A five-step remedial screw placement method to treat severe spinal deformity with free-hand transpedicular screw placement

Jing-Ming Xie · Zhi Zhao · Hua Yang · Ying-Song Wang ·
Ying Zhang · Tao Li · Ni Bi

Received: 30 May 2011 / Revised: 13 June 2012 / Accepted: 2 October 2012 / Published online: 16 October 2012
© Springer-Verlag Berlin Heidelberg 2012

Abstract

Purpose Severe spinal deformity is a complex morphological deformation that occurs and develops in three-dimensional space combined with abnormal development and morphology of anatomical structures, which presents great difficulties in the process of transpedicular screw placement. This study tried to explore the methods of transpedicular screw placement in surgical correction of severe spinal deformities.

Methods Surgical corrections through posterior approach were performed in all the 76 cases (mean age 20.4 years). The averaging preoperative Cobb's angle of scoliosis was $108.2^{\circ} \pm 33.6^{\circ}$ (range 100° – 170°). Among these patients, 34 cases were combined with kyphosis; the average Cobb's angle of kyphosis was 77.3° (range 63° – 160°). During operation, the screw tract was first established with the regular free-hand pedicle screw placement method. When this failed, in order to adjust the screw trajectory, a five-step remedial method was performed in the following order: (1) the “funnel” method; (2) exploring the pedicle exterior edge through the costotransverse joint; (3) exploring the superior and inferior edges of pedicle through the nerve root canal; (4) the vertebral plate fenestration; and (5) hemilaminectomy.

Results Among all 1,472 screws planned to be placed for the patients, 1,210 (82.2 %) were successfully placed after using the regular method, and 262 (17.8 %) failed in this stage. After applying the five-step remedial method, 256 of the failed 262 screws were successfully placed. Among them, 176 screws (68.8 %) were successfully placed after Step 1, 44 (17.2 %) after Step 2, 21 (8.2 %) after Step 3, 12 (4.7 %) after Step 4, and 3 (1.2 %) after Step 5. In only six, pedicles screws could not be placed eventually. No nerve or blood vessel damages occurred in all cases. All final screw positions were validated by CT.

Conclusion The five-step remedial method proved to be an effective supplementary method for transpedicular screw placement to treat patients with severe spinal deformities. The key points include a detailed preoperative plan, a meticulous hand drilling sensation, and an experienced probing technique for screw tract.

Keywords Spinal deformity · Transpedicular fixation · Free-hand

Introduction

Since the Harrington instrumentation system created the first milestone in the history of internal fixation during surgical treatment of spinal deformities, many breakthroughs have been made in the field, including Luque system, Cotrel and Dubousset (CD) system, TSRH system, ISOLA system, etc. Novel therapeutic concepts and models of spinal deformity treatment have been developed greatly. With the spread and improvement of the spine internal instrumentation system and surgical techniques, the application of transpedicular screw technique in spinal deformity is getting increasingly prevalent [1]. Because of the

J.-M. Xie (✉) · Z. Zhao · Y.-S. Wang · Y. Zhang · T. Li ·
N. Bi

Department of Orthopaedics, The 2nd Affiliated Hospital
of Kunming Medical University, 374# Dianmian Road,
Kunming 650101, Yunnan, People's Republic of China
e-mail: xiejingming@vip.163.com

H. Yang

Department of Orthopaedics, The Affiliated Hospital of Guiyang
Medical College, Guiyang 550001, Guizhou,
People's Republic of China

powerful corrective force and the good control for three-column structure of the spine, transpedicular screw–rod internal fixation for treatment of spinal deformity is proved to be a real three-dimensional correction, especially essential and significant for treating severe spinal deformities [2]. Pedicle screw directly connects the posterior structure of vertebrae to the anterior vertebral body with the pedicle, so that the force gained from the posterior corrective instruments can be directly conducted to the anterior vertebral body, thereby achieving the maximum three-dimensional corrective effect on spinal deformities. The pedicle screw–rod system has significant advantages over the hook/rod system or the hook/screw/rod hybrid system in correcting spinal deformities through the posterior approach, including a shorter segment of fixation, a more powerful corrective force and a better corrective effect, etc. [3, 4].

However, severe spinal deformity is not simply a complex morphological deformation that occurs and develops in three-dimensional space. Abnormal structures, including the vertebral body, pedicle, plate and spinous process, also present great difficulties in determining the location, position, and angles during the process of transpedicular screw placement. It is no wonder that the misplacement rate of thoracic pedicle screws in spinal deformity corrective surgery can be as high as 3–44.2 %, and the incidence of related complications caused by screw misplacement can be up to 0.9 % [1, 5, 6]. For patients with severe spinal deformities, accurate placement of pedicle screws is often extremely difficult using regular methods.

Based on our experience in treating spinal deformities with transpedicular screw technique, this study aimed to summarize a series of free-hand pedicle screw placement methods in treating severe spinal deformity after failure of regular screw placement, and to discuss their effectiveness and feasibility in clinical practice.

Patients and methods

This study included 76 patients with severe spinal deformities, who were treated in the Department of Orthopaedics, the 2nd Affiliated Hospital of Kunming Medical University from October 2004 to October 2008. Of these 76 patients, 31 were male and 45 were female, with a mean age of 20.4 years (range, 10–32 years). The preoperative Cobb's angle of scoliosis was from 100° to 170°, with an average of $108.2^\circ \pm 33.6^\circ$. Among these patients, 34 cases were combined with kyphosis; the Cobb's angle of kyphosis was from 63° to 160°, with an average of $77.3^\circ \pm 29.4^\circ$. There were various aetiologies among these 76 patients: 31 congenital spinal deformities, 19 neurofibromatosis, 18 neuromuscular scoliosis (subgroups

including 14 with Chiari malformation, 2 with tethered cord syndrome and another 2 with diplomyelia); 1 case was secondary to skeletal dysplasias; 7 cases were unclassified for lack of clear pathogenesis.

Before surgery, in addition to standing anteroposterior and lateral radiographs of the entire spine for every patient, spiral CT scanning of each spinal segment parallel to the pedicle longitudinal axis was performed, together with coronal and sagittal two-dimensional imaging reconstruction of each pedicle, to analyse the development of pedicle structure. To better determine the location, angle, and diameters of the screws during operation, we also measured for each patient the minimum transverse inner diameter of the narrowest site of the pedicle, the depth from the screw entry point to the front of the vertebral body, the transverse angle of the screw insertion, and the rotation angle of vertebrae.

All pedicle screws were inserted into thoracic and lumbar segments using a regular free-hand screw placement technique as described below, with the entry points determined by the corresponding anatomical markers [7, 8]. Screw trajectories were created using a 2-mm hand drill; once the screw tracts were established, a blunt probe with a tiny hook-tip was used to repeatedly probe the wall and bottom of the tract to ensure that they were all in osseous borders and there was no perforation through the osseous borders. If the screw tract could not be established successfully using the regular method, a five-step remedial screw placement method followed, as described in Fig. 1.

Step 1 The “funnel” method [9]: we first used the “funnel” method to search for the entry of pedicles before attempting to create the screw trajectories: a 5-mm ball-tipped burr was used to remove 4- to 5-mm cortex at the corresponding screw entry points. After that a curette was inserted into the hole to search for the pedicle entry. If it was difficult to find the pedicle entry, the ball-tipped burr was used again to remove more cortex bone around the entry point. The spongy bone was cleared using a curette to expose the “funnel” entry of the pedicle. Once the pedicle entry was confirmed, a 2-mm hand drill was used to create the screw trajectory. During the drilling process, the sensation of the hand drill smoothly passing through the cancellous bone in pedicle should be carefully monitored to ensure the tip and surrounding of the hand drill were all in osseous borders.

Step 2 exploring the pedicle exterior edge through the costotransverse joint: if the pedicle entry could not be found using “funnel” method, the transverse process of thoracic vertebra was excised to release and resect the costotransverse joint in order to expose the exterior edge of the pedicle. The screw trajectories were adjusted according to the location of the pedicle exterior edge as well as its alignment.

Fig. 1 Five-step remedial screw placement method. **a** A spine of deformity; **b** A regular free-hand screw placement technique; **c** Step 1 the “funnel” method: a curette was inserted into the hole to search for the pedicle entry; **d** Step 2 exploring the pedicle exterior edge; **e** Step 3 exploring the superior and inferior edges of pedicle through the

nerve root canal; **f** Step 4 the vertebral plate fenestration: the location and alignment of the pedicle was carefully explored along the vertebral canal. **g** Step 5 Hemilaminectomy: hemilaminectomy was performed to directly observe the full pedicle

Step 3 exploring the superior and inferior edges of pedicle through the nerve root canal: if the screw tracts could not be established successfully after step 2, it was necessary to expose the superior and inferior nerve root canals of the target segment and use a nerve dissector to explore the superior and inferior edges of the pedicles along the nerve root canals. With previous location of the exterior edge of the pedicle, the location and alignment of the pedicle were further confirmed, and then the screw trajectories were established with a 2-mm hand drill.

Step 4 The vertebral plate fenestration: if by step 3 the screw tract still could not be established successfully, unilateral vertebral plate fenestration could be performed. During this process, the structure of the facet joint should be protected without any damage. The location and alignment of the pedicle inner edge were explored using a nerve dissector along the vertebral canal, followed by the establishment of the screw trajectories.

Step 5 Hemilaminectomy: if none of the four steps described above was successful, a hemilaminectomy was necessary to enable direct observation of the full pedicle for screw trajectory establishment.

After successful establishment of screw tracts, screws with appropriate diameter and length could be selected and

inserted based on the preoperative CT measurements and hand sensation changes during the insertion of screws. If this five-step remedial screw placement method still did not succeed, pedicle screw placement in this segment might have to be abandoned, and the fixation segments should be adjusted according to the requirements for correction and fusion.

The correction efficacy was evaluated by X-ray examination within 1 week after operation. Screw placement was evaluated based on the CT scan results [10]. The specific evaluation includes: (1) whether the screw axis is completely inside the pedicle; (2) whether the screw penetrated any wall of the pedicle (including superior, inferior, lateral, medial walls); and (3) the level of perforation of pedicle wall by screws, if any:

Level I Perforation: a tiny part of the screw penetrated the wall.

Level II Perforation: the part of the screw penetrating the wall was less than one-half of the diameter of the screw.

Level III Perforation: the part of the screw penetrating the wall was larger than one-half of the diameter of the screw [11].

For those pedicles in which no planned screw tract was successfully established, the causes of failure were analysed.

Results

Out of the 1,472 screws that were planned to be inserted into the 76 patients, 1,466 screws were actually inserted (99.6 %). During operation, in all 76 patients, 1,210 screws (82.2 %) were placed using the regular method but 262 screws (17.4 %) failed at this stage, with at least one initial placement failure per patient. All these initially failed screw placements occurred in the thoracic vertebrae, with 138 (52.7 %) failed screws in the upper thoracic vertebra (T1–T3), 113 (43.1 %) in the middle thoracic vertebra (T4–T9), and 11 (4.2 %) in the lower thoracic vertebra (T10–T12). Of these failures, 243 screws were on the concave side of the deformities (92.7 %), and 19 on the convex side (7.3 %).

After using the five-step remedial screw placement method, 256 screws were placed successfully, accounting for 97.7 % of the screws that were not placed on the first attempt. Among them, 176 screws (68.8 %) were successfully placed using the “funnel method” (Step 1); 44 (17.2 %) were placed by exploring the pedicle exterior edge through the costotransverse joint (Step 2); 21 (8.2 %) were placed by exploring the superior and inferior edges of pedicle through the nerve root canal (Step 3); 12 (4.7 %) were placed by the vertebral plate fenestration (Step 4); and 3 (1.2 %) were placed after hemilaminectomy (Step 5) (Table 1).

There were six pedicles in which screws could not be placed as planned, so the fixation segments for pedicle screws were adjusted. These six pedicles were all on the concave side of the deformities.

There was no nerve, blood vessel damage or pleura perforation in any patient of this series. In the 256 screws placed into pedicles, postoperative CT examination confirmed that 237 pedicle screws were completely inside pedicles (92.6 %). There was no screw misplacement or screw perforation of the superior or inferior wall of pedicles. Of the five screws that penetrated the medial wall (1.9 %), all were level I perforations. Fourteen screws

penetrated the lateral wall (5.5 %), with 12 of them being level I perforations (4.7 %), two being level II perforations (0.8 %), and no level III perforation. During the process of deformity correction, no screw pullout or loosening occurred. The postoperative CT examination did not find any fracture in the pedicles.

On average, the postoperative coronal and sagittal correction rates were 52.5 and 64.8 %, respectively. In the 76 patients, there were 46 patients received posterior vertebral column resection (posterior VCR), and the coronal and sagittal correction rates were up to 63.9 and 76.9 %, respectively. None of the patients experienced obvious neurological deterioration after surgery. For the five patients with preoperative neurological deficit, the neurological functions were improved to different degrees.

The postoperative follow-up was 24–48 months, with an average of 30.4 months. During the follow-up period, no screw pullout, implant loosening, deformation, or breaking occurred. There were no consequential fractures in the pedicles, and the acquired correction loss was no more than 10 %.

Discussion

When applying transpedicular screw technique to treat spinal deformities, accurate insertion of screws is a key step in the internal fixation system to maximise its efficacy. However, the existence of complex three-dimensional deformities often makes it difficult for preoperative evaluation of the deformities. For extremely complex deformities, even through the multi-slice spiral CT scan combined with two- and three-dimensional reconstructive imaging was used, the structure of abnormal spinal segments could not be identified, especially in the apex region. Thus, the existing techniques provide limited guidance in preoperative planning and intraoperative transpedicular screw insertion. During the operational process, the vertebral rotation and abnormal development of pedicle,

Table 1 Free hand transpedicular screws placement with different methods

Patients	Planned screw placements	Actual placed screws	Successful screw placements during the first attempt	Successful screw placements after using the five-step remedial method	Screws placements in the different steps of the remedial method		Screws not be placed as planned
76	1472	1466	1210	256	Step 1	176 (68.8 %)	6
					Step 2	44 (17.2 %)	
					Step 3	21 (8.2 %)	
					Step 4	12 (4.7 %)	
					Step 5	3 (1.2 %)	
Percentage		99.6	82.2	17.4			0.4

Fig. 2 Male, 17 years, kyphoscoliosis associated with Chiari malformation. **a–d** Because of the presence of a severe 3D deformity, the preoperative radiograph could not display the deformed segments. Even with multislice spiral CT scan with three-dimensional reconstruction imaging, it was still difficult to clearly display the morphological structure of the segment with deformity. **e–f** postoperative radiograph: during the operation, posterior-only T11 vertebrae column resection was performed, and the deformity was corrected successfully. Titanium mesh cage containing autograft bone was used for fusion

vertebral plate, spinous process, and other anatomical structures would increase the difficulties and complications during pedicle screw placement. Particularly in the thoracic spine, the special morphological characteristics of the pedicles and the complex adjacent anatomical structures in this region combined with an extremely complex deformity make transpedicular screw insertion much more difficult and risky. Some investigators have tried to use the computer-assisted navigation system to guide transpedicular screw insertion and improved the success rate of pedicle screw placement in the treatment of some mild spinal deformity [12]. However, for patients with severe and complex three-dimensional deformities, it is difficult to use preoperative multi-slice spiral CT scan and other currently available imaging techniques to clearly display the morphology of abnormal spinal segments (Fig. 2). Due to the anatomical structure abnormalities in the apical spinal segments and the coverage from surrounding ribs, shoulder blades, and other osseous and soft tissues, intraoperative C-arm fluoroscopy is not clear enough either. Therefore, for these severe cases, computer-assistance navigation guidance technique is less effective in navigating pedicle screw placement. For these special reasons and situations, this study attempted to explore a method to guide transpedicular screw insertion more accurately and safely in treatment of severe spinal deformities. When regular method failed to establish the screw trajectory in pedicle, the five-step remedial method was attempted to insert the pedicle screw in place. Using such sequential approach, 97.7 % of pedicle screw placements eventually succeeded in our study.

Based on the developmental situation, thoracic pedicle morphology is classified into four types: type A pedicles with a large cancellous channel, type B with a small cancellous channel, type C with a cortical channel, and type D with an absent pedicle channel [13, 14]. For the type A or B pedicles with a cancellous channel, most screw placements can be successfully performed after the pedicle entries are found. In type C pedicles, for lack of a cancellous bone channel, it is hard to establish a tract in pedicle guided by the sensation of the hand drill passing through cancellous bone. All the six failure cases in our study were confirmed by postoperative CT scan to be type D pedicles. Because this type of pedicles is usually too thin and even without a channel structure, it is impossible to establish transpedicular trajectories even under direct observation of the pedicles (Fig. 3). In such case, the key to success of pedicle screw placements is to carefully feel the resistance during establishing screw trajectories, to judge whether the hand drill tip was in bone structure, and to carefully feel the hand drill smoothly passing through the cancellous bone as it moves forward. But even doing so does not ensure placement of screws in extremely complex deformities, because

Fig. 3 Female, 12 years, congenital scoliosis associated with syringomyelia. **a–b** Preoperative and postoperative radiographs. **c–f** Screws could not be placed as planned into the right T3, T4, T5, and T6 pedicles during operation. The postoperative CT scan confirmed that there was no channel structure in these four pedicles. The upside

fixation segment had to be moved from preoperatively planned T2 up to T1. During the operation, posterior-only T11 vertebrae column resection was performed, and the deformity was corrected successfully. Titanium mesh cage containing autograft bone was used for fusion

the structure of pedicles may not be clearly shown by preoperative CT scanning. Though in these special but rare cases, it cannot show clearly the structure of pedicles, preoperative CT scan assessment is generally very important and necessary in treatment of severe spinal deformities. When lack of detailed and comprehensive understanding of the development of the pedicle in the segment prior to surgery, the surgeon may feel helpless when encountering difficulties in screw placements and may not be able to accomplish the planned screw insertion. Some investigators have reported that when there are difficulties in the placement of the thoracic pedicle screws, screws can also be placed through the costovertebral joint [15]. However, the costovertebral joint is a joint structure and is unlikely to provide reliable biomechanical stability for screws. In addition, because severe deformity is often associated with abnormalities of the surrounding anatomical structures with major blood vessels and nerves shifting

away from the original places, screw placement through the costovertebral joint would greatly increase the risk of major vascular or nerve injury. Therefore, we believe that placement of the screws through the costovertebral joint should not be commonly used to treat patients with spinal deformities and should only be used with great caution as a last resort.

In the initial establishment and later adjustment process of the screw trajectory, a thin sharp hand drill with a 2-mm diameter should be used. The reason for this choice is that the pedicles in patients with severe deformities are usually tiny; a thin sharp hand drill can give the surgeon a much better hand sensation of drilling and at the same time leave more room for the trajectory adjustment if necessary. When the screw trajectory is established after several adjustments and the integrity of the bony walls of the pedicle are ensured, the screw diameter can be properly increased according to the hand sensation changes during screwing

the pedicle screw into pedicle in order to gain an optimal corrective force [16]. During the establishment of screw trajectory using a hand drill, the hand sensation used to perceive the situation of the trajectory walls is extremely important. This hand sensation includes four aspects: (1) the surgeon must be able to perceive that both the tip and surroundings of the hand drill are located in the bone structure of pedicle; (2) the bone cortex in the interior wall of the pedicle guides the forward movement of the hand drill; (3) during use of the hand drill, any forward movement must be extremely meticulous and careful to experience the sensation of the hand drill smoothly passing through the cancellous channel in pedicle; and (4) during the entire hand drill moving forward process, the tip of the hand drill must always be in contact with bone tissue. Any subtle changes in the process of hand drill forward movement must be carefully noted, and there must not be a sensation of drilling through a void or soft tissue. During the process of the screw trajectory establishment, the four aforementioned sensations must be present simultaneously. This combination of sensations is extremely important. At any time when there is an abnormal hand sensation, the hand drill must be immediately stopped and drawn back. A blunt probe with a tiny hook-tip should then be used to carefully palpate any abnormalities in the walls and the bottom of the pedicle before the surgeon decides to continue moving the hand drill forward along the original direction or to adjust the trajectory. Thus the hand sensation of drilling is a reliable and important guideline in choosing screw placement methods in clinical practice.

In addition to good hand sensation of drilling, we also emphasize the importance of using a probe to palpate the trajectory after its establishment. Due to the blockage by anatomical structures such as the chest, and abnormal structures in complex and severe deformities, intraoperative C-arm fluoroscopy cannot be enough to evaluate whether the establishment of screw trajectory is successful. The most reliable method to verify is to repeatedly palpate the screw trajectory to confirm the integrity of the walls and bottom of the trajectory without “soft spot”. It is necessary to carefully note the structural integrity of the four walls and the bottom of trajectory. If any “soft spot” or gap was felt in the trajectory, the attempt of establishing a trajectory must be stopped and adjusted. During the palpating process, the integrity of the four walls of the trajectory should be determined first; if there is a perforation, the specific location, depth, and size of the perforation, as well as whether the perforation range would expand with increased screw diameter, should all be further determined. Therefore, the surgeon’s sensitive and precise palpating during the screw trajectory establishing process is also a key factor to successful transpedicular screw placement.

For patients with severe spinal deformities, the pedicle at concave side is much thinner than the convex side in the same segment. In addition, the spinal cord and dura mater are much closer to the concave side. The width of the epidural space is less than 1 mm at the thoracic apical vertebral levels on the concave side, but between 3 and 5 mm on the convex side [17, 18]. Therefore, in the operational treatment of spinal deformity, pedicle screw placement on the concave side is more difficult and riskier than on the convex side. When selecting segments for pedicle screw placement during surgery, as many pedicle screws as possible should be placed on the convex side to provide adequate corrective force.

In the process of applying the five remedial methods, we also emphasize a “one-after-another” principle. The principle is not only related to the unclear preoperative CT pedicle observation, but also because each step increases the destruction of the spine and the risk of neurological damage. If the preoperative CT scanning shows pedicles with an absent pedicle channel, direct hemilaminectomy in consecutive segments is not a good choice, because performing this procedure in the consecutive segments is excessively invasive for the structure of spine and will create difficulties for the subsequent bone transplantation. Therefore, although all five steps have advantages and disadvantages, the order of application should not be randomly chosen; rather, the “one-after-another” principle must be strictly followed. Any next step must only be used when the previous step(s) fail(s) to establish the screw tract.

In conclusion, for patients with severe spinal deformities, the preoperative CT scan of the pedicle in the programmed segment to be fixed is very important, and an intensive preoperational plan must be made based on the CT scan results. For these patients, intraoperative C-arm fluoroscopy is of limited help in determining whether the screw trajectory has been successfully established. Instead, the surgeon’s sensitive hand sensation can help perceive the walls of the trajectory during the forward movement of the thin sharp hand drill. Precise and careful palpating trajectory technique is also a key to successful screw placement and a reliable criterion to judge the quality of the screw tract. When there are difficulties in pedicle screw placement during surgery using the regular methods, the sequential application of the five-step remedial method described in this study can achieve success for most screws placements. The order of the five steps should not be randomly chosen; rather, the “one-after-another” principle must be strictly followed.

Conflict of interest The authors did not receive grants or outside funding in support of their research for or preparation of this manuscript. They did not receive payments or other benefits or a

commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, education institution, or other charitable or nonprofit organization with which the author are affiliated or associated.

References

- Kim YJ, Lenke LG, Bridwell KH et al (2004) Free hand pedicle screw placement in the thoracic spine: is it safe? *Spine* 29:333–342
- Senaran H, Shah SA, Gabos PG et al (2008) Difficult Thoracic Pedicle Screw Placement in Adolescent Idiopathic Scoliosis. *J Spinal Disord Tech* 21:187–191
- Lehman RA, Lenke LG, Keeler KA et al (2008) Operative treatment of adolescent idiopathic scoliosis with posterior pedicle screw-only constructs minimum three-year follow-up of one hundred fourteen cases. *Spine* 33:1598–1604
- Kim YJ, Lenke LG, Cho SK et al (2004) Comparative analysis of pedicle screw versus hook instrumentation in posterior spinal fusion of adolescent idiopathic scoliosis. *Spine* 29:2040–2048
- Lee CS, Kim MJ, Ahn YJ et al (2007) Thoracic pedicle screw insertion in scoliosis using posteroanterior C-arm rotation method. *J Spinal Disord Tech* 20:66–71
- Zindrick MR, Knight GW, Sartori MJ et al (2000) Pedicle morphology of the immature thoracolumbar spine. *Spine* 25:2726–2735
- Suk SI, Kim WJ, Lee SM et al (2001) Thoracic pedicle screw in spinal deformities: are they really safe. *Spine* 26:2049–2057
- Parent S, Labelle H, Skalli W et al (2004) Thoracic pedicle morphology in vertebrae from scoliotic spines. *Spine* 29:239–248
- Xie JM, Wang YS, Zhang Y et al (2007) Operative skill of lower cervical transpedicle screw. *Orthop J China* 15:745–748
- Yossi S, Michael AM, Yoram A et al (2005) Accuracy and safety of thoracic pedicle screw placement in spinal deformities. *J Spinal Disord Tech* 18:522–526
- Feyza KG, Erhan EM, Hakan S et al (2006) Accuracy of pedicle screw placement for upper and middle thoracic pathologies without coronal plane spinal deformity using conventional methods. *J Spinal Disord Tech* 19:436–441
- Girardi FR, Cammisa FP Jr, Sandhu HS et al (1999) The placement of lumbar pedicle screws using computerized stereotactic guidance. *J Bone Joint Surg Br* 81:825–829
- Lenke LG, Watanabe K (2006) When to avoid pedicle screw fixation (abstract). In: The 41st Annual Meeting of the Scoliosis Research Society Pre-Course, Monterey, CA, 13 Sept 2006
- Watanabe K, Lenke LG, Matsumoto M et al (2010) A novel pedicle channel classification describing osseous anatomy: how many thoracic scoliotic pedicles have cancellous channels? *Spine* 35:1836–1842
- Klane KW, Richard O, Andrew TM et al (2006) Pullout strength of thoracic pedicle screw instrumentation: comparison of the transpedicular and extrapedicular techniques. *Spine* 31:355–358
- Xie JM, Wang YS, Zhao Z et al (2011) The safe placement of upper and middle thoracic pedicle screws in pediatric deformity. *J Spinal Disord Tech* 24(1):55–59
- Liljenqvist UR, Allkemper T, Hackenberg L et al (2002) Analysis of vertebral morphology in idiopathic scoliosis with use of magnetic resonance imaging and multiplanar reconstruction. *J Bone Joint Surg Am* 84-A:359–368
- Vaccaro AR, Rizzolo SJ, Balderston RA et al (1995) Placement of pedicle screws in the thoracic spine. Part II: an anatomical and radiographic assessment. *J Bone Joint Surg Am* 77:1200–1206