Comparison of Cervical Pedicle Screw Placement Accuracy With Robotic Guidance System Versus Image Guidance System Using Propensity Score Matching

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Study Design: A retrospective study.

Objective: To compare the accuracy of cervical pedicle screw (CPS) placement using a robotic guidance system (RGS) with that of using an image guidance system (IGS; navigation system) through propensity score matching.

Background: The RGS may provide accurate CPS placement, which may outperform IGS. However, no study has directly compared the accuracy of CPS placement with the RGS to that with the IGS.

Patients and Methods: We retrospectively reviewed the data of patients who had undergone cervical fusion surgery using CPS with the RGS or IGS. To adjust for potential confounders (patient demographic characteristics, disease etiology, and registration material), propensity score matching was performed, creating robotic guidance (RG) and matched image guidance (IG) groups. The accuracy of CPS placement from C2 to C6, where the vertebral artery runs, was evaluated on postoperative computed tomography images according to the Neo classification (grade 0 to grade 3). Furthermore, the intraoperative CPS revisions and related complications were examined.

Results: Using propensity score matching, 22 patients were included in the RG and matched groups each, and a total of 95 and 105 CPSs, respectively, were included in the analysis. In both the axial and sagittal planes, the clinically acceptable rate (grades 0 + 1) of CPS placement did not differ between the RG and matched IG groups (97.9% vs 94.3% and 95.8% vs 96.2%, respectively). The incidence of CPS revision was similar between the groups (2.1% vs 2.9%), and no CPS-related complications were documented. Meanwhile, the incidence of lateral breach (grades 1 + 2 + 3) was significantly lower in the RG group than in the matched IG group (1.1% vs 7.7%, $P = 0.037$).

Conclusion: The RGS and IGS can equally aid in accurate and safe CPS placement in clinical settings. Nonetheless, RGS can further reduce the lateral breach, compared with IGS.

Key Words: accuracy, cervical pedicle screw, navigation, robotics, robot, computer-assisted spine surgery, Cirq, vertebral artery, propensity score matching, cervical spine

(*Clin Spine Surg* 2024;37:E424–E432)

Cervical pedicle screw (CPS) allows for biomechanically strong fixation and is a reliable anchor in the surgical management of the cervical spine, compared with other fixation methods, such as lateral mass screws or lamina screws.[1–3] However, CPS placement is technically demanding due to the unique morphology of the cervical spine and the mobility of the cervical spine segment.[4–6] Further, misplaced CPSs can lead to not only neurological complications and loss of structural stability but also vertebral artery (VA) injury, which sometimes leads to fatal outcomes.[7–9]

A computer-assisted image guidance system (IGS), a so-called navigation system, was first described in 1995,[10] and has dramatically improved the accuracy of pedicle screw (PS) placement compared with conventional fluoroscopy.[11–13] IGS visualizes a three-dimensional relationship between the vertebrae and surgical instruments on a monitor in real-time, and surgeons place the PS while confirming its virtual trajectory. In thoracolumbar lesions, it aids in increasing the accuracy of PS placement and is especially useful for deformity surgery and revision cases.[14,15] It was also reported that, compared with fluoroscopic guidance, IGS could offer highly accurate CPS placement with clinically acceptable rates ranging from 91.9% to 96.5%.[16–18]

Basic research on robotic guidance systems (RGS) for PS placement bibliographically began in 2004.[19] The

Received for publication November 21, 2023; accepted February 28, 2024.
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This clinical study was approved by the Ethics Review Board of each institution (no. 2023-118 for Osaka Medical and Pharmaceutical University).
The device(s)/drug(s) is/are approved by the corresponding national agency for this indication.
M.N. has received royalties from Johnson & Johnson DePuy Synthes. The remaining authors declare no conflict of interest.
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DOI: 10.1097/BSD.0000000000001616

RGS has a fundamentally different concept compared with the IGS for PS placement, although the former has been mechanically developed based on the latter.[20] While the IGS provides visual guidance for PS placement, the RGS supports PS placement by directly and spatially guiding the surgeon down a preplanned trajectory. Specifically, the robotic unit mechanically indicates the planned trajectory through a cannula or drill guide tube in the operative field, and the surgeons create a pilot hole and place the PS according to the specified trajectory. Studies have reported that the RGS can provide accurate screw placement in the thoracolumbar region, which is equal to or superior to that achieved with the IGS.[21–23]

The clinical applications of RGS have been recently expanded to include the cervical spine. It can reportedly execute CPS placement accurately and safely.[24–27] However, no study has directly compared the accuracy of CPS placement using the RGS with that using the IGS. To date, the elimination of the surgeon's physiological hand tremors and fatigue during the procedure has been emphasized as a benefit of RGS in clinical practice;[28,29] however, it remains unclear whether RGS has any advantages regarding the accuracy of CPS placement when compared with IGS. Hence, the present study aimed to compare the accuracy of CPS placement with the RGS to that with the IGS through propensity score matching.

PATIENTS AND METHODS

Study Design and Participants

This was a retrospective review of patients who had undergone cervical fusion surgery using CPS with the assistance of IGS (navigation system) or RGS at our institution between 2016 and 2023. One of the authors performed all surgeries with the assistance of both the RGS and IGS. The inclusion criteria were as follows: (1) degenerative cervical myelopathy,[30] trauma, or spinal metastasis and (2) CPSs placed from C2 to C6, where the VA runs through the transverse foramen. The study protocol was reviewed and permission to conduct the study was granted by the Ethics Review Board of our institute.

All patients who had undergone cervical surgery using CPS with the assistance of an RGS after its introduction in March 2022 were included in the robotic guidance (RG) group. Patients who had undergone CPS implantation using an IGS during the relevant period were defined as the image guidance (IG) group. By propensity score matching, a matched IG group, which was adjusted for the potential effects of confounders with the RG group, was created (described later). The accuracy of CPS placement was then compared between the RG and matched IG groups.

Cervical Pedicle Screw Installation Procedure

The RGS used was the Cirq robotic system (BrainLab AG), a semiactive system for specifying the PS trajectory, composed of a workstation and a robotic unit without a footprint.

Under general anesthesia, the patients were placed in the prone position with the head maintained in a Mayfield holder, to which the reference array was attached (Fig. 1A). In all cases, an open technique using a midline approach was adopted.

After adequate exposure was obtained, an intraoperative computed tomography (iCT; SOMATOM Definition AS+SLIDE, Siemens) scan was performed (Fig. 1B). The images were transferred to the three-dimensional navigation system (Curve, BrainLab AG), and the registration was automatically performed. When the preoperative computed tomography (CT) images were used during the registration process, surface point registration was performed manually for each vertebra.

During the robotic procedure, the surgeon first planned the optimal CPS trajectory while referring to the virtual trajectory on a workstation monitor (Fig. 2). Subsequently, the robotic unit was manually moved close to the planned trajectory by the surgeon and then automatically fine-adjusted and locked. A drill guide

FIGURE 1. A, Preoperative positioning with the Cirq robotic system (arrowhead). The reference array was attached to the Mayfield holder (arrow). B, Intraoperative computed tomography image acquisition.

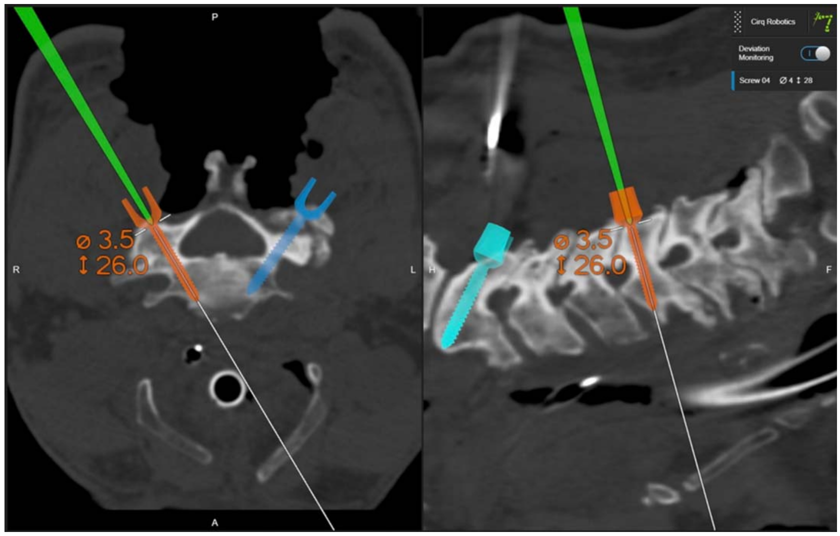

FIGURE 2. Screw planning on the monitor of the robotic guidance system workstation.

tube to create a pilot hole (Fig. 3A) was inserted into the sleeve holder at the head of the robotic arm, indicating the planned trajectory (Fig. 3B). The tip of the drill guide tube had fine spikes (Fig. 3C), which were dug into the bone anatomy to firmly fix the guide tube (Fig. 3D). In the IG group, for which the Curve navigation system (BrainLab AG) was utilized, the surgeon created a pilot hole through the stereotactic image-guided drill guide tube while confirming the CPS trajectory on the navigation monitor (Fig. 4). In both procedures, the surgeon used a 2.4 mm hand-drill to create a pilot hole and finally placed an appropriately sized CPS.

After CPS placement, its position was checked using C-arm fluoroscopy or iCT scanning. Malpositioned

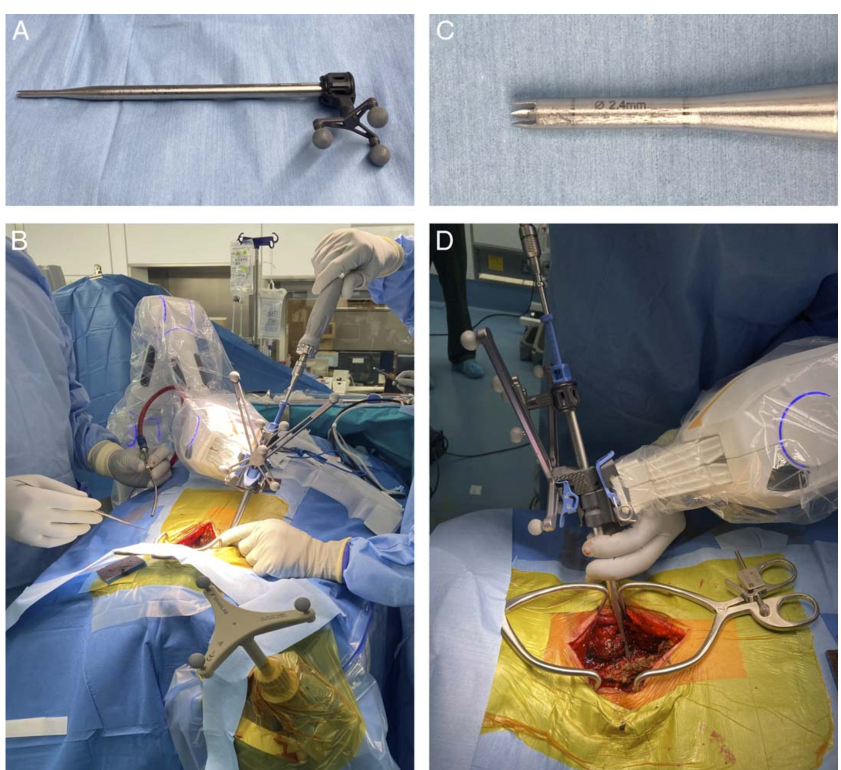

FIGURE 3. A, A drill guide tube used to create a pilot hole. B, A scene of the robotic procedure. C, The drill guide tube has fine spikes at its tip. D, The drill guide tube was firmly fixed, specifying the planned trajectory.

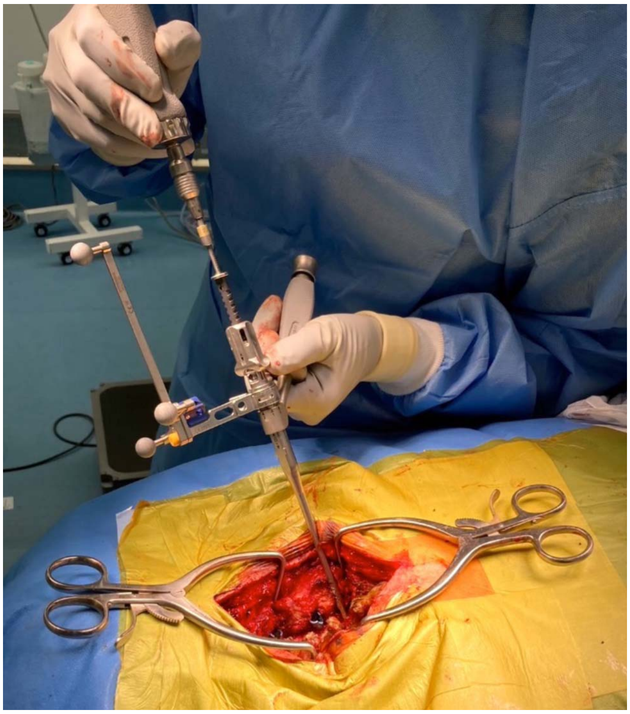

FIGURE 4. Navigation procedure with stereotactic image-guided drill guide tube.

screws, which may have caused neurovascular compromise, were removed or replaced.

Cervical Pedicle Screw Accuracy

The accuracy of CPS placement was evaluated on CT images according to the Neo classification: grade 0 (no breach), grade 1 (breach of <2 mm), grade 2 (breach of 2–4 mm), and grade 3 (breach of >4 mm).[8] This outcome was recorded separately in axial and sagittal planes. Grades 0 and 1 were considered clinically acceptable, whereas grades 2 and 3 were clinically nonacceptable.[24–26] In addition, intraoperative CPS revision, including screw replacement or removal, and CPS-related complications, such as neurological or VA injuries, were documented.

Surgical Characteristics and Anatomic Variables

Surgical characteristics, including the existence of concomitant decompression, number of fused segments, operative time, and estimated blood loss volume, were collected.

The anatomic variables included pedicle diameter (PD) and transverse pedicle angle (TPA) of the pedicles into which the CPSs were inserted (Fig. 5). These were assessed on preoperative CT images based on previous studies.[31] PD was defined as the pedicle isthmus diameter of the mediolateral in the axial plane or cephalocaudal in the sagittal plane. TPA was defined as the angle between the midline of the vertebral body and the mid-axis of the pedicle.

Propensity Score Matching Algorithm

To control for the potential effects of confounders, a propensity score matching algorithm was used before comparing the IG and RG groups. To estimate the propensity score, we fitted a logistic regression model using patient age, sex, body mass index, disease etiology (degenerative cervical myelopathy/trauma/spinal metastasis), and registration materials (preoperative or intraoperative CT scans). Each patient in the RG group was matched with a patient in the IG group with the closest estimated propensity score using the nearest-neighbor method, creating the matched IG group.

Statistical Analyses

Continuous variables were compared using the Wilcoxon signed-rank test, and categorical variables were compared using the Fisher exact test. Intra and interobserver reliability of the measurements for the accuracy of CPS placement, based on the Neo classification, was assessed using the kappa coefficient (κ).[32] P values of <0.05 were considered statistically significant. All statistical analyses were performed using JMP statistical package version 15 (SAS Institute Inc.).

RESULTS

Study Participants

Twenty-two patients [81.8% males; a mean age of 69.0 y (range, 49–93)] met the inclusion criteria for the RG group. During the relevant period, cervical fusion surgery under IGS assistance was performed on 106 patients who were assigned to the IG group. Of these, 22 patients [81.8% males; a mean age of 69.4 y (range, 44–88)] were selected for the matched IG group using propensity score matching.

Table 1 presents the demographic characteristics of the study population. Demographic characteristics including age, sex, body mass index, and disease etiology were statistically similar between the RG and matched IG groups. The registration materials used were also similar between the two groups.

Table 2 shows the implanted CPS and surgical characteristics of the RG and matched IG groups. Concomitant decompression was performed in 81.8% of the patients in both groups. The number of fused segments, operative time, and estimated blood loss volume were similar between the groups ($P = 0.422$, $P = 0.647$, and $P = 0.549$, respectively). In the RG and matched IG groups, 95 and 105 CPSs were placed, respectively. There were no significant differences in the laterality or spinal level of the implanted CPSs between the two groups ($P = 0.777$ and $P = 0.112$, respectively). The morphology of the pedicles where CPSs were placed, represented as PD in the axial and sagittal planes and TPA, did not differ between the two groups ($P = 0.896$, $P = 0.186$, and $P = 0.341$, respectively).

Accuracy of Cervical Pedicle Screw Placement

The intra and interobserver reliability of the CPS placement accuracy evaluation was acceptable with κ of

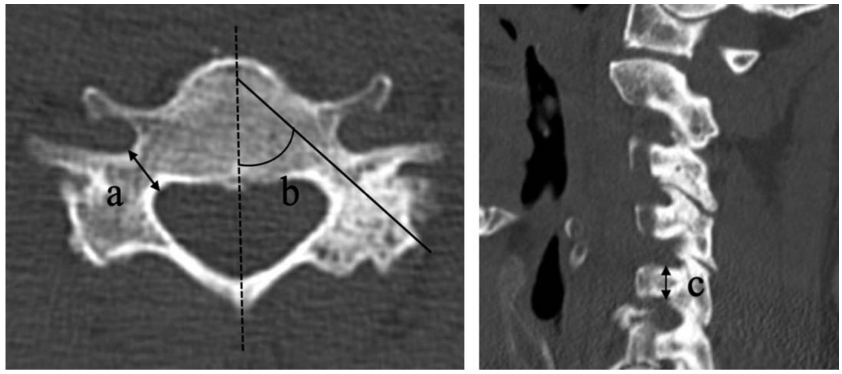

FIGURE 5. Anatomic variables. a, pedicle diameter (PD) in the axial plane. b, transverse pedicle angle. c, PD in the sagittal plane.

0.822 and 0.638, respectively. Data analysis was conducted using the evaluations made by the first examiner (Y.Y.), whose judgment was stricter.

Table 3 shows the accuracy of the CPS placement. In the axial plane, the distribution of the accuracy grade was not significantly different between the RG and matched IG groups ($P = 0.329$). No grade 3 CPS was observed in either group. The clinically acceptable rates (grades 0 + 1) did not differ between the two groups, with 97.9% and 94.3% in the RG and matched IG groups, respectively ($P = 0.284$). In the sagittal plane, there was no significant difference in the grade distribution of CPS accuracy between the two groups ($P = 0.742$). Similar to the axial plane, no grade 3 CPS was observed in any group. The clinically acceptable rate (grades 0 + 1) was similar between the RG and matched IG groups (95.8% vs 96.2%, respectively, $P > 0.999$). In the RG group, 2 of 95 CPSs required intraoperative revision. One CPS had a grade 2 medial/caudal breach, which was replaced using RGS, and the other had a grade 2 caudal breach, which was replaced by a lateral mass screw under the IGS assistance. In the matched IG group, 3 of 105 CPSs, including 2 with grade 2 medial/caudal breaches and 1 with grade 2 lateral breaches, were intraoperatively removed. Consequently, the incidence of intraoperative CPS revision was not significantly different between the RG and matched IG groups (2.1% vs 2.9%, $P > 0.999$; Table 3). Furthermore, the intraoperative revision rate was not significantly different between the iCT and C-arm fluoroscopic evaluations (2.9% vs 0%, respectively, $P > 0.999$). No CPS-related complications were documented in either group (Table 3).

Table 4 presents CPS accuracy according to the spinal level (C2 and C3–C6) between the RG and matched IG

TABLE 1. Patient Demographic Characteristics After Propensity Score Matching

Variable	RG group	Matched IG group	IG group	P*
No. patients	22	22	106	NA
Demographic characteristics				
Age (y)	69.0 ± 13.4	69.4 ± 12.5	69.0 ± 14.6	0.897
Sex (M)	18 (81.8)	18 (81.8)	55 (51.9)	1.000
BMI (kg/m^2)	23.8 ± 5.1	25.2 ± 3.8	23.6 ± 4.3	0.270
Etiology				
DCM	16 (72.7)	16 (72.7)	86 (81.1)	1.000
Trauma	4 (18.2)	4 (18.2)	16 (15.1)	—
Metastasis	2 (9.1)	2 (9.1)	4 (3.8)	—
Registration materials				
Preoperative CT scan	2 (9.1)	4 (18.2)	30 (28.3)	0.664
Intraoperative CT scan	20 (90.9)	18 (81.8)	76 (71.7)	—

Values are presented as the mean ± SD or number of cases (percentage), unless indicated otherwise.

*Statistical differences in variables between the RG and matched IG groups

BMI indicates body mass index; CT, computed tomography; DCM, degenerative cervical myelopathy; IG, image guidance; NA, not available; RG, robotic guidance.

TABLE 2. Comparison of Surgical and Anatomic Characteristics Between RG and Matched IG Groups

Variable	RG group	Matched IG group	P
No. patients	22	22	NA
Surgical characteristics			
Concomitant decompression	18 (81.8)	18 (81.8)	1.000
No. fused segments	6.2 ± 2.2	5.8 ± 2.1	0.422
Operative time (min)	286.1 ± 58.7	287.8 ± 73.7	0.647
Estimated blood loss (mL)	167.3 ± 145.8	157.0 ± 68.4	0.549
No. of implanted CPS	95	105	NA
Location of implanted CPS			
Laterality			
Right	46 (48.4)	54 (51.4)	0.777
Left	49 (51.6)	51 (48.6)	—
Spinal level			
C2	34 (35.8)	32 (30.5)	0.112
C3	0	7 (6.6)	—
C4	19 (20.0)	23 (21.9)	—
C5	19 (20.0)	21 (20.0)	—
C6	23 (24.2)	22 (21.0)	—
Anatomic variables			
PD			
Axial (mm)	6.3 ± 1.8	6.3 ± 1.7	0.896
Sagittal (mm)	7.3 ± 1.5	7.1 ± 1.6	0.186
TPA (degree)	34.6 ± 15.3	36.4 ± 15.8	0.341

Values are presented as the mean ± SD or number of cases/screws (percentage), unless indicated otherwise.

CPS indicates cervical pedicle screw; IG, image guidance; NA, not available; PD, pedicle diameter; RG, robotic guidance; TPA, transverse pedicle angle.

TABLE 3. Comparison of Accuracy of CPS Placement Between RG and Matched IG Groups

Grade	RG group	Matched IG group	P
No. implanted CPS	95	105	NA
Axial			
Grade 0	87 (91.6)	89 (84.8)	0.329
Grade 1	6 (6.3)	10 (9.5)	—
Grade 2	2 (2.1)	6 (5.7)	—
Grade 3	0	0	—
Grade 0+1	93 (97.9)	99 (94.3)	0.284
Sagittal			
Grade 0	88 (92.6)	95 (90.5)	0.742
Grade 1	3 (3.2)	6 (5.7)	—
Grade 2	4 (4.2)	4 (3.8)	—
Grade 3	0	0	—
Grade 0+1	91 (95.8)	101 (96.2)	> 0.999
Intraoperative CPS revision	2 (2.1)	3 (2.9)	> 0.999
CPS-related complication	0	0	NA

Values are presented as number of screws (percentages), unless otherwise indicated.

CPS indicates cervical pedicle screw; IG, image guidance; NA, not available; RG, robotic guidance.

groups. In the axial plane at C2, the distribution of CPS accuracy grade for the RG group was significantly superior to that for the matched IG group ($P = 0.049$); however, all CPSs for both groups were clinically acceptable with grade 0 or 1. In the sagittal plane at C2, the distribution of CPS accuracy grade was not statistically different between the two groups ($P > 0.999$); in addition, all the CPSs were clinically acceptable (grades 0 + 1), as with the axial plane. Intraoperative revisions were not identified in the C2 PSs. Regarding the subaxial cervical spine (C3–C6), there were no significant differences in the distribution of accuracy grade and clinically acceptable rate (grades 0 and 1) in the axial and sagittal planes. Moreover, the revision rate was similar between the two groups ($P > 0.999$).

Table 5 lists the accuracy grades considering the breach direction in the axial plane. In the RG and matched IG groups, medially breached CPSs (grade 1 + 2 + 3) were identified with a similarity rate of 7.4% and 7.7% of the cohort, respectively ($P > 0.999$). The rate of clinically unacceptable screws with the medial breach (grades 2 + 3) was also similar between the two groups (2.1% vs 4.8%, $P = 0.449$). Meanwhile, the incidence of laterally breached CPSs (grades 1 + 2 + 3) was significantly lower in the RG group than that in the matched IG group (1.1% vs 7.7%, $P = 0.037$), although the rates of clinically unacceptable screws with lateral breaches (grades 2 + 3) were similar in both groups (0% vs 1.0%, $P > 0.999$).

Table 6 summarizes the breach directions of the CPSs in the sagittal plane. As for the cephalad and caudal directions, the rates of breached CPS (grades 1 + 2 + 3) and nonacceptable screws (grades 2 + 3) were similar in the RG and matched IG groups.

DISCUSSION

The present study demonstrated that the accuracy of CPS placement with the RGS was clinically equal to that with the IGS. Nonetheless, the lateral breach of the CPS was lesser when utilizing the RGS than when utilizing the IGS.

Since the 2010s, several clinical studies have compared the accuracy of PS placement with the RGS to that with the IGS in the thoracolumbar region. These studies reported that the rate of acceptable PS placement using the RGS was in the range of 94.4%–99.4%, which was comparable to that using the IGS of 94.8%–95.5%.[21–23] Akazawa et al[33] compared the accuracy of PS placement with the RGS to that with the IGS during surgery for adolescent idiopathic scoliosis through propensity score matching and showed that the clinically acceptable rate with the RGS was significantly higher than that with the IGS (98.2% vs 91.1%). Thus, in the thoracolumbar region, the RGS can provide highly accurate PS placement, which is equal to or superior to that achieved with the IGS.

TABLE 4. Comparison of Accuracy of CPS Placement According to Spinal Level Between the RG and Matched IG Groups

Spinal Level	C2			C3 to C6		
Grade	RG group	Matched IG group	P	RG group	Matched IG group	P
No. implanted CPS	34	32	NA	61	73	NA
Axial						
Grade 0	34 (100)	28 (87.5)	**0.049**	53 (86.9)	61 (83.6)	0.506
Grade 1	0	4 (12.5)	—	6 (9.8)	6 (8.2)	—
Grade 2	0	0	—	2 (3.3)	6 (8.2)	—
Grade 3	0	0	—	0	0	—
Grade 0+1	34 (100)	32 (100)	NA	59 (96.7)	67 (91.8)	0.290
Sagittal						
Grade 0	33 (97.1)	31 (96.9)	> 0.999	55 (90.1)	64 (87.7)	0.709
Grade 1	1 (2.9)	1 (3.1)	—	2 (3.3)	5 (6.8)	—
Grade 2	0	0	—	4 (6.6)	4 (5.5)	—
Grade 3	0	0	—	0	0	—
Grade 0+1	34 (100)	32 (100)	NA	57 (93.4)	69 (94.5)	> 0.999
Intraoperative CPS revision	0	0	NA	2 (3.3)	3 (4.1)	> 0.999

Values are presented as number of screws (percentages), unless otherwise indicated.

Bold values indicate statistically significant differences ($P < 0.05$).

CPS indicates cervical pedicle screw; IG, image guidance; NA, not available; RG, robotic guidance.

TABLE 5. Details of CPS Breach in Axial Plane Between RG and Matched IG Groups

Breach direction/ grade	RG group (n = 95)	Matched IG group (n = 105)	*P*
Medial			
Grade 1	5 (5.3)	3 (2.9)	NA
Grade 2	2 (2.1)	5 (4.8)	—
Grade 3	0	0	—
All breaches (grade 1+2+3)	7 (7.4)	8 (7.7)	> 0.999
Grade 2+3	2 (2.1)	5 (4.8)	0.449
Lateral			
Grade 1	1 (1.1)	7 (6.7)	NA
Grade 2	0	1 (1.0)	—
Grade 3	0	0	—
All breaches (grade 1+2+3)	1 (1.1)	8 (7.7)	**0.037**
Grade 2+3	0	1 (1.0)	> 0.999

Values are presented as number of screws (percentages), unless otherwise indicated.

Bold values indicate statistically significant differences ($P < 0.05$).

CPS indicates cervical pedicle screw; IG, image guidance; NA, not available; RG, robotic guidance.

In the cervical region, IGS greatly improves the accuracy of CPS placement, compared with fluoroscopic guidance. Most studies have shown that the acceptable CPS placement was executed in ~> 95% of the screws when utilizing IGS,[16–18,34] while the corresponding values under the fluoroscopic guidance were in the range of 56.5%–87.7%.[8,9,35] A systematic review by Tarawneh et al,[13] analyzing 3055 CPSs placed with fluoroscopic guidance and 1223 CPSs placed with an IGS, showed that the navigation-guided technique was superior to the fluoroscopy-guided technique in terms of accuracy; further, the CPS-related complication rate was significantly lower with the navigation-guided technique than that with the fluoroscopy-guided technique (0.3% vs 1.9%). Consequently, the authors concluded that, compared with fluoroscopy, IGS could aid in more accurate CPS placement, reducing complication rates. Recently, the number of clinical studies on CPS placement using RGS has increased. An acceptable rate of CPS placement with RGS has been reported to range from 97.2% to 100%,[24–26] which might surpass the accuracy of CPS placement with the IGS. Nonetheless, no studies have directly compared RGS and IGS with regard to the accuracy of CPS placement; thus, it remains unclear whether the RGS is superior to the IGS in terms of the accuracy of CPS placement. To the best of our knowledge, the present study is the first to compare the accuracy of CPS placement with that of the IGS. Furthermore, propensity score matching was employed to eliminate potential confounders and evaluate the true advantage of the RGS compared with the IGS.

TABLE 6. Details of CPS Breach in Sagittal Plane between RG and Matched IG Groups

Breach Direction/ Grade	RG group (n = 95)	Matched IG group (n = 105)	*P*
Cephalad			
Grade 1	0	1 (1.0)	NA
Grade 2	0	0	—
Grade 3	0	0	—
All breaches (Grade 1+2+3)	0	1 (1.0)	> 0.999
Grade 2+3	0	0	NA
Caudal			
Grade 1	3 (3.2)	5 (4.8)	NA
Grade 2	4 (4.2)	4 (3.8)	—
Grade 3	0	0	—
All breaches (Grade 1+2+3)	7 (7.4)	9 (8.6)	0.800
Grade 2+3	4 (4.2)	4 (3.8)	> 0.999

Values are presented as number of screws (percentages), unless otherwise indicated.

CPS indicates cervical pedicle screw; IG, image guidance; NA, not available; RG, robotic guidance.

The present study showed that the clinical accuracy of CPS placement with the RGS was equal to that with the IGS. The location and anatomic characteristics of the pedicles, where the CPSs were installed, were similar between the two groups (Table 2), as was the distribution of the accuracy grade (Table 3). In the axial and sagittal planes, the rates of clinically acceptable CPS (grades 0 + 1) in the RG group were 97.9% and 95.8%, respectively, similar to the values of 94.3% and 96.2% in the matched IG group ($P = 0.284$ and $P > 0.999$, respectively; Table 3). The accuracy of CPS placement using RGS in the present study was mostly comparable to the results of a systematic review by Beyer et al,[27] which showed that 97.7% of 482 implanted CPSs were clinically acceptable. Furthermore, in the present study, the incidence of intraoperative CPS revision did not significantly differ between the RG and matched IG groups, and CPS-related complications were not observed in either group (Table 3). In addition, the similarity of CPS placement accuracy for the RG and matched IG groups was retained with separate analyses of C2 and subaxial levels of C3–C6, where the marked anatomic difference exists (Table 4). These results suggest that both the RGS and IGS can provide accurate and safe CPS placement in clinical settings.

Nonetheless, a detailed analysis considering the breach direction of the CPS identified a small but important difference between the RGS and IGS. When separately analyzing the cephalad and caudal breaches of CPSs in the sagittal plane, the incidence rates of all pedicle breaches (grades 1 + 2 + 3) or grades 2 and 3 CPSs between the RG and matched IG groups were comparable (Table 6). Meanwhile, when separately examining the medial and lateral breaches of CPSs in the axial plane, the incidence rate of a lateral breach (grades 1 + 2 + 3) was significantly lower in the RG group than in the matched IG group (1.1% vs 7.7%, $P = 0.037$; Table 5), although the incidence rates of clinically unacceptable CPSs (grades 2 + 3) in these groups were similar ($P > 0.999$). This result indicates that the lateral breach of the CPS, which possibly causes VA injury, can be further reduced when utilizing the RGS rather than the IGS.

CPS placed under fluoroscopic guidance is likely to deviate laterally for various reasons. First, the medial cortex of the pedicle is much thicker than the lateral cortex at the subaxial cervical level (C3–C7);[4] therefore, the probe or drill is likely to be displaced by the medial cortical cortex, deviating laterally. The second is the pressure of the retracted paravertebral muscle, which makes it difficult to make a more convergent trajectory.[8,36] Third, the pressure of the probe or drill can cause rotation of the vertebral body to the ipsilateral side, so that the pilot hole is more vertically prepared.[34,37] When utilizing the IGS, surgeons manually specify the CPS trajectory and create a pilot hole, even though the IGS provides visual support while displaying the virtual trajectory on the monitor. Hence, these issues have not been fundamentally resolved. In contrast, when utilizing the RGS, the drill guide tube was rigidly fixed by the fine spike at its tip and robotic unit, mechanically specifying the CPS trajectory (Fig. 3C, D). Therefore, the trajectory is unlikely to deviate when a pilot hole is drilled. Furthermore, excessive pressure on the vertebral body is unlikely to be applied and vertebral body rotation can be avoided. In a study by Kisinde et al,[26] examining 88 CPSs implanted with RGS, cortical breaches in the axial plane were identified in 14 (15.9%) CPSs, all of which were medial breaches. This result is consistent with the results of the present study.

This study had some limitations. First, the sample size was small, although a propensity score matching analysis was conducted to adjust for potential confounders between the RG and IG groups. A study with a larger sample size and a randomized controlled design may be a future challenge. Second, an open technique with a midline approach was used in all cases. Hence, the results of this study may not apply to percutaneous approaches. Finally, this study evaluated the accuracy of CPS placement using the Cirq robotic system. Nevertheless, besides this system, several robotic systems for PS placement are presently available.[38] Hence, the generalizability of our results for other systems should be verified.

CONCLUSION

The present study indicates that the RGS and IGS can equally aid in accurate and safe CPS placement in clinical settings. Nonetheless, the RGS can further reduce lateral breach, which may cause VA injury, compared with the IGS, and this might be a potential advantage of the RGS.

ACKNOWLEDGMENTS

The authors thank Daichi Fukushima (Johnson & Johnson Depuy Synthes) for technical support during surgery.

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