SPINE Volume 37, Number 25, pp E1580–E1587
©2012, Lippincott Williams & Wilkins

A Prospective Multicenter Registry on the Accuracy of Pedicle Screw Placement in the Thoracic, Lumbar, and Sacral Levels With the Use of the O-arm Imaging System and StealthStation Navigation

Erik Van de Kelft, MD, PhD,* F. Costa, MD,† D. Van der Planken, MD,* and F. Schils, MD‡

Study Design. An international, multicenter, prospective, postmarketing clinical registry to record the accuracy of pedicle screw placement, using the O-arm Complete Multidimensional Surgical Imaging System with StealthStation Navigation.

Objective. To evaluate the accuracy of pedicle screw placement in common neurosurgical practice and assess the patient's radiation exposure.

Summary of Background Data. Several imaging techniques have been used to increase accurate pedicle screw placement. The O-arm 3-dimensional (3D) imaging (Medtronic Navigation, Louisville, CO), an intraoperative computed tomographic (CT) scan, combined with an existing navigation system was reported to further increase accuracy of screw placement, especially because an intraoperative 3D scan provides information for screw adjustment before wound closure.

Methods. Patients already planned for instrumented spinal surgery were operated while using the O-arm as imaging device and the StealthStation Navigation (Medtronic Navigation, Louisville, CO) as navigation tool. At the end of all pedicle screw insertions, the placement was classified according to a validated method. The accuracy of pedicle screw placement based on the intraoperative 3D scan and the surgeon's perception of correct screw placement were assessed as well as the radiation doses the patient received during the entire procedure.

Results. During a 16-month period, a total of 1922 screws in 353 patients were evaluated. In 97.5%, the screws were correctly placed. Only 2.5% of the screws were considered as misplaced, and 1.8% of the screws were revised during the same procedure. When the surgeon perceived the screws to be correctly placed, the CT scan verified his assessment in 98.5% of the cases. The mean radiation dose was comparable with half the dose of a 64 multislice CT scan.

Conclusion. The use of the O-arm in combination with a navigation system increases the accuracy of pedicle screw placement. The accuracy of the surgeon's perception and the need to limit the radiation dose for the patient justify an additional CT scan only after careful assessment of the potential additional value.

Key words: O-arm, spinal surgery, screw placement, fluoroscopy, CT, 2D imaging, 3D imaging. **Spine 2012;37:E1580–E1587**

Since its introduction in spine surgery, pedicle screw insertion remains a challenge for every spine surgeon. Improper pedicle screw placement rarely results in permanent neurological damage but often results in reinterventions, persistent pain, claims, and increased costs. Commonly, the use of fluoroscopy is reported to result in 5% to 15% of misplaced screws.[1] During the past decades, navigation techniques have become increasingly important in spinal surgery.[2–7] The use of 2-dimensional (2D) fluoroscopic navigation partially reduced the number of misplaced screws, and navigation based on preoperative computed tomographic (CT) scan imaging is reported to provide even better results.[5,8,9] The incidence of screw misplacement decreased to approximately 4%, largely depending on the definition of "misplacement."[9–11] In a more recently published study, the use of additional intraoperative neurophysiological monitoring, besides navigation, did not result in significantly more accurate screw placement. These authors conclude that postoperative CT scan, therefore, is the ultimate proof of correct screw placement.[8] There is still much interest to have the number of misplaced screws be as low as possible, or close to 0%.

The latest development of intraoperative spine imaging is a full 360° rotation, 3-dimensional (3D) image (O-arm)

From the *Department of Neurosurgery, AZ Nikolaas, Sint Niklaas, Belgium; †Department of Neurosurgery, Istituto Clinico Humanitas, IRCCS, Rozzano, Milan, Italy; and ‡Department of Neurosurgery, Clinique Saint Joseph, Liège, Belgium.

Acknowledgment date: April 12, 2012. Revision date: August 20, 2012. Acceptance date: August 26, 2012.

The device(s)/drug(s) is/are FDA approved or approved by corresponding national agency for this indication.

Statistical analysis was performed by Crom Source, Belgium, and was sponsored by Medtronic.

Relevant financial activities outside the submitted work: board membership, consultancy, payment for lectures, educational presentations.

Address correspondence and reprint requests to Erik Van de Kelft, MD, PhD, Department of Neurosurgery, AZ Nikolaas, Moerlandstraat 1, B-9100 Sint-Niklaas, Belgium; E-mail: erik.vandekelft@neuro-chirurgie.org and erik.vandekelft@aznikolaas.be

DOI: 10.1097/BRS.0b013e318271b1fa

(Medtronic Navigation, Louisville, CO) system, which can be connected with an existent navigation system (StealthStation Navigation, Medtronic Navigation, Louisville, CO).[12] The theoretical advantages of the O-arm might be double: providing intraoperative 3D imaging to facilitate more accurate navigation and, additionally, an intraoperative CT scan can be obtained immediately after screw placement to confirm the optimal position during the intervention and giving the surgeon the option to correct the position of the screw before closure.

Recently, retrospective studies on a smaller number of patients considering pedicle screw placement in the cervical and thoracolumbar region using the O-arm and navigation have confirmed the great accuracy of pedicle screw placement.[12–14]

In a cadaver study, Santos *et al*[15] compared intraoperative O-arm 3D images of the screw trajectory with the screw placement observed upon dissection. In addition, the authors measured the surgeon's intraoperative perception of accurate screw placement by the same dissection. The surgeon's evaluation proved to correlate better with the dissection results than with the intraoperative O-arm 3D imaging.[16] As such, the value of intraoperative CT imaging as ultimate proof of correct pedicle screw placement can be questioned. Moreover, some authors and many clinicians are concerned about the radiation exposure for both patients and staff.

Therefore, we decided to perform a prospective multicenter clinical registry of thoracic, lumbar, and sacral pedicle screw placement when using the O-arm intraoperative navigation and imaging techniques in daily surgery practice of a larger patient cohort to assess the accuracy of screw placement, the need for adjustment, and the patients' radiation exposure.

Figure 1. Setup of the O-arm imaging system and StealthStation navigation.

MATERIALS AND METHODS

This was an international, multicenter, prospective, postmarketing clinical registry to record the accuracy of pedicle screw placement when using the O-arm Complete Multidimensional Surgical Imaging System with StealthStation Navigation (Figure 1). The registry took place in the daily practice setting at 3 neurosurgical centers in 2 countries (Belgium and Italy) between November 2009 and April 2011. All patients scheduled for spine surgery with pedicle screw insertion at the thoracic, lumbar, and/or sacral level were eligible for this registry if they were able to understand the information on the study and signed informed consent.

During the surgical procedure, but prior to pedicle screw insertion, intraoperative CT scan (O-arm) was obtained. The

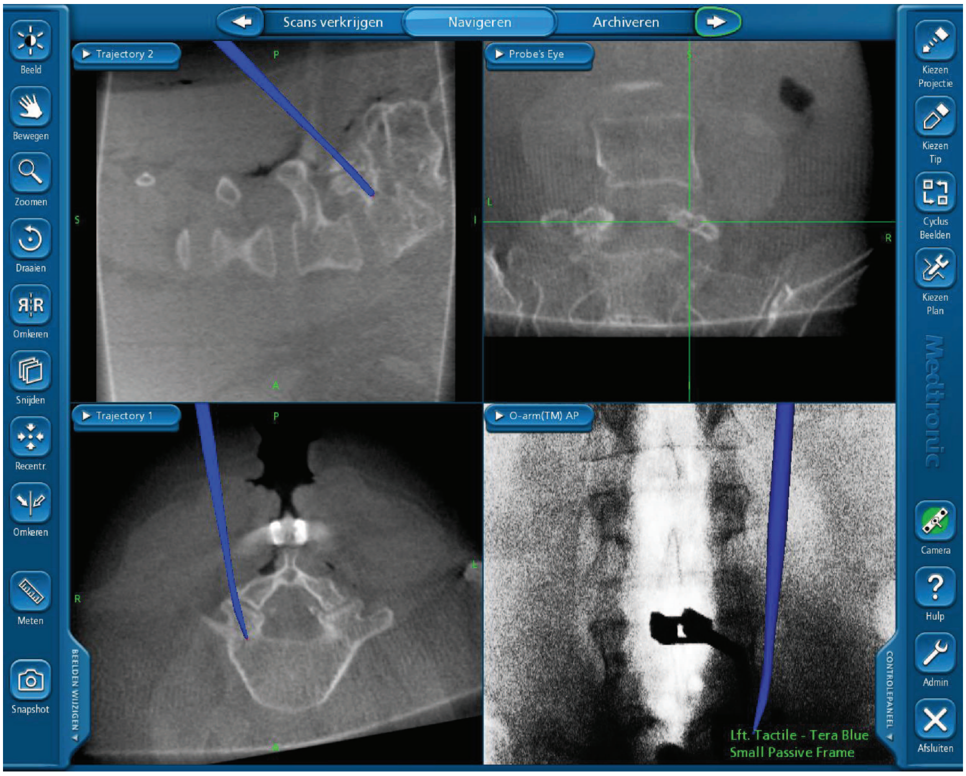

Figure 2. Image of the navigation screen obtained after the first O-arm scan. Three-dimensional images of the spine in the sagittal axial and coronal planes with pedicle finder in the right L5 pedicle.

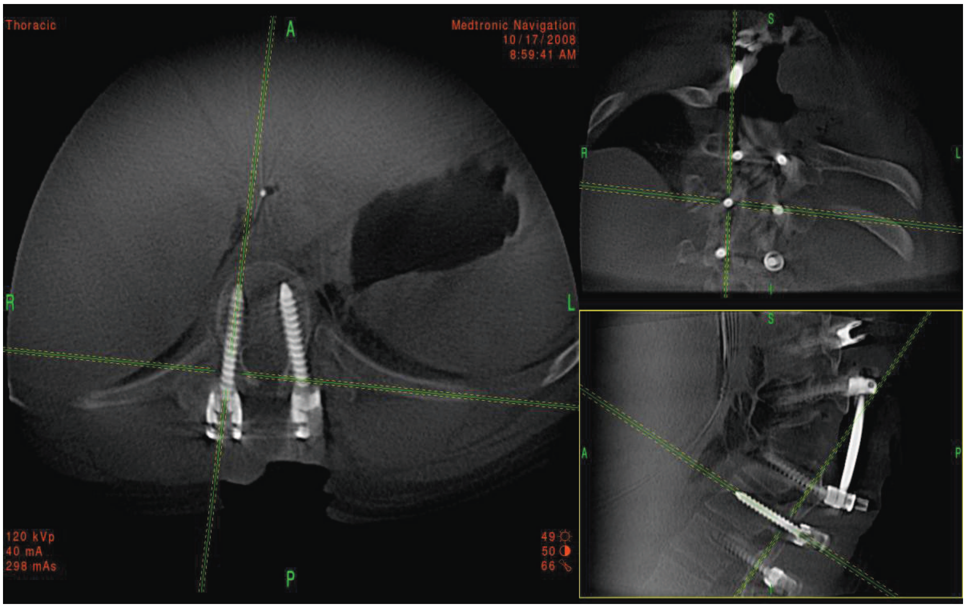

Figure 3. Image of the O-arm screen obtained after the second O-arm scan to verify the correct screw position. Each screw can be verified in the axial as well as in the coronal and sagittal views by scrolling over the screen.

3D images obtained were automatically transferred to the StealthStation Navigation system (Figure 2). We used these data and the different navigated tools to create the pedicle screw trajectory. The surgeon controlled the pedicle screw trajectory with a non-navigated ball tip probe after taping of the pedicle. He was asked to indicate whether the probed trajectory would result in correct screw placement or whether he did not feel confident about the position of at least 1 screw. In case he was confident with the trajectory, the screw was inserted, facilitated by a navigated screwdriver.

Once all screws were in place, their position was evaluated with a second intraoperative 3D scan with the O-arm (Figure 3). The positioning of each pedicle screw was classified as correct or misplaced.[17] Screw misplacement was defined as cortical perforation in axial, sagittal, or both views. This cortical perforation could be lateral, medial and anterior, endplate perforation (EP), and foraminal perforation (FP)[17] (Figure 4). Screw misplacements exceeding half the screw diameter and all screws with medial cortical perforation, FP, and EP were classified as unacceptable (indicated as red on Figure 4) and were revised during the same procedure. If screw revision was required, a third 3D scan was obtained to confirm the correct pedicle screw placement intraoperatively.

Demographic data, the indication for surgery, and the symptom duration were recorded preoperatively. The surgery type (open, minimal access spinal techniques [MAST] or percutaneous), implant type, number of placed screws, surgery duration, blood loss, radiation dose for the patient, occurrence of complications, confidence in the screw placement, and occurrence of O-arm failure were recorded as well.

The 2 primary endpoints of this registry were evaluation of the number of misplaced screws and the number of screw revision during the same surgery. The secondary endpoint of this study was an evaluation of the total radiation dose for the patient per procedure.

RESULTS

Patients were recruited from November 2009 to April 2011. A total of 1922 thoracic (n = 180), lumbar (n = 1510), and sacral (n = 230) pedicle screws in 353 patients were evaluated. All included patients were used for analysis purposes, but the percentages were calculated for the nonmissing data. Table 1 shows the demographic data of the patients included. The majority of the patients had degenerative diseases (degenerative disc disease, degenerative spondylolisthesis, or degenerative scoliosis) as the main indication for their surgery (75%).

Table 2 shows the surgery type, the surgery duration, the blood loss during surgery, the occurrence of complications, and the occurrence of O-arm failure. Suboptimal functioning of the O-arm occurred in 5.1%. A failure in both navigation and 2D or 3D mode occurred in 1 intervention out of 353. Table 3 shows the implant types per patient and the number of screws placed per patient. It also shows the confidence of the surgeon of correct screw placement.

Table 4 shows the data on screw positioning. Few screws (2.5%) were misplaced, and 1.8% of the screws needed intraoperative revision. Among the axial misplacements, lateral cortical perforation occurred most often, with 1 screw at thoracic level and 25 at lumbar level. This represents 70.3% of all axial misplacements (Figure 4). Among the vertical misplacements, EP occurred most often (85.7%) of all vertical misplacements. One EP was observed at thoracic level and 11 at lumbar level.

Table 4 also shows a comparison between the surgeon's confidence in the screw placement and the actual screw placement as evaluated by the intraoperative CT images. When the surgeon had complete confidence in the correct screw placement after probing the trajectory, 1.5% of the screws seemed to be misplaced and 1.0% of the screws needed to be revised. When the surgeon doubted the correct screw placement,

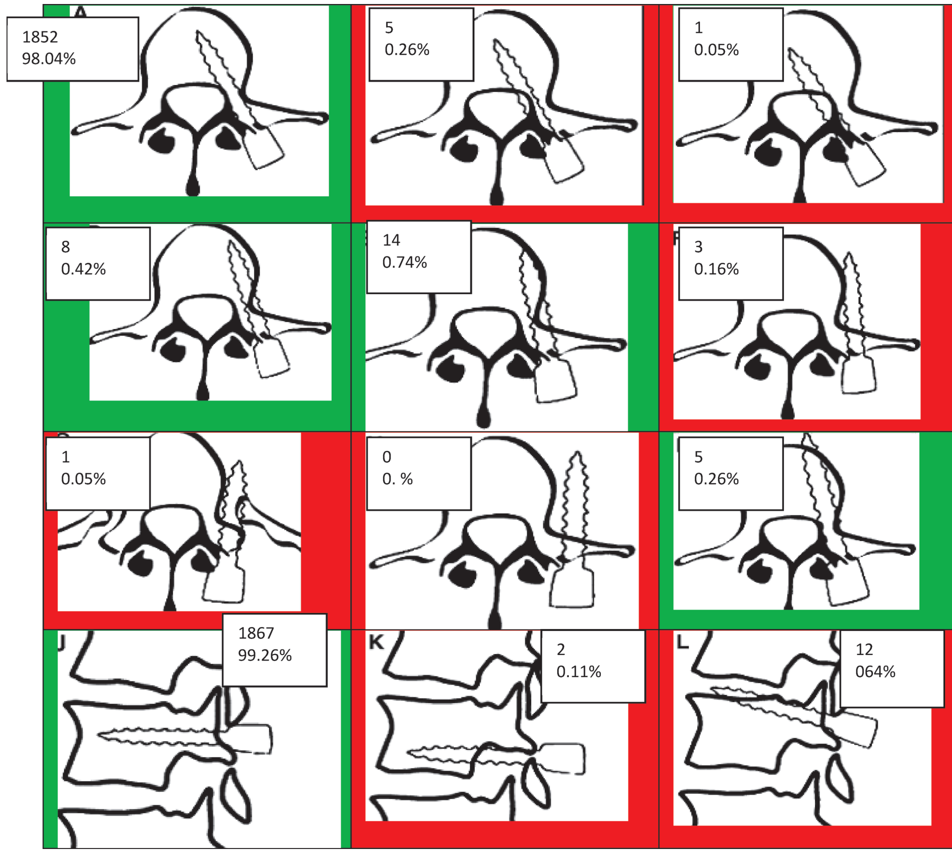

Figure 4. Types of screw placement according to the grading system. Placement in red boxes is classified as unacceptable. Placement in the green boxes is classified as acceptable. The figure indicates the number of screws and the percentage that have that type of placement.

12.0% of the screws proved to be misplaced and 10.2% of the screws needed to be revised.

Table 5 shows the total intraoperative radiation doses received by the patient during the entire procedure as reported by the O-arm dose report. The mean radiation dose was 10.6 ± 14.0 mGy or 1329.4 mGy cm^2 dose area product in 2-dimensional mode and 203.1 ± 279.3 mAs or 520.6 mGy cm dose length product in 3D mode. The radiation doses measured increased with increasing body weight. Furthermore, the total radiation dose was significantly higher when the procedure took place over more than 5 vertebrae (data not shown), because the O-arm shows only 5 consecutive vertebrae (in the lumbar region) at a time.

DISCUSSION

In this international, multicenter, prospective, postmarketing clinical registry, the placement of 1922 pedicle screws in 353 patients was intraoperatively evaluated by O-arm 3D scanning. According to our definition of "misplacement," this event occurred in only 2.5% of the screws, and only 1.8% of the screws needed to be revised intraoperatively, because we only revised the screws with cortical violation exceeding half the diameter of the screw and all screws with medial cortical perforation, FP, and EP. After these screw revisions, no patient left the operating room with unacceptable screw placement. As such in this study and based on intraoperative 3D imaging, pedicle screw placement was considered as acceptable for 100% of the screws. The percentage of screws that needed revision was also compared with the surgeon's confidence in the screw placement. Only 1% of the screws needed revision when the surgeon was confident in the screw placement, whereas, when the surgeon doubted the correct screw placement, 10.2% of the screws needed revision. The total radiation dose a patient received during 1 O-arm 3D scan was approximately half of the radiation dose of a 64 multislice CT scanner of the same body region.[18]

The results of this registry, in which pedicle screws were placed under computer-assisted guidance using the O-arm, indicate that we achieved a higher degree of accuracy for pedicle screw placement than the results described in the literature reporting the use of other tools for the same purpose.[12–14] In our study, 98.2% of the pedicle screws were accurately placed at thoracic, lumbar, or sacral level. This is similar to earlier findings deduced from smaller retrospective studies.[11–13,19–21] In a relatively small series of 40 pedicle screws, the misplacement rate was 7.5%, with 1 lateral and 2 medial cortical breaches. All breaches were graded 0 to 2 mm and were asymptomatic.[14] One study comparing the accuracy of freehand and O-arm–guided pedicle screw placement reached, respectively, 94.1% and 99% accuracy, but the definition of screw "misplacement" was rather vague.[22] The use of the combination of O-arm and intraoperative navigation provided better results than the use of a navigation based on preoperative scans.[5]

Although this study confirms the low rate of screw misplacement,[12] we suggest that a prospective randomized study

TABLE 1. Demographics

Sex	
Male	154 (44.6%)
Female	191 (55.4%)
Missing	8
Age (yr)	58.4 ± 15.0*
Height (cm)	171.1 ± 9.6*
Weight (kg)	78.3 ± 14.4*
Weight categories	
<60 kg	28 (8.1%)
≥60 kg and <80 kg	138 (40.0%)
≥80 kg	179 (51.9%)
Missing	8
Symptom duration (mo)	16.0 ± 27.4*
Surgery indication†	
Degenerative disc disease	126 (35.8%)
Degenerative spondylolisthesis	122 (34.7%)
Trauma	27 (7.7%)
Spondylolytic listhesis	26 (7.4%)
Degenerative scoliosis	21 (6.0%)
Tumor	9 (2.6%)
Other	27 (7.7%)
Missing	1

The percentages are based on the total number of patients with nonmissing information.

**Mean ± standard deviation.*

†Multiple answers were possible. Therefore, the percentages do not add up to 100.

TABLE 2. Surgery Details

Surgery Type	
Open	333 (94.3%)
MAST	11 (3.1%)
Percutaneous	11 (3.1%)
Missing	0
Surgery duration (hr)	1.8 ± 0.7*
Blood loss (mL)	138.4 ± 174.7*
Complications	
None	339 (97.7%)
Yes	8 (2.3%)
Missing	6
O-arm failure	
None	335 (94.9%)
Navigation	4 (1.1%)
2D or 3D mode	13 (3.7%)
Both navigation and 2D or 3D mode	1 (0.3%)
Missing	0

The percentages are based on the total number of patients with nonmissing information.

**Mean ± standard deviation.*

MAST indicates minimal access spinal techniques; 2D, 2-dimensional; 3D, 3-dimensional.

comparing the accuracy of pedicle screw placement with the freehand technique, fluoroscopy, or O-arm with Stealth Station Navigation would be more conclusive about the accuracy of the different techniques. Because of the low number of percutaneous or MAST surgeries included in this study, statistical analysis is not representative. Because probing the pedicle is more difficult due to lack of appropriate tactile and visual feedback in MAST methods, it would be interesting to evaluate this technique in a larger series of MAST procedures.

Regardless of the improved precision of scan and navigation system, there are still 2.5% of the screws that are not optimally placed. There are several explanations for these findings. First, there seems to be a difference in angulation between the virtual and the intraoperative images. Oertel *et al*[12] found a difference of 2.8° ± 1.9° between the virtual and the intraoperative pedicle screws, probably due to improper fixation of the tools to the implants. Another reason may be the inadequate fixation of the frame to the spinous process or the iliac crest, which results in minimal frame dislocation.

A second possible drawback when relying on intraoperative 3D scanning was recently suggested by Santos *et al*[15] in this same journal. In a cadaver study, they found a difference between the CT scan and the dissected observation. Moreover, probing of the screw trajectory with a non-navigated ball tip probe provided even more accuracy on the correct screw positioning than intraoperative CT scan.[16] As in clinical practice dissection of the spine to confirm adequate screw positioning is not possible, today, CT scanning can be considered the "gold standard" for the evaluation of screw positioning. The second finding of the study by Santos *et al* is the high level of correlation between the surgeon's feeling about correct screw positioning and the dissection findings.

In our study, the surgeon's perception of the correct screw placement was also judged by probing the screw trajectory. We found that if the surgeon was confident of correct screw placement, the risk of having a misplaced screw was only 1%. The results of the study by Santos *et al*[16] and our own findings suggest that an additional scan before wound closure, especially when the surgeon is confident of correct screw placement is not necessary. As such, we should be able to reduce the extra radiation exposure for the patient as well as the staff. The possibility to obtain an additional CT scan in case of any doubt is, however, of important value when doing this type of surgery.

TABLE 3. Implant Details

Implant Type per Patient	
Legacy	148 (44.6%)
Horizon peek	38 (11.5%)
Sextant	12 (3.6%)
Longitude	3 (0.9%)
Tenor	3 (0.9%)
Other	128 (38.6%)
Missing	21
Number of screws placed per patient	
1	0 (0.0%)
2	9 (2.7%)
3	1 (0.3%)
4	167 (49.7%)
5	1 (0.3%)
6	98 (29.2%)
>6	60 (17.9%)
Missing	17
Confidence in screw placement	
Confident in screw placement, but 3D check	313 (91.3%)
Not sure about correct position of at least 1 screw; 3D check	29 (8.5%)
No 3D check	1 (0.3%)
Missing	10

The percentages are based on the total number of patients with nonmissing information.

3D indicates 3-dimensional.

TABLE 4. Screw Positioning

Screw placement	
Correct placement	1834 (97.5%)
Misplacement	47 (2.5%)
In need of revision	34 (72.3%/1.8%)*
Missing	41
Total	1922
Perforation class	
Horizontal	
Medial cortical perforation	6 (16.2%)†
Lateral cortical perforation	26 (70.3%)†
Anterior cortical perforation	5 (13.5%)†
Vertical	
Endplate perforation	12 (85.7%)‡
Foraminal perforation	2 (14.3%)‡
Comparison between confidence in screw placement and actual screw placement	
Confident in placement of all screws	
Number of correctly placed screws	1642 (98.5%)§
Number of misplaced screws	25 (1.5%)§
Number of screws that needed revision	16 (1.0%)§
Missing	39
Total	1706
Not confident in placement of at least 1 screw	
Number of correctly placed screws	146 (88.0%)¶
Number of misplaced screws	20 (12.0%)¶
Number of screws that needed revision	17 (10.2%)¶
Missing	2
Total	168

The percentages are based on the total number of screws with nonmissing evaluation of screw placement.

**The percentages are based on the total number of misplaced screws/ percentage based on total number of screws with nonmissing evaluation of screw placement.*

†The percentages are based on the total number of misplaced screws with nonmissing information on horizontal perforation class.

‡The percentages are based on the total number of misplaced screws with nonmissing information on vertical perforation class.

§The percentages are based on the total number of screws with nonmissing assessment on placement in patients where the surgeon was confident in the screw placement.

¶The percentages are based on the total number of screws with nonmissing assessment on placement in patients where the surgeon was not confident in the screw placement.

The use of medical imaging techniques in general and intraoperative CT scan in particular always tries to balance the potential benefit for the patient with the additional radiation exposure.

Abul-Kasim *et al*[23] used a phantom chest and a cadaveric pig spine to assess the accuracy of the images obtained with 5 different scan parameters when using the O-arm.

The images were judged by 2 independent observers. The authors concluded that the radiation doses of the O-arm system could be reduced 5 to 13 times without negative impact on image quality with regard to information required for spinal surgery.[23] However, for our daily practice, we think a better image quality than the one judged as acceptable by the authors is needed to allow a reliable interpretation of the screw placement. During the last O-arm user meeting (Copenhagen, June 16–17, 2011), the plenum concluded that images obtained with 50% to 75% dose reduction were still suitable to judge outcome.

A dosimetry study revealed that during a 3D scan acquisition the radiation dose for the patient is approximately half of the radiation dose of a 64 multislice scanner.[18] These data are

TABLE 5. Irradiation Dose

Weight Class	Mode and Unit			
	2D Mode (mGy)	2D Mode (DAP)	3D Mode (mAs)	3D Mode (DLP)
<60 kg	12.4 ± 14.0	834.8 ± 1121.2	139.9 ± 221.4	379.6 ± 252.0
≥60 kg and <80 kg	9.4 ± 9.9	1236.8 ± 1525.4	205.2 ± 276.2	503.5 ± 336.9
≥80 kg	11.4 ± 16.7	1489.6 ± 1747.3	203.5 ± 290.0	548.4 ± 346.2
Total	10.6 ± 14.0	1329.4 ± 1612.5	203.1 ± 279.3	520.6 ± 334.9

The percentages are based on the total number of patients with nonmissing information.

2D indicates 2-dimensional; DAP, dose area product; 3D, 3-dimensional; DLP, dose length product.

confirmed in our study. However, the scattered dose and thus the exposure for the personnel seem comparable with that of the 64 multislice CT scanner for the same body region.[18] Also, Park *et al*[24] reports a better protection of the operators. In our setting, only 1 person stays in the operating theatre; as recommended as best practices by Medtronic, all the others leave the room.

We therefore recommend that the O-arm needs some further upgrades. First of all, all attempts should be done to reduce the radiation dose while providing optimal image quality. Furthermore, the 5.1% of O-arm failure during the procedure should be reduced in the near future. During the progress of the study, we noticed a decreasing trend of O-arm failures, which we interpret as a combination of the increasing experience in the use of the equipment and of the result of a number of equipment upgrades by the supplier. During the complete study, there was only one case of complete O-arm breakdown.

CONCLUSION

The use of intraoperative CT scan (O-arm) and a computerized navigation system has proven to be a useful tool to improve the accuracy of pedicle screw placement. The surgeon's perception of a correct pedicle screw trajectory may justify not obtaining an additional intraoperative CT scan. Optimization of the scan settings should further reduce the radiation exposure in the future.

➢ Key Points

- ❑ The use of the O-arm combined with the StealthStation Navigation, when compared with other imaging techniques and neurophysiological methods, increases the accuracy of pedicle screw placement, as assessed by an intraoperative 3D scan before wound closure.
- ❑ The surgeon's perception of accurate pedicle screw placement by blunt probing of the created canal proves to be very reliable.
- ❑ The ability to obtain an intraoperative 3D scan, in case of doubt of correct pedicle screw placement, allows revision before wound closure.

Acknowledgments

The authors thank Horace Hale for his critical reading and Nicole Van den Hecke for the administrative support.

References

1. Castro WH, Halm H, Jerosch J, et al. Accuracy of pedicle screw placement in lumbar vertebrae. *Spine (Phila Pa 1976)* 1996;21:1320–4.
2. Holly LT, Foley KT. Image guidance in spine surgery. *Orthop Clin North Am* 2007;38:451–61; abstract viii.
3. Holly LT, Foley KT. Percutaneous placement of posterior cervical screws using three-dimensional fluoroscopy. *Spine (Phila Pa 1976)* 2006;31:536–40; discussion 41.
4. Kosmopoulos V, Schizas C. Pedicle screw placement accuracy: a meta-analysis. *Spine (Phila Pa 1976)* 2007;32:E111–20.
5. Costa F, Cardia A, Ortolina A, et al. Spinal navigation: standard preoperative versus intraoperative computed tomography data set acquisition for computer-guidance system: radiological and clinical study in 100 consecutive patients. *Spine (Phila Pa 1976)* 2011;36:2094–8.
6. Schils F. O-arm guided balloon kyphoplasty: preliminary experience of 16 consecutive patients. *Acta Neurochir Suppl* 2011;109:175–8.
7. Schils F. O-arm-guided balloon kyphoplasty: prospective single-center case series of 54 consecutive patients. *Neurosurgery* 2011;68:250–6; discussion 6.
8. Alemo S, Sayadipour A. Role of intraoperative neurophysiologic monitoring in lumbosacral spine fusion and instrumentation: a retrospective study. *World Neurosurg* 2010;73:72–6; discussion e7.
9. Tian NF, Xu HZ. Image-guided pedicle screw insertion accuracy: a meta-analysis. *Int Orthop* 2009;33:895–903.
10. Laine T, Schlenzka D, Makitalo K, et al. Improved accuracy of pedicle screw insertion with computer-assisted surgery. A prospective clinical trial of 30 patients. *Spine (Phila Pa 1976)* 1997;22:1254–8.
11. Merloz P, Tonetti J, Pittet L, et al. Pedicle screw placement using image guided techniques. *Clin Orthop Relat Res* 1998;354:39–48.
12. Oertel MF, Hobart J, Stein M, et al. Clinical and methodological precision of spinal navigation assisted by 3D intraoperative O-arm radiographic imaging. *J Neurosurg Spine* 2011;14:532–6.
13. Larson AN, Santos ER, Polly DW Jr, et al. Pediatric pedicle screw placement using intraoperative CT and 3D image-guided navigation. *Spine (Phila Pa 1976)* 2012;37:E188–94.
14. Park P, Foley KT, Cowan JA, et al. Minimally invasive pedicle screw fixation utilizing O-arm fluoroscopy with computer-assisted navigation: feasibility, technique, and preliminary results. *Surg Neurol Int* 2010;1:44.
15. Santos ER, Ledonio CG, Castro CA, et al. The accuracy of intraoperative O-arm images for the assessment of pedicle screw position. *Spine (Phila Pa 1976)* 2012;37:E119–25.
16. Santos ER, Ledonio CG, Castro CA, et al. Validity of surgeon perception of navigated pedicle screw position: a cadaveric study. *Spine (Phila Pa 1976)* 2011;36:E1027–32.

17. Abul-Kasim K, Ohlin A, Strombeck A, et al. Radiological and clinical outcome of screw placement in adolescent idiopathic scoliosis: evaluation with low-dose computed tomography. *Eur Spine J* 2010;19:96–104.
18. Zhang J, Weir V, Fajardo L, et al. Dosimetric characterization of a cone-beam O-arm imaging system. *J Xray Sci Technol* 2009;17:305–17.
19. Foley KT, Smith MM. Image-guided spine surgery. *Neurosurg Clin N Am* 1996;7:171–86.
20. Schwarzenbach O, Berlemann U, Jost B, et al. Accuracy of computer-assisted pedicle screw placement. An in vivo computed tomography analysis. *Spine (Phila Pa 1976)* 1997;22:452–8.
21. Amiot LP, Lang K, Putzier M, et al. Comparative results between conventional and computer-assisted pedicle screw installation in the thoracic, lumbar, and sacral spine. *Spine (Phila Pa 1976)* 2000;25:606–14.
22. Silbermann J, Riese F, Allam Y, et al. Computer tomography assessment of pedicle screw placement in lumbar and sacral spine: comparison between free-hand and O-arm based navigation techniques. *Eur Spine J* 2011;20:875–81.
23. Abul-Kasim K, Soderberg M, Selariu E, et al. Optimization of radiation exposure and image quality of the cone-beam O-arm intraoperative imaging system in spinal surgery. *J Spinal Disord Tech* 2012;25:52-8.
24. Park MS, Lee KM, Lee B, et al. Comparison of operator radiation exposure between C-arm and O-arm fluoroscopy for orthopaedic surgery [published online ahead of print April 26, 2011]. *Radiat Prot Dosimetry* 2012;148:431–8.