



Safety and accuracy of spinal instrumentation surgery in a hybrid operating room with an intraoperative cone-beam computed tomography

Christian A. Bohoun¹ · Kentaro Naito¹ · Toru Yamagata^{1,2} · Samantha Tamrakar¹ · Kenji Ohata¹ · Toshihiro Takami¹ 

Received: 5 February 2018 / Revised: 20 March 2018 / Accepted: 28 March 2018 / Published online: 16 April 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Although spinal instrumentation technique has undergone revolutionary progress over the past few decades, it may still carry significant surgery-related risks. The purpose of the present study was to assess the radiological accuracy of spinal screw instrumentation using a hybrid operating room (OR) and quantify the related radiation exposure. This retrospective study included 33 cases of complex spine fusion surgeries that were conducted using a hybrid OR with a flat panel detector (FPD) angiography system. Twelve cases (36.4%) were cervical, and 21 (63.6%) were thoracolumbar. The average number of spine fusion levels was 3 and 4.8, respectively, at the cervical and thoracolumbar spine levels. A FPD angiography system was used for intraoperative cone-beam computed tomography (CBCT) to obtain multi-slice spine images. All operations were conducted under optimized radiation shielding. Entrance surface doses (ESDs) and exposure times were recorded in all cases. A total of 313 screws were placed. Satisfactory screw insertion could be achieved in all cases with safe screw placement in 97.4% and acceptable placement in 2.6%. None of the cases showed any significant anatomical violation by the screws. The radiation exposure to the patients was absolutely consistent with the desired ESD value, and that to the surgeons, under the annual dose limit. These results suggest that the hybrid OR with a FPD angiography system is helpful to achieve safe and precise spinal fusion surgery, especially in complex cases.

Keywords Cone-beam CT · Hybrid operating room · Radiation exposure · Spinal instrumentation · Surgical safety

✉ Toshihiro Takami
ttakami@med.osaka-cu.ac.jp

Christian A. Bohoun
chbohoun@gmail.com

Kentaro Naito
7110ken622@med.osaka-cu.ac.jp

Toru Yamagata
punchdrunkard830@yahoo.co.jp

Samantha Tamrakar
tamrakar.samantha@gmail.com

Kenji Ohata
kohata@med.osaka-cu.ac.jp

¹ Department of Neurosurgery, Osaka City University Graduate School of Medicine, 1-4-3 Asahi-machi, Abeno-ku, Osaka 545-8585, Japan

² Department of Neurosurgery, Osaka City General Hospital, 2-13-22 Miyakojima-hondori, Miyakojima-ku, Osaka 531-0021, Japan

Introduction

Spinal instrumentation technique has undergone revolutionary progress over the past few decades. This progress has significantly changed the surgical strategy for spine disease, for not only spinal trauma but also congenital diseases, cancer, infection, and aging degeneration. Hospitalization time has been reduced, patients are mobilized more rapidly, and the overall surgical outcome has improved. On the other hand, spinal instrumentation such as pedicle screws may carry a risk of neural or vascular injury [1, 2, 4, 13]. To avoid such surgery-related complications, intraoperative image guidance using fluoroscopy or CT-based computer navigation was developed. However, technical pitfalls and the means to avoid them need to be carefully considered [31]. More recently, a 3D-CT-based navigation system using intraoperative cone-beam computed tomography (CBCT) with a flat panel detector angiography module, also referred to as hybrid operating room (OR), has been actively developed to achieve more accurate and safe surgery [23]. Meanwhile, the associated

radiation exposure to the patients and surgeons remains a major concern. The purpose of the present study was to assess the radiological accuracy of spinal screw instrumentation using a hybrid OR system and quantify the related radiation exposure. The benefits and possible disadvantages of the hybrid OR system for spinal instrumentation surgery are discussed with a literature review.

Methods

Patients

This retrospective study included a total of 33 (23.2%) of 142 spine fusion surgeries in the study period from April 2014 to May 2017. The indication for use of hybrid OR with intraoperative CBCT imaging was carefully determined based on the complexity of the cases. So were indicated, cases of revision, multi-spine fusion, infectious, multi-trauma, and spinal deformity surgeries, while ordinary cases such as short fusion surgeries were usually completed using the conventional C-arm fluoroscopy. The patients included 22 men and 11 women, and their mean age at surgery was 62.8 years (range, 20–86 years). Twelve cases (36.4%) were cervical, and 21 (63.6%) were thoracolumbar. The average number of spine fusion levels was 3 and 4.8, respectively, at the cervical and thoracolumbar spine levels. Patients' characteristics are summarized in Table 1.

Hybrid OR system

Spinal instrumentation, such as the cervical pedicle screw (CPS), cervical lateral mass screw (CLMS), cervical translamina screw (CTL), thoracolumbar pedicle screw (TLPS), or lumbar cortical bone trajectory screw (LCBTS), was achieved using a fluoroscopy image guidance system. The initial insertion (screw or Kirschner wire) was conducted with free hands or assistance of a preoperative CT-based navigation module (Stealth Station, Medtronic, Inc., Memphis, TN, USA). A flat panel detector (FPD) angiography system AlluraClarity FD20 (Philips, Amsterdam, The Netherlands) was combined with a carbon-fiber operating table (Maquet, Germany) and used for intraoperative CBCT to obtain multi-slice spine images in the hybrid OR (Fig. 1). The size of the FPD was maximally 19 in, with a pulsed fluoroscopy rate of 7.5 p/s. The digital subtraction angiography frame rate was 30 f/s. Multi-slice spine images were then acquired immediately after the placement of spine instrumentation screws or temporary Kirschner wires to confirm their satisfactory and safe positioning, or the need of repositioning. After the placement of all instrumentation screws, local

Table 1 Patients' characteristics

Characteristic	No. (range)
Total no. of patients	33
Sex (male/female)	22/11
Mean age at surgery (years)	62.8 (20–86)
Average no. of spine fusion levels	
Cervical spine	3
Thoracolumbar spine	4.8
Preoperative diagnosis	
Cervical spine	
OPLL	5
Aging degeneration	2
Trauma	5
Infection	0
Thoracolumbar spine	
OPLL	0
Aging degeneration	14
Trauma	3
Infection	4

decompression, bilateral facet release, or interbody fusion was carried out if necessary. The rods, bent earlier according to the preoperative plan, were then applied to the screws and fully tightened. Bone grafting from local bone and beta tricalcium phosphate application were done to ensure adequate fusion.

Measurement of radiation exposure

All operations were conducted under optimized radiation shielding in the hybrid OR system. Entrance surface doses (ESDs) and exposure times were recorded in all cases in milliGray (mGy) and seconds, respectively, by radiological technicians. ESD can be measured at the center of the entrance surface in the X-ray beam field, and it includes backscattered radiation from the patient [20, 45]. In 23 cases, pocket radiation dosimeters (Hitachi, Tokyo, Japan) were placed inside and outside the protective suit of the principal surgeon to evaluate the radiation exposure to the surgeon during the surgery. Exposures are reported in microSievert (μ Sv).

Postoperative assessment of radiological accuracy of screw placement

The radiological accuracy of spinal instrumentation screws was evaluated based on the postoperative CT scans and defined retrospectively using our proposed grading scale (Table 2). Screw positions were classified into three grades based on the potential risk of neural or vascular injury: grade



Fig. 1 A flat panel detector angiography system. The flat panel detector is combined with a carbon-fiber operation table and used for intraoperative cone-beam computed tomography (CBCT) in the hybrid OR system. **a** A

flat panel detector angiography system is introduced after covering the operative site with sterile sheets. **b, c** Multi-slice spine images are obtained in a smooth and quick motion

0, safe placement; grade 1, minor cortical perforation without any possible clinical risks; and grade 2, major perforation associated with possible risks.

Statistical analysis

All data are expressed as means \pm standard deviation. Statistical analysis of correlations between two variables was performed using the Pearson correlation coefficient. JMP version 9.0 software (SAS Institute, Cary, NC) was used for all statistical analyses in the present study. Values of $p < 0.05$ were considered significant.

Results

A total of 313 screws were placed in 33 cases to stabilize the spine using the hybrid OR system during the study period. The intraoperative fluoroscopic images obtained using a FPD angiography system were of great quality, wide and long enough to cover even cases of long spine fusions (Figs. 2 and 3). The intraoperative axial reconstruction images acquired from the CBCT were comparable in terms of quality to postoperative CT images (Fig. 4). The radiological accuracy of the screws was grade 0 in 97.4% (305 of the 313 screws) (Fig. 5a–c), grade 1 in 2.6% (8 of the 313 screws) (Fig. 4d–f), and grade 2 in 0%. No neural or vascular complications closely associated with screw placement were encountered in the present study. A total of 8 of the 313 screws were found to perforate the bone cortex, classified as grade 1 radiological accuracy. Four cervical LMS or TLS were found to outstrip by less than 2 mm, 1 thoracolumbar PS outstripped by less than 5 mm, and 3 lumbar CBTS were protruding by less than 10 mm. Fortunately, no screw of grade 2 was found in the present study. The radiological accuracy of screw placement is summarized in Table 3.

Radiation exposure

The radiation ESD of cervical spine cases ranged from 6.38 to 30.62 mGy, with an average of 14.11 mGy, and that of the thoracolumbar spine cases ranged from 27.15 to 381.32 mGy, with an average of 113.01 mGy. The average fluoroscopy time per surgery including CBCT was 90.3 s (22.2–277.2 s) for the cervical spine cases and 210.9 s (43.0–508.8 s) for the thoracolumbar spine cases. Radiation exposures outside the surgeon's protective suit in cervical spine cases ranged from 1.0 to 15.0 μ Sv, with an average of 4.8 μ Sv, and from 0 to 3.0 μ Sv inside the protective suit, with an average of 0.25 μ Sv. These values in the thoracolumbar spine cases ranged from 7.0 to 146.0 μ Sv outside the protective suit, with an average of 54.1 μ Sv, and from 0 to 18.0 μ Sv, with an average of 5.7 μ Sv, inside the surgeon's protective suit. The radiation exposure data for the patients and surgeon are summarized in Table 4. A linear regression and correlation analysis of collected data showed no significant correlation between the number of spine fusion levels and the recorded exposure time, but there was a noteworthy correlation between exposure time and ESD ($p = 0.00005$; $r = 0.64602$), as well as between the exposure time and doses recorded outside ($p = 0.00003$; $r = 0.75411$) and inside ($p = 0.00003$; $r = 0.75689$) the surgeon's protective suit (Fig. 6).

Discussion

The latest technological advances for safe surgery

This study aimed to evaluate the benefits and possible disadvantages of a hybrid OR system, for spinal instrumentation surgery, in the context of the progressing intraoperative imaging technology. Its first benefit may be the fact that surgeons can avoid the high risk of instrumentation-related neural or

Table 2 Grading scale of the radiological accuracy of screw placement

Grade	Definition
0 Safe placement	Cervical pedicle screw Fully contained in the pedicle, no cortical perforation Cervical lateral mass or translaminar screw No cortical perforation Thoracolumbar pedicle screw Fully contained in the pedicle, no cortical perforation Lumbar cortical bone trajectory screw Lateral perforation (< 5 mm)
1 Minor perforation (clinically safe)	Cervical pedicle screw Lateral or medial perforation (< 2 mm) Cervical lateral mass or translaminar screw Lateral or medial perforation (< 2 mm) Thoracolumbar pedicle screw Lateral or ventral perforation (< 5 mm) Lumbar cortical bone trajectory screw Lateral perforation (< 10 mm)
2 Major perforation	Cervical pedicle screw Lateral or medial perforation (> 2 mm), Cervical lateral mass or translaminar screw Lateral or medial perforation (> 2 mm) Thoracolumbar pedicle screw Lateral or ventral perforation (> 5 mm) Lumbar cortical bone trajectory screw Lateral perforation (> 10 mm) or medial perforation

vascular injury, using a combination of intraoperative wide fluoroscopy, CBCT, and eventually navigation. Spinal instrumentation surgery has become essential to manage spinal pathologies related to aging degeneration, trauma, inflammation, and infection. However, factors like the individual anatomical variations, surgeon's experience, or material specifications

may expose patients to risks of screw misplacement and their potentially associated complications [1, 2, 4, 13]. To avoid these, various protocols such as rational use, as in the present study, of pulsed fluoroscopy combined with intraoperative CBCT may help accurately reach the initially planned goals while minimizing the risks. Furthermore, the addition of

Fig. 2 Illustrative case of degenerative cervical kyphosis that was operated in the hybrid OR system. **a** Preoperative plain radiograph, **b** Intraoperative fluoroscopic image, **c** Postoperative plain radiograph

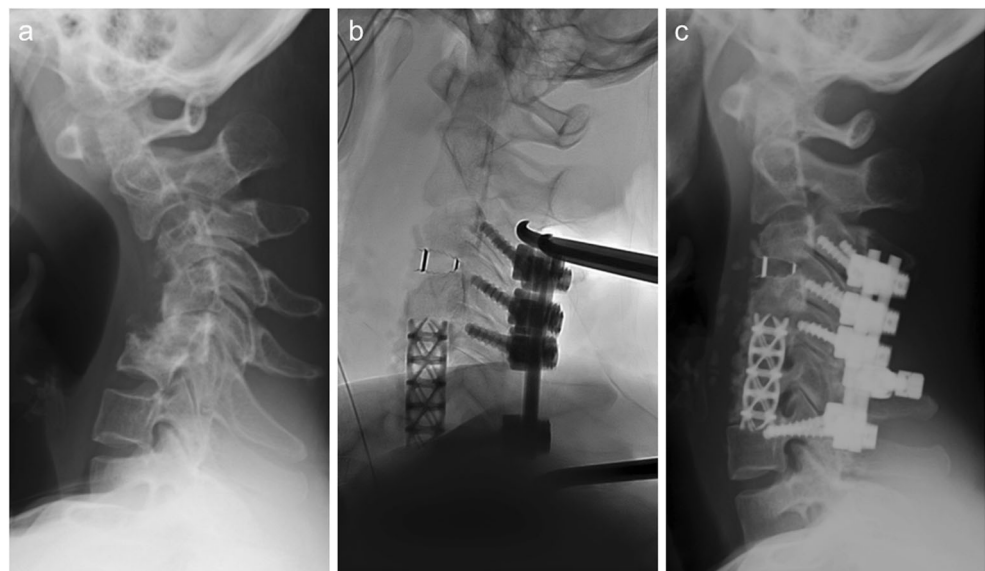
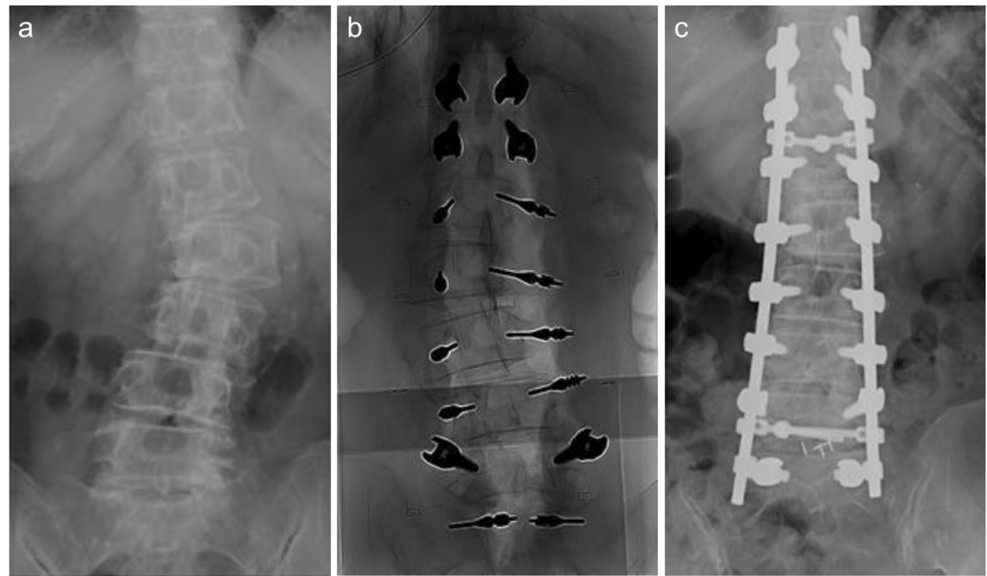


Fig. 3 Illustrative case of degenerative lumbar scoliosis that was operated in the hybrid OR system. **a** Preoperative plain radiograph. **b** Intraoperative fluoroscopic image. **c** Postoperative plain radiograph

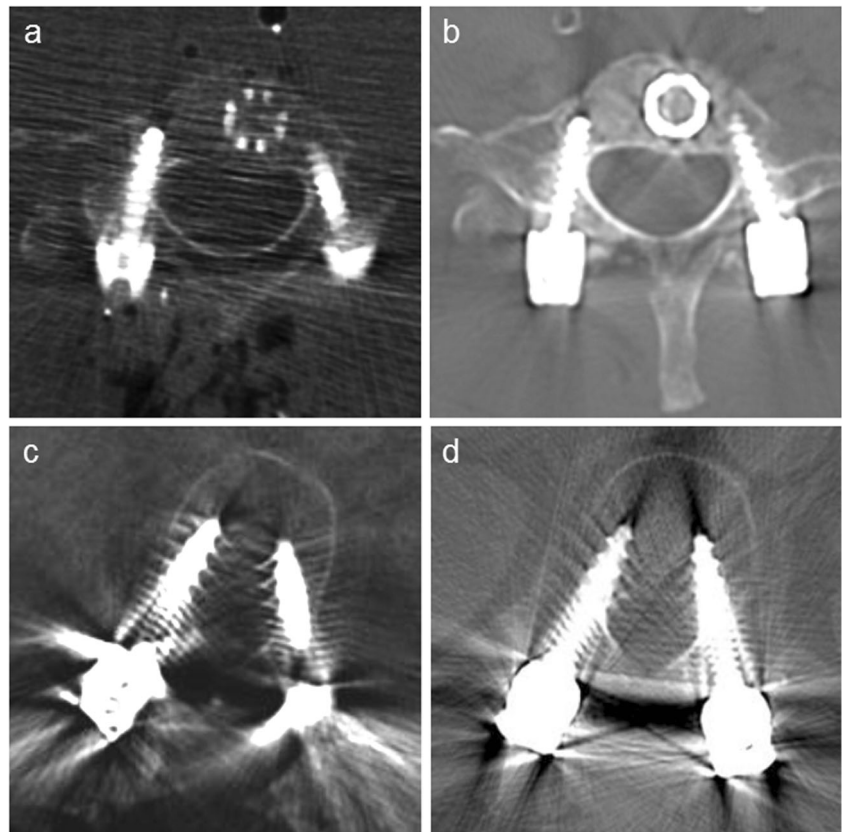


navigation reduces the need of extensive radiation exposure while providing extra precision [5, 44].

The latest technological advances in imaging systems, such as 3D navigation, intraoperative O-arm, or the hybrid OR system presented here, have brought the possibility of instant visualization of anatomical structures and guidance support during surgery [8, 23, 25]. Among these options, some modalities demonstrated better surgical precision than others

[35–37]. Though, the achieved accuracy taken alone could not suffice to determine the efficiency and must be weighed against the radiation exposure that accompanies it. From recent publications focusing on the surgical safety, it has emerged that spinal navigation was quite helpful for surgeons to place screws accurately, with higher success rates than the free-hand technique or standard fluoroscopy-guided surgery [6, 16, 22, 35]. Intraoperative CBCT offers helpful and reliable

Fig. 4 Comparison of axial reconstruction images. **a, c** Images obtained by using intraoperative CBCT. **b, d** Postoperative CT images



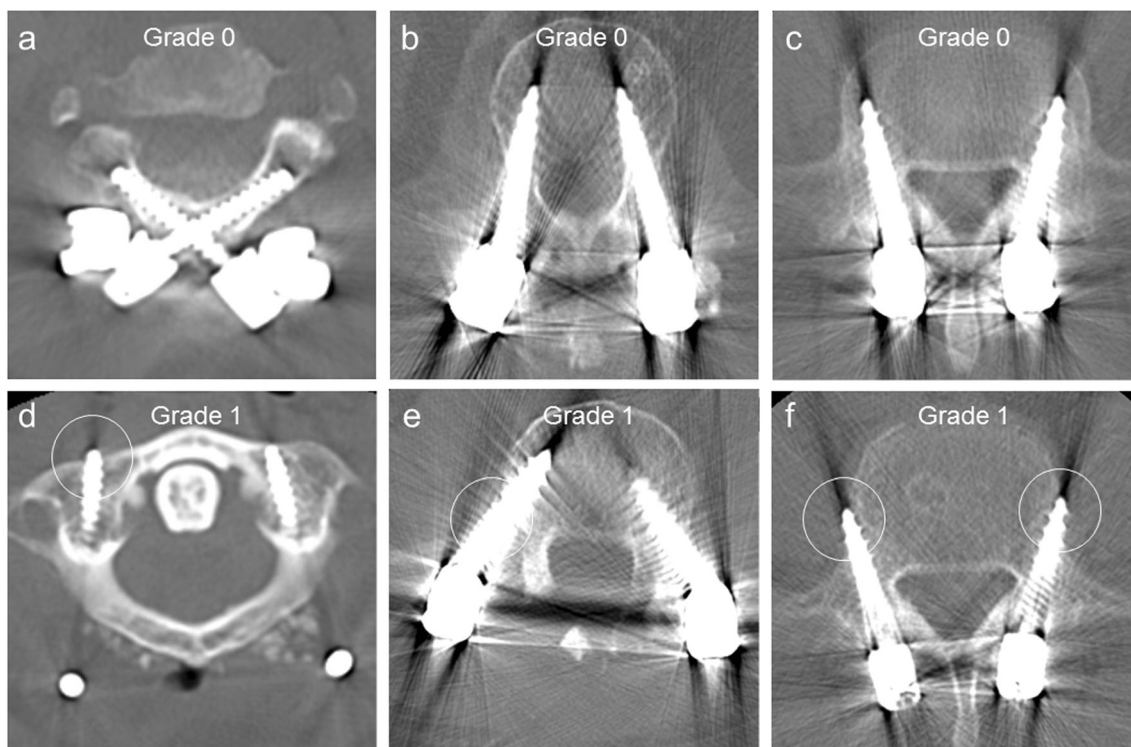


Fig. 5 Postoperative CT axial images. **a** C2 translaminar screws of grade 0. **b** lumbar pedicle screw of grade 0. **c** Lumbar cortical bone trajectory screw of grade 0. **d** C1 lateral mass screw of grade 1. **e** Lumbar pedicle screw of grade 1. **f** Lumbar cortical bone trajectory screw of grade 1

instant CT-like images of better clarity than those of conventional fluoroscopy, with reportedly the highest accuracy at all spinal levels, where used [19]. These images, once processed, also deliver high-quality 3D representations that are suitable for navigation during spinal surgery and indirectly help in reducing the overall radiation dose [33, 41].

No doubt remaining about the interest of navigation, two major types of CBCT systems are being actively used now for various spinal surgeries: the hybrid OR in this series and the

O-arm system. The accuracy for spinal screw placement in the present study was comparable to that obtained using the O-arm system (Table 5). Satisfactory screw insertion could be achieved in all our cases (100%), with safe screw placement (grade 0) in 97.4% and acceptable ones (grade 1) in 2.6%. None of the present cases showed any significant anatomical violation by the screws exposing the patient to neural, vascular, or any visceral injury. Our hybrid OR system modality of

Table 3 Radiological accuracy of screw placement

Grade	Type of screw	No.	Total no.	Percent
0	Cervical PS	77	305	97.4%
	Cervical LMS or TLS	62		
	Thoracolumbar PS	107		
	Lumbar CBTS	59		
1	Cervical PS	0	8	2.6%
	Cervical LMS or TLS	4		
	Thoracolumbar PS	1		
	Lumbar CBTS	3		
2	Cervical PS	0	0	0%
	Cervical LMS or TLS	0		
	Thoracolumbar PS	0		
	Lumbar CBTS	0		
			313	100%

Table 4 Radiation exposure

Patient	ESD (mGy)		Exposure time (s)	
	Average	Range	Average	Range
Cervical	14.11	6.38–30.62	90.3	22.2–277.2
Thoracolumbar	113.01	27.15–381.32	210.9	43.0–508.8
Desired ESD value ^a	<2000			
Surgeon	Outside protector (μSv)		Inside protector (μSv)	
	Average	Range	Average	Range
Cervical	4.8	1.0–15.0	0.25	0–3.0
Thoracolumbar	54.1	7.0–146.0	5.7	0–18.0
Limit dose ^b	<20,000/year			

^a The Japan Association of Radiological Technologists

^b International Commission Radiological Protection

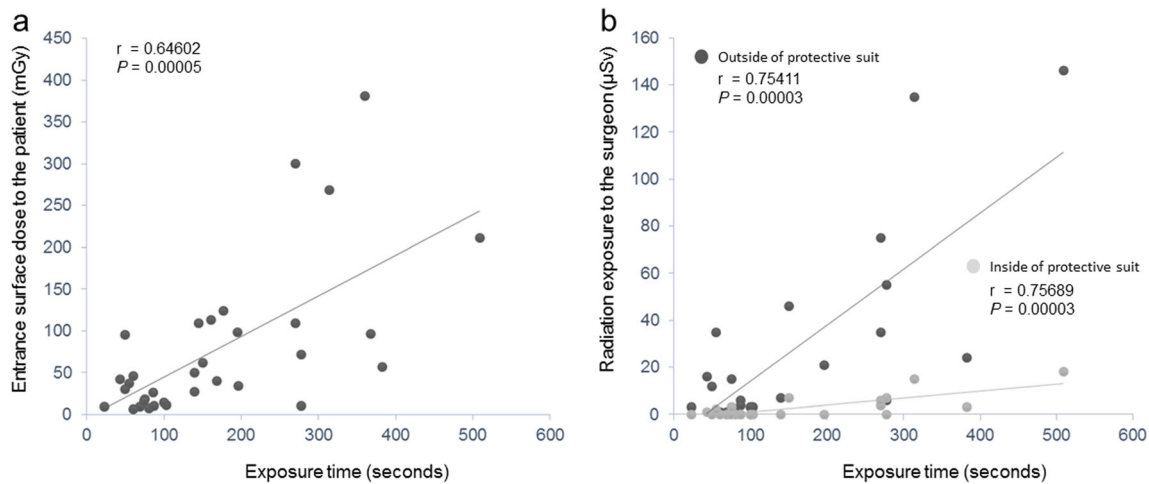


Fig. 6 Scatter plots with regression lines for correlation analysis. **a** Between the entrance surface dose (ESD) to the patient and exposure time and between **b** the radiation exposure to the surgeon and exposure time

intraoperative wide fluoroscopy and main usage of CBCT images allowed us to confirm the correct position of spinal instrumentation and to reposition any unsatisfactorily inserted screw. In addition to the comparable achievement capabilities to the O-arm, our hybrid OR CBCT can offer a great flexibility and provide wider 3D images than the O-arm system, making it a valuable tool for multilevel spinal fusion surgery.

Intraoperative radiation exposure

While the use of intraoperative CBCT has become popular and no doubt remains about its efficacy, concern about the intraoperative radiation exposure to surgeons and patients remains. A previous comparative clinical study demonstrated that the use of intraoperative CBCT resulted in higher radiation exposure than standard fluoroscopy during standard posterior fusion surgery for idiopathic scoliosis, whereas in vitro studies demonstrated decreased radiation exposure to the operator specifically [24, 36]. The recent developments have led to more complex systems, such as the O-arm that is being actively deployed now, but evaluations regarding its efficacy and safety of use are still needed [23, 28]. An anthropomorphic study put forward that O-arm system may expose patients to significant radiation doses [30]. A comparative phantom study demonstrated higher radiation doses to the surgeon by the O-arm than the C-arm in their 2D fluoroscopy mode [28], partly contrasting with the results found by other authors that suggested less radiation exposure for the surgeon in one series, but similarly, higher radiation exposure to the patient with the O-arm than the C-arm in both reports [39, 40]. Among the clinical series reported so far, Costa et al. demonstrated that the O-arm, as seen for the C-arm system, exposed patients to a higher radiation dose than standard fluoroscopy but concluded that their recorded doses were still acceptable when balancing with the advantages of the O-arm system [3]. Another author

concluded to higher radiation doses with O-arm system than those in their free-hand series, without any noticeable benefit in cases of screw placement for moderate idiopathic scoliosis [42]. It is well-understandable that CBCT devices may add radiation to the customary use of fluoroscopic sessions from standard fluoroscopy. The current recommendations for addressing this issue suggest a reduction of the fluoroscopic time, potentiating the use of navigation or preferring low-dose protocols [29]. Our series brings additional data that may help to compare the relative radiation exposure between the common CBCT devices being used currently. The radiation exposures encountered during spinal fusion surgeries with use of O-arm system in clinical series found in the literature are summarized in Table 5. Notwithstanding the fact that there are some differences in operative protocols, number of spine fusion, surgeon's experience, and method of evaluation among the available data, our imaging modality demonstrated acceptable results, in comparison to the O-arm system in terms of radiation exposure.

The levels of exposure may be affected by several factors, such as the surgeon's experience and fluoroscopy technician's aptitude, the extent of spinal fusion, and the intraoperative imaging modalities, which make standardization of these studies and strict comparison difficult [21]. Ipreburg et al., who analyzed their prospective study regarding patient radiation exposure during transforaminal lumbar endoscopic spine surgery, suggested that patients are likely to be exposed to higher doses of radiation during a surgeon's early experience [10]. Indeed, surgeon's evaluation capacity and agility are most likely to increase with time, allowing further avoidance of needless acquisitions. Distances to the radiation source and beam path are other essential factors affecting radiation exposure to the surgeon and operating staff. In addition, better devices and optimal system configurations may lead to higher efficiency and a better balance between the benefits and risks.

Table 5 Literature review of screw placement accuracy and radiation exposure in clinical series of spinal fusion surgery with O-arm

First author	Year	Intraoperative imaging system	Average no. of fusion levels	Screw placement			Radiation exposure (average)	
				No. of screws analyzed	% of safe placement	% of minor or major perforation	Patient	Surgeon
Silbermann J [38]	2011	O-arm	–	187	99	1	–	–
Ishikawa Y [11]	2011	O-arm	2.1	108	88.9	11.1	–	–
Oertel MF [26]	2011	O-arm	–	278	96.8	3.2	–	–
Patil S [27]	2012	O-arm	–	116	94.8	5.2	–	–
Houten [8]	2012	O-arm	–	205	97	3	–	–
Van de Kelft E [43]	2012	O-arm	–	1881	97.5	2.5	10.6 mGy (2D) 203.1 mAs (3D)	–
Ling JM [18]	2014	O-arm	–	467	95.3	4.7	–	–
Kotani T [17]	2014	O-arm	–	416	84.4	15.6	–	–
Shin MH [35]	2015	O-arm	–	124	91.9	8.1	–	–
Smith JD [37]	2016	O-arm	–	30	73	27	39.0 mGy	–
Costa F [3]	2016	O-arm	–	–	–	–	5.15 mSv	0.005 μ Sv
Kleck CJ [14]	2016	O-arm	–	158	81	19	–	–
Shimokawa N [34]	2017	O-arm	–	310	97.1	2.9	–	–
Safee MM [32]	2018	O-arm	1.38	–	–	–	62.0 mGy	–
Kobayashi K [15]	2018	O-arm	11	–	–	–	401 mGy	–
Urbanski W [42]	2018	O-arm	–	451	96	4	1071 mGy-cm	–
Present study		CBCT in a hybrid OR	Cervical 3 Th-L 4.8	313	97.4	2.6	14.11 mGy 113.01 mGy	4.8 μ Sv 54.1 μ Sv

The AlluraClarity FD20 system used in the present study comes with advantages that were described previously, among which is an improved algorithm for image noise reduction that allows higher-quality images for less acquisitions, and optimized functions that lower considerably the amount of radiation per acquisition [7]. The frame rate acquisitions in this study allowed no image deterioration by the system, contributed to containing the overall radiation exposure to both patient and surgeon. The radiation exposure to patients in the present study was absolutely consistent with the desired ESD value of less than 2000 mGy proposed by the Japan Association of Radiological Technologists [12]. Similarly, the radiation exposure to the surgeons stayed under the annual dose limit of 20,000 μ Sv recommended by the International Commission on Radiological Protection [9]. This leads us to the conclusion that the hybrid OR system used in the present study remains safe for routine spinal instrumentation surgery.

Conclusions

Our hybrid OR system allowed us to achieve precise surgery and was well suited for complex spinal fusion cases. Although concerns remain about the radiation exposure to both patients and surgeons, the data analyzed in the present study suggests that the hybrid OR with a FPD angiographic system is helpful

to achieve safe and accurate spinal fusion surgery, especially in complex cases.

Acknowledgements All of the authors are sincerely grateful to Mr. Koji Yokoyama, Mr. Shohei Sasaki, Mr. Akihiko Kakimi, Mr. Toshiyo Norimasa, and Mr. Yoshinori Takao for their technical contribution to intraoperative image guidance.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical approval and informed consent The authors certify that all applicable institutional and governmental regulations concerning the ethical use of clinical data were adhered to for the present study. This retrospective outcome analysis of spine surgery was approved by the ethics committee of Osaka City University Graduate School of Medicine.

References

1. Abumi K, Shono Y, Ito M, Taneichi H, Kotani Y, Kaneda K (2000) Complications of pedicle screw fixation in reconstructive surgery of the cervical spine. *Spine* 25:962–969
2. Carbone JJ, Tortolani PJ, Quartararo LG (2003) Fluoroscopically assisted pedicle screw fixation for thoracic and thoracolumbar injuries: technique and short-term complications. *Spine* 28:91–97
3. Costa F, Tosi G, Attuati L, Cardia A, Ortolina A, Grimaldi M, Galbusera F, Fomari M (2016) Radiation exposure in spine surgery

- using an image-guided system based on intraoperative cone-beam computed tomography: analysis of 107 consecutive cases. *J Neurosurg Spine* 25:654–659
4. Esses SI, Sachs BL, Dreyzin V (1993) Complications associated with the technique of pedicle screw fixation: a selected survey of ABS members. *Spine* 18:2231–2239
 5. Fomekong E, Pierrard J, Raftopoulos C (2017) Comparative cohort study of percutaneous pedicle screw implantation without versus with navigation in patients undergoing surgery for degenerative lumbar disc disease. *World Neurosurg* 111:e410–e417
 6. Gelalis ID, Paschos NK, Pakos EE, Politis AN, Arnaoutoglou CM, Karageorgos AC, Ploumis A, Xenakis TA (2012) Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. *Eur Spine J* 21:247–255
 7. Haas NA, Happel CM, Mauti M, Sahyoun C, Tebart LZ, Kececioglu D, Laser KT (2015) Substantial radiation reduction in pediatric and adult congenital heart disease interventions with a novel X-ray imaging technology. *Int J Cardiol Heart Vasc* 6:101–109
 8. Houten JK, Nasser R, Baxi N (2012) Clinical assessment of percutaneous lumbar pedicle screw placement using the O-arm multidimensional surgical imaging system. *Neurosurgery* 70(4):990–995
 9. International Commission Radiological Protection (2008) Recommendations of the International Commission on Radiological Protection ICRP Publication 103. Elsevier Ltd.
 10. Ipreburg M, Wagner R, Godschalx A, Telfeian AE (2016) Patient radiation exposure during transforaminal lumbar endoscopic spine surgery: a prospective study. *Neurosurg Focus* 40:E7
 11. Ishikawa Y, Kanemura T, Yoshida G, Matsumoto A, Ito Z, Tauchi R, Muramoto A, Ohno S, Nishimura Y (2011) Intraoperative, full rotation, three-dimensional image (O-arm)-based navigation system for cervical pedicle screw insertion. *J Neurosurg Spine* 15(5):472–478
 12. Japan Association of Radiological Technologists (2017) Available at <http://www.jart.jp/index.html>
 13. Jutte PC, Castelein RM (2002) Complications of pedicle screws in lumbar and lumbosacral fusions in 105 consecutive primary operations. *Eur Spine J* 11:594–598
 14. Kleck CJ, Cullimore I, LaFleur M, Lindley E, Rentschler ME, Burger EL, Cain CMJ, Patel VV (2016) A new 3-dimensional method for measuring precision in surgical navigation and methods to optimize navigation accuracy. *Eur Spine J* 25:1764–1774
 15. Kobayashi K, Ando K, Ito K, Tsushima M, Morozumi M, Tanaka S, Machino M, Ota K, Ishiguro N, Imagama S (2018) Intraoperative radiation exposure in spinal scoliosis surgery for pediatric patients using the O-arm® imaging system. *Eur J Orthop Surg Traumatol*. <https://doi.org/10.1007/s00590-018-2130-1>
 16. Kosmopoulos V, Schizas C (2007) Pedicle screw placement accuracy: a meta-analysis. *Spine* 32:E111–E120
 17. Kotani T, Akazawa T, Sakuma T, Koyama K, Nemoto T, Nawata K, Yamazaki A, Minami S (2014) Accuracy of pedicle screw placement in scoliosis surgery: a comparison between conventional computed tomography-based and O-arm-based navigation techniques. *Asian Spine J* 8(3):331–338
 18. Ling JM, Dinesh SK, Pang BC, Chen MW, Lim HL, Louange DT, Yu CS, Wang CME (2014) Routine spinal navigation for thoracolumbar pedicle screw insertion using the O-arm three-dimensional imaging system improves placement accuracy. *J Clin Neurosci* 21:493–498
 19. Mason A, Paulsen R, Babuska JM, Rajpal S, Burneikiene S, Nelson EL, Villavicencio AT (2014) The accuracy of pedicle screw placement using intraoperative image guidance systems. *J Neurosurg Spine* 20:196–203
 20. McParland BJ (1998) Entrance skin dose estimates derived from dose-area product measurements in interventional radiological procedures. *Br J Radiol* 71:1288–1295
 21. Mulconrey DS (2016) Fluoroscopic radiation exposure in spinal surgery: in vivo evaluation for operating room personnel. *Clin Spine Surg* 29:E331–E335
 22. Nakashima H, Sato K, Ando T, Inoh H, Nakamura H (2009) Comparison of the percutaneous screw placement precision of isocentric C-arm 3-dimensional fluoroscopy-navigated pedicle screw implantation and conventional fluoroscopy method with minimally invasive surgery. *J Spinal Disord Tech* 22:468–472
 23. Nottmeier EW (2012) A review of image-guided spinal surgery. *J Neurosurg Sci* 56:35–47
 24. O'Donnell C, Maertens A, Bompadre V, Wagner TA, Krengel W 3rd (2014) Comparative radiation exposure using standard fluoroscopy versus cone-beam computed tomography for posterior instrumented fusion in adolescent idiopathic scoliosis. *Spine* 39:E850–E855
 25. Overley SC, Cho SK, Mehta AI, Arnold PM (2017) Navigation and robotics in spinal surgery: where are we now? *Neurosurgery* 80: S86–S99
 26. Oertel MF, Hobart J, Stein M, Schreiber V, Scharbrodt W (2011) Clinical and methodological precision of spinal navigation assisted by 3D intraoperative O-arm radiographic imaging. *J Neurosurg Spine* 14(4):532–536
 27. Patil S, Lindley EM, Burger EL, Yoshihara H, Patel VV (2012) Pedicle screw placement with O-arm and stealth navigation. *Orthopedics* 35:e61–e65
 28. Park MS, Lee KM, Lee B, Min E, Kim Y, Jeon S, Huh Y, Lee K (2012) Comparison of operator radiation exposure between C-arm and O-arm fluoroscopy for orthopaedic surgery. *Radiat Prot Dosim* 148:431–438
 29. Pireau N, Cordemans V, Banse X, Irda N, Lichthere S, Kaminski L (2017) Radiation dose reduction in thoracic and lumbar spine instrumentation using navigation based on an intraoperative cone beam CT imaging system: a prospective randomized clinical trial. *Eur Spine J* 26:2818–2827
 30. Pitteloud N, Gamulin A, Barea C, Damet J, Raclou G, Sans-Merce M (2017) Radiation exposure using the O-arm® surgical imaging system. *Eur Spine J* 26(3):651–657
 31. Rahmathulla G, Nottmeier EW, Pirris SM, Deen HG, Pichelmann MA (2014) Intraoperative image-guided spinal navigation: technical pitfalls and their avoidance. *Neurosurg Focus* 36:E3
 32. Safaee MM, Oh T, Pekmezci M, Clark AJ (2018) Radiation exposure with hybrid image-guidance-based minimally invasive transforaminal lumbar interbody fusion. *J Clin Neurosci* 48:122–127
 33. Schafer S, Nithianathan S, Mirota DJ, Uneri A, Stayman JW, Zbijewski W, Schmidgunst C, Kleinszig G, Khanna AJ, Siewerdsen JH (2011) Mobile C-arm cone-beam CT for guidance of spine surgery: image quality, radiation dose, and integration with interventional guidance. *Med Phys* 38:4563–4574
 34. Shimokawa N, Takami T (2017) Surgical safety of cervical pedicle screw placement with computer navigation system. *Neurosurg Rev* 40:251–258
 35. Shin MH, Hur JW, Ryu KS, Park CK (2015) Prospective comparison study between the fluoroscopy-guided and navigation coupled with O-arm-guided pedicle screw placement in the thoracic and lumbosacral spines. *J Spinal Disord Tech* 28(6):E347–E351
 36. Smith HE, Welsch MD, Sasso RC, Vaccaro AR (2008) Comparison of radiation exposure in lumbar pedicle screw placement with fluoroscopy vs computer-assisted image guidance with intraoperative three-dimensional imaging. *J Spinal Cord Med* 31:532–537
 37. Smith JD, Jack MM, Ham NR, Bertsch JR, Arnold PM (2016) Screw placement accuracy and outcomes following O-arm-navigated atlantoaxial fusion: a feasibility study. *Glob Spine J* 6: 344–349
 39. Silbermann J, Riese F, Allam Y, Reichert T, Koepfert H, Gutberlet M (2011) 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* 20(6): 875–881
40. Tabaraee E, Gibson AG, Karahalios DG, Potts EA, Mobasser JP, Burch S (2013) 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* 38:1953–1958
 41. Theologis AA, Burch S, Pekmezci M (2016) Placement of iliosacral screws using 3D image-guided (O-Arm) technology and stealth navigation: comparison with traditional fluoroscopy. *Bone Joint J* 98-B:696–702
 42. Tjardes T, Shafizadeh S, Rixen D, Paffrath T, Bouillon B, Steinhausen ES, Baethis H (2010) Image-guided spine surgery: state of the art and future directions. *Eur Spine J* 19:25–45
 43. Urbanski W, Jurasz W, Wolanczyk M, Kulej M, Morasiewicz P, Dragan SL et al (2018) Increased radiation but no benefits in pedicle screw accuracy with navigation versus a freehand technique in scoliosis surgery. *Clin Orthop Relat Res*. <https://doi.org/10.1007/s11999-0000000000000204>
 44. Van de Kelft E, Costa F, Van der Planken D, Schils F (2012) 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. *Spine (Phila Pa 1976)* 37:E1580–E1587
 45. Villard J, Ryang YM, Demetriades AK, Reinke A, Behr M, Preuss A (2014) Radiation exposure to the surgeon and the patient during posterior lumbar spinal instrumentation: a prospective randomized comparison of navigated versus non-navigated freehand techniques. *Spine (Phila Pa 1976)* 39:1004–1009
 46. Yakoumakis E, Tsalafoutas IA, Nikolaou D, Nazos I, Koulentianos E, Proukakis C (2001) Differences in effective dose estimation from dose-area product and entrance surface dose measurements in intravenous urography. *Br J Radiol* 74:727–734