Epidemiology and Management of Iatrogenic Vertebral Artery Injury Associated With Cervical Spine Surgery

Ho Jun Yi
Department of Neurosurgery, Soonchunhyang University Bucheon Hospital, Bucheon, Korea

ABSTRACT

Iatrogenic vertebral artery injury (VAI) caused by surgical interventions involving the cervical spine is an uncommon but catastrophic complication associated with high morbidity or mortality due to ischemic stroke, intra- or extra-dural hemorrhage, and the formation of pseudoaneurysm or arteriovenous fistulae. In cervical spine surgeries, VAI may occur during the peri-or postoperative period. This may be induced by an anterior or posterior surgical approach. Despite advanced imaging techniques and increased anatomical knowledge, VAI during cervical spinal surgery remains a challenge. Techniques for managing VAI include hemostatic tamponade, ligation, microvascular repair or anastomosis, and endovascular management. We need to consider the risk of iatrogenic VAI as a complication in patients undergoing cervical spine surgeries and a better understanding of its mechanism and proper management.

Keywords: Cervical spine; Infarction, Surgery; Vertebral artery injury

INTRODUCTION

Cervical spine surgeries are performed to treat various conditions, such as degenerative diseases, trauma, infection, tumors, and deformity.\textsuperscript{22,53} Surgical procedures for cervical spine entail anterior, posterior, and combined (anterior and posterior) approaches.\textsuperscript{59} The various complications associated with cervical spine surgeries depend on the approach. An anterior approach is associated with dysphagia, esophageal injury, superior and recurrent laryngeal nerve palsy, and Horner’s syndrome.\textsuperscript{27,33} Dura tearing, epidural hematoma, nerve root damage, and infarction of spinal cord are induced by posterior approaches for cervical spine.\textsuperscript{22} In addition, vascular injury due to cervical spine surgeries is rare but fatal, and involve various blood vessels, including vertebral artery (VA), carotid artery, thyroid arteries, or internal jugular vein.\textsuperscript{24,45,55,57}

Especially, vertebral artery injury (VAI) is the most common vascular injury in cervical spine surgeries and potentially devastating complication. A recent systematic review by Turgut et al. showed that the most commonly injured vessels during cervical spine surgery were VA (86.6%).\textsuperscript{59} VAI can result in severe neurologic damage and even death due to acute and late-onset hemorrhage, arteriovenous fistulae (AVF), pseudoaneurysms, thrombosis, embolism, and cerebral ischemia.\textsuperscript{44,45} The incidence of iatrogenic VAI in cervical spine surgeries has yet to
Iatrogenic VAI is related to the anatomical characteristics of VA and accompanying anomalies. The VA comprises four segments (V4 to V1): The V1 originates in the subclavian artery, anterior to C7 transverse process, until the C6 transverse foramen. The V2 extends to the transverse foramen of C6–C1, while V3 arises in the superior aspect of the arch of the C1 to the foramen magnum. V4 extends from the intradural foramen magnum to basilar artery, and joins the contralateral VA. The VA and basilar artery provide posterior circulation to the brain. The VA is most vulnerable anterior to C7, lateral to C3-7, and posterior to C1-2. In addition, cadaveric or clinical studies revealed the anomalous course of VA in 2.7% to 5.4%. Advances in computed tomography angiography (CTA), magnetic resonance angiography (MRA), and conventional angiography revealed the anatomic features of VA. Assessments prior to cervical spine surgery can facilitate accurate surgical planning, and avoid complications. The review provides an understanding of VAI in cervical spine surgery along with the side effects associated with each surgical procedure, and the management strategy and precautions to prevent such complications.

EPIDEMIOLOGY AND CLINICAL FINDINGS OF VAI

Recent systematic reviews indicate that the most common cause of VAI in cervical spine surgeries was drilling (20.6 to 61%) or instrumentation (16% to 31.44%). Other causes of VAI are soft tissue retraction, removal of an ossified posterior longitudinal ligament, dissection with cautery, and VA manipulation. Mechanisms of vascular injury during cervical spine surgery reported by Turgut et al. include laceration (most common, 41.24%), pseudoaneurysm (16.49%), arterial dissection (5.67%), thrombosis, emboli or occlusion (4.64%), and AVF (2.58%). Symptoms after cervical spine surgery for VAI may be immediate or manifest several years later. Clinical findings of iatrogenic VAI include intraoperative bleeding, posterior circulation infarcts, neck swelling, hypotension, dyspnea, altered consciousness, hemorrhagic shock, and death, or may be asymptomatic. The majority of symptoms associated with VAI occur immediately, but delayed symptoms may be associated with hemorrhagic complications due to ruptured pseudoaneurysm or AVF. Furthermore, ischemic complications during the delayed period may be associated with emboli due to partially occluded or damaged VA. Dominant VA (about 42% to 50%) was more frequent on the left side, with diameters of equal size found only in 6%—26%. Therefore, the occurrence of VAI during manipulation on the left side requires increased attention. Furthermore, the patency of posterior inferior cerebellar artery (PICA) originating in VA is important because the VAI induces lateral medullary infarction due to abnormal distribution of the PICA, if it is not compensated by collateral circulation.

IATROGENIC VAI ACCORDING TO SURGICAL APPROACHES

Anterior approach

Anterior cervical disectomy and fusion and anterior cervical corpectomy and fusion

Approximate 0.3% to 0.5% of vascular injuries occur during the anterior cervical approach, and
the most frequently involved vessel is the VA.\textsuperscript{20,28,55} Vaccaro et al. reported that VAI occurred in the more cephalad vertebrae, during excessive lateral drilling, disc removal, placement of the plate and screws out of the midline, and in cases with tumor or infection.\textsuperscript{56} Likewise, VAI was related to coarse lateral drilling of the uncovertebral joint or neural foramen for decompression, especially with bone softening secondary to infection or tumor.\textsuperscript{32,45,54} Other factors, including instrumentation, probe maneuver for lateral exploration, cautery dissection, and prolonged neck hyperextension induce VAI.\textsuperscript{2,34,58} Drilling was the most frequent cause of VAI in previously reported cases.\textsuperscript{20} Therefore, surgeons should be prudent when drilling the uncovertebral joint or neural foramen, and avoid coarse extensive lateral drilling.\textsuperscript{52} In addition, exposure of the dural root sleeve should not exceed 5 mm in removal of the Luschka joint.\textsuperscript{20} Anatomic variations of VA are associated with increased risk of VAI. Therefore, preoperative computed tomography (CT) and magnetic resonance imaging (MRI) findings should be reviewed carefully to determine the appropriate management strategy and to avoid VAI. In addition, the loss of landmarks during anterior cervical approach is highly associated with VAI.\textsuperscript{20,45} The safe limit for drilling is an anatomical landmark, which is the insertion site of the longus colli muscles or the uncovertebral joint and should be maintained.\textsuperscript{45}

**Posterior approach**

**C1-2 screw fixation**

Most VAIIs in the posterior cervical approach are associated with C1-2 fusion. The trans-articular screw fixation involving C1-2, in which a screw is inserted through the C2 pars interarticularis to the facet joint of C1-2, is a popular technique in posterior C1-2 fusion.\textsuperscript{20} However, this technique increase the risk of VAI, due to the anatomical proximity and anomaly (high riding) of the VA around cranio-cervical junction.\textsuperscript{41,46} The incidence of VAI in C1-2 trans-articular screw fixation was approximately 4.1% to 8.2% in previous studies.\textsuperscript{36,59} Before the procedure, surgeons evaluate to the anatomical structures around C1 and C2 via CT and MRI images to determine the correct screw trajectory. Furthermore, CTA or MRA are essential to detect the VA status and accompanying anomalies, such as a high riding VA.\textsuperscript{18,40} Other technique, such as the C1 lateral mass with C2 pedicle screw insertion was widely used to decrease the risk of VAI, compared with trans-articular screw.\textsuperscript{20}

**Posterior subaxial cervical screw fixation**

VAI in posterior cervical pedicle screw insertion is rarely reported. Abumi et al.\textsuperscript{1} reported only one (0.6%) case of VAI in 180 patients with cervical pedicle screw. In addition, posterior cervical lateral mass screw insertion is associated with a low risk of VA and decreased stability, compared with pedicle screw.\textsuperscript{12,40}

**Posterior cervical laminectomy, laminoplasty, and foraminotomy**

VAI in posterior cervical laminectomy, laminoplasty, and foraminotomy is extremely rare. Diao et al.\textsuperscript{50} reported pseudoaneurysm at Rt. V3 after C2-7 laminectomy and instrumentation. VAI was triggered by drilling of the C1 posterior arch.\textsuperscript{10} Pristley presented a case of AVF after unilateral posterior cervical foraminotomy.\textsuperscript{47} Obermüller et al.\textsuperscript{42} reported a patient with delayed VAI following dorsal cervical foraminotomy.

**MANAGEMENT OF VAI IN CERVICAL SPINE SURGERIES**

Most cases of VAI during cervical spine surgery involve sudden, non-pulsatile, copious bright red bleeding, which is different from bone bleeding or injury to the surrounding
There is still no consensus for the definitive treatment strategy of VAI. However, the three major goals are as follows: 1) control of local hemorrhage, 2) prevention of immediate ischemic complication of vertebra-basilar system, and 3) prevention of other cerebrovascular complications, such as pseudo-aneurysm or emboli. In addition, the management of iatrogenic VAI encompasses both bleeding control with maintenance of patent posterior blood circulation in the acute period, and treatment of additional vascular abnormalities in the delayed phase. The treatment strategies for VAI in cervical spine surgeries are summarized in FIGURE 1. In the event of VAI, the surgeon should notify to the anesthesiologist accordingly. Fluid replacement or transfusion is needed to maintain blood flow and volume, and reduce the risk of posterior circulation ischemia and hypovolemia. The next step is VAI management for resuscitation.

**Surgical treatment**

Intraoperative surgical management of VAI includes hemostatic tamponade, microvascular repair or anastomosis, and ligation of the VA. First, bleeding during VAI should be controlled via direct tamponade with hemostatic agents, such as Gelfoam, Surgicel, or FloSeal (Baxter Biosciences, Vienna, Austria). Control of hemorrhage by direct hemostatic tamponade can be effective and easy, but this technique has several disadvantages, including uncontrolled bleeding with hypovolemic shock, ischemic damage by VA occlusion, delayed hemorrhage or ischemia due to the formation of pseudo-aneurysm or AVF. Therefore, conventional angiography is strongly recommended, when bleeding control is achieved with direct hemostatic tamponade. Fortunately, some studies report good outcomes using only anti-coagulation after tamponade, but almost all cases require further evaluation and management following VAI. According to the status of VA, secondary management after tamponade should be considered, such as endovascular treatment, surgical clipping,
repair, anastomosis or ligation. Even in non-dominant VA injury and the ipsilateral PICA flow is adequately filled by the contralateral VA, a more reliable treatment such as ligation or clipping rather than a hemostatic tamponade is better to prevent delayed hemorrhage or pseudo-aneurysm. Microvascular primary repair or anastomosis restores normal blood flow and minimizes the risk of immediate or delayed complications. However, it is technically difficult to suture given the extensive VAI site. The suture of damaged VA requires a sharp margin. Massive bleeding, VAI within the bony canal and surrounding venous plexus, and prolonged hemodynamic instability can hinder the management. Therefore, microvascular primary repair or anastomosis is indicated when it is technically feasible in cases of dominant VAI involving hemodynamically stable patients without interference from the surrounding structures.

Permanent occlusion with surgical ligation or clipping is another option for iatrogenic VAI. This technique can diminish the risk of hemorrhagic complications, but it is associated with significant morbidities of cerebellar infarction, lower cranial nerve paresis, hemiplegia, altered consciousness, and high mortality rate. Therefore, it should be performed only when blood supply to the posterior circulation by the contralateral VA is sufficient. In addition, ligation of VA should be done at both proximal and distal, because only proximal ligation can induce formation of pseudo-aneurysm or AVF, and delayed embolic infarct. As mentioned before, more than 50% of population is left dominance and about 25% is co-dominance, so more attention should be paid to ligation of left VA. The risk of brain stem infarction following VA occlusion was estimated at 3.1% in the left side and 1.8% in the right, and mortality rate associated with unilateral VA ligation was 12%. Furthermore, hypoplasia and aplasia of VA should be an obstacle for ligation or clipping of VA. In the normal population, 5.7% of hypoplasia and 1.8% of aplasia in left VA were reported compared with 8.8% of hypoplasia and 3.1% of aplasia in right VA. However, the VA status might facilitate in decision making in VA ligation, but cannot guarantee a favorable outcome. Furthermore, VA ligation is associated with the risk of nerve root injury due to poor visualization of operative field.

Endovascular treatment
Nowadays, endovascular management for VAI is widely facilitated by its advances in techniques and devices. In case of iatrogenic VAI, intra-operative or urgent conventional angiography along with emergent bleeding control is recommended. Conventional angiography in VAI can identify the exact injury mechanism and site, and evaluate the status of bilateral VA and collateral circulation. Actually, there may be limitation to get a trained endovascular team and equipment as soon as hemodynamic instability is discovered. However, recent trends suggest that the popularization of endovascular treatment for cerebrovascular disease has led to increased availability of experienced interventionists with well-equipped angio-suites or hybrid operating rooms at several institutions, and improved access to angiography with endovascular treatment for VAI. VA occlusion with coil is an option in VAI if a patent contralateral VA or sufficient collateral posterior circulation blood flow is identified in conventional angiography. Destructive intervention, complete occlusion of VA with coil has benefits in bleeding control, reduces recurrence and emboli, compared with other VA saving endovascular techniques. However, insufficient blood flow of the contralateral VA can lead to ischemic strokes in brain stem and cerebellum. Therefore, permanent VA occlusion with coil should be considered carefully to uncontrolled bleeding, in patients with tolerable collateral flow in posterior circulation and patent contralateral VA. Furthermore, VA trapping with coil embolization should be performed
at both proximal and distal portions of the VAI segment to reduce pseudo-aneurysm or recurrence. Simple coiling or stent assisted coiling can be performed in patients with pseudo-aneurysm without active bleeding via adequate hemostasis. 37)

A covered stent, single or multiple stent, and flow diverter can be considered as treatments to maintain the patency of damaged VA. The covered stent for VAI can completely seal the laceration by wrapping the membrane, and stop active bleeding. 58) However, most covered stents are rigid and have limited application in neurovascular disease. The rigidity of the covered stent makes it hard to pass and acquire adequate wall apposition at curved vessel, such as V3 and V4 segment. 31) Therefore, covered stent can be a treatment option for injuries of V1 or V2 segment with its straight course. Single or multiple stenting with self-expandable stents can be considered for the treatment of pseudoaneurysm or dissection accompanying VA laceration, rather than active bleeding status. Flow diverter application has been reported recently for VAI, and in most cases it was used to treat the pseudo-aneurysm rather than active bleeding. 31,51) A flow diverter in VAI is effective for treatment of non-active bleeding pseudoaneurysm, but the application of flow diverter in VAI is restricted in Korea due to the medical insurance system. A covered stent is recommended for the control of active bleeding in non-curved portions, whereas a self-expandable stent or flow diverter is preferred in curved vessels without active bleeding.

Although successful surgical or endovascular treatment for VAI was achieved in acute phase, serial follow up imaging studies for vascular status are essential to evaluate the delayed hemorrhagic or ischemic complications due to the formation of pseudo-aneurysms or AVF during the post-operative periods. 20) Likewise, postoperative angiography without abnormal findings during the acute phase does not rule out subsequent pseudoaneurysm or AVF. The pseudoaneurysm was not apparent in early postoperative CTA or MRA, but can occur later and result in bleeding or AVF formation. Delayed hemorrhagic or embolic infarcts due to these vascular abnormalities appear days or years post-VAI. 5,7,29,34) Therefore, patients with suspected or definitive VAI should be evaluated via CTA, MRA, or conventional angiography to determine the vascular status of VAI during late periods. A pseudoaneurysm or AVF can be treated with the endovascular techniques including coil embolization, stent-assist coil embolization, self-expandable stenting, covered stents, or flow diverter. 17,34,47,51,55) Spinal AVF can be treated with as usual manner, such as coil, isobutyl cyanoacrylate, or ONYX embolization by trans-arterial or venous approach.

STRATEGIES FOR PREVENTION OF VAI

CT and MRJ images should be carefully reviewed in the pre-operative period. If necessary, additional imaging studies including CTA, MRA, and conventional angiography should be considered for further evaluation. The location of the VA and its association with bone and surrounding structures should be demonstrated. 45) It is important to identify the VA status including ectasia, tortuosity, and anomaly. Based on these images, the surgeon should determine the precise extent of dissection and decompression. Especially in posterior approach, the safe trajectory for screw placement as well as the dimensions of the pedicles or lateral masses should be reviewed to avoid VAI. If there is VA anomaly, additional prophylactic procedures such as exposure of the VA for proximal and distal placement of encircling vascular loops or sutures may be considered. 40) In addition, alternative surgical approaches, including anterior to posterior or posterior to anterior strategies, should be
considered. During the peri-operative period, identification of midline and other anatomic
landmarks is important for safe dissection and instrumentation. A blunt dissection,
coarse and extensive drilling should be avoided. Intraoperative imaging techniques such
as fluoroscopy, CT, or navigation may be useful, especially in difficult cases.\textsuperscript{5,15,20} Surgeons
should minimize intraoperative manipulation and/or retraction of the vascular structures to
avoid VAI in cervical spine surgeries.\textsuperscript{24,57} Furthermore, an experienced neurovascular surgeon,
and a neuro-interventionist with endovascular equipment are essential to provide immediate
conventional angiography and prompt management for VAI in cervical spine surgery.

CONCLUSIONS

Nowadays, cervical spine surgeries for various pathologies are commonly performed with
advanced imaging techniques and increased anatomical knowledge. However, they are
associated with a potential risk of iatrogenic VAI which is a rare but fatal complication.
Therefore, all of surgeons should remember that VAI can occur any time during or after the
surgery regardless of the surgical approach (anterior and/or posterior) for the cervical spine.
Prevention is the best strategy for any iatrogenic VAI. Every effort should be made to prevent
VAI, including understanding the vascular status, identification of anatomical anomaly,
proper surgical planning, and closed monitoring peri/post- operative periods. Furthermore,
surgeons should be aware of the possibility and appropriate management strategies for VAI.
Hemostatic tamponade, microvascular repair or anastomosis can be performed as needed.
Surgical ligation or permanent clipping should only be attempted if the contralateral VA
provides adequate collateral circulation. Recent advances in endovascular treatment have
led to increased interventions in iatrogenic VAI. In the event of VAI, local bleeding control is
the first step. An immediate conventional angiography is recommended, followed by serial
dendovascular treatment and closed monitoring of the patient.

ACKNOWLEDGMENTS

I wish to thank Professor Je Hoon Jung, as an Editor-in-Chief for his helpful suggestions in
preparing this manuscript. This study was supported by the National Research Foundation of
Korea (NRF-2021R1G1A109479711) and the Soonchunhyang University Research Fund.

REFERENCES

1. Abumi K, Shono Y, Ito M, Taneichi H, Kotani Y, Kaneda K. Complications of pedicle screw fixation in
reconstructive surgery of the cervical spine. \textit{Spine (Phila Pa 1976)} \textbf{25}:962-969, 2000
\texttt{PUBMED} | \texttt{CROSSREF}
2. Afana HB, Abuhadrous NMM, Elsharkawy AE. Bithalamic infarction (artery of percheron occlusion) after
anterior cervical discectomy and fusion. \textit{Case Rep Neurol Med} \textbf{2019}:9438089, 2019
\texttt{PUBMED} | \texttt{CROSSREF}
3. An TY, Kang DH, Kim DH. Anastomosis and endovascular treatment of iatrogenic vertebral artery injury.
\textit{Korean J Neurotrauma} \textbf{17}:204-211, 2021
\texttt{PUBMED} | \texttt{CROSSREF}
4. Burke JP, Gerszten PC, Welch WC. Iatrogenic vertebral artery injury during anterior cervical spine surgery.
\textit{Spine J} \textbf{5}:508-514, 2005
\texttt{PUBMED} | \texttt{CROSSREF}
5. Carl B, Bopp M, Pojskic M, Voellger B, Nimsky C. Standard navigation versus intraoperative computed tomography navigation in upper cervical spine trauma. Int J CARS 14:169-182, 2019

6. Choi JW, Lee JK, Moon KS, Kim YS, Kwak HJ, Joo SP, et al. Endovascular embolization of iatrogenic vertebral artery injury during anterior cervical spine surgery: report of two cases and review of the literature. Spine (Phil Pa 1976) 31:E891-E894, 2006

7. Cosgrove GR, Théron J. Vertebral arteriovenous fistula following anterior cervical spine surgery. Report of two cases. J Neurosurg 66:297-299, 1987

8. Curuyo LJ, Mason HC, Bohlman HH, Yoo JU. Tortuous course of the vertebral artery and anterior cervical decompression: a cadaveric and clinical case study. Spine (Phil Pa 1976) 25:2860-2864, 2000

9. Daniels AH, Riew KD, Yoo JU, Ching A, Birchard KR, Kranenburg AJ, et al. Adverse events associated with anterior cervical spine surgery. J Am Acad Orthop Surg 16:729-738, 2008

10. Diao Y, Sun Y, Wang S, Zhang F, Pan S, Liu Z. Delayed epidural pseudoaneurysm following cervical laminectomy and instrumentation in a patient with canal stenosis secondary to skeletal fluorosis: a case report. Medicine (Baltimore) 97:e9883, 2018

11. Dolati P, Eichberg DG, Thomas A, Ogilvy CS. Application of pipeline embolization device for iatrogenic pseudoaneurysms of the extracranial vertebral artery: a case report and systematic review of the literature. Cureus 7:e356, 2015

12. Dunlap BJ, Kairaikovic EE, Park HS, Sokolowski MJ, Zhang LQ. Load sharing properties of cervical pedicle screw-rod constructs versus lateral mass screw-rod constructs. Eur Spine J 19:729-738, 2008

13. Epstein NE. From the neurointerventional lab...intraoperative cervical vertebral artery injury treated by tamponade and endovascular coiling. Spine J 3:404-405, 2003

14. Eskander MS, Drew JM, Aubin ME, Marvin J, Franklin PD, Eck JC, et al. Vertebral artery anatomy: a review of two hundred fifty magnetic resonance imaging scans. Spine (Phil Pa 1976) 35:2035-2040, 2010

15. Freidberg SR, Pfeifer BA, Dempsey PK, Tarlov EC, Dube MA, Day JD, et al. Intraoperative computerized tomography scanning to assess the adequacy of decompression in anterior cervical spine surgery. J Neurosurg 94:8-11, 2001

16. Gantwerker BR, Bajaj AA, Maughan PH, McDougall CG, White WL. Vertebral artery injury during cervical discectomy and fusion in a patient with bilateral anomalous arteries in the disc space: case report. Neurosurgery 67:E874-E875, 2010

17. Garcia Alzamora M, Rosahl SK, Lehmberg J, Klisch J. Life-threatening bleeding from a vertebral artery pseudoaneurysm after anterior cervical spine approach: endovascular repair by a triple stent-in-stent method. Case report. Neuroradiology 47:282-286, 2005

18. Goel A, Prasad A, Shah A, Sasane S, Hawaldar A, Biswas C, et al. Transarticular fixation following mobilization of “high-riding” vertebral artery. Oper Neurosurg (Hagerstown) 20:E322-E325, 2021

19. Grabovski G, Cornett CA, Kang JD. Esophageal and vertebral artery injuries during complex cervical spine surgery--avoidance and management. Orthop Clin North Am 43:63-74, 2012

20. Guan Q, Chen L, Long Y, Xiang Z. Iatrogenic vertebral artery injury during anterior cervical spine surgery: a systematic review. World Neurosurg 106:715-722, 2017

21. Guo F, Dai J, Zhang J, Ma Y, Zhu G, Shen J, et al. Individualized 3D printing navigation template for pedicle screw fixation in upper cervical spine. PLoS One 12:e0171509, 2017

22. Harel R, Stylianou P, Knoller N. Cervical spine surgery: approach-related complications. World Neurosurg 94:1-5, 2016
23. Harms J, Melcher RP. Posterior C1-C2 fusion with polyaxial screw and rod fixation. *Spine (Phila Pa 1976)* 26:2467-2471, 2001

24. Härtl R, Alimi M, Abdellatif Boukebir M, Berlin CD, Navarro-Ramirez R, Arnold PM, et al. Carotid artery injury in anterior cervical spine surgery: Multicenter cohort study and literature review. *Global Spine J* 7:71S-75S, 2017

25. Hong JM, Chang CS, Bang OY, Yong SW, Joo IS, Huh K. Vertebral artery dominance contributes to basilar artery curvature and peri-vertebrobasilar junctional infarcts. *J Neurol Neurosurg Psychiatry* 80:1087-1092, 2009

26. Hong JT, Lee SW, Son BC, Sung JH, Yang SH, Kim IS, et al. Analysis of anatomical variations of bone and vascular structures around the posterior atlantal arch using three-dimensional computed tomography angiography. *J Neurosurg Spine* 8:230-236, 2008

27. Hsu WK, Kannan A, Mai HT, Fehlings MG, Smith ZA, Traynelis VC, et al. Epidemiology and outcomes of vertebral artery injury in 1682 cervical spine surgery patients: an AOSpine North America multicenter study. *Global Spine J* 7 Suppl:21S-27S, 2017

28. Inamasu J, Guiot BH. Vascular injury and complication in neurosurgical spine surgery. *Acta Neurochir (Wien)* 148:375-387, 2006

29. Jecko V, Rué M, Castetbon V, Berge J, Vignes JR. Vertebral artery (V2) pseudo-aneurysm after surgery for cervical schwannoma. How to prevent it and a review of the literature. *Neurochirurgie* 61:38-42, 2015

30. Jung HJ, Kim DM, Kim SW, Lee SM. Emergent endovascular embolization for iatrogenic vertebral artery injury during cervical discectomy and fusion. *J Korean Neurosurg Soc* 50:520-522, 2011

31. Katsaridis V, Papagiannaki C, Violarlis C. Treatment of an iatrogenic vertebral artery laceration with the Symbiot self expandable covered stent. *Clin Neurol Neurosurg* 109:512-515, 2007

32. Khan SA, Coulter I, Marks SM. Iatrogenic vertebral artery injury secondary to vessel tortuosity in a grossly degenerate cervical spine. *Br J Neurosurg* 28:423-425, 2014

33. Kim M, Choi I, Park JH, Jeon SR, Rhim SC, Roh SW. Airway management protocol after anterior cervical spine surgery: Analysis of the results of risk factors associated with airway complication. *Spine (Phila Pa 1976)* 42:E1058-E1066, 2017

34. Lo WB, Nagaraja S, Saxena A. Delayed hemorrhage from an iatrogenic vertebral artery injury during anterior cervical discectomy and successful endovascular treatment-report of a rare case and literature review. *World Neurosurg* 99:811.e1-811.e18, 2017

35. Lunardini DJ, Eskander MS, Even JL, Dunlap JT, Chen AF, Lee JY, et al. Vertebral artery injuries in cervical spine surgery: Analysis of the results of risk factors associated with airway complication. *Spine (Phila Pa 1976)* 42:E1058-E1066, 2017

36. 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

37. Maughan PH, Ducruet AF, Elhadi AM, Martirosyan NL, Garrett M, Mushtaq R, et al. Multimodality management of vertebral artery injury sustained during cervical or cranio cervical surgery. *Neurosurgery* 73:ons271-ons281, 2013

38. Méndez JC, González-Llanos F. Endovascular treatment of a vertebral artery pseudoaneurysm following posterior C1-C2 transarticular screw fixation. *Cardiovasc Intervent Radiol* 28:107-109, 2005

39. Nam KH, Sung JK, Park J, Cho DC. End-to-end anastomosis of an unanticipated vertebral artery injury during c2 pedicle screwing. *J Korean Neurosurg Soc* 48:363-366, 2010
40. Neo M, Matsushita M, Iwashita Y, Yasuda T, Sakamoto T, Nakamura T. Atlantoaxial transarticular screw fixation for a high-riding vertebral artery. *Spine (Phila Pa 1976)* 28:666-670, 2003

41. Neo M, Fujibayashi S, Miyata M, Takemoto M, Nakamura T. Vertebral artery injury during cervical spine surgery: a survey of more than 5600 operations. *Spine (Phila Pa 1976)* 33:779-785, 2008

42. Obermüller T, Wostrack M, Shibain E, Pape H, Harmening K, Friedrich B, et al. Vertebral artery injury during foraminal decompression in “low-risk” cervical spine surgery: incidence and management. *Acta Neurochir (Wien)* 157:1941-1945, 2015

43. Padhi R, Kandasamy S, Kumaran B, Bheemarao PM, Kumaran S. Endovascular management of iatrogenic vertebral artery transection during anterior cervical spine surgery: a case report. *Neurospline* 18:245-249, 2021

44. Park HK, Jho HD. The management of vertebral artery injury in anterior cervical spine operation: a systematic review of published cases. *Eur Spine J* 21:2475-2485, 2012

45. Peng CW, Chou BT, Bendo JA, Spivak JM. Vertebral artery injury in cervical spine surgery: anatomical considerations, management, and preventive measures. *Spine J* 9:70-76, 2009

46. Prabhuc VC, France JC, Voelker JL, Zoarski GH. Vertebral artery pseudoaneurysm complicating posterior C1-2 transarticular screw fixation: case report. *Surg Neurol* 55:29-33, 2001

47. Priestley R, Bray P, Bray A, Hunter J. Iatrogenic vertebral arteriovenous fistula treated with a Hemobahn stent-graft. *J Endovasc Ther* 10:657-663, 2003

48. Richter M, Mattes T, Cakir B. Computer-assisted posterior instrumentation of the cervical and cervicothoracic spine. *Eur Spine J* 13:50-59, 2004

49. Rosenthal P, Latchaw RE, Kim KD. Anomalous vertebral artery injured during anterior cervical discectomy: a case report. *Spine (Phila Pa 1976)* 38:E1567-E1570, 2013

50. Schroeder GD, Hsu WK. Vertebral artery injuries in cervical spine surgery. *Surg Neurol Int* 4:S362-S367, 2013

51. Shakir HJ, Rooney PJ, Rangel-Castilla L, Yashar P, Levy EI. Treatment of iatrogenic V2 segment vertebral artery pseudoaneurysm using Pipeline flow-diverting stent. *Surg Neurol Int* 7:104, 2016

52. Shen FH, Samartzis D, Khanna N, Goldberg EI, An HS. Comparison of clinical and radiographic outcome in instrumented anterior cervical discectomy and fusion with or without direct uncovertebral joint decompression. *Spine J* 4:629-635, 2004

53. Smith JS, Ramchandran S, Lafage V, Shaffrey CI, Ailon T, Klineberg E, et al. Prospective multicenter assessment of early complication rates associated with adult cervical deformity surgery in 78 patients. *Neurosurgery* 79:378-388, 2016

54. Tumialan LM, Wippold FJ 2nd, Morgan RA. Tortuous vertebral artery injury complicating anterior cervical spinal fusion in a symptomatic rheumatoid cervical spine. *Spine (Phila Pa 1976)* 29:E343-E348, 2004

55. Turgut M, Akhaddar A, Turgut AT, Hall WA. Iatrogenic vascular injury associated with cervical spine surgery: a systematic literature review. *World Neurosurg* 159:83-106, 2022

56. Vaccaro AR, Ring D, Scuderi G, Garfin SR. Vertebral artery location in relation to the vertebral body as determined by two-dimensional computed tomography evaluation. *Spine (Phila Pa 1976)* 19:2637-2641, 1994

57. Wakao N, Takeuchi M, Nishimura M, Riew KD, Kamiya M, Hirasawa A, et al. Risks for vascular injury during anterior cervical spine surgery: prevalence of a medial loop of vertebral artery and internal carotid artery. *Spine (Phila Pa 1976)* 41:293-298, 2016
58. Wangqin R, Xu K, Mokin M, Uribe J, Rojas H, Ren Z. Covered stent to salvage iatrogenic vertebral artery injury with uncontrolled bleeding in the operating room setting. *World Neurosurg* **122**:282-286, 2019

59. Wright NM, Lauryssen C; American Association of Neurological Surgeons/Congress of Neurological Surgeons. Vertebral artery injury in Cl-2 transarticular screw fixation: results of a survey of the AANS/CNS section on disorders of the spine and peripheral nerves. *J Neurosurg* **88**:634-640, 1998

60. Xin C, Luo WT, Zhao WY, Dong LX, Xiong ZW, Li ZW, et al. Combined endovascular and surgical treatment for brain arteriovenous malformations in biplanar hybrid operating room. *Curr Med Sci* **41**:782-787, 2021

61. Yamazaki M, Okawa A, Furuya T, Sakuma T, Takahashi H, Kato K, et al. Anomalous vertebral arteries in the extra- and intraosseous regions of the craniovertebral junction visualized by 3-dimensional computed tomographic angiography: analysis of 100 consecutive surgical cases and review of the literature. *Spine (Phila Pa 1976)* **37**:E1389-E1397, 2012