International Journal of Surgery Science 2021; 5(3): 359-364

E-ISSN: 2616-3470
P-ISSN: 2616-3462
© Surgery Science
www.surgeryscience.com
2021; 5(3): 359-364
Received: 25-04-2021
Accepted: 15-06-2021

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Precision of atlantoaxial screw placement during computed tomography-assisted navigation system-assisted surgery: Single-level registration of the vertebrae

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DOI: https://doi.org/10.33545/surgery.2021.v5.i2f.968

Abstract
Objective: A well-known method for treating atlantoaxial instability is posterior screw fixation using a C1 lateral mass screw and a C2 pedicle screw. Yet, due to the intricate anatomical anatomy of this area, screw malposition might happen. This study used a preoperative computed tomography (CT)-based navigation system with a single-level vertebral registration approach to assess the accuracy and risk factors of cortical breach following the insertion of the C1 lateral mass and/or C2 pedicle screw.
Methods: Patients who had preoperative CT-based navigation for the implantation of a C2 pedicle screw and/or a C1 lateral mass at the university hospital between January 2013 and March 2020 were included in this retrospective cohort analysis. Inside the pedicle (grade 0), out of the pedicle 2 mm (grade I), from 2 to 4 mm (grade II), and > 4 mm were the classifications for screw deviation (grade III). Using the use of multivariate analysis, the risk of cortical breach was assessed.
Results: 42 patients had 78 C1 lateral masses and 71 C2 pedicle screws implanted. 133 grade 0 screws (89.3%) were placed accurately, followed by 14 grade I screws (9.4%) and two grade II screws (1.3%). No vertebral artery damage or neurological impairment was connected to this method, and no screws needed to be repositioned. The multivariate analysis also revealed that the cortical rupture had a diameter of less than 5 mm.
Conclusions: A preoperative CT-based navigation system with a single-level registration approach might be used to insert C1 lateral mass securely and successfully and C2 pedicle screws. The C1 lateral mass and C2 pedicle diameters are risk factors for cortical rupture.

Keywords: Atlantoaxial C1 lateral mass C2 pedicle Navigation system Pedicle screws

1. Introduction

Due to the anatomy of the atlantoaxial vertebral complex, its proximity to vascular and neural structures, and the requirement for a high degree of accuracy to avoid complications, posterior screw fixation of the upper cervical spine using C1 lateral mass screws (C1LM) and C2 pedicle screws (C2PS) is challenging. Nevertheless, since it was first described by Goel *et al.* [1] and later published by Harms *et al.* utilising polyaxial screws and rods, this approach has been frequently employed. [2] Regrettably, anatomical variations such the high-riding vertebral artery (HRVA), the tiny C2-pedicle diameter, and the persisting first intersegmental vertebral artery may have an impact on this treatment. [3, 4] A small C2-pedicle diameter and the prevalence of HRVA have both been reported to occur in 8–31% of patients in various studies. Even when carried out by skilled surgeons, the instrumentation of the C1LM-C2PS based on anatomic landmarks or intraoperative fluoroscopy is remarkably inaccurate. The frequency of the breach varies between 5 and 21%. Neurosurgery has made use of navigation systems. For the fixation of the C1-C2 junction, preoperative cervical computed tomography (CT) and spinal navigation may increase cortical screw placement precision and reduce exposure to fluoroscopy radiation. In particular, while treating atlantoaxial instability, the value of registering the intraoperative navigation system before screw insertion has not been adequately examined. The aim of this study, using a preoperative CT-based navigation system with single-level vertebral bodies, was to investigate the reliability of C1LM and C2PS as well as the prognostic variables for breach rates.

2. Materials and methods

From January 2013 to March 2020, the College Hospital performed a retrospective evaluation of all consecutive patients who underwent C1LM or C2PS screw insertion utilising a preoperative CT-based navigation system. The placement of screws was guided by a frameless stereotactic image-guidance system (Spine and Trauma 3D module; Brain Lab, Munich, Germany). A top surgeon had implanted C1LM or C2PS screws in each patient (TO). Without postoperative CT scans, patients were not included. Clinical information was recorded, including sex, age, and the cause of cervical spine instability. Also, anaesthetic records were used to collect operating information, such as the kind of procedure, blood loss, problems, and operation time, which is the period of time from the first incision to closure. Neurological state, screw insertion precision, and fusion rates were the end measures. Preoperative CT was performed on all patients to measure the C1LM and C2PS diameters and determine how they relate to the foramen transversarium, as reported in prior research [6]. This information was given to a navigation system. Using postoperative CT images, the screw accuracy was assessed by two independent reviewers. Four degrees of screw placement were established [10]: Grade 0: no perforation with the screw correctly put into the pedicle; Grade 1: mild perforation; Grade 3: complete perforation; >4 mm.

2.1. Surgical procedure

Vertebral single-level registration The patient was first positioned in a prone posture with the head in a cushioned holder and a skull tong with continuous traction or restrained in a Mayfield clamp following anaesthesia induction. The cervical spine's correct alignment was then quickly confirmed using lateral fluoroscopy. The bone transplant was then prepped and draped to be harvested from the posterior iliac crest. The medial side of the C1 lateral mass, the medial border of the C2 pars interarticularis, and the C2-3 facet joints were exposed with the use of a typical posterior midline approach and muscle and soft tissue dissection. Following sufficient exposure, we attached the vertebrae through a process known as "single-level vertebral registration." Vertebral single-level registration the patient was first positioned in a prone posture with the head in a cushioned holder and a skull tong with continuous traction or restrained in a Mayfield clamp following anaesthesia induction. Lateral fluoroscopy was used to immediately establish that the cervical spine was aligned correctly. The posterior iliac crest was then prepared and wrapped in preparation for the bone transplant. Using a standard posterior midline approach and muscle and soft tissue dissection, the medial side of the C1 lateral mass, the medial border of the C2 pars interarticularis, and the C2-3 facet joints were revealed. In order to connect the navigation tracking device (Brain Lab) to the spine at the same level of instrumentation as that used to prepare for the navigator system registration, we attached the vertebrae after adequate exposure using a procedure known as "single-level vertebral registration." For the purpose of C1 registration and instrumentation, the reference frame was positioned on the posterior tubercle of C1. In addition, the C2 spinous process was installed with the frame for C2 registration and instrumentation.

At each step of the instrument's orientation of the probe on anatomical landmarks, the navigation system's accuracy was checked. The C1 lateral mass's starting position and trajectory were then confirmed using a navigation probe. The inferior midpoint of the C1 lateral mass, which connects to the inferior aspect of the posterior arch, serves as the beginning point for the C1 lateral mass. The 2.5 mm drill bit with a drill guide was used to drill a slightly convergent trajectory in the posteroanterior plane and parallel to the posterior arch of C1 in the sagittal plane, as seen on the navigator probe. Subsequently, after drilling the hole, a navigator probe was inserted to confirm the trajectory of the drill hole, and the integrity of the drill hole track walls was verified using a ball-tipped feeler.

The hole was tapped, and a 3.5 mm polyaxial screw of an appropriate length was then inserted into the C1 lateral mass. The entry point of the C2 pedicle was the superior medial quadrant of the isthmus surface of C2, which was confirmed under the navigator guidance. The entry point was initially marked at 2 mm. A high-speed burr followed by a 2.5 mm twist hand drill and recheck of the track of the pilot hole was then made using a navigator probe. Subsequently, the integrity of all direction walls of the hole was checked with a ball-tip probe. The screw hole was tapped, and a 3.5 mm polyaxial screw of an appropriate length was inserted. To complete the screw-rod construct, a rod was then secured across the screw heads of C1 and C2. After applying rods connected to the screws, intraoperative fluoroscopy was performed to ensure actual sagittal alignment. Next, a rectangular cortico-cancellous iliac bone graft was fixed between the posterior arch of C1 and lamina of C2, according to the modified Gallie's technique. Alternatively, a cancellous iliac bone graft or artificial graft was placed over the decorticated C1 posterior arch and C2 lamina surfaces. Finally, C2 translaminar screws or C3 lateral mass screws provide alternative C2 screw fixation when the C2 pedicle cannot be inserted because it is too narrow or fractured.

Table 1: summarization of Patient demographics

Characteristics	Number (%)
Total number of patients	42
Mean of age ± SD, (years)	43.5 ± 22.7
(range)	(2,85)
Male	27 (64.3)
Diagnosis - Trauma	32 (76.2)
- Rheumatoid arthritis	6 (14.3)
- Spinal tumor	4 (9.5)
Procedure - C1LM + C2PS	21 (50)
- C1LM + C2PS/C2 laminar	6 (14.3)
- C1LM + C3, C4, or C5	11 (26.2)
- C2 – C5 or C7	3 (7.2)
- Occiput – C1C2	1 (2.4)
Bone graft - Onley iliac bone graft	11 (26.2)
- Onley artificial bone graft	4 (9.5)
- Gallie's or Sonntag's technique	25 (59.5)
- No bone graft	2 (4.8)
Operative time, mean ± SD (mins)	299 ± 54
(range)	(120, 420)
Estimated blood loss, mean ± SD (mL)	249 ± 167
Mean follow-up (months)	13.2 ± 14.1
(range)	(0,48)
Surgical site infection	4 (9.5)

2.2. Statistical analysis

Continuous variables are presented as means and standard deviations. We used Fisher's exact test or the Pearson chi-square test for categorical variables. Both univariate and multivariate analyses were used to identify the factors associated with the risk of cortical breach. Statistical significance was set at $P < 0.05$. Analyses were performed using R version 3.6.1 software (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

Forty-two patients underwent neuro navigation of the posterior C1- C2 spine fixation by single-level vertebral registration, including 27 men and 15 women with a mean age of 43.5 ± 22.7 years (22–85 years). The conditions for surgery were trauma in 32 patients (76.2 %), rheumatoid arthritis in six (14.3 %), and spinal tumor in four (9.5 %). The procedures comprised 27 cases of C1 lateral mass screws with C2 pedicle, short C2 pars or laminar C2 screws, 11 of C1 lateral mass to C3, C4 or C5 lateral mass screws, three of C2 pedicle to C3, C5 or C7, and a case of occiput to C2. Twenty-five patients (59.5 %) underwent sublaminar wiring and interlaminar bone grafting, and 15 patients only underwent bone grafting between the posterior rings of the C1 and C3 lamina. The mean operative time was 299 ± 54 min (120–420 min). There was no evidence of mispositioning or navigational inaccuracy during instrumentation in any of the patients. No vertebral artery, nerve root, or spinal cord injury occurred during intraoperative or postoperative surgery. Intraoperative estimated blood loss ranged from 50 to 1,000 mL, averaging 249 ± 167 mL. Surgical site infections occurred in four patients (9.5 %), which were successfully treated with open debridement, occlusive dressing, and intravenous antibiotics. No hardware failure occurred in this study. Patient demographics are summarized in Table 1.

Table 2: The patients' neurological status compared between the preoperative and postoperative periods is shown in Table

Age group (years)					
<40 ref			**ref**		
40–60 1.36	0.40–4.63	0.619	1.49	0.33–6.77	0.609
>60 0.97	0.27–3.55	0.967	0.53	0.10–2.85	0.463
Female 2.02	0.71–5.75	0.186	2.07	0.43–9.94	0.362
Trauma 1.63	0.52–5.07	0.399	0.92	0.17–4.97	0.926
Right side 2.37 screw	0.78–7.20	0.127	2.83	0.80–9.94	0.093
Pedicle 15.14	4.47–51.3	< 0.001	15.69	4.42–55.76	< 0.001

The patients' neurological status compared between the preoperative and postoperative periods is shown in Table 2. No new neurologic deficits were observed due to screw misplacement. However, one patient developed a new-onset neurological deficit due to the progression of an underlying brain tumor. The mean follow-up was 13.2 ± 14.1 months (0–48 months). A total of 155 atlantoaxial screws were placed in 42 patients, comprising 78 screws in the C1 lateral mass, 59 in the C2 pedicle, 12 in the short C2 pars, and six in the C2 translaminar. Short C2 pars or C2 translaminar or C3 lateral mass screws were intentionally used as the instrumentation site when the C2 anatomy was not conducive to screw placement (small diameter or pars interarticularis fracture). The incidence of an HRVA and small-diameter C2 pedicle (< 0.001), respectively (Fig. 3). The results showed that a large pedicle diameter resulted in a safer screw positioning. The C1 lateral mass and C2 pedicle diameters were both < 4 mm and had a 52.3 % risk of cortical breach. A surgical site diameter of 4–4.9 mm, 5–5.9 mm, 6–6.9 mm, or ≥ 7 mm, had a 23.8 %, 15 %, 4.5 %, and 0 % risk of cortical breach, respectively (Fig. 4). Regarding the pedicle diameter, the difference between the nonperforated and perforated groups was also significant (P = 0.001) (Fig. 5). The univariate and multivariate analysis results are presented in Table 3. When the multivariate analysis was applied, the independent factor associated with non-perforated pedicle screws (grade 0) increased (>5 mm) —pedicle diameter (OR 15.7, P < 0.001).

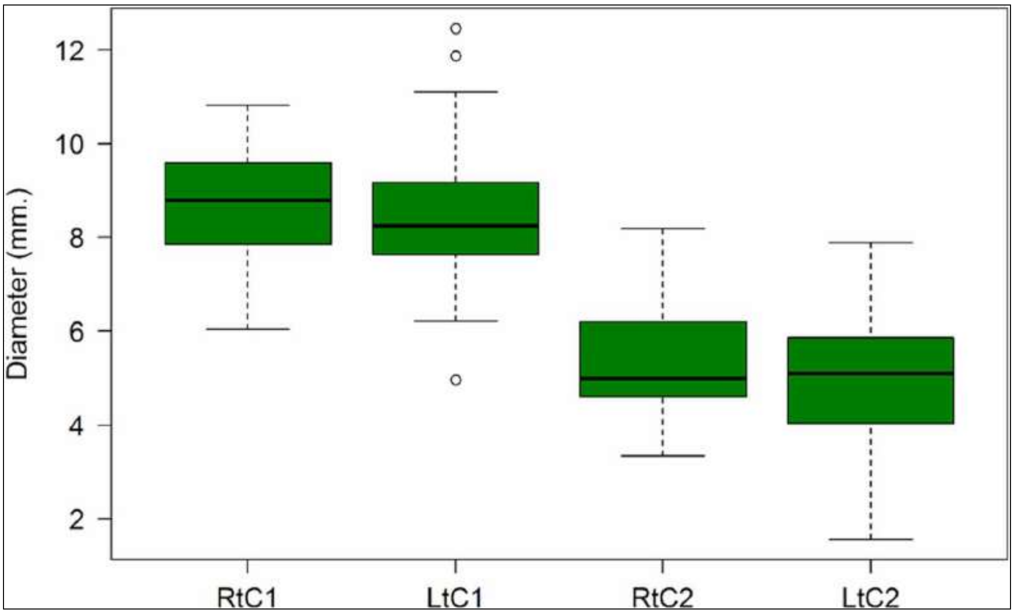

Fig 3: The incidence of an HRVA and small-diameter C2 pedicle

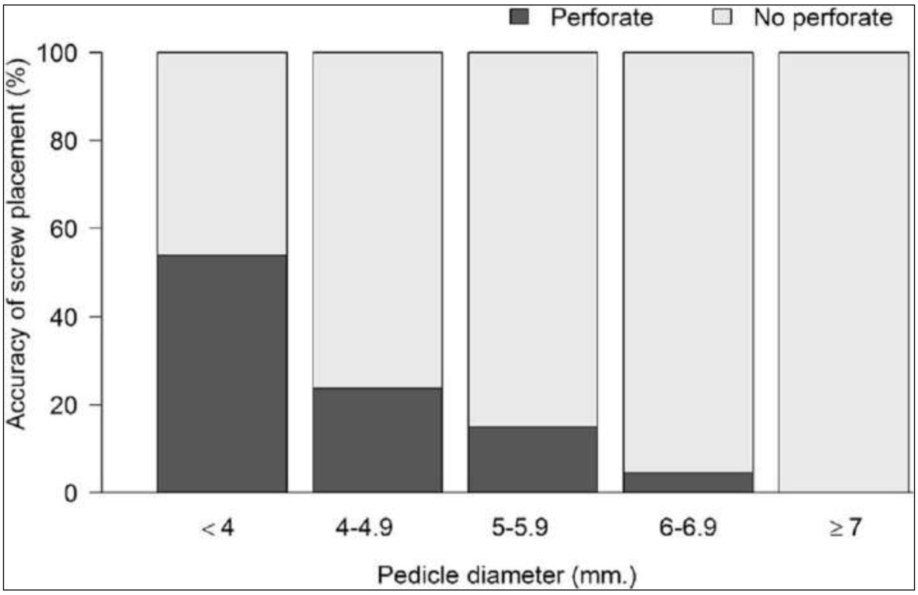

Fig 4: A surgical site diameter

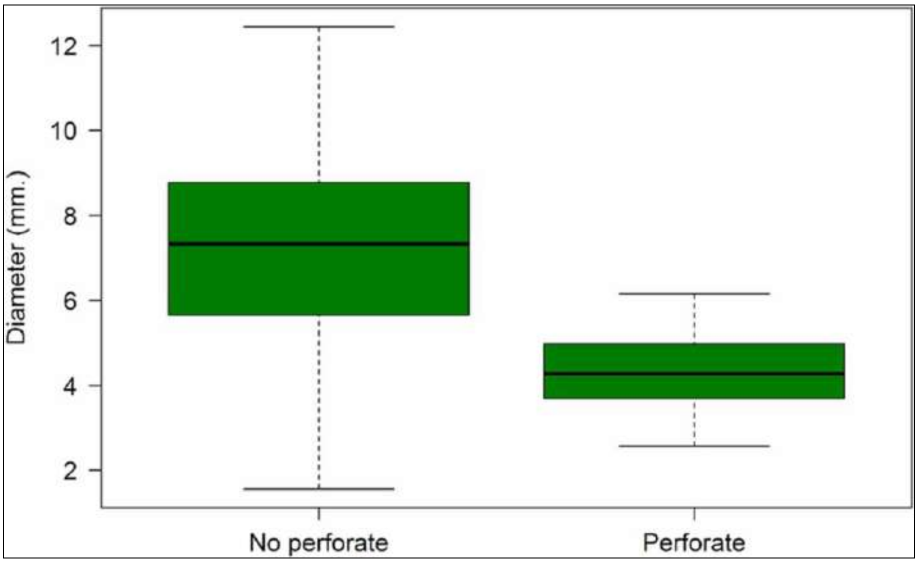

Fig 5: the difference between the nonperforated and perforated groups was also significant (P = 0.001)

4. Discussion

The placement of C1 lateral mass screws and C2 pedicle screws poses a potential risk for cortical breaches. The preoperative CT-based navigation system has been shown to help in C1C2 screw placement. [11] Generally, preoperative CT imaging examines the pathology of injuries and studies the size of the C1 lateral mass and C2 pedicle. This CT dataset can be used with the navigation system and has many advantages, such as surgical procedure planning, enhancing the screw implantation accuracy, and decreasing radiation exposure from intraoperative fluoroscopy. By this single-level vertebral registration method, 149 screws were placed in the C1 lateral mass and C2 pars pedicle: 133 screws (89.3 %) had no cortical perforation and a placement accuracy of grade 0, 14 screws (9.4 %) for grade I, and II screws (1.3 %) for grade II. However, no screws protruded into the spinal cord or completely outside the pedicles, and no vertebral artery injuries were observed. Therefore, no screws needed to be revised. Another clinical study by Kim *et al.* [11] reported 81.1 % accurate placement in 18 patients (58 screws) who underwent C1 lateral mass - C2 pedicle screw fixation using a preoperative CT-based navigation system, and 8.6 % frequency of grade I and 10.3 % for grade II. Two vertebral artery occlusions were observed but without neurological deterioration

However, conventional C-arm fluoroscopy usually helps the C2 pedicle or the C1 lateral mass screw placement in cervical spine surgery. The incidence of the screws fully contained in the pedicle ranges from 53.3 to 96.4 % for freehand or intraoperative fluoroscopy-guided techniques. [12–18] The incidence of the breach rate was high in several cases. However, this method requires considerable experience. Moreover, screw insertion using this technique is less accurate than that of the navigator system. Therefore, a preoperative CT-based navigation system may be more accurate for screw placement because it provides good quality images and can help the surgeon assess the trajectories of the screw on the axial, sagittal, and coronal planes for C1/C2 instrumentation. [19] However, a preoperative CT-based navigation system does not provide real-time imaging and allows for intraoperative changes in vertebral anatomy during patient positioning or surgical manipulation. Hence, we prevented vertebral anatomical changes using the intraoperative single-level vertebral registration technique, as described (Fig. 2). The navigator system registered the patients using the reference array attached to the posterior C1 protuberant ring for C1 registration, while for C2, it was fixed to the C2 spinous process. Thus, the surgeon should be careful in cases of displaced Jefferson and hangman's fractures, which have high rates of change in vertebral anatomy. Real-time images, such as intraoperative 3D fluoroscopy, O-arm, or intraoperative CT combined with the navigation system, are safer and more accurate in these circumstances. This system can help the surgeon re-correct after the screw placement malposition during surgery, reducing the likelihood of required reoperation. [20, 21] However, these tools are unavailable in many hospitals, entail radiation exposure, consume a long time, and are expensive. Additionally, the image quality of the intraoperative 3D fluoroscopy was insufficient, approximately 10 %, due to interfering artifacts. [22] The incidence of the breach rate of each method is shown in Table 4. The narrow diameter of the C1 lateral mass and C2 pedicles leads to a higher screw malposition rate. [13, 14, 22] The relatively higher rate of cortical breach at the C2 pedicle compared with the C1 lateral mass in our study may be why the C2 pedicle size is less than the C1 lateral mass. The mean axial C1 lateral mass and C2 pedicle diameters were 8.6 ± 1.44 mm (5–12.5 mm) and 5.1 ± 1.3 mm (1.6–8.2 mm, P < 0.001), respectively. Our study found that when the C1 lateral mass and C2 pedicle diameters were < 5 mm, there was a higher chance of developing cortical breach. Furthermore, we observed a downward trend in the perforated screw when the diameters of the C1 lateral mass and C2 pedicle were larger. Currently, no criteria for the diameter of the C1 lateral mass or C2 pedicle that minimize the risk of cortical breach exist. However, this study found that a < 5 mm diameter of the C1 lateral mass and C2 pedicle was associated with a significantly higher cortical breach (OR 15.7, 95 %CI: 4.42–55.76). Muller *et al*. described a pedicle size < 5 mm as a significant risk factor for screw misplacement. [13] Alosh *et al*. reported that the rate of cortical breach among patients with a pedicle diameter ≤ 6 mm was nearly twice that of patients with a pedicle diameter of > 6 mm. [14] Jacob *et al*. reported that a C2 pedicle diameter of < 6.6 mm was a risk factor for a screw perforation. [22] Determination of C1 lateral mass diameter and C2 pedicle on axial preoperative CT sections may predict which patients are at significant risk of cortical breach during surgery. A limitation of the present study is its retrospective design; therefore, there was no comparison with other methods. Furthermore, comparisons with other studies may not be appropriate because of the variance of patient characteristics, including pathologies, fracture types, site of the C1 lateral mass or the C2 pedicle, and surgeon experience.

5. Conclusion
This study applied preoperative CT-based navigation system using single-level vertebral registration for C1 lateral masses and C2 pedicle screws safely and accurately. However, the risk of cortical breach may be associated with the diameter of the C1 lateral mass and C2 pedicle. We found that a < 5 mm diameter of the C1 lateral mass and the C2 pedicle was associated with a significantly higher level of cortical breach.

Funding disclosure(s) statement
No financial support was received for the conduct of this research work. The authors declare no conflicts of interest.

CRediT authorship contribution statement
Thakul Oearsakul: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.
Thara Tunthanathip: Conceptualization, Formal analysis, Methodology, Writing – review & editing. Anukoon Kaewborisutsakul: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing.
Declaration of Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References
1. Goel A, Laheri V. Plate and screw fixation for atlanto-axial subluxation, Acta Neurochir. (Wien). 1994;129:47–53. https://doi.org/10.1007/BF01400872.
2. Harms J, Melcher RP. Posterior C1–C2 fusion with polyaxial screw and rod fixation, Spine. 2001;26:2467–2471. https://doi.org/10.1097/00007632- 200111150-00014. [
3. Chen Q, Brahimaj BC, Khanna R, Kerolus MG, Tan LA, David BT, *et al*., Posterior atlantoaxial fusion: a comprehensive review of surgical techniques and relevant vascular anomalies, J. Spine Surg. 2020;6:164–180. 10.21037/ jss.2020.03.05.
4. Lin X, Zhu HJ, Xu Y, Zheng T, Lin FY, Yin XM. Prevalence of vertebral artery anomaly in upper cervical and its surgical implications: A systematic review, Eur. Spine J. 2021;30:3607–3613. https://doi.org/10.1007/s00586-021-07015-8.
5. Wajanavisit W, Lertudomphonwanit T, Fuangfa P, Chanplakorn P, Kraiwattanapong C, Jaovisidha, S. Prevalence of high-riding vertebral artery and morphometry of C2 pedicles using a novel computed tomography reconstruction technique, Asian Spine J. 2016;10:1141–1148. https://doi.org/10.4184/ asj.2016.10.6.1141.
6. Yuwakosol P, Oearsakul T, Tunthanathip T. Morphometry of the C2 pedicle and lamina in Thai patients, Asian J. Neurosurg. 2020;15:39–44. https://doi.org/ 10.4103/ajns.AJNS_312_19.
7. Paramore CG, Dickman CA, Sonntag VK, The anatomical suitability of the C1–2 complex for transarticular screw fixation, J. Neurosurg. 1996;85:221–224, https://doi.org/10.3171/jns.1996.85.2.0221.
8. Wakao N, Takeuchi M, Nishimura M, Riew KD, Kamiya M, Hirasawa A, *et al*., Vertebral artery variations and osseous anomaly at the C1–2 level diagnosed by 3D CT angiography in normal subjects, Neuroradiology. 2014;56:843–849. https:// doi.org/10.1007/s00234-014-1399-y.
9. Yang YL, Zhou DS, He JL. Comparison of isocentric C-arm 3-dimensional navigation and conventional fluoroscopy for C1 lateral mass and C2 pedicle screw placement for atlantoaxial instability, J. Spinal Disord. Tech. 2013;26:127–134, https://doi.org/10.1097/BSD.0b013e31823d36b6.
10. Neo M, Sakamoto T, Fujibayashi S, Nakamura T. The clinical risk of vertebral artery injury from cervical pedicle screws inserted in degenerative vertebrae, Spine. 2005;30:2800–2805, https://doi.org/10.1097/01.brs.0000192297.07709.5d.
11. Kim SU, Roh BI, Kim SJ, Kim SD. The clinical experience of computed tomographic-guided navigation system in c1–2 spine instrumentation surgery, J. Korean Neurosurg. Soc. 2014;56:330–333. https://doi.org/10.3340/ jkns.2014.56.4.330.
12. 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. Clinical article, J. Neurosurg. Spine. 2009;11:15–22. https://doi.org/ 10.3171/2009.3.SPINE08166.

13. Mueller CA, Roesseler L, Podlogar M, Kovacs A, Kristof RA. Accuracy and complications of transpedicular C2 screw placement without the use of spinal navigation, Eur. Spine J. 2010;19:809–814. https://doi.org/10.1007/s00586-010-1291-3.
14. Alosh H, Parker SL, McGirt MJ, Gokaslan ZL, Witham TF, Bydon A, *et al*., Preoperative radiographic factors and surgeon experience are associated with cortical breach of C2 pedicle screws, J. Spinal Disord. Tech. 2010;23:9–14. https://doi.org/10.1097/BSD.0b013e318194e746.
15. Tessitore E, Bartoli A, Schaller K, Payer M. Accuracy of freehand fluoroscopyguided placement of C1 lateral mass and C2 isthmic screws in atlanto-axial instability, Acta Neurochir. (Wien). 2011;153:1417–1425. https://doi.org/ 10.1007/s00701-011-1039-9.
16. Hu Y, Kepler CK, Albert TJ, Yuan ZS, Ma, WH Gu YJ.,*et al*., Accuracy and complications associated with the freehand C-1 lateral mass screw fixation technique: a radiographic and clinical assessment, J. Neurosurg. Spine. 2013;18:372–377, https://doi.org/10.3171/2013.1.SPINE12724, PubMed, http://ncbi. nlm.nih.gov/23373564.
17. Bydon M, Mathios D, Macki M, De la Garza-Ramos R, Aygun N, Sciubba DM, *et al*., Accuracy of C2 pedicle screw placement using the anatomic freehand technique, Clin. Neurol. Neurosurg. 2014;125:24–27. https://doi.org/10.1016/j. clineuro.2014.07.017.
18. Hojo Y, Ito M., Suda K, Oda I, Yoshimoto H, Abumi K. A multicenter study on accuracy and complications of freehand placement of cervical pedicle screws under lateral fluoroscopy in different pathological conditions: CT-based evaluation of more than 1,000 screws, Eur. Spine J. 2014;23:2166–2174. https://doi.org/ 10.1007/s00586-014-3470-0.
19. Fiorenza V, Ascanio F. Safety and efficacy of posterior atlanto-axial stabilization using intraoperative navigation system with preoperative computed tomographic scan, World Neurosurg. 2019;129:110–119, https://doi.org/10.1016/j. wneu.2019.05.242.
20. Czabanka M, Haemmerli J, Hecht N, Foehre B, Arden K. Liebig T, *et al*., Spinal navigation for posterior instrumentation of C1–2 instability using a mobile intraoperative CT scanner, J. Neurosurg. Spin. 2017;27:268–275. https://doi. org/10.3171/2017.1. SPINE16859.