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Clinical Article

Inferolateral Entry Point for C2 Pedicle Screw Fixation in High Cervical Lesions

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Objective : The purpose of this retrospective study was to evaluate the efficacy and safety of atlantoaxial stabilization using a new entry point for C2 pedicle screw fixation.

Methods : Data were collected from 44 patients undergoing posterior C1 lateral mass screw and C2 screw fixation. The 20 cases were approached by the Harms entry point, 21 by the inferolateral point, and three by pars screw. The new inferolateral entry point of the C2 pedicle was located about 3-5 mm medial to the lateral border of the C2 lateral mass and 5-7 mm superior to the inferior border of the C2-3 facet joint. The screw was inserted at an angle 30° to 45° toward the midline in the transverse plane and 40° to 50° cephalad in the sagittal plane. Patients received followed-up with clinical examinations, radiographs and/or CT scans.

Results : There were 28 males and 16 females. No neurological deterioration or vertebral artery injuries were observed. Five cases showed malpositioned screws (2.84%), with four of the screws showing cortical breaches of the transverse foramen. There were no clinical consequences for these five patients. One screw in the C1 lateral mass had a medial cortical breach. None of the screws were malpositioned in patients treated using the new entry point. There was a significant relationship between two group (p=0.036).

Conclusion : Posterior C1-2 screw fixation can be performed safely using the new inferolateral entry point for C2 pedicle screw fixation for the treatment of high cervical lesions.

Key Words : Atlantoaxial fixation · C2 pedicle screw · Entry point.

INTRODUCTION

The surgical management of atlantoaxial instability has evolved over the past three decades due to advances in instrumentation and understanding of spinal biomechanics. C1-C2 transarticular fixation with posterior wiring is an important surgical technique for the treatment of atlantoaxial instability resulting from trauma, tumors, inflammatory disease, and congenital malformations[3,7,22]. This technique demonstrates biomechanical superiority over posterior wiring alone and higher associated fusion rates[2]. However, C1-C2 transarticular fixation with posterior wiring carries a risk of iatrogenic injury to the vertebral artery (VA) in cases of high riding and anomalously positioned VA[16,33]. Disadvantages of this technique include the inability of clinicians to achieve intraoperative reduction and difficulties applying the technique in obese patients. This technique is also contraindicated in patients with damage to the posterior column and fixed severe anterior dislocations of the atlas.

Atlantoaxial stabilization with C1 lateral mass and C2 pedicle screws using polyaxial screw-rod fixation, as described by Harms and Melcher in 2001[9], provides comparable stability to transarticular screw fixation[18,19]. Early clinical experiences with this technique have demonstrated that it is better for preventing VA injury than is transarticular screw placement[1,5,28]. Atlantoaxial stabilization with C1 lateral mass and C2 pedicle screws has other advantages, such as the possibility of intraoperative reduction, and is less challenging than the placement of transarticular screws. However, despite these advantages, the technique is still associated with risk of VA injury. Recent reports suggest that C2 pedicle screw placement has nearly the same risk of VA injury as does transarticular fixation, and that the position of the transverse foramen of C2 is the major limiting factor for the placement of C2 pedicle screws[23,35]. Therefore, we have endeavored to reduce cortical breaches of the transverse foramen and VA injury and by designing a new inferolateral entry point for atlantoaxial stabilization.

The purpose of this retrospective study was to evaluate the efficacy and safety of atlantoaxial stabilization using a new inferolateral entry point for C2 pedicle screw fixation.

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MATERIALS AND METHODS

We undertook a retrospective review of the medical records of 51 patients who were treated with posterior C1 lateral mass and C2 screw fixation for upper cervical instability at our institute between October 2004 and January 2010. Seven cases that also underwent occipitocervical fusion and extended fixation to the subaxial spine were excluded from the sample. Therefore, data were collected for 44 patients, 28 males and 16 females. Patient ages ranged from 4 to 84 years, with a mean age of 47.7 years. Of the 44 cases, 21 were diagnosed with traumatic fractures, 13 with transverse ligament injuries, five with os odontoideum, four with rheumatoid arthritis and one with retro-odontoid pseudotumor (Table 1). All of the patients underwent preoperative cervical spine radiographs, three-dimensional angiography computed tomography (CT) scans with sagittal and coronal reconstruction, and/or magnetic resonance imaging (MRI).

Table 1. Summary of characteristics in 44 patients

Characteristics	Value
Sex	
Male	28
Female	16
Age (yrs)	
Average	47.7
Range	4-84
Indication of op	
Traumatic fracture	21
Transverse ligament injury	13
Os odontoideum	5
Reumatoid arthritis	4
Retro-odontoid pseudotumor	1
Follow-up duration (mos)	
Average	18.6
Range	6-53

Surgical technique

Each patient was placed in the prone position under general anesthesia with fiberoptic intubation. The patient's head was neutral or slightly flexed in a military like posture. A midline incision was made to expose the posterior elements of the upper cervical spine from the caudal rim of the foramen magnum to the edge of the C3 lamina and laterally to the external edges of the articular processes. After the C1 posterior arch was exposed completely, we marked the entry point in the center of the C1 lateral mass. After drilling through the C1 posterior arch via the notching technique, a pilot hole was carefully made with a high-speed drill at the midpoint of the posterior arch of C1. After further hand drilling and tapering, polyaxial titanium screws with a diameter of 3.5-4.0 mm and length of 28-32 mm were inserted. The C1 lateral mass screw was directed 10-20° medially and cephalad, aiming at the anterior tubercle under fluoroscopic guidance. Individual anatomical variation in the C1-2 complex, such as bony and vascular (V3 segment) anomalies, was evaluated for each patient. Pars screw fixation with screws 3.5-4.0 mm in diameter and 12-14 mm in length was performed in three patients. The entry point was 3 mm rostral to the inferior edge of the lateral mass and was directed toward the superior facet-pars junction. For 20 patients treated using the Harms technique (group 1), the entry point of the C2 pedicle screw was located at the superior and medial quadrant of the lateral mass surface (Fig. 1A). The direction of the C2 pedicle screw was approximately 20° to 30° medial and cephalad (Fig. 2A) with a screw 3.5-4.0 mm in diameter and 20-32 mm in length, guided directly by the superior and medial surfaces of the C2 isthmus, taking into account individual anatomic variations. In the remaining patients, the new inferolateral entry point for the C2 pedicle screw (group 2) was located at the inferior and lateral quadrants of the lateral mass of C2. After careful evaluation of V3 segment anomalies, the pedicle diameter, and medial and cephalad angulations of screw passage on preoperative 3D angiography CT, the pars was identified, and the superior and medial borders of the pedicle were delineated in the spinal canal. The new inferolateral entry point of the C2 pedicle was about 3-5 mm medial to the lateral border of the C2 lateral mass and 5-7 mm superior to the inferior border of the C2 facet joint (Fig. 1A). The direction of the screw used in the C2 pedicle had a more convergent and more cephalad trajectory than that used in the Harms technique (Fig. 1A, B). The screw was positioned at 30° to 45° toward the midline in the transverse plane (Fig. 2D, E) and at 40° to 50° cephalad in the sagittal plane (Fig. 2B, C) with 3.5-4.0 mm in diameter and 20-32 mm in length. There

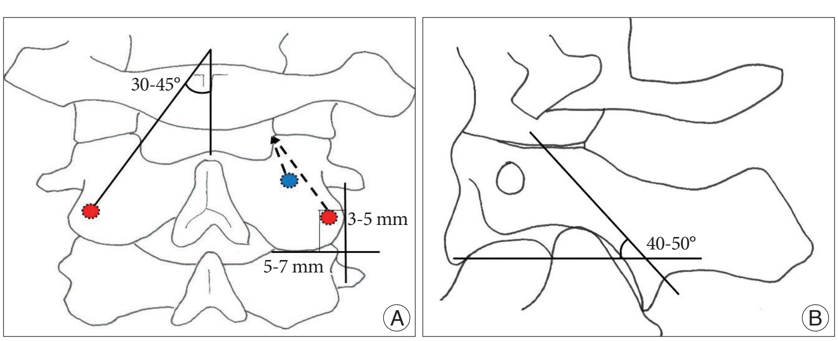

Fig. 1. The comparison of two different entry points. As the Harms technique, the entry point (blue circle) for the C2 pedicle screw is used at the superior and medial quadrant of the isthmus surface. On the other hand, the inferolateral entry point (red circle) for the C2 pedicle screw is used at the inferior and lateral quadrant of the lateral mass of C2. The inferolateral entry point for the C2 screw fixation about 3-5 mm medial to the lateral border of C2 lateral mass and 5-7 mm superior to the inferior border of C2-3 facet joint and 30° to 45° towards the midline in the transverse plane in posterior view (A) and 40-50° cephalad in lateral view (B) with more convergent and more cephalad trajectory (perforated line) (A).

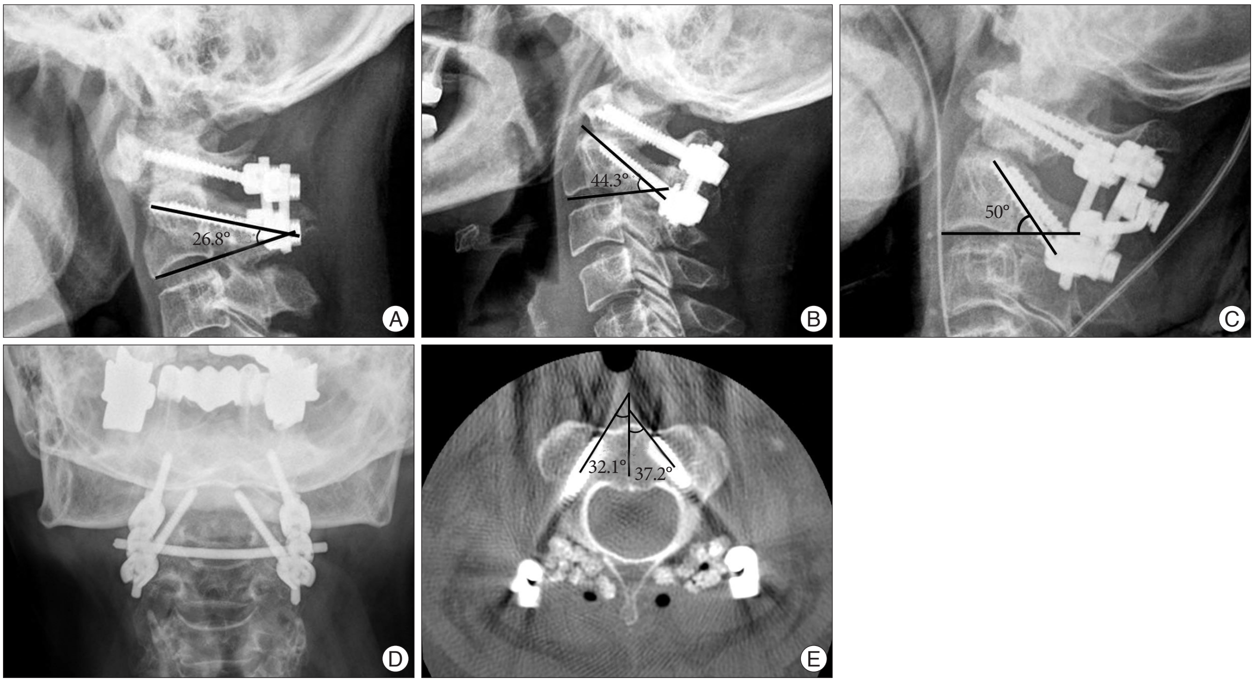

Fig. 2. The inferolateral entry point is a more medial angulation (D and E) and more cephalad trajectory (B and C) than the Harms technique (A). In cases with high risks of vertebral artery injury, the surgical technique using the C2 screw fixation not to penetrate the pedicle entirely but to insert to the superior facet-pars junction could be performed (C).

would be no otherwise confusion in determing the inferolateral entry point compared with the Harms technique, if the entry point would be located below half surface of the C2 lateral mass in the lateral radiograph and determined with considering personal anatomical variation of the C2 lateral mass. The trajectory of the screw was defined using the superior and medial aspects of the C2 pedicle as a guide. After placing all screws, we attempted to reduce the C1-2 complex just before fixing the joint with screws to achieve anatomical alignment. C1-2 instability was reduced by either pushing the C2 spinous process and pulling the C1 posterior arch or by extending the head. Rods were contoured to form physiologic lordosis and were connected to the screws. The instrumentation used Summit (DePuy Spine) or Vertex (Medtonic Sofamor Danek).

We decorticated the surfaces of the C1 and C2 posterior elements. Of the 41 cases, five were treated by wiring with strut iliac bone grafts, and 39 were treated with synthetic bone grafts. Synthetic bone allografts (hydroxyapatite, bongros-HA, Daewoong Pharm. Co., Ltd., Korea) were used alone and placed over the decorticated surfaces. Except for the five cases treated by wiring with strut iliac bone grafts, the wounds were closed in a standard fashion over a suction drain.

All patients were instructed to wear a Philadelphia-type cervical collar for 8-12 weeks after surgery and were encouraged to attempt ambulation one day after surgery. Patients were followed-up with clinical examinations, radiographs and/or CTs.

Differences between groups were analyzed using Pearson's Chi-square tests and Fisher exact tests in SPSS 12.0 for Windows. *p*-values <0.05 were considered statistically significant.

RESULTS

No other intraoperative complications were observed. No patients experienced postoperative worsening of neurological function related to the procedure. No evidence of spinal cord injury or cerebrospinal leakage was detected in any patient. Radiographs taken immediately after surgery showed satisfactory screw placement and reduction in nearly all of the patients. After surgery, 16 patients showed improvement of 1.25 Frankel grades.

The positioning of the C2 screw was evaluated via postoperative CT scans. We defined correctly inserted screws as those observed passing through the C2 pedicle to the C2 body without breaching the cortex of the pedicle, including the transverse foramen. Of a total of 176 inserted C1 and C2 screws, only five were malpositioned (2.84%). However, of the 88 screws inserted into C2, 4.54% were malpositioned, indicating that the insertion of C2 screws in the C2 pedicle was more difficult. Although screw threads slightly penetrated the C2 transverse foramen in four patients, there were no associated VA injuries or clinical consequences. Among the malpositioned C2 pedicle screws, all of them were in patient group 1, which included patients treated by the Harms technique, and none were associated with clinical consequences. There were no malpositioned screws in group 2 patients, who were treated using the new inferolateral entry point. The statistical significance between two groups was observed ($p=0.036$) (Table 2). Of a total of 88 screws that were inserted into the C1 lateral mass, one screw passed into the spinal canal but was not associated with any postoperative neurologic

Table 2. C2 pedicle screw breaching (p=0.036)

	Number of screw	Number of breaching case
Harms entry point	40	4
Inferolateral entry point	42	0
Pars screw	6	0

deterioration.

Four patients complained of postoperative occipital paresthesia due to manipulation of the C2 ganglion. In three of these patients, the paresthesia subsided spontaneously. The remaining patient complained of persistent paresthesia requiring medication. Two patients in whom we sectioned the C2 nerve root did not complain of any related symptoms. We observed subacute cerebellar infarction in the posterior inferior cerebellar artery territory during the early postoperative stage in one patient with traumatic head injury for reasons unrelated to surgery. Three patients with superficial wound infections were treated conservatively with antibiotics and local wound care. The mean follow-up duration was 18.4 months (range, 6-53 months).

DISCUSSION

In 1986, Magerl and Seeman[17] first described direct transarticular C1-C2 screw fixation combined with posterior wiring techniques for bony fusion. This technique provided greater stability in rotator motion than did the posterior wiring technique and results in higher fusion rates than does wiring alone[6,8,31]. Although this technique does not require intact posterior vertebral elements, there is a potential risk of spinal cord injury when passing the sublaminar wires under the lamina[2,18,22,24]. Additionally, this technique is limited for use in patients with anatomical variations such as a high riding transverse foramen, anomalous VA position, severe cervicothoracic kyphosis or non-reducible C1-C2 subluxation[2,22].

New techniques were developed by Goel and Harms to overcome the limitations of transarticular screw fixation. Recently, many surgeons have performed C1 lateral mass and C2 pedicle screw fixation in high cervical lesions. This technique has several advantages including low risk of neurovascular injury and obviating the manipulation of C1 or C2 screws. Although the risk of VA is low in C1 lateral mass and C2 pedicle screw fixation[1,5,28], some risk remains and can result in serious complications. Harms and Melcher's technique is considered to be less demanding and to be associated with decreased risk of VA injury compared to C1 lateral mass and C2 pedicle screw fixation in high cervical lesions[1,5,28]. However, recent reports indicate that C2 pedicle screw placement has nearly the same risk of VA injury as transarticular fixation, and that VA injury is still a limiting factor for successful C1-2 fixation[23,35]. Our surgical experiences with 44 cases of high cervical lesions clearly support this finding.

Several methods should be considered to minimize VA injury during surgery. First, preoperative vascular and bony anomalies, such as V3 segment anomalies or posterior ponticuli, should be evaluated by 3D angiography CT and/or MRI. Second, occipitocervical fusion, transarticular fixation, superior lateral mass screws, C1 hooks, or posterior arch screws were surveyed in cases of V3 segment anomalies. Third, short C2 pars screws or translaminar screw fixation may be options in cases of high-riding VA or medially positioned VA[13]. Recent biomechanical studies suggest that translaminar screw fixation is less rigid than pars screw fixation[14,15], and clinical studies suggest that higher pseudoarthrosis rates are also associated with translaminar screw fixation[20,27,32]. Although some studies found that C2 pars screwing is biomechanically similar to transarticular fixation and is similarly safe and effective[11,21], the short lengths of the resulting pars screw passages do not guarantee stability, especially in areas of low bone quality.

Some previous studies have compared the effects of different entry points for C2 screws (Table 3)[4,10,22,25,26,29,30,34]. In 1993, Smith et al.[29] suggested an entry point 3-5 mm above the center of the C2-3 facet, with the screw oriented cranially 20° to 30° degrees and medially 15° to 20°. In 1996, Ebraheim et al.[4] suggested a similar entry point to that used in the Goel-Harms technique, 5 mm inferior to the superior border of the C2 lamina and 7 mm lateral to the lateral border of the spinal canal. The trajectory of the screw in this technique is 30° medial and 20˚ cephalad. In 1996, Abumi et al.[4,25] suggested using the superior margin of the lamina of C2 as a landmark for screw penetration into the lateral mass of C2. The insertion angle of the screw for the C2 pedicle was 15-25° medial to the midline in the transverse plane and slightly cephalad in the sagittal plane.

In 2006, Yeom et al.[34] reported using subarticular screws with an entry point 3 mm inferior to the posterior articular surface and angled 30° to 40° toward the anterosuperior articular process of C2. The screw was inserted close to the superomedial border of the superior articular process. The breaching rate of C2 screws associated with this technique was only 2.5%. However, this procedure is accompanied by a risk of bleeding from the epidural venous plexus during dissection because more advanced dissection is required, and the C2 roots must be occasionally sacrificed. This procedure requires highly skilled surgeons.

In 2009, Sciubba et al.[26] described a very high entry point at the lateral aspect of the C2 lateral mass, just 1.75 mm caudal to the transition of the lateral mass into the C2 pars. This technique is associated with low risk of VA injury because it involves relatively more medial angulation than do the other techniques. However, as in cases of high-riding VA, enlarged transverse foramina and hypoplastic pedicles, the risk of VA injury remains similar to those associated with other techniques. Moreover, if the screw does not penetrate the pedicle, stability is sacrificed due to the use of short screws. The risk of bleeding is also elevated due to the risk of dissection of the epidural venous plexus.

In 2010, Hoh et al.[10] suggested an entry point 3 mm rostral to

Table 3. Descriptions of C2 screw

Authors	Entry point	Trajectory	Comments
Magerl and Seeman (1986)	The posterior C2 cortex 2-3 mm above the C2 inferior facet joint & 3 mm lateral to the medial border of the C2-3 facet	Posterior cortex of the anterior C-1 arch 0-10° medially	Transarticular screw Highly fusion rate Need preop. Reduction Limitation to anatomical variations*
Smith et al. (1993)	3-5 mm above the center of the C2-3 facet	Cranially 20-30° Medially 15-20°	Similar to risk of VA injury with respect to other techniques
Goel (1994) and Harms (2001)	The cranial and medial quadrant of the isthmus surface (5 mm inferior to the superior border of C2 lamina and 7 mm lateral to the lateral border of the spinal canal)	20-30° in a convergent and cephalad direction Guided directly by the superior and medial surface of the C2 isthmus	C2 pedicle screw Possible to Intraoperatives reduction Less limitation to anatomical variations but, risk of VA injury is still remained
Ebraheim et al. (1996)	5 mm inferior to the superior border of the C2 lamina & 7 mm lateral to the lateral border of the spinal canal	Medially 30° Cranially 20°	Smilar to Goel and Harms techniques
Abumi et al. (1996)	The superior margin of the lamina of C2 was a landmark for the point of screw penetration into the lateral mass of C2	Medially 15-25° slightly cephald	Similar to risk of VA injury with respect to other techniques
Yeoms et al. (2006)	3 mm inferior to the posterior articular surface	30-40° angled toward the anterosuperior articular process of C2	Subarticular screw High bleeding risk Similar to risk of VA injury with respect to other techniques
Sciubba et al. (2009)	lateral aspect of the C2 lateral mass, at just 1.75 mm caudal to the transition of the lateral mass into the C2 pars	Very high & lateral entry point Cephalad trajectory is determined by the slope of the pars or isthmus	Low risk of VA injury with respect to other techniques But, possible to Less stable in case of anatomical variations (not penetrated pedicle) Bleeding risk
Hoh et al. (2010)	3 mm rostral to the inferior aspect of the lateral mass	Similar to transarticular screw	Long pars screw, not pedicle screw Similar risk of VA injury to transarticular screw due to less medial trajectory Much larger skin incision

*Anatomical variations mean high-riding VA, anomalous transverse foramen, narrow pedicle (<4 mm), cervicothoracic kyphosis, obese, or non-reducible C1-2 subluxation. VA : vertebral artery

the inferior aspect of the lateral mass, as in the transarticular screw technique. Such a trajectory is used not with a true pedicle screw, but with a long pars screw. This technique involves less medial angulation, and therefore the risk of VA injury is increased in cases of high-riding VA, enlarged transverse foramina and hypoplastic pedicles. Additionally, such a steep cephalad angulation is required that much larger incisions or separate, more caudal stab incisions are frequently necessary to achieve the appropriate angulation.

Despite the number of previous studies examining the effects of different trajectories and entry points, the risk of VA injury has remained almost constant. Therefore, we proposed a new, inferolateral entry point of the C2 pedicle to reduce the risk of VA injury. We experienced four breached screws that threatened to cause VA injury when using the Harms technique, despite employing a cautious surgical technique. Using 3D angiography CT scans with sagittal and coronal reconstructions, we evaluated the diameters and angles of pedicles and the shapes of lateral mass-pars. We concluded that more medial angulation through an entry point that is more lateral than those used in previous studies would be required to reduce the risk of VA injury. Recent CT studies support this hypothesis[10,12,30]. Howington et al.[12] examined ten cadavers and found that the average medial and cephalad angulations measured 35.2° and 38.8°, respectively. Smith et al.[30] reported that the overall mean pedicle width was 5.8±1.2 mm and the overall mean pedicle transverse angle was 43.9±3.9°. Hoh et al.[10] reported that a 15° medial trajectory through the pars increases pars length by approximately 3.5% compared to that of a screw with 0° medialization. Therefore, the use of 10-15° of medialization may allow for longer screw length. We also found that the use of a more inferior entry point with a more cephalad trajectory enabled us to secure sufficient screw length without penetration of the pedicle into the C2 body.

Our new inferolateral point for C2 pedicle screw fixation is about 3-5 mm medial to the lateral border of the C2 lateral mass and 5-7 mm superior to the inferior border of the C2-3 facet joint, aiming toward the superior and medial wall of the C2 pedicle 30° to 45° toward the midline in the transverse plane and 40° to 50° cephalad in the sagittal plane. Our results indicate that the use of the inferolateral entry point for the C2 pedicle screw reduces the risks of screw malpositioning and VA injury (p=0.036). The inferolateral entry point allows more medial angulation, thereby lowering the risk of VA injury. When the course of the VA is normal or there is sufficient pedicle diameter (>5 mm) for pedicle screw fixation as reported by Yoshida et al.[35], we performed conventional pedicle screw fixation through the pedicle into the C2 body. However, in cases with high risks of VA injury such as high-riding VA, aberrant VA courses, or narrow pedicles (<5 mm), we performed screw fixation without penetrating the pedicle but achieved fixation to the superior facet-pars junction with fixing our eyes on lateral radiograph (Fig. 2C). Although this procedure sometimes requires slightly larger skin incisions due to the more cephalad angulation required in patients with short necks, obese patients, or patients with thoracic kyphosis, in most cases, the skin incision is not as long as that required for transarticular fixation and is similar to conventional skin incisions that are made following skin retraction to preserve angulation. The use of recent surgical techniques incorporating computer-assisted navigation systems increases the accuracy of C2 pedicle screw fixation. When such navigation is used, greater safety and accuracy may be achieved.

Although the clinical and radiological improvements demonstrated by the current study are significant, formal biomechanical evaluations and longer follow-ups of a large series of patients are needed to clarify the clinical effectiveness and safety of our new C2 pedicle screw fixation technique.

CONCLUSION

C1-2 fixation using an inferolateral entry point for C2 screw fixation is a safe and effective alternative technique for the surgical treatment of high cervical lesions. However, biomechanical evaluations and longer follow-ups of large patient series are needed to clarify the clinical effectiveness and safety of this technique.

References

1. Chen JF, Wu CT, Lee SC, Lee ST : Posterior atlantoaxial transpedicular screw and plate fixation. Technical note. **J Neurosurg Spine 2** : 386-392, 2005
2. Coyne TJ, Fehlings MG, Wallace MC, Bernstein M, Tator CH : C1-C2 posterior cervical fusion : Long-term evaluation of results and efficacy. **Neurosurgery 37** : 688-692; discussion 692-693, 1995
3. Dickman CA, Sonntag VK : Posterior C1-C2 transarticular screw fixation for atlantoaxial arthrodesis. **Neurosurgery 43** : 275-280; discussion 280-281, 1998
4. Ebraheim N, Rollins JR Jr, Xu R, Jackson WT : Anatomic consideration of C2 pedicle screw placement. **Spine (Phila Pa 1976) 21** : 691-695, 1996
5. Goel A, Desai KI, Muzumdar DP : Atlantoaxial fixation using plate and screw method : a report of 160 treated patients. **Neurosurgery 51** : 1351-1356; discussion 1356-1357, 2002
6. Grob D, Crisco JJ 3rd, Panjabi MM, Wang P, Dvorak J : Biomechanical evaluation of four different posterior atlantoaxial fixation techniques. **Spine (Phila Pa 1976) 17** : 480-490, 1992
7. Haid RW Jr, Subach BR, McLaughlin MR, Rodts GE Jr, Wahlig JB Jr : C1-C2 transarticular screw fixation for atlantoaxial instability : a 6-year experience. **Neurosurgery 49** : 65-68; discussion 69-70, 2001
8. Hanson PB, Montesano PX, Sharkey NA, Rauschning W : Anatomic and biomechanical assessment of transarticular screw fixation for atlantoaxial instability. **Spine (Phila Pa 1976) 16** : 1141-1145, 1991
9. Harms J, Melcher RP : Posterior C1-C2 fusion with polyaxial screw and rod fixation. **Spine (Phila Pa 1976) 26** : 2467-2471, 2001
10. Hoh DJ, Liu CY, Wang MY : A radiographic computed tomography-based study to determine the ideal entry point, trajectory, and length for safe fixation using C-2 pars interarticularis screws. **J Neurosurg Spine 12** : 602-612, 2010
11. Hott JS, Lynch JJ, Chamberlain RH, Sonntag VK, Crawford NR : Biomechanical comparison of C1-2 posterior fixation techniques. **J Neurosurg Spine 2** : 175-181, 2005
12. Howington JU, Kruse JJ, Awasthi D : Surgical anatomy of the C-2 pedicle. **J Neurosurg 95** : 88-92, 2001
13. Kim SY, Jang JS, Lee SH : Posterior atlantoaxial fixation with a combination of pedicle screws and a laminar screw in the axis for a unilateral high-riding vertebral artery. **J Korean Neurosurg Soc 41** : 141-144, 2007
14. Lapsiwala SB, Anderson PA, Oza A, Resnick DK : Biomechanical comparison of four C1 to C2 rigid fixative techniques : anterior transarticular, posterior transarticular, C1 to C2 pedicle, and C1 to C2 intralaminar screws. **Neurosurgery 58** : 516-521; discussion 516-521, 2006
15. Lehman RA Jr, Dmitriev AE, Helgeson MD, Sasso RC, Kuklo TR, Riew KD : Salvage of C2 pedicle and pars screws using the intralaminar technique : a biomechanical analysis. **Spine (Phila Pa 1976) 33** : 960-965, 2008
16. Madawi AA, Casey AT, Solanki GA, Tuite G, Veres R, Crockard HA : Radiological and anatomical evaluation of the atlantoaxial transarticular screw fixation technique. **J Neurosurg 86** : 961-968, 1997
17. Magerl F : Stable posterior fusion of the atlas and axis by transarticular screw fixation. **Cervical Spine 1** : 322-327, 1987
18. Melcher RP, Puttlitz CM, Kleinstueck FS, Lotz JC, Harms J, Bradford DS : Biomechanical testing of posterior atlantoaxial fixation techniques. **Spine (Phila Pa 1976) 27** : 2435-2440, 2002
19. Paramore CG, Dickman CA, Sonntag VK : The anatomical suitability of the C1-2 complex for transarticular screw fixation. **J Neurosurg 85** : 221-224, 1996
20. Parker SL, McGirt MJ, Garcés-Ambrossi GL, Mehta VA, Sciubba DM, Witham TF, et al. : Translaminar versus pedicle screw fixation of C2 : Comparison of surgical morbidity and accuracy of 313 consecutive screws. **Neurosurgery 64** : 343-348; discussion 348-349, 2009
21. Payer M, Luzi M, Tessitore E : Posterior atlanto-axial fixation with polyaxial C1 lateral mass screws and C2 pars screws. **Acta Neurochir (Wien) 151** : 223-229; discussion 229, 2009
22. Reilly TM, Sasso RC, Hall PV : Atlantoaxial stabilization : clinical comparison of posterior cervical wiring technique with transarticular screw fixation. **J Spinal Disord Tech 16** : 248-253, 2003
23. Resnick DK, Lapsiwala S, Trost GR : Anatomic suitability of the C1-C2 complex for pedicle screw fixation. **Spine (Phila Pa 1976) 27** : 1494-1498, 2002
24. Richter M, Schmidt R, Claes L, Puhl W, Wilke HJ : Posterior atlantoaxial fixation : biomechanical in vitro comparison of six different techniques. **Spine (Phila Pa 1976) 27** : 1724-1732, 2002
25. Roy-Camille R, Saillant G, Mazel C : Internal fixation of the unstable cervical spine by a posterior osteosynthesis with plates and screws in Sherk HH, Dunn EJ, Eismont FJ (eds) : **The Cervical Spine**, ed 2. Phila-

delphia : JB Lippincott, 1989, pp390-403
26. Sciubba DM, Noggle JC, Vellimana AK, Alosh H, McGirt MJ, Gokaslan ZL, et al. : Radiographic and clinical evaluation of free-hand placement of C-2 pedicle screws. **J Neurosurg Spine 11** : 15-22, 2009
27. Sciubba DM, Noggle JC, Vellimana AK, Conway JE, Kretzer RM, Long DM, et al. : Laminar screw fixation of the axis. **J Neurosurg Spine 8** : 327-334, 2008
28. Shen FH, Samartzis D, Jenis LG, An HS : Rheumatoid arthritis : evaluation and surgical management of the cervical spine. **Spine J 4** : 689-700, 2004
29. Smith MD, Anderson P, Grady MS : Occipitocervical arthrodesis using contoured plate fixation. An early report on a versatile fixation technique. **Spine (Phila Pa 1976) 18** : 1984-1990, 1993
30. Smith ZA, Bistazzoni S, Onibokun A, Chen NF, Sassi M, Khoo LT : Anatomical considerations for subaxial (C2) pedicle screw placement : a radiographic study with computed tomography in 93 patients. **J Spinal Disord Tech 23** : 176-179, 2010
31. Stillerman CB, Wilson JA : Atlanto-axial stabilization with posterior transarticular screw fixation : technical description and report of 22 cases. **Neurosurgery 32** : 948-954; discussion 954-955, 1993
32. Wang MY : Cervical crossing laminar screws : early clinical results and complications. **Neurosurgery 61** : 311-315; discussion 315-316, 2007
33. Wright NM, Lauryssen C : Vertebral artery injury in C1-2 transarticular screw fixation : results of a survey of the AANS/CNS section on disorders of the spine and peripheral nerves. American Association of Neurological Surgeons/Congress of Neurological Surgeons. **J Neurosurg 88** : 634-640, 1998
34. Yeom JS, Won JH, Park SK, Kwon YJ, Yoo SM, An YH, et al. : The subarticular screw : A new trajectory for the c2 screw. **J Korean Soc Spine Surg 13** : 75-80, 2006
35. Yoshida M, Neo M, Fujibayashi S, Nakamura T : Comparison of the anatomical risk for vertebral artery injury associated with the C2-pedicle screw and atlantoaxial transarticular screw. **Spine (Phila Pa 1976) 31** : E513-E517, 2006