ways, navigation has facilitated the development of MIS, as it has allowed surgeons to

overcome the main limitation of MIS surgery, which is that of limited direct visualization.

This article will discuss and review the literature on the common general applications of navigation technology in MIS spine surgery: percutaneous pedicle screw fixation, vertebral augmentation (i.e., vertebroplasty/kyphoplasty), minimally invasive transforaminal lumbar interbody fusion (MIS TLIF), and lateral/oblique lumbar interbody fusion (LLIF/OLIF).

Navigated Percutaneous Pedicle Screw Fixation (Table 1)

The most common application of computer navigation in spine surgery is in pedicle screw placement. Since surgeons began placing pedicle screws as spinal fixation anchors, many published studies have focused on screw placement accuracy, given the potential catastrophic consequences of screw malposition. There has been increasing emphasis on limiting approach-related morbidity with percutaneous screws being placed with minimizing muscle stripping and injury. However, with the advantages of minimal tissue damage, came at the cost of losing direct visualization of anatomic landmarks which was mitigated by the heavy use of

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Table 1 Navigated percutaneous pedicle screw placement

Author	Year	Level of evidence	No. of patients (screws)		Study group	Control group	Screw accuracy rate (%)		Screw malposition rate	
			Nav MIS group	Control group			Nav MIS group	Control group	Nav MIS group	Control group
Section 1: navigated versus non-navigated MIS percutaneous pedicle screws										
Nakashima et al. [2]	2009	III	33 (150)	34 (150)	MIS 3D fluoroscopy nav	MIS 2D fluoroscopy	92.7	84.7	7.3% (11/150)	15.3% (23/150)
Wood and Mannion	2011	III	43 (186)	24 (110)	MIS 3D nav intra-op CT	MIS 3D nav pre-op CT	98.4	93.6	1.6% (3/186)	6.4% (7/110)
Yang et al. [3]	2012	II	42 (210)	34 (152)	MIS 3D nav intra-op CT	MIS 2D fluoroscopy	97.0	92.8	3.0% (6/202)	7.2% (11/152)
Bourgeois et al. [4]	2015	III	518 (213-2)	(4248)	MIS 3D fluoroscopy nav	MIS 2D fluoroscopy	99.7	86.9 (pooled published data)	0.3% (7/2132)	13.1%
Ohba et al. [5]	2016	III	19 (122)	9 (72)	MIS 3D nav intra-op CT	2D fluoroscopy	93.4	86.1	6.6% (8/122)	13.8% (10/72)
Innocenzi et al. [6]	2017	III	56 (230)	59 (236)	MIS 3D nav intra-op CT	2D fluoroscopy	86.1	76.3	13.9% (32/230)	23.7% (56/236)
Fomekong et al. [7]	2018	III	66 (276)	102 (438)	MIS 3D nav intra-op CT	2D and 3D fluoroscopy	94.6 (97.1% including < 2 mm breach)	82.0 (95.5% including < 2 mm breach)	2.9% (> 2 mm)	4.5% (> 2 mm)
Section 2: navigated versus non-navigated MIS percutaneous pedicle screws										
Yson et al. [10]	2013	III	64 (125)	124 (245)	MIS 3D nav intra-op CT	Open 3D nav intra-op CT				
Tian et al. [11]	2014	II	68 (136)	74 (148)	MIS 3D nav intra-op CT	Open 3D nav intra-op CT				
Santos et al. [9]	2015	III	71 (387)	128 (601)	MIS 3D nav intra-op CT	Open 3D nav intra-op CT				
Innocenzi et al. [6]	2017	III	56 (230)	43 (218)	MIS 3D nav intra-op CT	Open 3D nav intra-op CT	86.1	92.7	13.9% (32/230)	7.3% (16/218)
Section 3: navigated minimally invasive percutaneous pedicle screws without comparison										
Gianaris et al. [28]	2013	IV	15 (88)	None	MIS 3D nav intra-op CT	None	98.9%	N/A	1.1% (1/88)	N/A
Kim et al. [29]	2014	IV	48 (290)	None	MIS 3D nav intra-op CT	None	96.6%	N/A	3.4% (10/290)	N/A

Table 1 (continued)

Author	Intraoperative screw revision rate		Facet violation rate		Fluoroscopy time/radiation dose		Screw insertion time (min)	
	Nav MIS group	Control group	Nav MIS group	Control group	Nav MIS group	Control group	Nav MIS group	Control group
Section 1: navigated versus non-navigated MIS percutaneous pedicle screws								
Nakashima et al. [2]								
Wood and Mannion								
Yang et al. [3]					6.6 s	9.6 s	3.65	4.43
Bourgeois et al. [4]								
Ohba et al. [5]			3.8% (3/79)	30.5% (11/36)				
Innocenzi et al. [6]								
Fomekong et al. [7]					365.6 mGy/m ²	571.9 mGy/m ²		
Section 2: navigated versus non-navigated MIS percutaneous pedicle screws								
Yson et al. [10]			4.0% (5/125)	26.5% (65/245)				
Tian et al. [11]			3.7% (5/136)	14.9% (22/148)				
Santos et al. [9]	2.1% (8/387)	2.7% (16/601)						
Innocenzi et al. [6]								
Section 3: navigated minimally invasive percutaneous pedicle screws without comparison								
Gianaris et al. [28]								
Kim et al. [29]								

intraoperative fluoroscopy. Unfortunately, this brought about significantly increased radiation exposure, not only to the patient but more so to the surgical team, with repetitive use of fluoroscopy. Many surgeons who are hesitant to adopt MIS techniques in their practice cite increased radiation exposure as one of the reasons for not doing so [1].

With the use of computer navigation, surgeons could reap the benefits of minimally invasive surgery and, at the same time, improve screw placement accuracy and minimize radiation exposure. In 2009, Nakashima et al. [2] published a retrospective study comparing navigated MIS versus MIS screws placed using conventional fluoroscopy. They found that the navigated group had better accuracy than the fluoroscopy group (92.7% vs. 84.7%). Other studies published since that also compared MIS navigation against MIS conventional fluoroscopy and likewise consistently found superior screw placement accuracy when computer navigation was utilized [3–7], with accuracy rates ranging from 86.1% [6] to 99.7% [4].

Wood and Mannion [8] compared two navigation techniques: one utilizing intraoperatively acquired CT images versus an older method utilizing preoperative CT scans requiring intraoperative registration. They found that the newer method using intraoperative CT yielded more accurate screw placement (98.4% vs. 93.6%, P value = 0.03).

Santos et al. [9] compared intraoperative screw revision rates between navigated MIS and navigated open screw placement and found that there was no significant difference in intraoperative revision rate (2.1% vs. 2.7%) (P = 0.0004). None of the patients needed a reoperation for screw revision in their series. Innocenzi et al. [6] published a series comparing 4 groups of pedicle screw placement, among which were navigated MIS and navigated open screw placement, which showed a higher screw malposition rate in the MIS group (13.9% vs. 7.3%) (P = 0.0263).

Two studies looked at facet joint violation rates [10, 11]. Yson et al. [10], in a series of 188 patients (370 screws), found significantly lower cranial (top end of construct) facet violation rates with navigated percutaneous screws versus navigated open screws (4.0% vs. 26.5%) (P < 0.0001). The authors attributed this to enhanced ability to achieve a more medial trajectory and lateral screw entry point with the percutaneous technique compared to open screw placement. Similarly, Tian et al. [11], in a prospective comparative (level 2) study of 142 patients (284 screws), found lower facet violation rates in navigated percutaneous versus navigated open screws (3.7% vs. 14.9%).

Most studies have utilized an optical camera that is able to track passive reflective markers/spheres and required direct line of sight between the camera and the spheres. Images are obtained from either preoperative or intraoperative CT, and registration is either manual (point by point) or automated (where the camera is able to “see” the scanner by detecting

active or passive markers on the scanner as well at the time of image acquisition). A cadaveric study by von Jako [12] in 2010 utilized electromagnetic field (EMF) navigation. They placed 122 screws in 8 cadavers, 62 screws placed under fluoroscopic guidance, and 60 screws under EMF guidance. They found EMF to have statistically significant improvements in the lumbar spine, both ideal trajectory (62.7% vs. 40%, P = 0.01) and rate of pedicle breaches (16.2% vs. 42.5%, P = 0.01), but overall found a non-significant change in overall accuracy rate between the two techniques (83% vs. 71%, P = 0.12).

Overall, these studies show generally high accuracy rates when MIS/percutaneous screws are placed, utilizing navigation technology. Those studies that utilized a control group, either fluoroscopy guided or freehand using anatomic landmarks, consistently showed higher accuracy rates with navigation.

Navigated Vertebral Augmentation (Vertebroplasty/Kyphoplasty) (Table 2)

The indications for percutaneous cement augmentation for osteoporotic or pathologic/metastatic compression fractures are controversial, with studies supporting either that they provide significant pain relief for suffering patients or that they are no better compared to sham/placebo interventions. Augmentation may be performed either with (kyphoplasty) or without (vertebroplasty) the use of balloon inflation prior to cement injection. Several studies have looked at the use of navigation technology for cement augmentation procedures.

In 2005, Villavicencio et al. [13] published a small series comparing navigated kyphoplasty in 11 patients with non-navigated kyphoplasty in 9 patients. There was no significant difference in operative time; however, they found a significant reduction in fluoroscopy time (81.3 s in the navigated group vs. 293.2 s in the non-navigated group) (P = 0.02). In their conclusion, the authors emphasized the advantage of significant reduction in radiation exposure with the use of navigation.

Izadpanah et al. [14] also looked at fluoroscopy time; additionally, they also measure radiation dose via dose area product (DAP) [14]. They found decreased fluoroscopy times in the navigation group (99 s vs. 175 s for thoracic levels; 74 s vs. 165 s for lumbar levels). They also found decreased radiation dose in the navigation group (1245 cGy/cm² vs. 1972 cGy/cm² for thoracic levels; 1318 cGy/cm² vs. 2105 cGy/cm² for lumbar levels).

Sun et al. [15] looked at needle positioning accuracy and cement extravasation rates between navigated and non-navigated kyphoplasty cases. They found a lower rate of need for needle adjustment in the navigation group (5.3% vs. 33%), significance not analyzed. Cement extravasation rates were, however, similar between the two groups (31% navigation

Table 2 Navigated vertebroplasty/kyphoplasty

Author	Year		Number of patients	Number of vertebral levels		Level of evidence	Type of navigation	Comparison group	Needle malposition rate		Cement extravasation
	Nav group	Non-nav group		Nav group	Non-nav group				Nav group	Non-nav group	
Villavicencio et al. [13]	2005	11	9	14	10	III	3D fluoroscopy navigation	Biplanar fluoroscopy			
Izadpanah et al. [14]	2009	29	30	30	30	III	3D fluoroscopy navigation	Biplanar fluoroscopy			
Sun et al. [15]	2009	38	21	49	26	III	2D fluoroscopy navigation	Biplanar fluoroscopy	5.3% (2/38)	33% (7/21)	31% (9/38)
Tam et al. [30]	2010	10	None	13	None	III	CT with fluoroscopic overlay	None	8% (> 5 mm from planned path), 25% (> 5 mm of target)		25% (3/13)
Schils [31]	2011	54	None	76	None	IV	MIS 3D nav intra-op CT	None			
Sembrano et al. [16]	2015	21	9	36	11	III	MIS 3D nav intra-op CT	Biplanar fluoroscopy	2.8% (1/36)	3/11 (27%), 2 repositioned	22% (8/36)

Author	Cement extravasation	Operative time (min)		Fluoroscopy time		Radiation dose		Complications	Patient-reported outcomes	Other outcomes
		Nav group	Non-nav group	Nav group	Non-nav group	Nav group	Non-nav group			
Villavicencio et al. [13]		60 (1-level)	69.2 (1-level)	81.3 s (including "spine" time)	293.2 s			None	None	Reduced radiation exposure in nav cases
Izadpanah et al. [14]		68.5 (2-level)	61 (thoracic)	99 s (thoracic)	175 s (thoracic)	1245 cGy/cm ² (thoracic)	1972 cGy/cm ² (thoracic)	1 hematoma requiring I&D	None	2 navigation clamps loosened requiring new data set acquisition
Sun et al. [15]	33% (7/21)	62 (lumbar)	57 (lumbar)	74 s (lumbar)	165 s (lumbar)	1318 cGy/cm ² (lumbar)			None	Decrease in radiation in navigated group
Tam et al. [30]		67.8	112.1					1 CSF leak (non-nav)	None	
Schils [31]	17%	38		3.1 mm/procedure		220 mGy/procedure		3 with cement extravasation, all asymptomatic	None	
Sembrano et al. [16]	36% (4/11)			2.5 mm/level	125 s/level	166 mGy/level		None	VAS pre-op = 8.4; 2 weeks = 1.9	
				98 s/level				LE weakness (nav), immediate decompressive laminectomy, with partial return of motor function	None	

(nav), 33% non-nav). Similarly, Sembrano et al. [16] compared navigated versus non-navigated kyphoplasty and found a much lower needle malposition rate in the navigation group (2.8% vs. 27%, $P = 0.04$). However, there was again no significant difference in cement extravasation rates (22% nav vs. 36% non-nav). The authors attributed this to the fact that needle positioning was directly dependent on the navigation, whereas cement is injected in a fluid state and follows paths of least resistance.

Navigated MIS TLIF (Table 3)

TLIF is perhaps the most commonly performed interbody fusion approach in the lumbar spine, mainly because of its versatility (i.e., could be performed at any level) and utilization of a single position and approach for decompression, access to the disc space, and screw placement. This procedure can be performed either via conventional open posterior approach or via muscle-splitting minimally invasive approach (MIS TLIF).

The first report on navigated MIS TLIF was by Kim et al. [17] in 2008. They compared 10 patients who had 2D fluoroscopy-based navigated MIS TLIF versus 8 patients who had non-navigated surgery. In their description of the technique, navigation was used to select skin incision site, to dock the tubular retractor at the right angle in line with the target disc level, and to place the pedicle screws. They found 100% screw accuracy in both groups, but with significantly lower fluoroscopy time in the navigated group (147.2 s vs. 57.1 s, $P = 0.02$). Other published case series (level IV studies) using computer navigation for MIS TLIF included Luo et al. [18], Cho et al. [19], and Zhang et al. [20]. In these reports, it would seem that navigation was used primarily for percutaneous pedicle screw placement including planning of skin incision. After screw placement, the TLIF procedure itself usually proceeded with little use or need for navigation.

Two retrospective comparative studies have been published [21, 22]. Tian et al. [21] compared 30 3D image-based navigated MIS TLIF cases against 31 non-navigated open TLIF cases. For the MIS TLIF group, navigation was used to plan skin incisions and to place screws. They found reduced OR time, blood loss, postoperative drain output, and pain in the navigated group. Xu et al. [22] reported on 74 consecutively navigated MIS TLIF cases and compared the first 25 with the latter 74 cases. They found decreased surgical and anesthesia time in the latter group attributable to the learning curve. They concluded that it takes ~25 cases to become proficient at navigated MIS TLIF.

Navigated LLIF/OLIF (Table 4)

LLIF, also commonly referred to as extreme/direct lumbar interbody fusion (XLIF or DLIF, respectively), and OLIF are

minimally invasive approaches to lumbar interbody fusion performed with the patient in the lateral decubitus position. The basic difference is that LLIF is a transpsoas approach and OLIF passes anteriorly to the psoas. The use of intraoperative imaging is necessary because of the limited direct visualization inherent in minimally invasive surgery. It is thus a natural evolution of these procedures for surgeons to seek ways to mitigate radiation exposure by using navigation technology.

In 2015, Park [23] reported on a series of 8 patients on whom LLIF with intraoperative CT computer navigation was performed, and concluded that computer navigation for LLIF procedures is feasible and safe. In 2018, Jiang et al. [24] published a comparative retrospective study on 18 patients who underwent a similar navigated LLIF procedure versus 15 patients who underwent non-navigated surgery. They found no difference in operative time or fusion rates but found significantly lower fluoroscopy time in the navigated group (13.5 s vs. 53.2 s). Notably, all the surgeries in their series were performed for spinal tuberculosis.

For the OLIF procedure, Zhang et al. [25] published in 2017 a retrospective study comparing 22 patients who underwent intraoperative CT navigated OLIF versus 20 patients who underwent conventional OLIF with 2D fluoroscopy. They also found significantly lower radiation exposure to both the patient (44.6 mGy vs. 9.4 mGy) and the surgeon (44.6 mGy vs. 0 mGy). Operative time was slightly longer in the navigated group (2.5 h vs. 2.3 h) but not statistically significant. The authors concluded that navigation is a safe alternative to fluoroscopy for OLIF, and that it can eliminate radiation exposure to the surgeon and decrease exposure to the patient. In the same year, DiGiorgio et al. published on a larger series of 49 patients who underwent similar navigated OLIF [26]. They reported improvement in back and leg pain scores postoperatively.

In 2018, Sellin et al. [27] reported on a small series of 4 patients who underwent simultaneous OLIF and percutaneous pedicle screw fixation using intraoperative CT-guided navigation in the lateral position. While the authors clearly described using navigation for screw placement, it was less clear whether and how it was used for the OLIF portion of the procedure as well.

Conclusion

Computer navigation technology, as applied to minimally invasive spine surgery, has been consistently shown to significantly enhance accuracy in placing spinal instrumentation, thus increasing safety for the patient, likely improving the biomechanical performance of the construct and reducing costly injuries and reoperations. It has also shown significant promise in reducing radiation exposure and dose and may help mitigate the harmful long-term effects of ionizing radiation. It

Table 3 Review of transforaminal lumbar interbody fusion studies with results focused on screw accuracy, fusion rate, and fluoroscopy time

Author	Year		Number of patients		Level of evidence		Type of navigation and comparison		Other details		Fluoroscopy time (s)	
	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group
Kim et al. [17]	2008	10	8		III	None	Standard fluoroscopy	Cadaveric arm (18 levels)		57.1		147.2
Cho et al. [19]	2012	20			IV	None	None	Accuracy of cutaneous fixed dynamic reference frame				
Luo [18]	2012	16			IV	None	None	Real-time EMG monitoring in MIS TLIF surgery				
Tian et al. [21]	2017	30	31		III	Open TLIF	Open TLIF					
Zhang et al. [25]	2017	17			IV	None	None	MIS TLIF bilateral decompression through unilateral approach				
Xu et al. [22]	2018	25	49		III	Late group (patients 26–74)	Late group (patients 26–74)	Single surgeon learning curve study of 74 consecutive patients				

Author	Screw accuracy (%)		Fusion rate (%)		Complications		Patient-reported outcomes		Other outcomes	
	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group	Study group	Comparison group
Kim et al. [17]	100	100			1 Dural tear in standard fluoroscopy				Reduced radiation exposure in the navigated group	
Cho et al. [19]	95.10	None			Not reported		Not reported		Not reported	
Luo [18]	95.30		100		Not reported		Improved VAS and ODI scores at 3-month and 18-month follow-up			
Tian et al. [21]	93.33	73.39	96.67	93.55	MISS group, 1 epidural hematoma, 1 transient radiculopathy		MISS TLIF: less immediate post-op pain, no difference in ODI post-op, no difference in pain scores at 3 months, 1 year, or 2 years		MISS decreased EBL, post-op hospitalization, time to rehab, but no difference in ODI at 3 months, 1 year, and 2 years	
Zhang et al. [25]					2 transient paresthesias		JOA improved, 49.73%; ODI went from 41.96 pre-op to 23.06 at 1 year; VAS lower back went from 4.00 pre-op to 0.18 at 1 year; VAS leg 3.59 pre-op to 0.24 post-op			
Xu et al. [22]			84	81.63	Early group, 12% Late group, 6.12%				Decreased surgical time, anesthesia time when comparing the late group to the early group	

Table 4 The effects of navigation on lateral lumbar interbody fusion and oblique lumbar interbody fusion

Author	Year	Number of patients		Cages placed		Level of evidence	Type of navigation	Comparison group	Surgical approach	Fusion rate (%)
		Nav group	Comp group	Nav group	Comp group					
Park [23]	2015	8		22		IV	CT image-guided navigation	None	LLIF approach	
Zhang et al. [25]	2017	22	20	33	31	III	CT image-guided navigation	Non-navigated fluoroscopy	OLIF approach	
DiGiorgio et al. [26]	2017	49		86		IV	CT image-guided navigation	None	OLIF approach	
Jiang et al. [24]	2018	18	15	18	15	III	Navigated fluoroscopy	Non-navigated fluoroscopy	LLIF approach	100
Sellin et al. [27]	2018	4		4		IV	CT image-guided navigation	None	OLIF-simultaneous pedicle screw placement	

Author	Fusion rate (%)		Surgeon radiation exposure (mGy)		Patient radiation exposure (mGy)		Operating time (h)		Patient-reported outcomes
	Comp group	Nav group	Nav group	Comp group	Nav group	Comp group	Nav group	Comp group	
Park [23]									
Zhang et al. [25]		No exposure		44.59 (\pm 26.65)	9.38	44.59 (\pm 26.65)	2.49 (\pm 1.35)	2.30 (\pm 1.17)	In Smiley-Webster scale, all patients had “excellent” or “good” outcomes VAS back pre-op 7.17 to 4.10 post-op; VAS leg pre-op 6.15 to 1.20 post-op
DiGiorgio et al. [26]									
Jiang et al. [24]	100								
Sellin et al. [27]			63.21				2.3 (\pm 0.28)		

is thus highly advisable for MIS surgeons to learn about and adopt navigation technology into our respective practices.

Compliance with Ethical Standards

Conflict of interest Jonathan N. Sembrano, MD has a research support from NuVasive, Inc. Sharon C. Yson, MD received a research support from SI-Bone, Inc. Jeffrey J. Theismann has no conflicts of interest.

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- Of major importance

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