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Research article

C2 pedicle screw insertion assisted by mobilization of the vertebral artery in cases with high-riding vertebral artery

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ABSTRACT

Objective: To describe the feasibility, safety and efficacy of mobilization of the vertebral artery for C2 pedicle screws in cases with the high-riding vertebral artery (HRVA).

Methods: During the period January 2020 to September 2022, fifteen patients underwent posterior occipitocervical fixation in our department. All patients had unilateral HRVA on at least one side that prohibited the insertion of C2 pedicle screws. There were 2 males and 13 females aged 47 ± 11.9 years (range: 17–64 years). After the correction of the vertical dislocation during the operation, the C2 pedicle screw insertion and occipitocervical fixation and fusion were performed using the vertebral artery mobilization technique. A routine three-dimensional reconstructed CT examination was executed to confirm the trajectory of C2 pedicle screws post-operation, and a CT angiography examination was performed when necessary. Neurological function was assessed using the Japanese Orthopedic Association (JOA) scale. The preoperative and postoperative JOA score and the main radiological measurements, including anterior atlantodental interval (ADI), the distance of odontoid tip above Chamberlain line, and clivus-canal angle (CCA), were collected and compared by paired *t*-test.
Results: All 15 patients had atlas assimilation, among which 12 patients had C2–C3 fusion (Klippel-Feil syndrome). Mobilization of the HRVA was successfully completed, and C2 pedicle screws were then fulfilled after the vertebral artery was protected. There was no injury to the vertebral artery during the operation. Meanwhile, no severe surgical complications such as cerebral infarction or aggravated neurological dysfunction occurred during the perioperative period. Satisfactory C2 pedicle screw placement and reduction were reached in all 15 patients. All the patients achieved bone fusion 6 months after surgery. No looseness and shift of internal fixation or reduction loss was observed during the follow-up period. Compared to the preoperative, the postoperative JOA score and the main radiological measurements were remarkably improved and statistically significant.
Conclusions: C2 pedicle screw insertion assisted by mobilization of the vertebral artery is safe and considerably effective, providing a choice for internal fixation in cases with high-riding vertebral arteries.

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1. Introduction

For congenital basilar invagination (BI) and atlantoaxial dislocation (AAD) patients, rigid internal fixation is essential condition for intraoperative reduction. C2 pedicle screw has been widely used in upper cervical surgery, since it can provide a 3-column fixation with biomechanical superiority [1,2]. Therefore, the C2 pedicle screws are recommended preferentially. However, the risk of VA injury persists during the placement of the C2 pedicle screw owing to high-riding vertebral artery(HRVA) accompanied by a narrow C2 isthmus [2–4]. Patients with congenital BI combined with AAD demonstrate a greater prevalence of HRVAs. Moreover, the HRVA is the dominant or single-branch blood supply usually. Once injured, it could lead to catastrophic complications, comprising brain stem infarction, vertebral-basilar artery insufficiency, and even death. In order to avoid the risk of vertebral artery injury, several alternative techniques were used in these cases, such as C2 translaminar screws, C2 pars/short pedicle screws, or extension of fixed segment extension. Nonetheless, the cervical posterior column fixation is significantly worse regarding fixation strength and potential for reduction maneuvers compared with the three-column pedicle screw fixation [1–3,5]. Additionally, the extension of the fixed segment will inevitably induce the loss of cervical mobility and accelerate the adjacent segment degeneration. In this report, the novel C2 pedicle screw insertion technique, which is assisted by mobilization of the vertebral artery in HRVA cases accompanied by a narrow C2 isthmus, is described. During the surgery, the loop of the vertebral artery in the transverse foramen is mobilized inferiorly or laterally under the microscope, and the screw passes through the transverse foramen. Multi-cortical fixation piercing through the three columns can be achieved while the injury to the vertebral artery is avoided. The Department of Neurosurgery of the First Affiliated Hospital of USTC applied this technique to treat BI and AAD patients along with HRVA.

1.1. Materials and methods

The study protocol was approved by the institutional review board of our institute, and performed from January 2020 to September 2022. Informed consent was waived due to the retrospective nature of the study. Our retrospective review included 15 patients. In these patients, 15C2 pedicle screws were inserted for occipitocervical fixation and fusion with the vertebral artery mobilization technique. All 15 patients suffered from BI with AAD and atlas assimilation, requiring atlantoaxial reduction and stabilization. Unilateral high-riding vertebral artery accompanied by a narrow C2 isthmus was observed in all the patients.

Preoperatively, flexion-extension lateral radiographs, CT scans with reconstruction views, and MR images were performed for all patients to ascertain the diagnosis. CTA with multi-planar reconstruction was employed to identify anatomical anomalies in C2, such as HRVA, hypoplasia of the isthmus, and other malformations. Neurological function was assessed with the Japanese Orthopedic Association (JOA) scale. Additionally, the preoperative JOA score and the main radiological measurements, such as anterior atlanto-dental interval (ADI), the distance of the odontoid tip above the Chamberlain line, and clivus-canal angle (CCA), were collected. The demographic, clinical, and radiological data of patients are summarized in Table 1.

HRVA was assessed that the C2 pedicle isthmus height was $\leq$5 mm and/or the internal height was $\leq$2 mm on the sagittal reconstructed computed tomography (CT) image targeting 3 mm lateral to the cortical margin of the spinal canal wall at C2 [1,3]. The narrow pedicle was assessed when the width of the narrowest portion of the pedicle visible on the axial CT images was $\leq$4 mm [6].

1.2. Surgical technique

The surgical methods of congenital BI with AAD have been relatively mature [7,8]. All the patients underwent occipitocervical fixation and fusion due to atlanto-occipital fusion. Continuous skeletal traction was performed after anesthesia during the operation, and transoral or posterior atlantoaxial joint release was executed when necessary, followed by the cervical screw placement. Then, the cantilever force was applied for reduction. After fixation, massive cancellous bone obtained from the posterior iliac crest was placed

Table 1
Patient characteristics.

Patient Number	Sex	Age (yrs)	Chief complaints	Additional radiological anomalies	HRVA
1	F	42	Extremity weakness, paresthesia	Congenital C2–3 fusion, syringomyelia	Left side
2	F	51	Extremity weakness, paresthesia	None	Left side
3	F	57	Neck pain	Congenital C2–3 fusion	Left side
4	F	52	Lower cranial nerve dysfunction	None	Left side
5	F	17	Neck pain	Congenital C2–3 fusion, Chiari malformation, syingomyelia	Right side
6	F	59	Paresthesia, extremity weakness	Congenital C2–3 fusion, syingomyelia	Left side
7	F	56	Neck pain，extremity weakness，paresthesia	Congenital C2–3 fusion	Left side
8	M	49	Gait disturbances，limb weakness	Congenital C2–3 fusion, syingomyelia	Right side
9	M	47	Extremity numbness	None	Left side
10	F	26	Extremity weakness，ataxia	Congenital C2–3 fusion, Chiari malformation， syingomyelia，	Left side
11	F	53	Neck pain，extremity numbness and weakness	Congenital C2–3 fusion	Right side
12	F	50	Extremity numbness and weakness	Congenital C2–3 fusion	Right side
13	F	64	Extremity numbness	Congenital C2–3 fusion	Left side
14	F	45	Neck pain， extremity numbness	Congenital C2–3 and C6-7 fusion	Right side
15	F	40	Extremity numbness and weakness，ataxia	Congenital C2–3 fusion	Left side

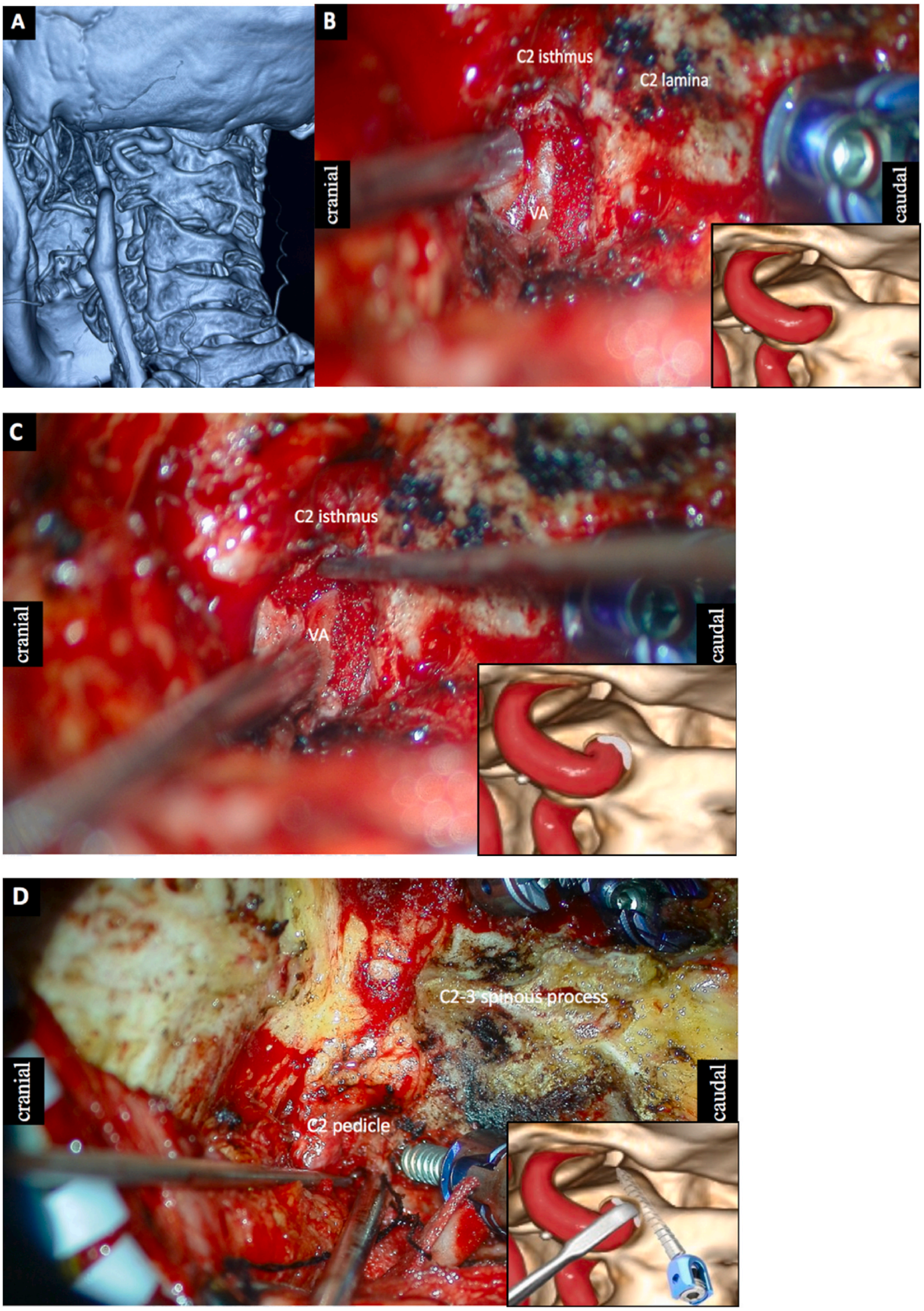

Fig. 1. Surgical procedure and illustration of C2 pedicle screw insertion assisted by mobilization of the vertebral artery in cases with HRVA. A: Routine 3D reconstructed CTA examination was performed, for understanding the surface topography and the course of the vertebral artery. B: The segment of HRVA exiting the C2 transverse foramen was exposed gently under the microscope. C: The loop of the vertebral artery was mobilized inferiorly and/or laterally with dissectors, and gelfoam sponge was packed between the artery and the pedicle. D: The C2 pedicle screw was inserted safely under direct vision , after the vertebral artery are mobilized.

over the decorticated surfaces of occipital bone and C2. All the surgeries were performed by a single surgeon.

The insertion process of the C2 pedicle screw at the HRVA side (Fig. 1). Specifically, the axis lamina, isthmus, and the outer lower margin of the transverse foramen were exposed under the microscope. Later, the vertebral artery was explored using blunt dissection from the lateral side through soft manipulation (Fig. 1B). Afterward, retrograde separation was performed along the vertebral artery on the basis of the vertebral artery being protected. The thin layer of bone covering the upper part of the isthmus was removed by the high-speed drill with Kerrison rongeur, and the lower part of the extra-transverse foramen was uncovered if necessary. The HRVA was gently shifted outward and downward using a microscopic nerve dissector, and the tension of the vertebral artery loops was felt. Furthermore, the bony exposure was enlarged to increase the freeboard of the vertebral artery if necessary, while the displacement of the vertebral artery was completed by filling the isthmus with gelatin sponge as well as between the lower part of the superior articular eminence and the vertebral artery loops (Fig. 1C). Under the microscope, a pilot hole was made at the point of projection of the vertebral plate in the internal superior wall of the vertebral arch using a 2-mm high-speed burr. It was drilled progressively deeper along the limit of the internal superior wall of the vertebral arch. If there was no bleeding, the hand drill was slowly and deeply drilled. Thus, the surgeon could feel the process of the drill departing the transverse foramen and rupturing into the cortical bone again (Fig. 1D). The screw insertion process, especially the passage of the screw through the transverse foramen, can be implemented under microscopic monitoring.

1.3. Follow-up methods and observation indexes

The cervical lateral radiographs and sequential CT scanning with 3D reconstruction views of the craniocervical junction area were reviewed within 3 days after the operation. The ADI, the distance of the odontoid tip above the Chamberlain line, and the CCA were calculated. The lateral film of the cervical spine was reviewed one month postoperatively to check for loosening or displacement of screws. The cervical MR was reviewed three months after the surgery, and the JOA score of the cervical spine was assessed six months after the surgery. The cervical CT was examined to assess bone fusion. In the absence of fusion, the cervical CT and MR were reviewed six months later until a continuous bone bridge was formed between the occipital and cervical regions.

1.4. Statistical analysis

The statistical package SPSS 19.0 (SPSS Inc., USA) was applied for data analysis, and the measurement data were expressed as $\bar{x} \pm s$. Paired samples *t*-test was conducted for the inter-group comparison. $P < 0.05$ indicated statistically significant differences.

2. Results

2.1. Surgical condition and perioperative complications

Fifteen patients have been successfully treated with occipitocervical fixation and fusion. The high-riding vertebral artery was displaced with a pedicle screw (3.5 mm in diameter and 20–30 mm in length) inserted. On average, the surgery was performed for 186 min, no vertebral artery injury occurred intra-operatively, and no blood transfusion was performed. No severe surgical complications such as cerebral infarction or worsening of neurological dysfunction emerged in this group during the perioperative period. All the patients were discharged successfully.

2.2. Clinical efficacy

Postoperatively, all the patients exhibited varying degrees of relief in their symptoms, with more remarkable improvements in neck pain, ataxia, and limb numbness and weakness. During 6-month postoperative follow-up, 15 cases demonstrated a favorable response concerning the JOA scores compared with the preoperative scores, with the score increasing from (13.1 ± 1.9) preoperatively to (15.6 ± 1.1) postoperatively ($P < 0.05$).

2.3. Imaging and follow-up

The postoperative cervical sagittal CT revealed that AAD was corrected to various extents in all 15 patients. Additionally, the ventral compression of the medulla oblongata was released, and the clivus-canal angle was improved, contributing to the desired surgical outcome. The C2 pedicle screws were well positioned and inserted into the vertebral body via the upper part of the transverse foramen. In this way, a multi-cortical fixation was developed through three columns. Radiologically, the ADI decreased from (6.8 ± 2.4) mm preoperatively to (2.2 ± 1.2) mm postoperatively ($P < 0.05$); the distance of the odontoid tip above the Chamberlain line decreased from (9.9 ± 2.5) mm preoperatively to (5.1 ± 2.3) mm postoperatively ($P < 0.05$)). The CCA increased from (122.0 ± 11.2) preoperatively to (135.1 ± 8.2) postoperatively ($P < 0.05$).

No screw loosening was observed on the lateral film of the cervical vertebra at 1 month postoperatively. MR at 3 months postoperatively suggested a noticeable enhancement in ventral compression of the medulla oblongata. Patients with preoperative combined Chiari malformation and/or syringomyelia exhibited varying degrees of upward displacement of the tonsils and reduction of the syringomyelia. Fusion was confirmed demonstrated on the sagittal CT image taken 6 months after the surgery. Typical cases are shown in Figs. 2–4.

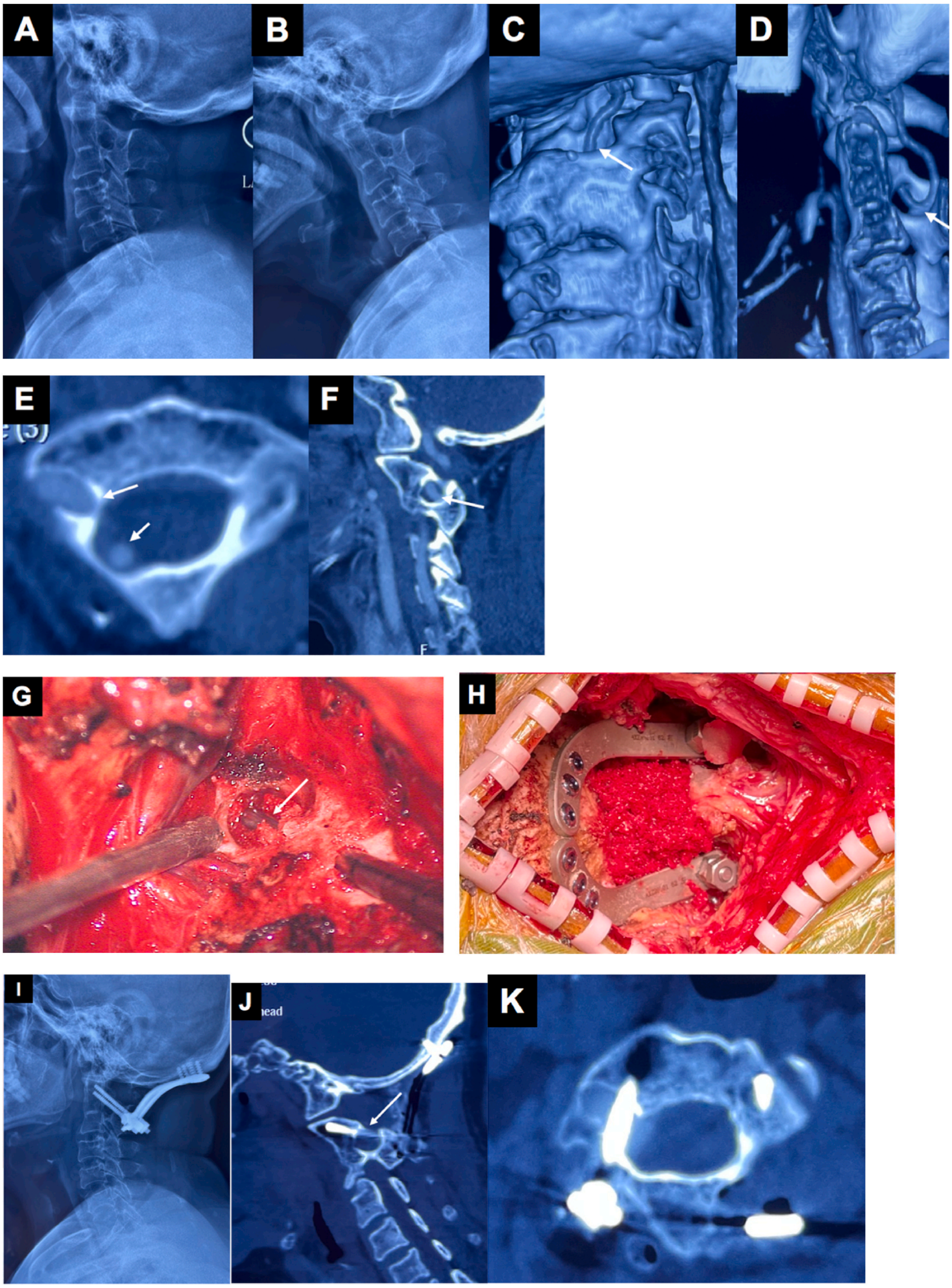

Fig. 2. Case 11. A 53-year-old woman presented with neck pain, paresthesia and weakness of left extremities. A and B: Preoperative dynamic radiograph showing atlantoaxial instability, atlas assimilation and C2-3 fusion. C and D: CTA with multiplanar reconstruction demonstrating the right VA(arrow) enters spinal canal directly from C2 transverse foramen. E and F: CTA confirming HRVA(arrow) with a narrow C2 pedicle at the right side. G: Gentle Drilling of the bone above the isthmus, exposed the loop of vertebral artery and mobilized it inferiorly for C2 pedicle screw insertion. H: Using the plate screw instrumentation, occipitocervical fixation and fusion was performed. I: Postoperative x-ray showing complete reduction of the dislocation. J and K: Postoperative sagittal and axial CT scan showing a bone defect (arrow) above the isthmus, and the screw passed through the transverse foramen via mobilization of the vertebral artery.

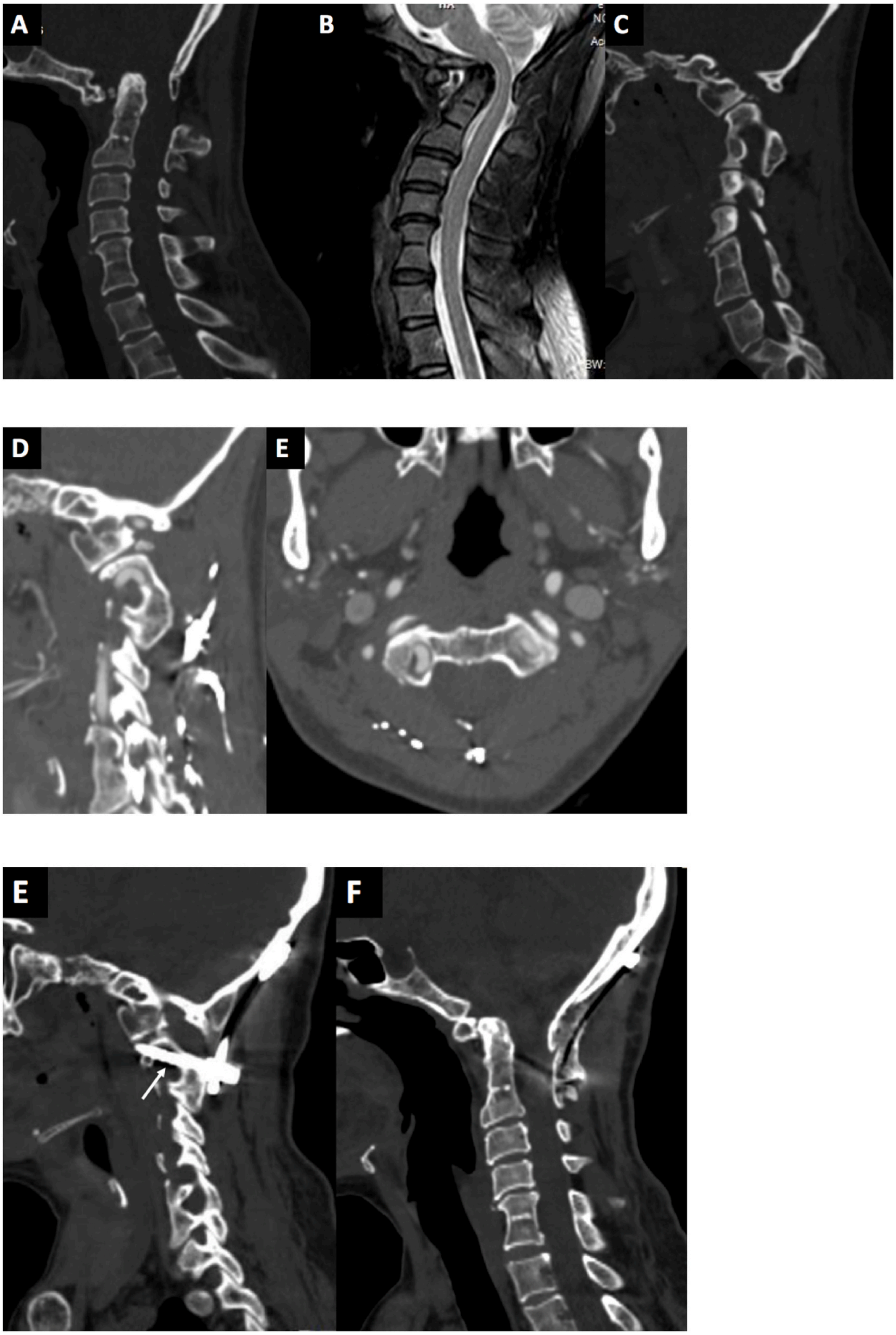

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Fig. 3. Case 14. A 45-year-old woman presented with extremity weakness and paresthesia. A: Preoperative sagittal reconstruction CT scan showing BI and AAD, with Klippel-Feil syndrome. B: T2 weighted sagittal MRI showing obvious ventral compression of the cervicomedullary junction. C, D and E: CT and CTA confirming HRVA with a narrow C2 pedicle at the right side. E and F: Postoperative sagittal CT scans showing the C2 pedicle screw passed through the inner top of the transverse foramen(arrow) and the reduction of AAD was satisfactory.

3. Discussion

The C2 pedicle screw, as it can provide a 3-column fixation, possesses optimal biomechanical properties and is widely applied in upper cervical spine surgery [1,2]. Biomechanical studies have described that the C2 pedicle screw is twice as strong as the isthmus or translaminar screw regarding the anti-pulling strength [9,10]. The congenital BI combined with AAD requires immediate stability and intraoperative reduction, as well as a cervical screw bearing an excellent anti-pulling strength. Thus, the C2 pedicle screw is the preferred clinical option [1,2,5,11].

A high-riding vertebral artery is highly prevalent among patients with craniocervical junction malformations. Pars screws, translaminar screws, transarticular screws, or extended fixation segments were used to replace the C2 pedicle screws to avoid injury of the vertebral artery during the insertion of C2 pedicle screws. Posterior column fixation, which weakened the rigidity of internal fixation, was a prerequisite for reduction and fusion and was critical for a successful procedure [1,5,11,12]. Thus, lengthening the fixed segment brought about the excessive loss of cervical mobility and accelerated degeneration of adjacent cervical spine segments.

Several authors have modified the conventional C2 pedicle screw placement to reduce the risk of vertebral artery injury in patients with a high-riding vertebral artery. The "in-out-in" technique, reported by Gao Yanzheng et al. [13], in which the screw perforated the transverse foramen to form a multi-cortical pedicle screw, failed to protect the vertebral artery from injury during the procedure and therefore contraindicates unilateral vertebral artery supply and high-riding vertebral artery, rendering it of minimal clinical value. The "C2 cortical screw" technique introduced by Kim et al. [12] and the “C2 Parsicle” screw introduced by Kepler et al. [14] essentially move the screw entry point inward. Meanwhile, the screw trajectory is directed as far as possible away from the cancellous bone area. Nevertheless, injury to the vertebral artery remains entirely unavoidable in cases where the high span of the vertebral artery is pronounced. The "C2 medial pedicle screw technique" reported by Du et al. [11] deviated the screw trajectory more medially and thus intentionally breached the spinal canal to create a medial window for the screw placement. Then, the screw can be advanced into the vertebral body, providing a three-column fixation of the axis. There is a risk of spinal cord injury and cerebrospinal fluid leakage when screws enter the spinal canal. In 2020, Professor Goel [15] from India first reported the technique of vertebral artery mobilization-assisted screw placement in cases with high-riding vertebral artery. The technique of vertebral artery mobilization distinguishes itself from the avoidance philosophy of these methods in that the vertebral artery is proactively exposed under microscopic manipulation and the pedicle screw is safely inserted under direct visualization after mobilization of the vertebral artery.

The current definition of a high-riding vertebral artery is evaluated by CT measurements. It fails to reflect the relationship between the C2 pedicle and the vertebral artery. However, the violation of the transverse foramen by misplaced screw does not necessarily imply an injury to the vertebral artery [1,2,5]. Agrawal et al. [16] analyzed the CTA findings of 259 patients and revealed that the vertebral artery was variable in its position within the C2 transverse foramen, occupying a mean transverse foraminal cross-sectional area of 37.3 %. Thus, the vertebral artery possesses a certain degree of mobility within the transverse foramen, laying a theoretical foundation for the feasibility of displacement of the vertebral artery. Additionally, Harman F et al. [17] conducted insertion of C2 pedicle screw after vertebral artery mobilization on human cadavers, confirming that vertebral artery mobilization can reduce the risk of neurovascular injury from an anatomical perspective, especially applicable to patients with HRVA. CTA was routinely performed preoperatively in enrolled patients, and the high-riding vertebral artery was a dominant or single-branch supply, in close proximity to the lateral wall of the C2 pedicle.

The mobilization of the vertebral artery is not a challenge for neurosurgeons trained in microsurgery. The alignment of the vertebral artery based on the position of the transverse foramen of the cardinal spine is preoperatively illuminated on CTA volumetric reconstructions without removing the bone images [4,18,19]. In most cases, the vertebral artery loop was loosely bound to the inner wall of the foramen, and the vertebral artery presented a mobility degree within the transverse foramen. The high-riding vertebral artery was gently dissected from the transverse foramen outward and downward using a microscopic nerve stripper. Meanwhile, a moist gelatin sponge was filled above the vertebral artery loop. The passage of a screw with a diameter of 3.5 mm was sufficiently accommodated through microscopic exploration of the medial aspect of the vertebral artery collaterals within the transverse foramen, contributing to avoiding excessive and brutal manipulation and thus minimizing the harassment of the vertebral artery. If the vertebral artery is poorly dissociated, the lateral wall of the transverse foramen can be opened under a microscope to release the tension of the vertebral artery. Following the displacement of the vertebral artery, screw insertion was conducted under microscopic supervision, and the screw passed above the transverse foramen into the vertebral body. The limited depth drilling and scouting were utilized to proceed slowly and step by step to minimize the risk of vertebral artery injury.

The vertebral artery mobilization technique with C2 pedicle screw insertion was performed successfully in 15 patients without vertebral artery injury or postoperative cerebral infarction. Post-operative imaging demonstrated an impressive reduction of AAD, with no loosening of the internal fixation, displacement or loss of repositioning. The JOA scores of the cervical spine improved noticeably six months after surgery compared to the preoperative score, with a statistically significant difference. Sagittal CT exhibited the presence of a continuous bone bridge between the occipital neck and a successful fusion of the bone graft. Thus, the implantation of the C2 pedicle screw was safe and effective in cases with high-riding vertebral arteries under direct visualization after mobilization of the vertebral artery. Additionally, the multi-cortical screw penetrated all three columns and was biomechanically reliable, laying a

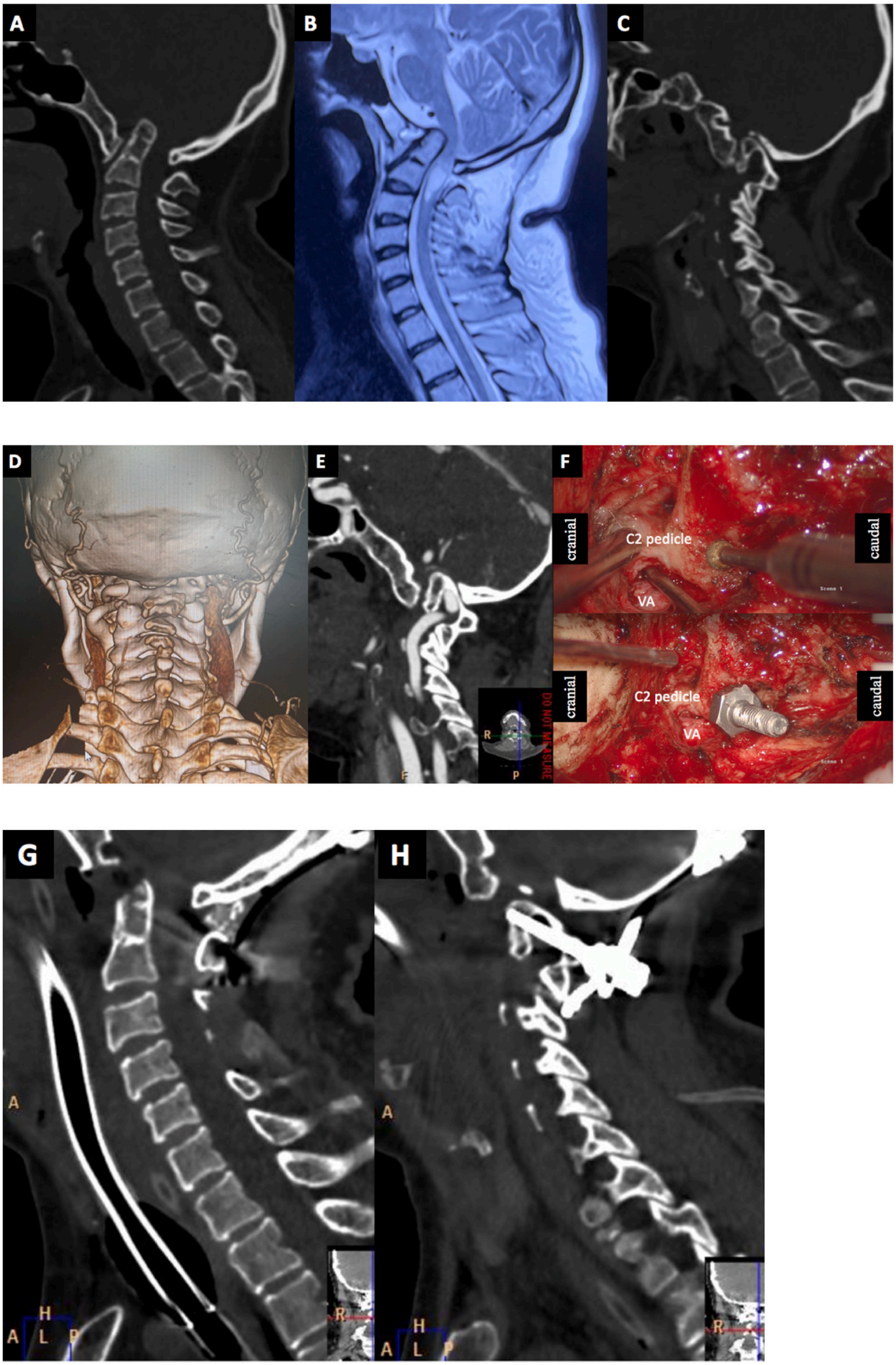

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Fig. 4. Case 15. A 40-year-old woman presented with ataxia , extremity numbness and weakness. A: Preoperative sagittal reconstruction CT scan showing BI, AAD, atlas assimilation and C2-3 fusion. B: Ventral severe compression of the cervicomedullary junction, with intramedullary high-signal lesion on T2-weighted MRI. C: The sagittal CT implying HRVA with a narrow C2 pedicle at the left side. D and E: CTA with multiplanar reconstruction and sagittal CT confirming HRVA with single-branch blood supply at the left side. F: The vertebral artery was exposed and mobilized with gelfoam inferiorly and laterally under the microscope. G: Postoperative sagittal CT scan showing anatomical reduction of the basilar BI and AAD. H: Postoperative sagittal scan showing the C2 pedicle screw passed through the transverse foramen achieving three-column fixation.

foundation for intraoperative reduction and fusion.

The potential risk associated with the mobilization of the vertebral artery is venous plexus hemorrhage [15]. A more pronounced venous plexus hemorrhage could occur when the vertebral artery is exposed in the transverse foramen. Improper manipulation can cause high blood loss and compromise the surgical fields and surgical safety. Benefiting from the delicate manipulation under the microscope, none of the patients from this group suffered any blood transfusion. If intraoperative bleeding from the venous plexus is raging, direct compression is most effective in stopping the bleeding and avoiding repeated attempts to identify the bleeding point leading to increased blood loss. The hemostatic effect can be improved with hemostatic materials such as gelatin sponges and hemostatic gauze. Furthermore, vertebral artery injury is a rare but dangerous complication. During the operation, the vertebral artery should be gently separated under the microscope on the lateral side of the transverse foramen along the route of the vertebral artery. While using the high-speed drill, the vertebral artery should be protected by the instruments on the side of the vertebral artery to avoid direct injury due to negligence. Besides, the screw should be inserted as far as possible along the upper edge of the pedicle after vertebral artery mobilization, so as to avoid continuous oppression on the vertebral artery loop.

This technology fully leverages the advantages of micro-neurosurgery, breaking through the limitations of the C2 pedicle screw implantation in cases with HRVA. Unlike the avoidance concept of posterior column fixation, it directly exposes and mobilizes the vertebral artery to assist with multi cortical screw implantation, ensuring the strength of internal fixation and maximizing the retention of cervical mobility. The fixed segments of the 12 patients complicated with C2-3 fusion in this group did not exceed the level of C3, and all the patients in this group were satisfied with intraoperative reduction. There were no postoperative complications such as internal fixation loosening, displacement, or loss of reduction. However, the operation of this technique is relatively complicated compared to simple posterior column fixation, especially when expanding the outlet of the transverse foramen of the vertebral artery, which must be completed under a microscope. Exposure and mobilization of the vertebral artery still pose certain risks and require careful operation.

In patients with congenital BI combined with AAD, there are many variations in the blood supply and course of the vertebral artery. Before surgery, it is necessary to carefully review the imaging characteristics and have a clear understanding of the course of the vertebral artery to avoid blind manipulation. In addition, the displaced vertebral artery is separated from the screw by gelatin sponge. Although no adverse reactions have been observed during follow-up, it remains to be seen whether the screw will stimulate the vascular wall and cause stenosis of the vertebral artery in the long term as the artery continues to pulsate.

In conclusion, C2 pedicle screw insertion assisted by mobilization of the vertebral artery is safe and remarkably effective, providing a better choice for internal fixation in cases with high-riding vertebral arteries. It can offer a 3-column rigid fixation of the axis while avoiding vertebral artery injury with remarkable clinical efficacy. In the future, additional biomechanical and clinical studies should be performed to further evaluate its safety and efficacy.

Funding

None.

Ethical statement

The study was approved by the ethics committee of the First Affiliated Hospital of USTC(2023-RE-004)and informed consent was obtained from all participants.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Jiang Liu: Writing – review & editing, Writing – original draft, Investigation, Data curation. **Li Jia:** Methodology. **Minghui Zeng:** Software, Methodology. **Hao Xu:** Investigation, Formal analysis. **Rui Zhang:** Writing – review & editing, Conceptualization. **Qi Pang:** Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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