Percutaneous fixation of thoracolumbar vertebral fractures

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Introduction
Thoracolumbar (TL) fractures are the second most common fractures after hip fractures.¹,² At the TL junction (T11-L2), TL fractures comprise three-quarters of total spinal injuries.³ Most TL fractures occur at a young age, motor vehicle accidents being the most common cause. The incidence of these fractures is increased in the elderly and their occurrence is one of the markers of osteoporosis.⁴,⁵ The main goals of treating TL fractures are: (1) to protect neural elements and maintain/restore neurologic function; (2) to prevent or correct segmental collapse and deformity; (3) to prevent spinal instability and pain; (4) to permit early ambulation and return to function; and (5) to restore normal spinal mechanics.⁶ It is unanimously agreed that vertebral fractures associated with neurologic deficit should undergo surgical decompression, fixation and fusion;⁷,⁸ however, surgical treatment of patients with vertebral fractures without neurological deficit is still controversial.⁹ Unstable (> 50% loss of anterior vertebral height, > 20° angular deformity and contiguous fractures) thoracic compression and burst fractures could collapse into further kyphosis.⁶,¹⁰ There is some evidence that patients who accepted surgery in these cases have shown better clinical and radiological outcomes than patients managed non-operatively,¹¹ with improved local kyphosis at long-term follow-up.¹²

Classically, surgical treatment consisted of internal fixation and arthrodesis using open approaches.⁶ Percutaneous pedicle targeting was first described by Dick et al in
1985 for diagnosis of degenerative disc disease. Foley et al reported, in 2001, the first case of degenerative disease managed by percutaneous fixation, while Assaker first reported, in 2004, the management of vertebral fracture with percutaneous fixation. Since then, many publications were issued describing the advantages and disadvantages of this technique.

The aim of this paper is to review the available literature and to meet the following objectives: (1) describe the pedicle targeting technique, (2) determine the advantages and limitations of percutaneous fixation of TL fractures; and (3) determine the controversies surrounding this method.

Pedicle screw insertion technique

Pedicle screw insertion could be carried out under general, local or spinal (epidural) anaesthesia. We favour general anaesthesia as it is associated with less patient discomfort. Minimally invasive or percutaneous pedicle screw placement was made easier with the advent of cannulated screws. The surgical procedure may be fluoroscopy-assisted or, recently, navigation-assisted.

Fluoroscopy-assisted technique

Fluoroscopy is one of the limiting factors of this technique as it is imperative to obtain true anteroposterior (AP) and lateral views of the desired vertebra.

The patient is positioned on a radiolucent table (or a Jackson frame) and accurate AP and lateral true views are obtained. We prefer the use of two fluoroscopy machines (Fig. 1) as this renders this technique easier even for inexperienced users, since AP and lateral views can be obtained simultaneously. When the pedicle of the desired vertebra is localized, the skin entry point is marked 1 cm lateral to the pedicle. As a more convergent and straightforward pedicle screw trajectory is preferred, the entry point should be at 2–3 o’clock in the right pedicle and 9–10 o’clock in the left pedicle (Fig. 2).

Local anaesthesia is applied from the skin to the pedicle in order to decrease post-operative pain. A skin incision is made and depends greatly on the instrumentation type: older instrumentations require bigger skin incisions. The incision of the TL fascia should be wider than the skin incision. The Jamshidi needle is then introduced through the desired entry point: this is ideally localized at the junction between the articular facet and the transverse process (Fig. 3a). This will ensure a truly convergent screw placement. Care should be taken not to insert the screw through the facet joint. The Jamshidi needle is then advanced into the pedicle with simultaneous control on the AP and lateral views: when the Jamshidi needle is in the middle of the pedicle on the AP view, it should have passed the middle of the pedicle on the lateral view, and when the tip of the needle arrives at the posterior border of the vertebral body on the lateral radiograph, it should not be touching the inner border of the pedicle on the AP view. This is in contrast to the technique for vertebral augmentation, as a safety zone of 3 mm medially should be left in this case. The tip of the needle is only allowed to

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Fig. 1 Positioning of the patient with two fluoroscopy machines for anteroposterior and lateral imaging. (Adapted from Sebaaly et al). Fig. 2 AP fluoroscopy showing the desired pedicular entry points at 2–3 o’clock in the right pedicle and 9–10 o’clock in the left pedicle.
touch the inner pedicle wall on the AP radiograph when it has passed the posterior wall (Fig. 3b and c). The needle should always be parallel to the vertebral endplates on lateral film when advancing into the vertebra.

The guide wire is advanced into the vertebral body with care not to pass the anterior cortex (risk of injury of the greater vessels) (Fig. 3d). The trickiest step is to remove the Jamshidi needle without removing the guide wire. Prono-supination is used to retract the needle while the guide wire is maintained with a Kocher clamp. When guide wires are inserted in all desired vertebrae, the AP fluoroscopy machine can be drawn out of the operative field to ensure a more ergonomic work space.

Pedicle preparation then begins, using cannulated instruments such as awls and taps while the instruments’ depth is frequently checked on lateral imaging (Fig. 3e). The screws are then inserted and the guide wire removed after the tip of the pedicle screw passes the posterior border of the vertebral body on the lateral radiograph. One pitfall to avoid is the bending of the guide wire while tapping and inserting the screw as this might result in guide wire breakage. To avoid this complication, the guide wire should be removed as soon as the screw tip enters the vertebral body at the posterior vertebral wall (Fig. 3e).

After insertion of all desired screws, contouring of the rods is performed and these are inserted and locked in place. Final AP and lateral imaging should be obtained to control the construct.

In the immediate post-operative period, no bracing is required. Pain is managed for a limited period of time with acetaminophen and narcotic medication. Most patients can be released on the second post-operative day if pain is acceptable, neurologic examination is normal and all other associated injuries are addressed.

Navigation-assisted technique

With the advent of navigation, there is increasing use of this technology in spine centres as it renders safer and faster insertion of pedicle screws. The technique described here uses the O-ARM (Medtronic, Sofamor, Memphis, TN, USA) as an image acquisition system and Stealthstation TREON™ system (Medtronic Sofamor Danek, Memphis, TN, USA) as a navigation system. After positioning, the first step of this technique is inserting the reference. We prefer a percutaneous iliac bolt reference guide (Fig. 4a). Care should be taken that the reference guide does not block the navigation field. O-ARM image acquisition is then carried out. We prefer the use of two images on the navigation panel: axial and sagittal cuts (Fig. 4b).

The skin incision is marked in a similar fashion to the fluoroscopy-assisted technique. The insertion of the navigated Jamshidi needle follows the same principles of the
technique described above. The use of guide wires in this technique is optional. If a guide is used, we perform an AP and lateral imaging (equivalent to fluoroscopy) using the O-ARM just to check the correct position of the guide wires as some cortical breaches may occur during the learning curve of this navigation-assisted percutaneous instrumentation technique (Fig. 5). To ensure rapid insertion of the screws, we tape all the screws using the navigated tap (Fig. 4c). Screw insertion is made easier with the navigation model (Fig. 4d) and rod insertion is performed similarly to the fluoroscopy-assisted technique described above (Fig. 4e).

Percutaneous internal fixation for traumatic fractures

Advantages of percutaneous fixation

The most important theoretical advantage of percutaneous fixation of vertebral fractures is less tissue dissection. Regev et al showed that the multifidus muscle motor nerve was injured in up to 80% of patients in open procedures compared with only 20% in patients operated on with the percutaneous technique.18 The preservation of muscle innervation would result in less muscle scarring and atrophy as shown on post-operative muscle enzyme dosage19 and MRI.20 This same study showed better muscle strength preservation in the percutaneous group.20 This less traumatic approach to spinal muscle should theoretically result in decreasing post-operative pain. Jiang et al found better function and lower pain scores in the percutaneous group compared with the open cohort,21 the same result as shown in other papers.2 On the other hand, Lee et al found no difference in VAS scores between the percutaneous group and the open fixation group.22 Similarly, a recent meta-analysis showed no difference in medium-term follow-up pain between both techniques.23 This could be explained by the higher heterogeneity between the different studies.24 Even though no differences in pain scores at long-term follow-up were observed, percutaneous fixation resulted in lower VAS scores at early follow-ups (three months), resulting in early mobilization (caused by better spinal stability).22,25-27 This allows patients to ambulate earlier and thus to be less exposed to bed rest complications and ulcers.20,22 This will result in a significant decrease of patients’ hospital stay (mean decrease of 5.72 days),24 thus decreasing the hospitalization cost, including the cost of the osteosynthesis material, with an average gain of €1159.11 per patient.21,28 Another possible advantage of percutaneous fixation is decreased bleeding and operative time. Many authors showed lower blood loss in percutaneous fixation when...
compared with standard open fixation in their series. Merom et al. found 50 mL less blood loss using the percutaneous technique. Nonetheless, this result was not statistically significant.29 Yet others found a significantly decreased blood loss with the minimally invasive technique.21,22,26,27 When these results are pooled into a meta-analysis, percutaneous fixation resulted in significant surgical bleeding reduction of 285.44 mL with a relative reduction of 1.67.23,24

Operative time depends greatly on the experience of the operating surgeons. As a matter of fact, early reports showed no difference between the two techniques.29 More recent publications, in which operating surgeons have completed their learning curve, showed decreased operative time compared with open techniques.21,22,26,30 When data from randomized trials are pooled together, percutaneous fixation resulted in a significant reduction of operative time by a mean of 18.83 minutes.23,24

Fluoroscopy-controlled pedicle screw placement is associated with better screw positioning compared with a freehand technique. Ringel found only 3% of unacceptable screw placements using the percutaneous technique, while Ni et al. found 6.7% screw misplacements overall but without neurological involvement.31 Nonetheless, one meta-analysis showed that there was no difference in terms of screw malpositioning between percutaneous (3.0%) versus open fixation (4.2%).24 One should note that the freehand technique tends to malposition the screw medially, whereas the malpositioned screw under fluoroscopy tended to be in the ‘safer’ lateral zone (Fig. 5).32

Finally, the infection rate with percutaneous fixation seems to be decreased compared with open fixation. Schmidt et al. had no infection in their series of 74 patients with percutaneous fixation,33 whereas Ni et al. showed one infection in 36 patients (2.7%).31 These rates of infection are somewhat below the known infection rate in trauma cases when open fixation is performed. In fact, the meta-analysis by Phan et al. showed that infection rates were significantly lower in the percutaneous fixation cohort compared with the open fixation cohort (0.3% vs 3.4%, respectively; relative risk (RR) = 0.36).24

**Drawbacks of percutaneous fixation**

Percutaneous instrumentation of a fractured vertebra requires the use of fluoroscopy, thus increasing the exposure to the patient and the surgeon. Rampersaud et al. studied the exposure in a cadaveric study, showing that surgeons’ hands were 10 to 12 times more exposed to radiation in a short segment fixation compared with a standard femoral nailing. They also showed that the surgeon’s chest received 25 times more radiation if the surgeon was on the same side as the radiation source compared with when he was on the other side.34 The newer technology with intra-operative cone-beam CT intends to address this drawback while increasing pedicle screw position accuracy. In a matter of fact, correct pedicle screw placement increased significantly using this technology.32,35,36 Surgeon and surgical team exposure to radiation was significantly reduced, but the patient was more exposed to radiation with this technology.37 The patient’s radiation exposure could be decreased using ‘low dosage’ or ‘paediatric dosage’ protocols.38 Still, this technology requires financial investment in the operating room (reinforced floor, lead protected room, etc.) as well as in the acquisition system along with the navigator and ancillary.39

Another possible drawback of percutaneous fixation of TL fractures seems to be the learning curve. Many authors commented on the challenges faced in their initial cases, with increased incidence of complications caused by facet joint violations, screw misplacement and subsequent need for additional operative procedures.40-42 In 2014, Sclafani et al. published a systematic review correlating complications to the technique learning curve.43 They found that screw malposition and loosening depend largely on the surgeon’s experience. They stated that 20 to 30 cases are required to complete the learning curve for this technique. Experts stress the importance of completing this learning curve to decrease overall complications, including mechanical and infectious ones.44 Nonetheless, when compared with other minimally invasive (MIS) techniques (MIS decompression, MIS anterior interbody fusion, etc.), percutaneous screw fixation is associated with the shortest and easiest learning curve.43

**Controversies**

Surgical management of neurologically intact vertebral fractures is still controversial and analysing the indications of surgical treatment is beyond the scope of this review.
Nonetheless, two points should be emphasized. First, the local and regional kyphotic deformities are among the least studied parameters in non-operative treatment. In fact, the TLICS scoring system was criticized for not incorporating the local kyphosis in the treatment algorithm. Moreover, the latest meta-analysis by Sonali et al showed no difference between non-operative and operative treatments in pain and clinical outcomes but showed better kyphosis correction with operative treatment. However, one question remains: is fusion necessary for long-term kyphosis prevention? Lyu et al compared open instrumentation and fusion with open fixation and percutaneous fixation. They found no difference in kyphosis reduction with the three techniques and concluded that percutaneous fixation alone without grafting is sufficient for treating these fractures. The same conclusion was also reached by other authors. Meta-analysis data showed no difference of kyphosis correction at the immediate postoperative period or at the last follow-up between these three techniques. The fixation would act as an internal brace and could be removed afterwards. Kim et al evaluated motion at the fractured level after removal of the implants in percutaneous fixation of burst fractures, and showed motion preservation at the fractured level with good clinical results. Finally, there may be a risk of facet violation and a subsequent risk of facet osteoarthritis (OA) even after instrumentation removal. Tromme et al evaluated more than 1000 screws inserted percutaneously for fractures with several interesting findings. The facets were moderately breached in 15% of cases and severely damaged in only 0.6% of cases. Moderate OA was found in 9.6% of cases, while 1.2% of cases showed severe OA. Complete fusion was found in 1%, whereas partial fusion was evidenced in 2.6% of cases. The main risk factors for facet violation and fusion were age, increased BMI and type B fractures.

Anterior support for posterior fixation is another controversy, and decision for anterior support is still based on the load sharing classification (LSC) described by McCormack et al in 1994. Many authors encourage the use of anterior support when the LSC score is > 6. Anterior support could be made by minimally invasive approach (mini-open, thoracoscopy) for corpectomy and cage insertion. However, these anterior approaches are less familiar to spine surgeons, with higher complications (up to 7.8% vascular injuries), and they often require access surgeons. In addition, these recommendations are based on an old classification, while newer and more powerful instrumentations are now available for the operating surgeon. For instance, Kanna et al showed no loss of reduction nor increasing kyphosis in a series of 32 patients with LSC ≥ 7 operated with short segment posterior fixation (including the fractured vertebra) with no implant failure.

Classically, treatment of TL fractures consisted of a long construct with three levels of fusion above and two levels of fusion below the fracture, together with the three-point bending fixation to prevent kyphotic deformity. The classical long construct is somehow technically difficult because of the multiple positions needed for the fluoroscopic machine together with the inability to use transverse connectors necessary for this long construct. In 1994, Dick et al described a technique adding a screw to the fractured vertebra with the advantages of incorporating fewer motion segments into the fusion mass, with less operative time and bleeding. This also increased the axial, sagittal and torsional stiffness of the construct. The use of this technique obviates the need for a long construct (Fig. 6). Some authors described even shorter constructs to decrease fusion levels. Wei et al described mono-segmental fixation. They showed better operative time and average blood loss but kyphosis reduction loss for LSC ≥ 7. Others found that only increased BMI (> 30) is a risk factor for kyphosis in short segment fixation including the fractured vertebra. Adding screws at the fractured level decreased the mechanical complications related to instrumentation failure and increased construct stiffness by 31% with better support of the fractured vertebral body during flexion-extension loading. A biomechanical study evaluated the strain on the instrumentation in short segment instrumentation. They showed maximal strain in four screw constructs (including monosegmental); however, adding at least one screw at the fractured level significantly decreased the strain on screws and rods. Finally, a recent study showed no increase of blood loss or operative time when screws are added at the fractured level.

One could argue that most studies compared percutaneous fixation with open reduction and fusion in patients with type A (according to AO classification) fractures where the fracture is inherently stable. Type B fractures, especially B2, where ligamentous instability is present, leads to a weak scar compared with bony B1 fractures and could lead to long-term instability and neurological compromise. Nonetheless, the conclusions drawn on type A fractures could be extended to neurologically-intact type B fractures. In fact, Grossbach et al compared open fixation with percutaneous fixation in distraction type B fractures. They found no difference in kyphosis reduction loss in both groups at final follow-up, with more patients in the percutaneous fixation group undergoing implant removal. These same results were found by Dong et al, who evaluated regional kyphotic angle as well as vertebral height.

Finally, spinal canal compromised by a bony fragment without neurological compromise remains a relative indication of open fixation and decompression. Yet, some authors showed reduction of the canal compromised from 43% to 23% in well reduced fractures treated percutaneously. These results are comparable with those obtained when open reduction and fusion are performed.
Fig. 6 A 55-year-old woman was the victim of a fall from the second floor. Initial X-ray and CT scanner showed A2 L3 fracture (A-B). She was operated with percutaneous fixation with instrumentation of the fractured vertebra in its left pedicle (C-D).

Fig. 7 Algorithm for treating thoracolumbar vertebral fractures.
Authors’ recommendations

Based on this review, we propose a treatment algorithm for TL fractures (Fig. 7). Patients who present with neurological signs should undergo posterior (and/or anterior) decompression and fusion. Detailed evaluation of the fracture of neurologically intact patients is mandatory. Type C and B2 fractures (ligamentous injuries) should undergo fusion since the ligamentous healing is mechanically weak, therefore increasing the risk of instability. Type B1 and A4 fractures, as well as type A2 fractures, could undergo percutaneous short segment fixation with screws at the fractured level. A1 and A3 fractures with a loss of 50% of anterior height or 20° of local kyphosis could undergo the same treatment. Whenever possible, the fractured vertebra should be instrumented with a minimum of one screw.

Conclusion

Percutaneous fixation in type A and B1 fractures meets the main goals of treating TL vertebral fractures, by protecting neural elements, preventing collapse, deformity, instability and pain and allowing early mobilization and return to function. This technique, while having a steep learning curve with increased surgeon and patient exposure to radiation, minimizes tissue dissection, operative time after adequate training, post-operative pain and infection rate when compared with open reduction, fixation and fusion. More stability is acquired by adding screws at the level of the fractured vertebra. This allows for shorter constructs, shorter operative time, less blood loss and increased mobility. However, for more unstable fractures (type B2 and C fractures), fusion with a complementary anterior intervention or with an open posterior approach is necessary to compensate for the weak ligamentous healing.

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REFERENCES

1. Melton LJ, Kallmes DF. Epidemiology of vertebral fractures: implications for vertebral augmentation. Acad Radiol 2006;13:538-545.
2. Wang H, Zhou Y, Li C, Liu J, Xiang L. Comparison of open versus percutaneous pedicle screw fixation using the sextant system in the treatment of traumatic thoracolumbar fractures. Clin Spine Surg 2017;30:E239-E246.
3. Irwin ZN, Arthur M, Mullins RJ, Hert RA. Variations in injury patterns, treatment, and outcome for spinal fracture and paralysis in adult versus geriatric patients. Spine 2004;29:796-802.
4. Sebaaly A, Nabhane L, Issa EL, Khoury F, Kreichati G, El Rachkidi R. Percutaneous cement augmentation for osteoporotic vertebral fractures. EFORT Open Rev 2017;2:293-299.
5. Sebaaly A, Rizkallah M, Bachour F, et al. Percutaneous fixation for thoracolumbar burst fractures without neurologic deficit: a meta-analysis. Spine (Phila Pa 1976) 2012;37:570-579; discussion S104.
6. McClain RF. The biomechanics of long versus short fixation for thoracolumbar spine fractures. Spine (Phila Pa 1976) 2006;31(11 Suppl):S70–S79; discussion S104.
7. Vaccaro AR, Lim MR, Hurlbert RJ, et al. Surgical decision making for unstable thoracolumbar spine injuries: results of a consensus panel review by the Spine Trauma Study Group. J Spinal Disord Tech 2006;19:1-10.
8. Reinhold M, Audigé L, Schnake KJ, et al. A0 spine injury classification system: a revision proposal for the thoracic and lumbar spine. Eur Spine J 2013;22:2184-2201.
9. Wood KB, Buttermann GR, Phukan R, et al. Operative compared with nonoperative treatment of a thoracolumbar burst fracture without neurologic deficit: a prospective randomized study with follow-up at sixteen to twenty-two years. J Bone Joint Surg [Am] 2015;97-A:3-9.
10. Mattei TA, Hanovnikian JH, Dinh D. Progressive kyphotic deformity in comminuted burst fractures treated non-operatively: the Achilles tendon of the Thoracolumbar Injury Classification and Severity Score (TLICS). Eur Spine J 2014;23:2255-2262.
11. Siebenga J, Leferink VJM, Segers MJM, et al. Treatment of traumatic thoracolumbar spine fractures: a multicenter prospective randomized study of operative versus non-surgical treatment. Spine 2006;31:2881-2890.
12. Gnanenthiran SR, Adie S, Harris IA. Nonoperative versus operative treatment for thoracolumbar burst fractures without neurologic deficit: a meta-analysis. Clin Orthop Relat Res 2012;470:567–577.
13. Dick W, Kluger P, Magerl F, Woerdßerö R, Zäch G. A new device for internal fixation of thoracolumbar and lumbar spine fractures: the “fixateur interne”. Paraplegia 1985;23:225-232.

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14. Foley KT, Gupta SK, Justis JR, Sherman MC. Percutaneous pedicle screw fixation of the lumbar spine. *Neurosurg Focus* 2010;10:E10.

15. Assaker R. Minimal access spinal technologies: state-of-the-art, indications, and techniques. *Joint Bone Spine* 2004;71:459-469.

16. Nakahara M, Yashuhara T, Inoue T, et al. Accuracy of percutaneous pedicle screw insertion technique with conventional dual fluoroscopy units and a retrospective comparative study based on surgeon experience. *Glob Spine J* 2016;6:322-328.

17. Tabaraei E, Gibson AG, Karahalios DG, et al. Intraoperative cone beam-computed tomography with navigation (O-ARM) versus conventional fluoroscopy (C-ARM): a cadaveric study comparing accuracy, efficiency, and safety for spinal instrumentation. *Spine* 2013;38:1953-1958.

18. Regev GJ, Lee YP, Taylor WR, Garfin SR, Kim CW. Nerve injury to the posterior ramus medial branch during the insertion of pedicle screws: comparison of mini-open versus percutaneous pedicle screw insertion techniques. *Spine* 2009;34:1239-1242.

19. Lehmann W, Usmaev A, Ruecker A, et al. Comparison of open versus percutaneous pedicle screw insertion in a sheep model. *Eur Spine J* 2008;17:857-865.

20. Kim D-Y, Lee S-H, Chung SK, Lee H-Y. Comparison of multifidus muscle atrophy and trunk extension muscle strength: percutaneous versus open pedicle screw fixation. *Spine* 2005;30:123-129.

21. Jiang XZ, Tian W, Liu B, et al. Comparison of a paraspinous approach with a percutaneous approach in the treatment of thoracolumbar burst fractures with posterior ligamentous complex injury: a prospective randomized controlled trial. *J Int Med Res* 2012;40:1743-1756.

22. Lee J-K, Jang J-W, Kim T-W, et al. Percutaneous short-segment pedicle screw placement without fusion in the treatment of thoracolumbar burst fractures: is it effective? Comparative study with open short-segment pedicle screw fixation with posteroslateral fusion. *Acta Neurochir (Wien)* 2013;155:2305-2312.

23. McNamry SJ, O’leary SC, Kim JS, et al. Open versus minimally invasive fixation techniques for thoracolumbar trauma: a meta-analysis. *Glob Spine J* 2016;6:186-194.

24. Phan K, Rao PJ, Mobbs RJ. Percutaneous versus open pedicle screw fixation for treatment of thoracolumbar fractures: systematic review and meta-analysis of comparative studies. *Clin Neural Neurosurg* 2015;2015:85-92.

25. Lyu J, Chen K, Tang Z, et al. A comparison of three different surgical procedures in the treatment of type A thoracolumbar fractures: a randomized controlled trial. *Int Orthop* 2016;40:1233-1238.

26. Vanek P, Bradac O, Konopkova R, et al. Treatment of thoracolumbar trauma by short-segment percutaneous transpedicular screw instrumentation: prospective comparative study with a minimum 2-year follow-up. *J Neurosurg Spine* 2014;20:150-156.

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

28. Maillard N, Buffenoir-Billet K, Hamel O, et al. A cost-minimization analysis in minimally invasive spine surgery using a national cost scale method. *Int J Surg* 2015;13:68-73.

29. Merom L, Raz N, Hamud C, Weisz I, Hanani A. Minimally invasive burst fracture fixation in the thoracolumbar region. *Orthopedics* 2009;32:orthospere.com/view.asp?id=38353.

30. Grossbach AJ, Dahdaleh NS, Abel TJ, et al. Flexion-distraction injuries of the thoracolumbar spine: open fusion versus percutaneous pedicle screw fixation. *Neurosurg Focus* 2013;35:E2.

31. Ni W-F, Huang Y-X, Chi Y-L, et al. Percutaneous pedicle screw fixation for neurologic intact thoracolumbar burst fractures. *J Spinal Disord Tech* 2010;23:530-537.

32. Gelalis ID, Paschos NK, Pakos EE, et al. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. *Eur Spine J* 2012;21:247-255.

33. Schmidt OI, Strasser S, Kaufmann V, Strasser E, Gahr RH. Role of early minimal-invasive spine fixation in acute thoracic and lumbar spine trauma. *Indian J Orthop* 2007;41:374-380.

34. Rampersaud YR, Foley KT, Shen AC, Williams S, Solomito M. Radiation exposure to the spine surgeon during fluoroscopically assisted pedicle screw insertion. *Spine* 2000;25:2637-2645.

35. Tang J, Zhu Z, Sui T, Kong D, Cao X. Position and complications of pedicle screw insertion with or without image-navigation techniques in the thoracolumbar spine: a meta-analysis of comparative studies. *J Biomed Res* 2014;28:228-239.

36. 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.

37. Mendelsohn D, Strelzow J, Dea N, et al. Patient and surgeon radiation exposure during spinal instrumentation using intraoperative computed tomography-based navigation. *Spine* 2016;41:343-354.

38. Su AW, Luo TD, McIntosh AL, et al. Switching to a pediatric dose O-arm protocol in spine surgery significantly reduced patient radiation exposure. *J Pediatr Orthop* 2016;36:621-626.

39. Sebaaly A, Riouallong G, Zaraa M, Joffrey P. The added value of intraoperative CT scanner and screw navigation in displaced posterior wall acetabular fracture with articular impaction. *Orthop Traumatol Surg Res* 2016;102:947-950.

40. Park Y, Ha JW, Lee YT, Sung NY. Cranial facet joint violations by percutaneously placed pedicle screws adjacent to a minimally invasive lumbar spinal fusion. *Spine* 2011;36:295-302.

41. Patel RD, Graziano GP, Vanderhave KL, Patel AA, Gerling MC. Facet violation with the placement of percutaneous pedicle screws. *Spine* 2011;36:E1749-E1752.

42. Knox JB, Dai JM, Orzechowski JR. Superior segment facet joint violation and cortical violation after minimally invasive pedicle screw placement. *Spine* 2011;36:213-217.

43. Scalfani JA, Kim CW. Complications associated with the initial learning curve of minimally invasive spine surgery: A systematic review. *Clin Orthop Relat Res* 2014;472:1711-1717.

44. Cappuccio M, Amendola L, Paderni S, et al. Complications in minimally invasive percutaneous fixation of thoracic and lumbar spine fractures. *Orthopedics* 2013;36:6729-6734.

45. Dai L-Y, Jiang L-S, Jiang S-D. Posterior short-segment fixation with or without fusion for thoracolumbar burst fractures: a five to seven-year prospective randomized study. *J Bone Joint Surg-Am* 2009;91:1033-1041.

46. Kim HS, Kim SW, Ju CI, et al. Implant removal after percutaneous short segment fixation for thoracolumbar burst fracture: does it preserve motion? *J Korean Neurosurg Soc* 2014;55:77-77.

47. Tromme A, Charles YP, Schuller S, et al. Osteoarthritis and spontaneous fusion of facet joints after percutaneous instrumentation in thoracolumbar fractures. *Eur Spine J* 2017. doi: 10.1007/s00586-017-5173-9.

48. McCormack T, Karaikovic E, Gaines RW. The load sharing classification of spine fractures. *Spine* 1994;19:1741-1744.
49. Court C, Vincent C. Percutaneous fixation of thoracolumbar fractures: current concepts. Orthop Traumatol Surg Res 2012;98:900-909.

50. Quraishi NA, Konig M, Booker SJ, et al. Access related complications in anterior lumbar surgery performed by spinal surgeons. Eur Spine J 2013;22(suppl 1):S16-S20.

51. Kanna RM, Shetty AP, Rajasekaran S. Posterior fixation including the fractured vertebra for severe unstable thoracolumbar fractures. Spine J 2015;15:256-264.

52. Dick JC, Jones MP, Zdeblick TA, Kunz DN, Horton WC. A biomechanical comparison evaluating the use of intermediate screws and cross-linkage in lumbar pedicle fixation. J Spinal Disord 1994;7:402-407.

53. Wei F-X, Liu S-Y, Liang C-X, et al. Transpedicular fixation in management of thoracolumbar burst fractures. Spine 2010;35:1.

54. Formica M, Cavagnaro L, Basso M, et al. Which patients risk segmental kyphosis after short segment thoracolumbar fracture fixation with intermediate screws? Injury 2016;47:529-534.

55. Norton RP, Milne EL, Kaimrajh DN, et al. Biomechanical analysis of four-versus six-screw constructs for short-segment pedicle screw and rod instrumentation of unstable thoracolumbar fractures. Spine J 2014;14:1734-1739.

56. Li C, Zhou Y, Wang H, Liu J, Xiang L. Treatment of unstable thoracolumbar fractures through short segment pedicle screw fixation techniques using pedicle fixation at the level of the fracture: a finite element analysis. PLoS One 2014;9:e99156.

57. Schroeder GD, Harrop JS, Vaccaro AR. Thoracolumbar trauma classification. Neurosurg Clin N Am 2017;28:23-29.

58. Yang H, Shi JH, Ebraheim M, et al. Outcome of thoracolumbar burst fractures treated with indirect reduction and fixation without fusion. Eur Spine J 2017;20:380-388.

59. Wang S-T, Ma H-L, Liu C-L, et al. Is fusion necessary for surgically treated burst fractures of the thoracolumbar and lumbar spine? A prospective, randomized study. Spine 2006;31:2646-2652.