Cervical reconstruction using cervical pedicle screws (CPSs) offers greater stability as compared with other techniques, and the use of these screws has increased in recent years. Nonetheless, CPS insertion carries the risk of serious complications, such as injury to the vertebral artery (VA), spinal cord, and nerve roots. Fortunately, computer-assisted surgery has been effective in improving CPS insertion accuracy. During the previous decade, a preoperative 3D CT–based navigation system was the main technique of choice for CPS insertion. However, the intervertebral anatomical relationships while the patient is prone during surgery may not match the preoperative CT data obtained while the patient is supine. This discrepancy has led to navigation errors and prolonged surgical time because of the need for point or surface registration for each vertebra.

Abbreviations used in this paper: CPS = cervical pedicle screw; DSA = destructive spondyloarthropathy caused by hemodialysis; RA = rheumatoid arthritis; VA = vertebral artery.

This article contains some figures that are displayed in color online but in black and white in the print edition.
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Intraoperative 3D image–based navigation can reduce this discrepancy and may provide greater accuracy and safety during CPS insertion. For example, the Iso-C3D–based navigation system (Siemens Medical Solutions) has been described as accurate and effective for intraoperative 3D image–based navigation. We have previously reported on the use and limitations of this navigation system for CPS insertion. Similarly, the O-arm (Medtronic) is an intraoperative full-rotation, multidimensional image system (Fig. 1) with the potential to become a new computer-assisted surgery device that allows CPS insertion with intraoperative high-definition 3D navigation (Fig. 2). In addition, the O-arm has a unique form and function as compared with similar systems. Previously, Nottmeier and Young documented their navigation experience with intraoperative 3D imaging (O-arm and Iso-C3D) in the upper cervical spine. To our knowledge, however, no reports on the use of the O-arm for CPS insertion exist. The aim of our study was to retrospectively examine the reliability of CPS placement using O-arm navigation and to elucidate its advantages and disadvantages.

Methods

Between April and December 2009, we performed posterior instrumentation of the occipitocervical, cervical, and cervicothoracic spine using CPSs in 21 consecutive patients (108 CPSs) at the Spine Center, Konan Kosei Hospital in Konan, Japan. The sample included 9 men and 12 women, and the mean age at surgery was 67.2 years (range 42–83 years). The procedure was performed for the following cervical disorders: occipitocervical or cervical lesions caused by rheumatoid arthritis (RA) in 10 patients, trauma in 6 patients, spondylotic myelopathy with cervical kyphosis in 2 patients, metastatic vertebral tumor in 2 patients, and destructive spondylarthropathy caused by hemodialysis (DSA) with RA in 1 patient (Table 1). Occipitocervical fixation was performed in 6 patients, and cervical or cervicothoracic fixation was performed in the remaining 15. A laminectomy or laminoplasty was performed when necessary. A single group of surgeons with sufficient experience in performing posterior CPS fixations inserted all 108 CPSs.

Intraoperative, Full-Rotation, 3D Image–Based Navigation System

The O-arm was used with the Medtronic StealthStation (Medtronic, Inc.) during CPS insertions (Fig. 2). The O-arm provides 2D fluoroscopic and full 3D reconstructions throughout posterior procedures, automatically transferring these data to the navigation system. In our study, an image of the patient’s spine was obtained within 26 seconds, and a 3D reconstructed image was obtained within 60 seconds. The aforementioned data could be used for navigation immediately without anatomical registration, thus decreasing operation time and avoiding errors associated with registration.

The amount of radiation resulting from a single spin ranged between 40 and 125 kV (25–100 mA). In addition, we could obtain $x \times 10 \times 10 \times 15$ cm$^3$ 3D image volume (usually 5–6 cervical vertebra levels) in a single spin.

TABLE 1: Summary of characteristics in 21 patients who underwent CPS insertion

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>sex (M/F)</td>
<td>9/12</td>
</tr>
<tr>
<td>mean age in yrs (range)</td>
<td>67.2 ± 10.4 (42–83)</td>
</tr>
<tr>
<td>follow-up in mos (range)</td>
<td>13.1 (9.8–16.9)</td>
</tr>
<tr>
<td>diagnosis</td>
<td></td>
</tr>
<tr>
<td>RA</td>
<td>10</td>
</tr>
<tr>
<td>trauma</td>
<td>6</td>
</tr>
<tr>
<td>CSM</td>
<td>2</td>
</tr>
<tr>
<td>DSA + RA</td>
<td>1</td>
</tr>
<tr>
<td>metastatic tumor</td>
<td>2</td>
</tr>
</tbody>
</table>

* CSM = cervical spondylotic myelopathy.
Surgical Procedure

General anesthesia was induced, patients were placed prone on a Jackson table, and a carbon-fiber Mayfield 3-point cranial fixation device was affixed (Fig. 3). As an additional safety precaution, we performed intraoperative spinal cord monitoring for all cervical surgeries. Preoperatively, the O-arm was wrapped in a plastic drape and prepared for use in all procedures. A posterior approach with a midline incision was performed in all patients, and CPSs were placed before laminoplasty or laminectomy.

After a posterior exposure and correct alignment, the navigation reference frame was attached to the spinous process of a vertebra from C-3 to C-7, and 3D CT data were obtained using the O-arm. After the navigation was ready, an entry point was determined. We reconfirmed the screw trajectory using a navigation probe, inserted a small pedicle probe, and then inserted CPSs in 2 vertebrae above and below the vertebra on which the navigation reference frame had been placed. Vertebrae apart from the reference frame required reconfirmation of the accuracy of navigation. If the navigation error in the vertebrae was > 1 mm, we moved the reference frame to that vertebra, executed another spin of the O-arm, and obtained a renewed intraoperative 3D image for navigation.

After each CPS was inserted unilaterally, we reconfirmed navigation accuracy by touching the anatomical landmark with the probe to avoid errors. The CPS diameter used in all patients in this study was 3.5 mm. Laminectomy, laminoplasty, or tumor resection was performed as necessary. Diameters and lengths of all cervical pedicles into which the screws would be inserted were measured on preoperative 3D CT images. In addition, if a preoperative CT angiography study revealed VA anomalies, we did not use CPSs. Instead, we utilized other fixation devices, such as lateral mass screws or lamina hooks, or we performed CPS insertion on only one side to avoid intraoperative neurovascular injury related to severe malposition of the CPSs.

Postoperative Management

All patients who underwent occipitocervical fixation were immobilized using a halo fixation device. For patients who underwent short-segmental fixation, we used semi-rigid collars, such as a soft neck collar or a Philadelphia collar, according to the number of segments fixed and the extent of osteoporosis. Postoperative immobilization was routinely maintained for 1–3 months.

Accuracy of CPS Insertion

The accuracy of all CPS placements was evaluated with postoperative CTs in the multiplanar view, as defined by Neo et al.12 Cervical pedicle screw positions were classified into 4 grades: Grade 0, no perforation and the screw was completely contained in the pedicle; Grade 1, perforations < 2 mm (that is, less than half of the screw diameter); Grade 2, perforations ≥ 2 but < 4 mm; and Grade 3, perforations ≥ 4 mm (that is, complete perforation).

Results

The mean operative time was 219 minutes (range 80–352 minutes), and the mean estimated blood loss was 723 ml (range 186–2500 ml). The mean follow-up period was 13.1 months (range 9.8–16.9 months), and the average number of instrumented segments was 2.1 (range 1–6 segments). In this study, successful fusion criteria included the presence of a homogeneous fusion mass at the posterior part of the lamina and lateral mass, including the facet joint, as well as no clear zone around the CPS on CT. The fusion rate of all patients 1 year after surgery was 90.5% (19 of 21 patients). The 2 cases that did not achieve fusion at the 1-year mark were both cases of metastatic tumors in which we had not performed bone grafting. These data are summarized in Table 2.

Clinical Complications

There were no intraoperative or postoperative complications directly caused by CPS insertion into the cervical pedicles, such as injury to the VA, spinal cord, or nerve root. Thus, no CPSs were removed as a result of neurovascular complications during surgery or the follow-up period. Postoperatively, 2 patients showed painful radiculopathy caused by foraminal stenosis at the fixed intervertebral levels. In both of these patients, cervical anterior spondylolisthesis was almost completely reduced by an intraoperative translation maneuver with CPSs. One patient had C-7 radiculopathy and the other had C-8 radiculopathy. Both patients were treated conservatively without CPS replacement, and their symptoms improved within 3 weeks. Another patient had a deep wound infection in the 2nd postoperative week. This case was successfully managed by removing the CPSs with surgical debridement and anterior cervical fixation with a fibular bone graft. In addition, 1 patient with RA underwent treatment for sepsis caused by a bedsore. Two other patients had temporary delirium. During the follow-up period, no patient required CPS removal because of complications related to insertion.

Accuracy of CPS Placement

One hundred eight CPSs were inserted into the cervical pedicles of vertebrae from C-2 to C-7. The number of screws inserted at each level was as follows: C-2, 24; C-3, 15; C-4, 20; C-5, 20; C-6, 19; and C-7, 10. Evalua-
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### Illustrative Cases

#### Case 1

This 70-year-old woman with DSA and RA presented with severe progressive myelopathy. Magnetic resonance imaging showed severe spinal cord compression. Computed tomography showed a severely destructive intervertebral change at the C3–4 level, vertical subluxation, and atlantoaxial dislocation. We performed a laminoplasty to correct the cervical kyphosis or improvement of an undesirable state of the craniocervical junction. Note, however, that severe CPS malposition can cause neurovascular damage, such as injury to the spinal cord, nerve root, or VA. Such injury necessitates more accurate CPS positioning by using an improved insertion technique. Abumi et al., who used the conventional technique, reported a perforation rate of 6.7% (45 of 664 screws) and 2 screws among 45 that caused radiculopathy.

Pedicle diameters in the cervical spine are smaller than those in the thoracic or lumbar spine, and there are differences in the intervertebral anatomical relationships between preoperative CT data and intraoperative findings. Thus, intraoperative 3D image–based navigation may be more appropriate for cervical spine procedures. In the present study, in which CPS malpositioning was defined as any screw placement rated Grade 2 or above, the malposition rate was 2.8%. According to the results of this study and others, perforations due to CPS insertion do not necessarily cause clinical complications, but a larger CPS perforation can increase the risk of neurovascular injury, which in turn can cause catastrophic intraoperative or postoperative complications. Others have reported CPS perforation rates ranging from 2% to 2.8%, as determined with 3D fluoroscopy. Based on these reported rates, O-arm–based navigation can improve the accuracy of CPS insertion to an extent equal to other 3D fluoroscopy–based navigation systems. Note, however, that the results achieved using 3D image–based navigation would not be complete in preventing CPS malpositioning. Therefore, the combined use of intraoperative 3D image–based navigation with other techniques, such as a funnel technique, may provide more accurate CPS placement.

#### Case 2

This 60-year-old woman had a C6–7 dislocation fracture with severe neck pain without neurological deficit. After inducing general anesthesia in the patient, we reduced the dislocation by using the intraoperative 3D reconstructed O-arm image and successfully performed CPS placement with O-arm navigation (Fig. 5).

#### TABLE 2: Summary of results in 21 patients who underwent CPS insertion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>operating time in min</td>
<td>219</td>
</tr>
<tr>
<td>mean range 80–352</td>
<td></td>
</tr>
<tr>
<td>blood loss in ml (range)</td>
<td>723 (186–2500)</td>
</tr>
<tr>
<td>no. of fusion segments</td>
<td>2.1 ± 1.91</td>
</tr>
<tr>
<td>mean range 1–6</td>
<td></td>
</tr>
<tr>
<td>no. of CPSs</td>
<td>108</td>
</tr>
<tr>
<td>total</td>
<td></td>
</tr>
<tr>
<td>at C-2</td>
<td>24</td>
</tr>
<tr>
<td>at C-3</td>
<td>15</td>
</tr>
<tr>
<td>at C-4</td>
<td>20</td>
</tr>
<tr>
<td>at C-5</td>
<td>20</td>
</tr>
<tr>
<td>at C-6</td>
<td>19</td>
</tr>
<tr>
<td>at C-7</td>
<td>10</td>
</tr>
<tr>
<td>postop CPS evaluation (%)</td>
<td></td>
</tr>
<tr>
<td>Grade 0</td>
<td>96 (88.9)</td>
</tr>
<tr>
<td>Grade 1</td>
<td>9 (8.3)</td>
</tr>
<tr>
<td>Grade 2</td>
<td>3 (2.8)</td>
</tr>
<tr>
<td>clinical complications</td>
<td></td>
</tr>
<tr>
<td>deep wound infection</td>
<td>1</td>
</tr>
<tr>
<td>sepsis due to bed sore</td>
<td>1</td>
</tr>
<tr>
<td>iatrogenic foraminal stenosis</td>
<td>2</td>
</tr>
<tr>
<td>delirium</td>
<td>2</td>
</tr>
</tbody>
</table>

#### Discussion

Cervical pedicle screws provide significantly greater stabilization than other fixation devices and stronger pull-out strength than lateral mass screws. Therefore, they can be used for severe deformities of the cervical spine or RA-related cervical spine complications, which require correction of cervical kyphosis or improvement of an undesirable state of the craniocervical junction. Note, however, that severe CPS malposition can cause neurovascular damage, such as injury to the spinal cord, nerve root, or VA. Such injury necessitates more accurate CPS positioning by using an improved insertion technique. Abumi et al., who used the conventional technique, reported a perforation rate of 6.7% (45 of 664 screws) and 2 screws among 45 that caused radiculopathy.

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Results of our and other relevant studies together suggest that intraoperative 3D image–based navigation can facilitate CPS placement but cannot completely prevent CPS malpositioning. Several possible reasons for the occasional occurrence of CPS malpositioning exist. First, perhaps the CPSs are being forced to the midline by the posterior cervical muscles while instruments, such as awls, probes, taps, and screwdrivers, are being utilized during screw insertion. Second, in the CPS insertion techniques applied thus far, the use of a navigation device and system has been limited to determining insertion points and inspecting prepared entry points. We have not yet inserted CPSs by using the navigation system throughout the entire procedure given the lack of a suitable navigation device. Third, during surgery, cervical alignment can easily change when force is applied on the cervical spine while creating a hole, introducing an awl, or inserting CPSs, and therefore lordosis of the cervical spine increases and the spine rotates. The ensuing discrepancy of alignment between the 3D image and CPS insertion would reduce navigation accuracy, except on the vertebra with the navigation reference frame. For this reason, the surgical procedure should be carefully monitored to prevent problems related to this discrepancy.

Fourth, human error can also cause a malpositioned CPS. For example, a surgeon can overlook an unstable navigational reference frame or malfunctioning hardware like the navigation system, navigation probe, and so forth. Moreover, the surgeon must carefully watch the surgical site and the navigation monitor while using the navigational technique. Ultimately, the limitations of an intraoperative computer system can largely be overcome with increased surgical experience.

The O-arm has some substantial benefits. First, the system can offer higher-resolution intraoperative 3D images as compared with those of other intraoperative 3D fluoroscopy systems. With existing 3D fluoroscopy, it is difficult to obtain images suitable for an intraoperative evaluation of the implant position after spinal instrumentation, because the 3D image is of lower quality than the recent multidetector helical CT scans. Note, however, that the 3D images obtained using the O-arm have nearly the same quality as those of recent multidetector helical CT scans. We can therefore determine a clear implant position despite the spinal instrumentation. Second, robotic movements allow 2D fluoroscopy views and multiplanar 3D images in any direction (anteroposterior, lateral, and oblique).
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without much effort. Preoperatively, once the O-arm is wrapped in a plastic drape, all moving parts in the gantry are enclosed, and this system can easily obtain 2D and 3D images as often as necessary while keeping the surgical site sterile. In this regard, the O-arm has an advantage over existing 3D fluoroscopy, which obtains 3D images by movement of the C-arm throughout the 190° scan over a surgical site. Third, the preparation time for O-arm–based navigation is shorter than for existing 3D fluoroscopy–based navigation systems.\(^1\) Furthermore, intraoperative 3D image–based navigation systems do not need point-to-point surface matching, a factor that increases their use for further surgery without landmarks. In addition, the O-arm system requires about 5 minutes to set the reference frame to start CPS insertion, and the cost per patient using O-arm navigation does not change as compared with other popular methods of spinal navigation, such as the Iso-C3D in Japan. Nevertheless, the initial cost of the O-arm is much higher than that of the Iso-C3D. These features could offer more safety and accuracy in surgeries.

Nevertheless, the O-arm has some considerable limitations. The chassis of the O-arm is 823 × 2812 × 1933 mm, requiring additional equipment that occupies a larger space. Moreover, the system requires additional staff for operation. It is also more expensive than other C-arm systems. Furthermore, the O-arm form restricts the intraoperative working space when surgeons use real-time 2D fluoroscopy (Fig. 7). Note that this study is not a comparative study, and therefore the results cannot be interpreted as confirming the validity of the O-arm’s benefits over other imaging systems. A comparative study including other methods of imaging should be conducted in the future. Finally, the use of the O-arm exposes patients to a high dose of radiation. And, according to our knowledge, there are no reports on radiation doses during the

Fig. 5. Case 2. Lateral radiograph (A) showing a C6–7 lateral dislocation. Postoperative radiograph (B) showing good reduction. Postoperative CT scans (C and D) demonstrating CPS placements of Grade 0 at C-6 and C-7.

Fig. 6. Case 3. Lateral radiograph (A), CT (B), and MR image (C) showing pathological fractures at C-2 and C4–5, a metastasis from renal carcinoma. Postoperative lateral radiograph (D) showing occipitocervical fixation performed with O-arm–based navigation. Postoperative CTs (E and F) obtained at C-4 and C-5, showing Grade 2 CPS insertions on the right side. Intraoperative navigation images (G) obtained before CPS insertion, showing an acceptable trajectory of the pedicle screw (Grade 0).
Fig. 7. Photograph showing the working space restricted by the O-shaped tube during CPS insertion via real-time 2D fluoroscopy.

use of the O-arm. Hence, the radiation dose in this setting should be studied further.

Conclusions

The use of the O-arm navigational system offers high-resolution 2D and 3D images and enables clean and accurate CPS insertion. Furthermore, it has other potentially substantial benefits for cervical spine instrumentation. Even with current optimized technology, however, CPS perforation cannot be completely prevented. Minor violations (Grade 1, 8.3%), which would not cause significant complications, as well as major pedicle violations (Grade 2, 2.8%), which can cause catastrophic complications, were observed. Therefore, the combination of intraoperative 3D image-based navigation and other techniques may result in more accurate CPS placement.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Kanemura. Drafting the article: Ishikawa, Kanemura. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Ishikawa. Administrative/technical/material support: Kanemura. Study supervision: Kanemura.

References