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A New Classification of High-Riding Vertebral Artery for Safe C2 Screw Placement

Mingjun Xi
Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.
Beixi Bao
Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.
Xiaoxia Qu
Department of Radiology, Beijing Tongren Hospital, Capital Medical University, Beijing, China.
Jianhua Tao
Department of Radiology, Beijing Tongren Hospital, Capital Medical University, Beijing, China.
Xiaokang Cheng
Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.
Jiaguang Tang
tryytjg2019@163.com

Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

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Title page

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Author List:

1、MingJun Xi

Affiliations: Institutional Affiliations: Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

Email: ximingjun041921@163.com

2、Beixi Bao

Affiliations: Institutional Affiliations: Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

Email: bxsol@163.com

3、Xiaoxia Qu

Affiliations: Department of Radiology, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

Email: xiaoxia.qu@foxmail.com

4、Jianhua Tao

Affiliations: Department of Radiology, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

Email: tjhpeak@163.com

5、Xiaokang Cheng

Affiliations: Institutional Affiliations: Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

Email: drcxkzlx@163.com

Xiaokang cheng

6、JiaGuang Tang（Corresponding Author）

Institutional Affiliations: Department of orthopedics, Beijing Tongren Hospital, Capital Medical University, Beijing, China.

Email: tryytjg2019@163.com

Tel: 13911003227

A New Classification of High-Riding Vertebral Artery for Safe C2 Screw Placement

I.Abstract

Background: The high-riding vertebral artery (HRVA) is the most common V3 segment variant and significantly increases the risk of C2 screw placement. However, existing classifications system lack direct integration with surgical planning. This study proposes a novel HRVA classification system based on parameters directly relevant to C2 isthmic screw fixation. Methods: We retrospectively analyzed 243 HRVA sides from 211 patients who underwent posterior atlantoaxial fusion between 2016 and 2025. Using standardized CTA measurements, we quantified the C2 isthmus width and the maximum intraosseous trajectory length for a 3.5 mm C2 isthmic screw. Based on these parameters and the screw length required for adequate purchase (9-14 mm), HRVA was classified into four subtypes (A、B、C、D). Inter-observer reliability was assessed using the Kappa test.Results: The distribution was: Type A (isthmus width ≥3.5 mm) in 18 (7.4%), Type B (width <3.5 mm, length ≥14 mm) in 46 (19%), Type C (width <3.5 mm, length 9-14 mm) in 178 (73%), and Type D (width <3.5 mm, length <9 mm) in 1 (0.4%). The CC combination was most common (53%) in bilateral cases. Inter-observer reliability was excellent for both measurements (κ=0.895) and classification (κ=0.827). Conclusions: This novel classification, based on C2 isthmus width and intraosseous screw trajectory length, provides a practical, surgeon-oriented tool for preoperative risk stratification and individualized screw placement strategy in patients with HRVA, potentially improving surgical decision-making. Further prospective multicenter studies are warranted to validate its clinical

utility.

Key words： Atlas and Axis; Variations in Vertebral Artery Course; CTA; C1-C2 Screw Fixation; Preoperative Planning

II. Background

Atlantoaxial instability can lead to patient neck pain and even neurological dysfunction. Reduction and fixation are among the most important methods for treating this condition. Fixation using C1 lateral mass screw combined with C2 pars screw is currently the most widely used method(1-5).However, due to the special anatomical characteristics of the atlantoaxial vertebrae, the risk associated with screw placement in this region is much higher than in other segments of the spine. Particularly, vertebral artery course variations often occur in this area, further increasing the surgical risk(6, 7). The most common variant is the high-riding vertebral artery (HRVA), with an incidence of 25.3%(7). Due to its unique course, it can reduce the available space for C2 screw insertion, thereby increasing surgical risk(8, 9). Therefore, a thorough understanding of the impact of HRVA on C2 screw placement is of great importance. In our clinical practice, we observed that among patients with HRVA, the difficulty of screw placement varies considerably. To further quantify the risk posed by HRVA to C2 screw fixation, this study enrolled patients with HRVA who underwent posterior atlantoaxial fusion with internal fixation at our institution between 2016 and 2025. Using a standardized measurement protocol, we measured the width of the C2 isthmus and the maximum intraosseous trajectory length of the C2 isthmic screw in each patient. A scatter plot was generated with the C2 isthmus width on the X-axis and the maximum

intraosseous screw trajectory length on the Y-axis. Based on the actual screw dimensions (3.5 × 3.5 mm) and the required screw length of 9-14 mm for adequate purchase(10), HRVA was classified into four subtypes—A, B, C, and D—and the risk of C2 screw placement associated with each subtype was analyzed.

III. Materials and Methods

1.Study Subjects

This study retrospectively collected imaging data from patients who underwent posterior atlantoaxial surgery at our institution between January 2016 and December 2025. Among these, 211 patients were identified as having high-riding vertebral arteries (HRVA), of whom 32 had bilateral HRVA. A total of 243 HRVA sides were ultimately included in this study.

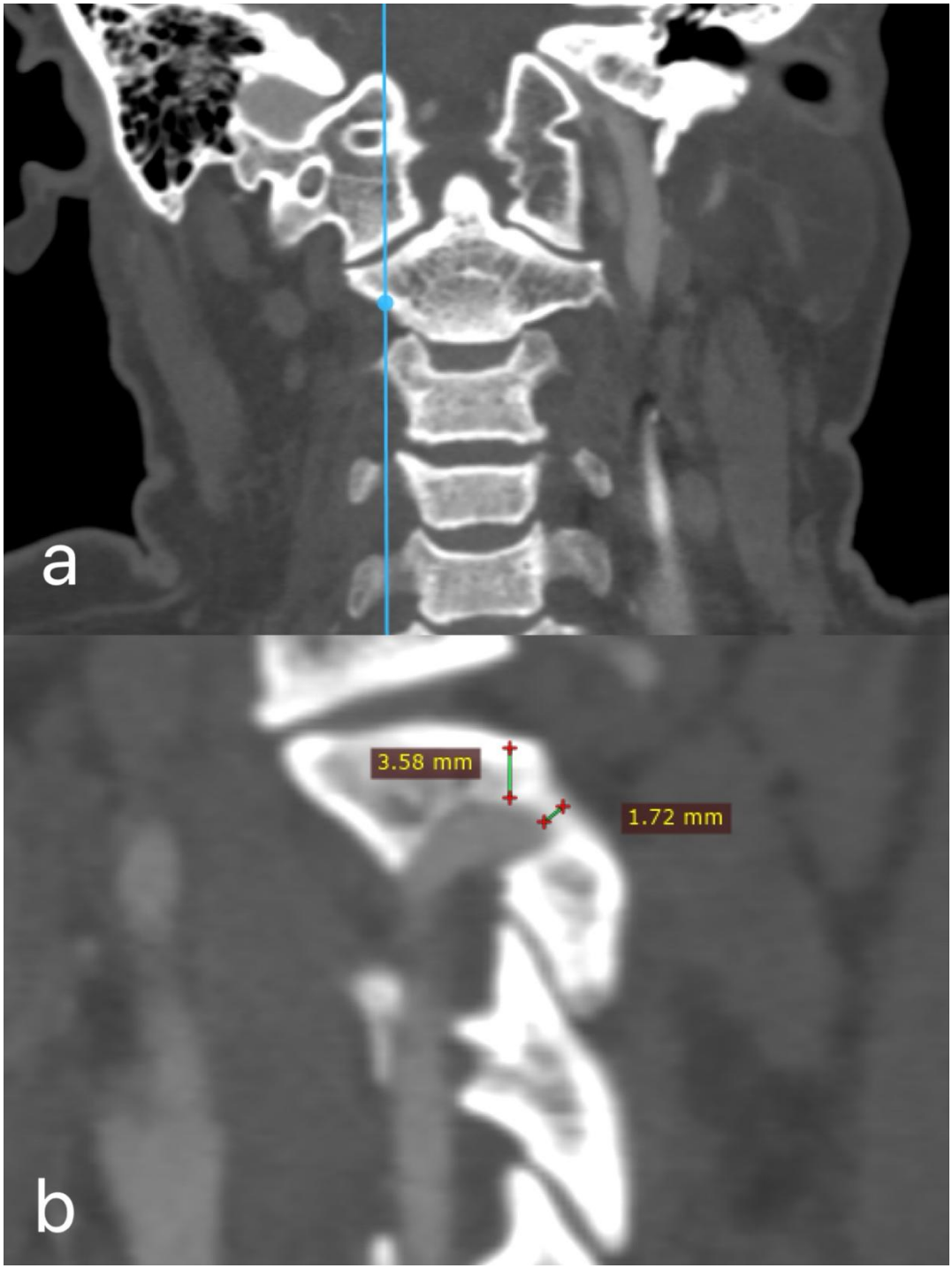
2. Inclusion and Exclusion Criteria

2.1 Inclusion Criteria:(1) age ≥ 18 years;(2) no gender restrictions;(3) the CTA imaging scan range completely covers the craniocervical junction region (from the aortic arch to the skull base) and the image quality meets the requirement for clear discrimination of bony structures and the vertebral artery;(4) The vertebral artery course conform to the definition of a high-riding vertebral artery.

2.2 Exclusion Criteria were as follows:(1) presence of secondary bone structure abnormalities that may interfere with measurements, such as atlantoaxial fracture, occipitalization of the atlas, tumors, severe degeneration, or prior surgery history in this region;(2) severe artifacts, or the vertebral artery is not clearly visualized due to hypoplasia or occlusion, preventing accurate measurement.

3. Definition of High-Riding Vertebral Artery:The high-riding vertebral artery was defined as an internal height of the C2 vertebra of less than 2 mm, or an isthmus height of the C2 less than 5 mm, measured on the sagittal plane located 3 mm medial to the inner border of the spinal canal(11). (Fig.1)

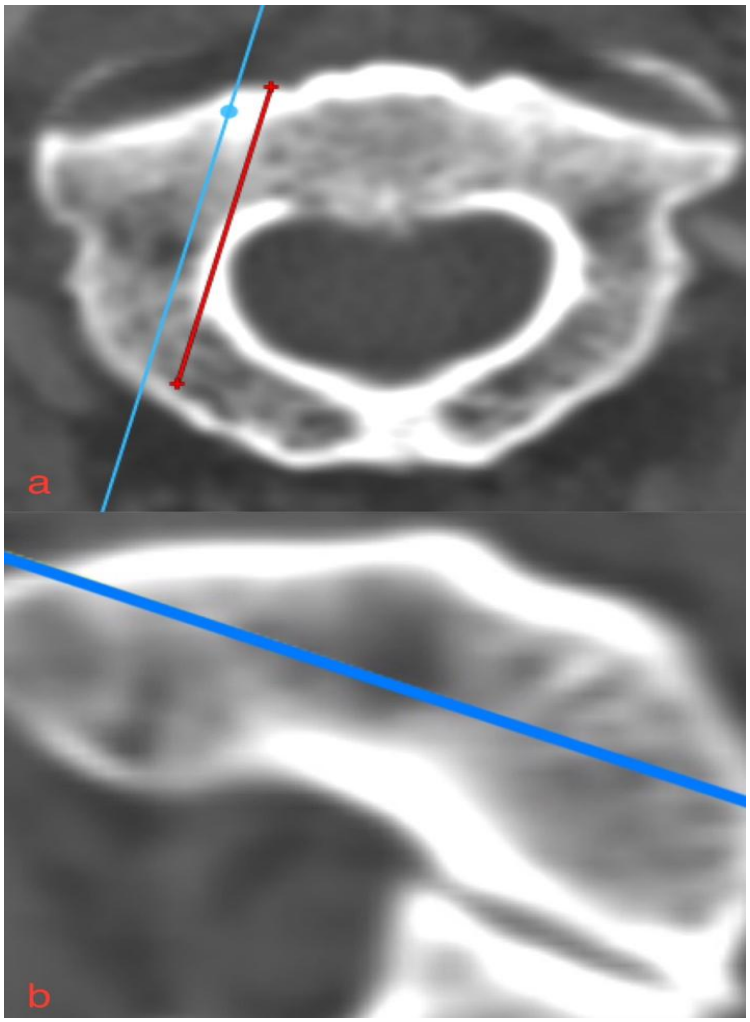
Figure 1: Definition of High-Riding Vertebral Artery



4. Measurement Methods and Definitions of C2 Isthmus Width and Maximum Intraosseous Trajectory Length of the C2 Isthmic Screw

To ensure comparability of the measured data, a standardized measurement protocol was adopted in this study. On the sagittal plane, the blue reference line was adjusted to be parallel to the C2 isthmus. On the axial plane, the blue reference line was adjusted to form a 5-degree angle with the midline and positioned 2 mm from the medial border of the spinal canal. (Fig.2)

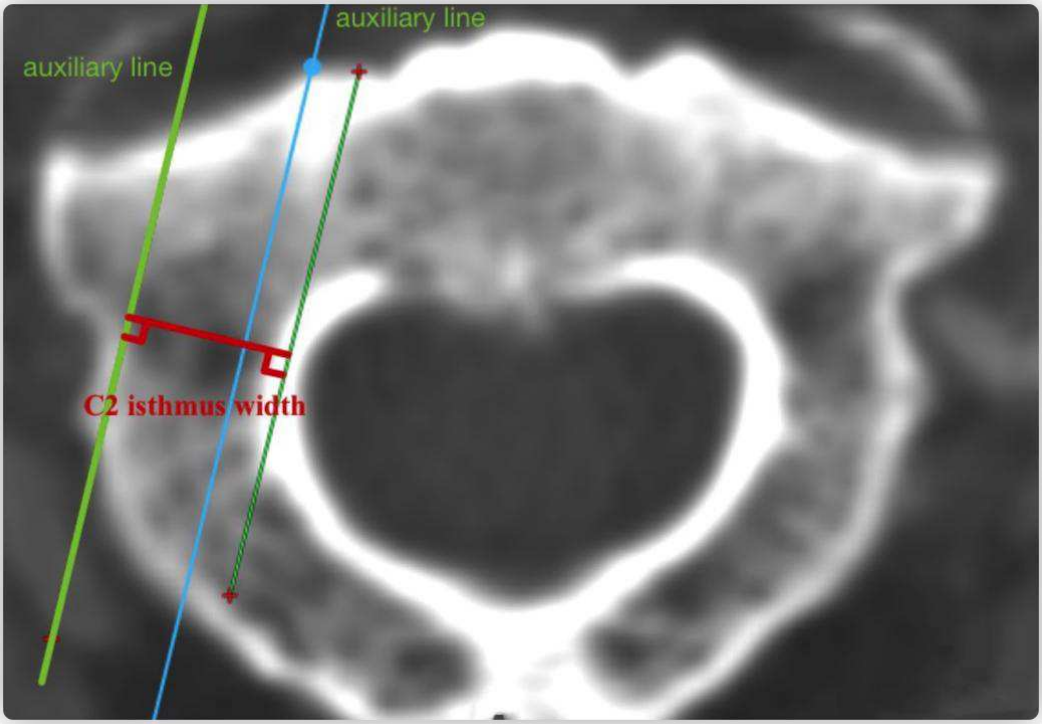
Figure 2: Measurement method of C2 isthmus width and the maximum introsseous trajectory Figure caption: Length of C2 isthmus screw



4.1 Measurement of C2 Isthmus Width

To measure the C2 isthmus width, two auxiliary lines parallel to the planned C2 isthmus screw trajectory were drawn on the axial plane. One line was aligned with the medial border of the spinal canal, and the other with the border of the vertebral artery course. The perpendicular distance between these two parallel lines was measured as the C2 isthmus width. (Fig.3)

Figure 3: Measurement method and definition of C2 isthmus width



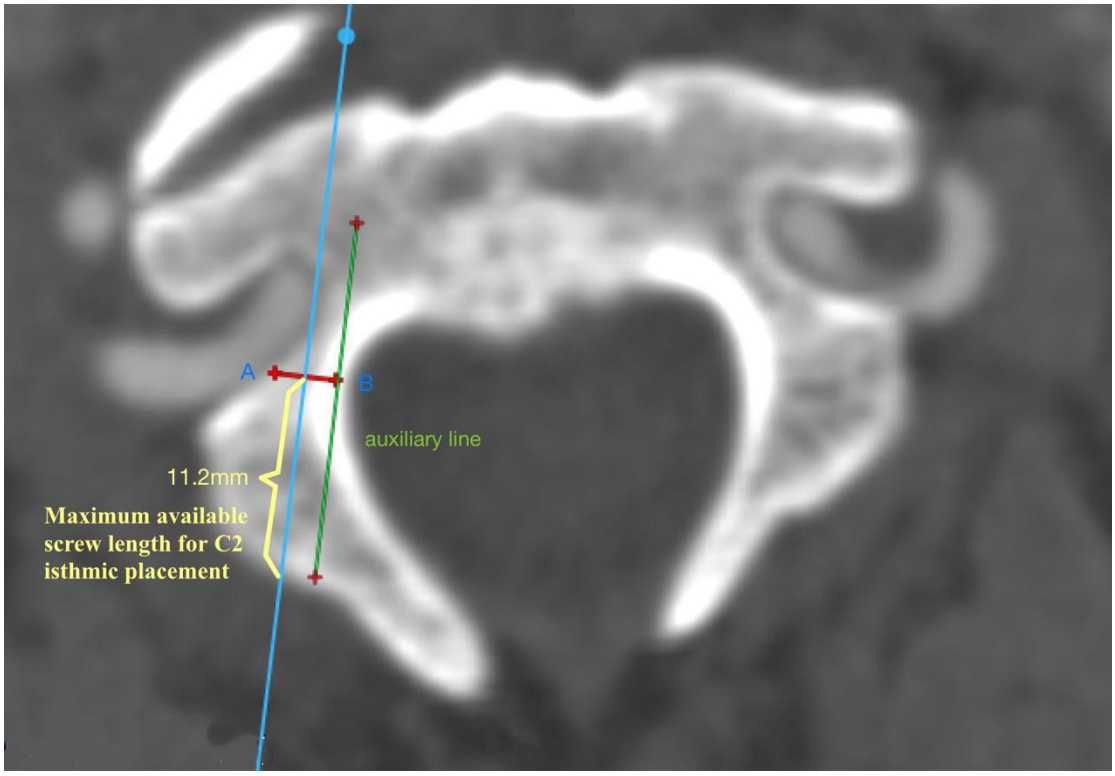
4.2 Measurement of the Maximum Intraosseous Trajectory Length for C2 Isthmus Screws

4.2.1. C2 Isthmus Width ≥ 3.5 mm: the C2 isthmus width is greater than the diameter of the C2 isthmus screw, the theoretical maximum intraosseous trajectory length for the C2 isthmus screw equals the entire length of the C2 isthmus. (Fig.3)

4.2.2 C2 Isthmus Width < 3.5 mm: the maximum intraosseous width of the screw trajectory is less than 3.5 mm. To measure the maximum intraosseous trajectory length,

first, draw a line parallel to the entry trajectory direction, tangent to the medial border of the spinal canal. Then, draw a perpendicular line (represented in red) to this parallel line, with a length of 3.5 mm, intersecting both the parallel line and the boundary of the vertebral artery course (intersection points A and B). The distance from the blue line (representing the screw's entry point/path) to this red perpendicular segment is then measured as the maximum intraosseous trajectory length for the C2 isthmus screw. (Fig. 4).

Figure 4: Measurement and definition of the maximum introsseous trajectory length of C2 isthmus screw when C2 isthmus width is less than 3.5 mm



5. Classification Method and Definitions of High-Riding Vertebral Artery Subtypes

A scatter plot was generated with the C2 isthmus width on the X-axis and the maximum intraosseous trajectory length of the C2 isthmic screw on the Y-axis. Based on the actual screw diameter of 3.5 mm and the required screw length of 9–14 mm(10) for adequate

purchase, HRVA was classified into four subtypes:Type A: C2 isthmus width ≥ 3.5 mm;Type B: C2 isthmus width < 3.5 mm, with C2 isthmus length ≥ 14 mm;Type C: C2 isthmus width < 3.5 mm, with 9mm ≤ C2 isthmus length < 14 mm;Type D: C2 isthmus width < 3.5 mm, with C2 isthmus length < 9 mm. (Fig. 5 and 6)

Figure 5: Classification of high-riding vertebral artery — imaging findings

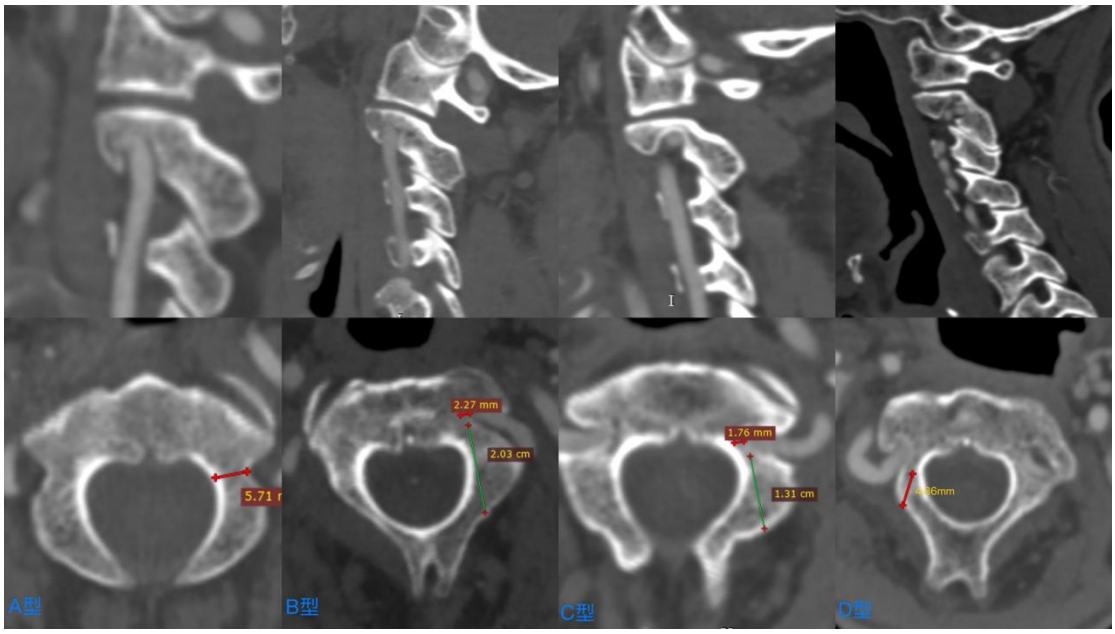
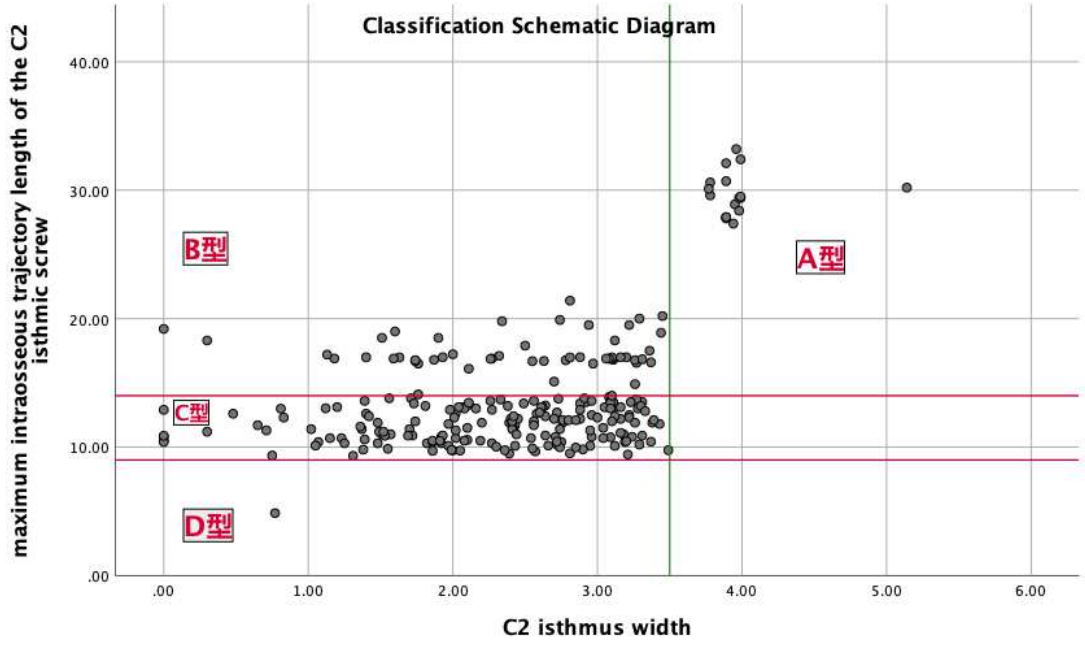


Figure 6: Classification of high-riding vertebral artery — scatter plot



5. Clinical Data

5.1 Surgical Approach: Posterior atlantoaxial fusion with C2 isthmic screw and C1 lateral mass screw internal fixation.

5.2 Ethics and Informed Consent: The study protocol was reviewed and approved by the Ethics Committee of Beijing Tongren Hospital, approval number: MR-11-26-084745, approval date: September 30, 2026. All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

6. Consistency Assessment of Data Measurement and Classification System

This study utilized RadiAnt DICOM Viewer for image review and measurement of risk parameters. To minimize the influence of subjective factors on the measurement results, all measurements and classifications in this study were independently performed by two senior attending physicians using the standardized measurement protocol and classification system described above. Inter-observer consistency was first assessed for the measured parameters and classifications, with the Kappa test used to evaluate classification consistency. The final data were calculated as the average of the two observers' results.

7. Statistical Analysis

Statistical analyses were performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA). Categorical data were presented as counts (percentages). Continuous data were first tested for normality using the Shapiro-Wilk test; variables with a normal

distribution were expressed as mean ± standard deviation, while those without a normal distribution were expressed as median (interquartile range). Inter-observer consistency was assessed using the Kappa test, with a Kappa value > 0.81 indicating excellent agreement. The distribution of HRVA subtypes (A/B/C/D) was described as counts (percentages). Differences in the distribution of subtypes across sex and side were analyzed using the Pearson chi-square test; when the expected frequencies did not meet the assumptions of the chi-square test, the Fisher exact test or likelihood ratio test was applied as a correction. The distribution of subtype combinations in patients with bilateral HRVA was described as counts (percentages). All tests were two-tailed, and a P value < 0.05 was considered statistically significant.

IV. Results

4.1 Patient Screening Flow

The initial cohort of this study included 638 patients scheduled for posterior atlantoaxial surgery. Among them, 12 patients were excluded due to age younger than 18 years, 6 were excluded due to suboptimal quality of head and neck CTA images, 6 were excluded due to basilar invagination, and 403 were excluded for not conform to the definition of high-riding vertebral artery. 211 patients met the diagnostic criteria for HRVA, of whom 32 had bilateral HRVA.Ultimately, a total of 243 HRVA sides included in this study.

4.2 Baseline Characteristics of Patients

Among the 211 patients, there were 132 males (54.3%) and 111 females (45.7%). The mean age of the patients was 63.0 ± 12.5 years, with a mean age of 61.0 ± 11.7 years

for males and 65.0 ± 13.1 years for females. Of the 243 HRVA sides, 32 patients (15.2%) had bilateral HRVA (Table 1).

Table 1: Baseline Characteristics of the Patients (n=243)

Characteristic	Value
Total number of patients	211
Male, (%)	132(54%)
Female, (%)	111(46%)
Mean age±SD	63±12.5
Mean age±SD, Male	61±11.7
Mean age±SD, Female	65±13.1
Number of vertebral arteries included	243
Bilateral high-riding vertebral artery	32
Caption: Baseline Characteristics of the Patients (n=243). Data are presented as mean ± SD or n (%). SD, standard deviation.	

4.3 Normality Test

Normality tests were performed on the C2 isthmus width and the maximum intraosseous trajectory length of the C2 isthmic screw. Both tests indicated that neither variable followed a normal distribution. The median C2 isthmus width was 2.56 mm with a standard deviation of 0.90 mm, and the median maximum intraosseous trajectory length of the C2 isthmic screw was 12.50 mm with a standard deviation of 5.12 mm (Table 2).

Table 2: Shapiro-Wilk test of normality

Variable	Median(mm)	Shapiro-Wilk test (P value)
C2 isthmus width	2.6±0.9	<0.001
Maximum Intraosseous Trajectory Length of C2 Isthmus Screws	12.5±5.1	<0.001
Captions: Shapiro-Wilk test of normality. Data are presented as median ± SD. SD, standard deviation. A P value < 0.05 indicates a non-normal distribution.		

4.4 Distribution of Subtypes

A scatter plot was generated with the C2 isthmus width on the X-axis and the maximum intraosseous trajectory length on the Y-axis. Using the clinically common C2 isthmic screw dimensions of 3.5 × 3.5 mm and the required screw length of 9-14mm(10) for adequate purchase as thresholds, the 243 HRVA sides were classified into four subtypes. Type C accounted for 178 sides (73%), Type B for 46 sides (19%), Type A for 18 sides (7%), and Type D for 1 side (0.4%). (Table 3)

Table 3: Distribution of high-riding veltebral artery subtypes

Type	n (%)
A-type	18(7%)
B-type	46(19%)
C-type	178(73%)
D-type	1(0.4%)
Total	243

Caption: Distribution of high-riding vertebral artery subtypes. Data are presented as n (%). Percentages may not sum to 100 due to rounding.

4.5 Distribution of Subtypes by Sex and Side

4.5.1 Sex Distribution

No statistically significant difference was observed in the sex distribution among the different HRVA subtypes (Table 4).

Table 4: Chi-Square Test for the Distribution of High-Riding Vertebral Artery Subtypes Across Sex

	Value	df	Asymp.sig. (2-side)
Pearson Chi-Square	5.280	4	.260
Likelihood Ratio	6.410	4	.171
Valid Cases	243		

Caption: Chi-Square Test for the Distribution of High-Riding Vertebral Artery Subtypes Across Sex.

Type A comprised 18 sides, including 9 male (50%) and 9 female (50%). Type B comprised 46 sides, including 20 male (43%) and 26 female (57%). Type C comprised 178 sides, including 100 male (56%) and 78 female (44%). Type D comprised 1 side, including 1 male (100%) and 0 female (0%) (Table 5).

Table 5: Distribution of High-Riding Vertebral Artery Subtypes by Sex

Subtype	Male	Female	Total
Type A	9(50%)	9(50%)	18
Type B	20(44%)	26(56%)	46

Type C	100(56%)	78(44%)	178
Type D	1(100%)	0	1
Total	130	113	243
Caption: Distribution of High-Riding Vertebral Artery Subtypes by Sex. Data are presented as n (%).			

4.5.2 Side Distribution

The overall difference inside distribution among the different HRVA subtypes did not reach statistical significance (Table 6).

Table 6: Chi-Square Test for the Distribution of High-Riding Vertebral Artery Subtypes Across Positions

	Value	df	Asymp.sig. (2-side)
Pearson Chi-Square	9.141	4	.058
Likelihood Ratio	10.396	4	.061
Valid Cases	243		
Caption: Chi-Square Test for the Distribution of High-Riding Vertebral Artery Subtypes Across Positions.			

Type A comprised 18 cases, including 11 left (61%) and 7 right (39%). Type B comprised 46 cases, including 26 left (57%) and 12 right (43%). Type C comprised 178 cases, including 100 left (56.2%) and 78 right (43.8%). Type D comprised 1 case, including 0 left and 1 right (Table 7).

Table 7: Distribution of High-Riding Vertebral Artery Subtypes by Laterality

Subtype	Left	Right	Total

Type A	11(61%)	7(39%)	18
Type B	26(57%)	20(43%)	46
Type C	100(56.2%)	78(43.8%)	178
Type D	0	1(100%)	1
Total	145	98	243
Caption: Distribution of High-Riding Vertebral Artery Subtypes by Laterality. Data are presented as n (%).			

4.6 Distribution of Subtype Combinations in Bilateral HRVA

Among the 211 patients with HRVA included in this study, 32 patients (15%) had bilateral HRVA. The distribution of subtype combinations in bilateral cases was as follows: CC combination in 17 cases (53%), BB combination in 5 cases (16%), BC combination in 4 cases (13%), AC combination in 3 cases (9%), DC combination in 1 case (3%), AA combination in 1 case (3%), and AB combination in 1 case (3%). (Table 8).

Table 8: Distribution of Bilateral High-Riding Vertebral Artery Subtype Combinations

Combinaton	n	Percentage
CC	17	53%
BB	5	16%
BC	4	13%
AC	3	9%
DC	1	3%

AB	1	3%
AA	1	3%
Total	32	100%
Caption: Distribution of Bilateral High-Riding Vertebral Artery Subtype Combinations. Data are presented as n (%).		

4.7 Mean C2 Isthmus Width and Maximum Intraosseous Trajectory Length of the C2 Isthmic Screw by HRVA Subtype

Based on the measurement results, the mean C2 isthmus width was 3.9 mm for Type A, 2.5 mm for Type B, 2.3 mm for Type C, and 2.4 mm for Type D. The mean maximum intraosseous trajectory length of the C2 isthmic screw was 28.9 mm for Type A, 17.5 mm for Type B, 11.7 mm for Type C, and 4.45 mm for Type D (Table 9).

Table 9: Mean C2 Isthmus Width and Maximum Intraosseous Trajectory Length of the C2 Isthmic Screw by Type

Type	Mean C2 Isthmus Width (mm)	Mean Maximum Intraosseous Trajectory Length of the C2 Isthmic Screw (mm)
Type A	3.9	28.9
Type B	2.5	17.5
Type C	2.3	11.7
Type D	2.4	4.45
Caption: Mean C2 Isthmus Width and Maximum Intraosseous Trajectory Length of the C2 Isthmic Screw by Type.		

4.8 Consistency Assessment of Parameter Measurements and Classification

4.8.1 Consistency Assessment of Parameter Measurements

For 243 vertebral arteries, the interobserver κ was 0.895, indicating almost perfect agreement. This supports the Reliability and reproducibility of our Measurement system (Table.10)

Table 10: Reliability for the Vertebral Artery Measurement System

Agreement Measure	Value	Asymptotic Standard Error	Approximate T	Asymptotic Significance
Kappa	0.895	0.057	10.066	0.000
Valid Cases	243			
Caption: Reliability for the Vertebral Artery Measurement System. Kappa value > 0.81 indicates excellent agreement.				

4.8.2 Consistency Assessment of Classification

For 243 vertebral arteries, the interobserver κ was 0.827, indicating substantial to almost perfect agreement. This supports the Reliability and reproducibility of our Vertebral Artery Classification system. (Table.11)

Table 11: Reliability for the Vertebral Artery Classification system

Agreement Measure	Value	Asymptotic Standard Error	Approximate T	Asymptotic Significance

Kappa	0.827	0.049	10.273	0.000
Valid Cases	243			
Caption: Reliability for the Vertebral Artery Classification System. Kappa value > 0.81 indicates excellent agreement.				

V. Discussion

1. Theoretical Basis of the Proposed Classification System

In clinical practice, a longer intraosseous screw trajectory generally provides greater stability. When the maximum intraosseous trajectory length of the screw exceeds 14 mm, it can provide favorable biomechanical stability(12). Furthermore, if the screw can traverse the full length of the C2 isthmus to achieve bicortical purchase, its stability is further enhanced(13). However, in patients with HRVA, the C2 isthmus width is often smaller than the screw diameter; therefore, excessively long screws carry an increased risk of vertebral artery injury. To avoid such injury, relatively shorter screws are typically used. When the screw length ranges from 9 to 14 mm, although not the first choice, it can still provide favorable biomechanical stability and may serve as an alternative to bicortical screw fixation(10). Studies have demonstrated that screw pullout strength depends on the screw major diameter, the length of thread engagement, bone shear strength, and the thread shape factor(14). In cervical spine screws, each 1mm reduction in intraosseous screw length decreases pullout strength by approximately 16 N(15). In C2 fixation, although a 14mm isthmic screw provides favorable biomechanical stability, its osseous purchase is significantly inferior to that of longer C2 screws(10). When the intraosseous trajectory length falls below 9mm,

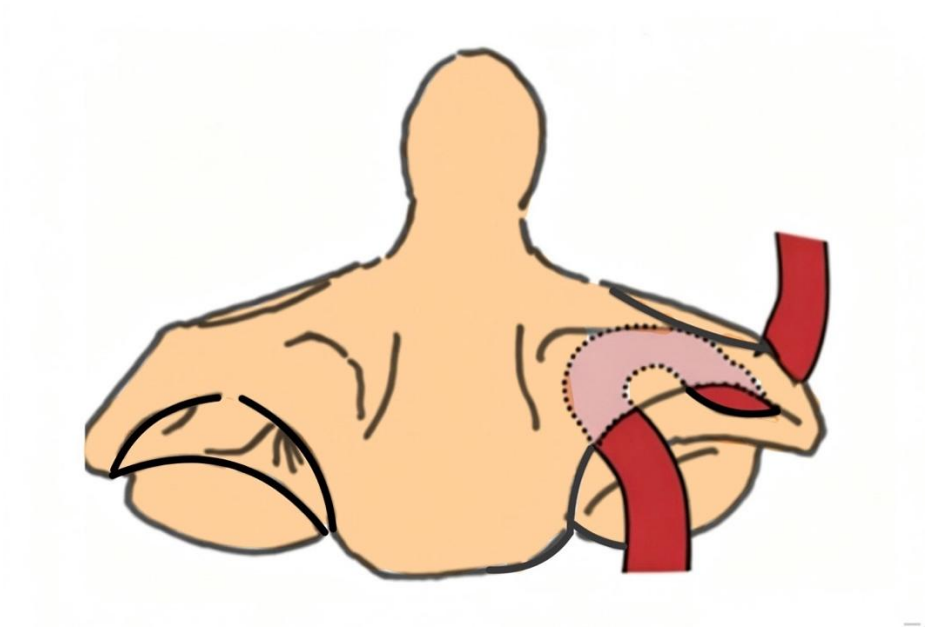
more than 2.5 times the diameter of a 3.5 mm screw, the effective thread engagement length becomes insufficient to generate reliable osseous purchase. Although no study to date has demonstrated poor stability of screws shorter than 9mm, biomechanical studies of spinal screws consistently indicate that even a few millimeters of intraosseous thread engagement can substantially reduce pullout strength(16). Therefore, this study adopted 14 mm and 9 mm as the thresholds for the maximum intraosseous trajectory length of the C2 isthmic screw to classify HRVA into four subtypes: A, B, C, and D.

2. Advantages of the Proposed Classification System

The high-riding vertebral artery (HRVA) is the most common variant of the V3 segment of the vertebral artery, with an incidence of approximately 25.3%. It also represents the variant posing the greatest risk to C2 screw placement, as injury to the vertebral artery can lead to catastrophic consequences(8). Therefore, a thorough understanding of the risk profile and course characteristics of HRVA is of paramount importance. During clinical surgery, we observed that screw placement in some HRVA cases is relatively straightforward and safe, whereas in others it is considerably more challenging and hazardous. This underscores the need to further quantify the internal risk associated with HRVA and to establish a classification system.To date, Klepinowski, T(17) have classified HRVA into three subtypes based on the original definition of a high-riding vertebral artery: Type I, C2 isthmus height < 5 mm with C2 medial height > 2 mm; Type II, C2 isthmus height > 5 mm with C2 internal height < 2 mm; and Type III, C2 isthmus height < 5 mm with C2 internal height < 2 mm. Appropriate screw trajectories are selected for each type based on the degree of C2

isthmus narrowing. Du, Y(18) further expanded upon Klepinowski's classification by adding two additional subtypes: the absent C2 internal height type and the absent C2 isthmus height type. However, these classification systems have notable limitations: they are not integrated with actual clinical surgical practice, and they fail to capture the fundamental mechanism underlying the high risk of C2 isthmic screw placement in HRVA.The fundamental cause of the elevated risk lies in it courses through the C2 transverse foramen, which narrows the C2 isthmus and consequently reduces the available space for screw insertion(Fig. 7).

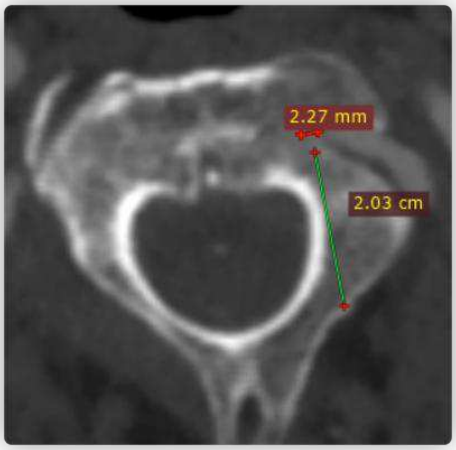
Figure 7: Medial deviation of the high-riding vertebral artery as it passes through the C2 transverse foramen



Based on our actual measurements, among the 243 HRVA sides, 225 (93%) had a C2 isthmus width smaller than the screw diameter of 3.5 mm, while only 18 sides (Type A) exceeded 3.5 mm. When the isthmus width is less than 3.5 mm, the maximum allowable screw insertion depth is further restricted. Since HRVA is a three-dimensional course variation, the medial deviation can be further subdivided into an

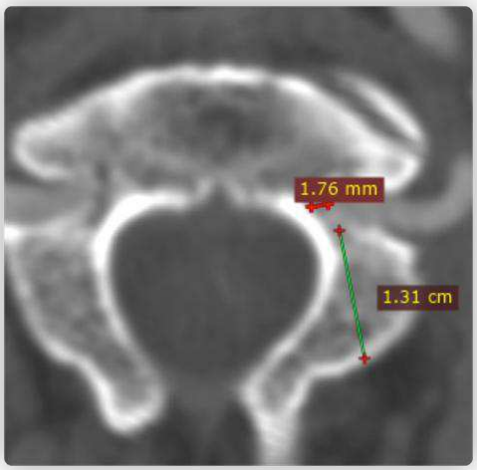
anteromedial course and a posteromedial course. For the anteromedial type—Type B—although the C2 isthmus width is smaller than the screw diameter, the anteromedial course does not compromise the achievable screw insertion depth within the C2 isthmus (Fig. 8).

Figure 8: High-riding vertebral artery — Type B



Our measurements confirmed that the mean maximum intraosseous trajectory length of the C2 isthmic screw in Type B was 17.5 mm. In contrast, for the posteromedial types—Types C (Fig. 9)

Figure 9: High-riding vertebral artery — Type C



and D (Fig. 10)

Figure 10: High-riding vertebral artery — Type D



—the risk of screw placement is relatively higher. This course variant combines medial and posterior deviation, thereby limiting the achievable screw insertion depth. In clinical practice, the screw trajectory must be carefully planned to maximize intraosseous purchase, and the appropriate screw length must be selected with close attention to insertion depth during placement. This study also analyzed the subtype combinations in patients with bilateral HRVA. The CC combination was the most prevalent, accounting for 53% of cases. This finding has direct clinical implications: Type C substantially limits the achievable screw insertion depth due to its posteromedial course, making screw placement technically demanding and carrying a higher risk of vertebral artery injury. Therefore, when a Type C HRVA is identified on preoperative CTA on one side, the surgeon should maintain a high index of suspicion for a contralateral Type C and prepare for bilateral challenging screw placement. This finding has significant value for preoperative planning: when a Type C HRVA is identified on preoperative CTA on one side, the surgeon should maintain a high index of suspicion for a contralateral Type C. Furthermore, no DD, AD, or BD combinations

were observed in bilateral cases, which may be attributable to the extremely low overall incidence of Type D (0.4%). Notably, asymmetric bilateral combinations (BC, AC, DC, and AB) accounted for 9 cases (28.1%), suggesting that in nearly one-third of bilateral HRVA patients, the two sides have different subtypes. Therefore, surgeons should avoid preoperative planning based on only one side in patients with bilateral HRVA.

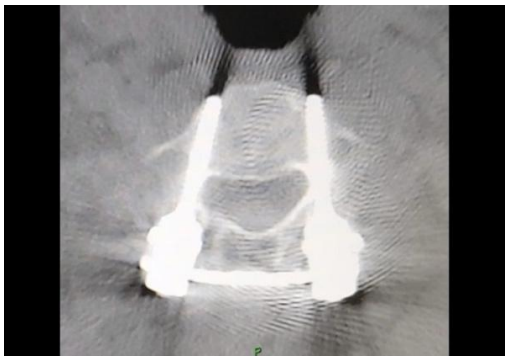
3. Screw Placement Strategies for Different Subtypes in Clinical Practice

The screw placement strategies described below are derived from our actual surgical experience in 211 patients who underwent posterior atlantoaxial fusion at our institution between 2016 and 2025.

Type A

Since the C2 isthmus width in this subtype exceeds 3.5 mm, isthmic screw placement is feasible. To achieve stronger fixation, a longer screw may be selected to penetrate the anterior cortex of the C2 vertebral body, thereby achieving bicortical purchase. However, it should be noted that during screw insertion, the trajectory angle must be adjusted to avoid the vertebral artery course (Fig. 11).

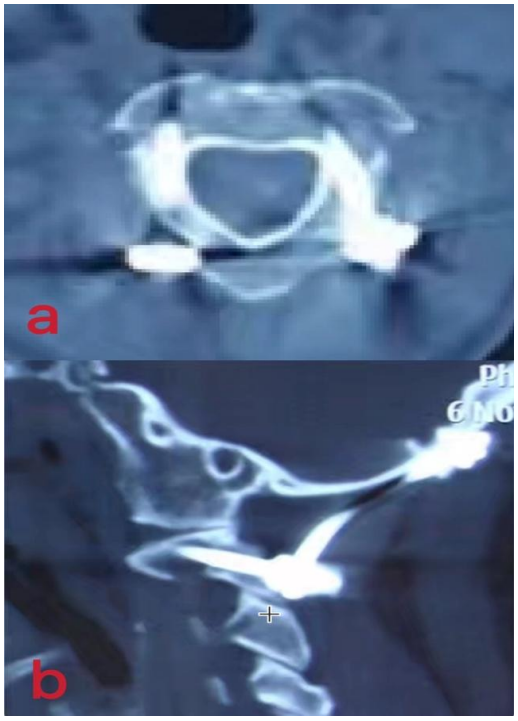
Figure 11: Actual screw placement images of Type A



Type B

Although the C2 isthmus width in this subtype is smaller than the screw diameter, its anteromedial course provides sufficient screw insertion depth. In clinical practice, a relatively shorter screw is typically selected for this subtype to avoid vertebral artery injury resulting from excessive insertion depth. (Fig. 12)

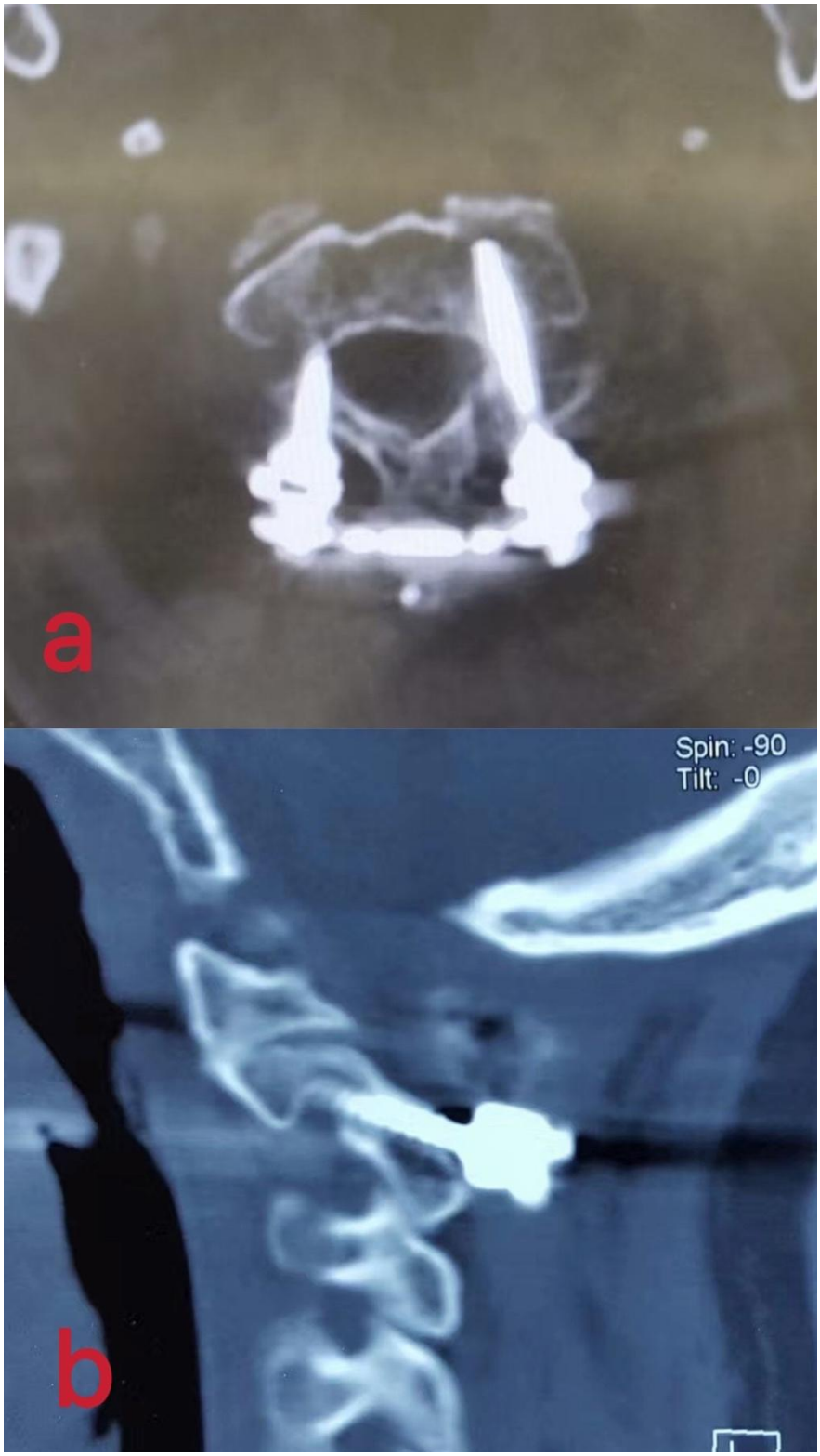
Figure 12: Actual screw placement images of Type B



Type C

This subtype carries a relatively higher risk, as its posteromedial course substantially limits the achievable screw insertion depth. In clinical practice, screw stability should be comprehensively assessed in conjunction with the patient's bone mineral density. During screw placement, an appropriate trajectory angle should be selected to maximize intraosseous purchase, and the insertion depth must be carefully monitored to avoid vertebral artery injury (Fig.13).

Figure 13: Actual screw placement images of Type C



Furthermore, for this subtype, an anterior approach for screw placement may be considered to increase the intraosseous trajectory length of the screw (Fig. 14).

Figure 14: Anterior approach for screw placement



Type D

In this subtype, the vertebral artery deviates medially and, at the same time, courses more posteriorly, further restricting the achievable screw insertion depth. Only one case of Type D was identified in this study. In actual surgical practice, for this subtype, we abandoned isthmic screw placement and instead utilized C2 laminar screw fixation (Fig. 15).

Figure 15: Actual screw placement images of Type D



Additionally, for this subtype, an anterior approach for screw placement may also be

considered to achieve a greater insertion depth (Fig. 14).

In summary, this study reconstructed the classification system of HRVA from the perspective of the C2 isthmus width and the maximum intraosseous trajectory length of the C2 isthmic screw—parameters of greater concern to surgeons—while incorporating the three-dimensional course of the vertebral artery. This approach overcomes the limitations of previous classification systems, such as those proposed by Klepinowski and Du, which relied solely on two-dimensional parameters including C2 isthmus height and medial height. The proposed classification can be rapidly interpreted on preoperative CTA, enabling surgeons to identify high-risk sides at an early stage and select the appropriate screw diameter and length.

Limitations

This study has several limitations. First, the sample size was relatively small and derived from a single center, with only one case of Type D identified. Future studies with larger sample sizes are warranted. Second, this study was a single-center radiological measurement and actual surgical screw placement analysis, without incorporating clinical outcome measures such as postoperative complications, screw position grading, or long-term fusion rates. Therefore, the differential risk levels among different HRVA subtypes and the clinical efficacy of the classification system cannot be directly demonstrated. Future multicenter prospective studies are planned, in which individualized screw placement strategies will be developed based on the proposed classification system, and parameters including intraoperative vertebral artery injury, postoperative CT-based screw position grading, neurological function

improvement, and fusion rates will be systematically recorded to further validate the clinical efficacy and safety of this classification.

Future Perspectives

In the future, the sample size can be further expanded, and prospective studies can be conducted to further demonstrate the clinical validity of this classification system. Additionally, the classification can be integrated with robotic navigation systems, training the robot for C2 screw placement in different HRVA subtypes, thereby improving the precision and accuracy of robotic screw placement.

Declaration

Ethics approval and consent to participate

The study protocol was reviewed and approved by the Ethics Committee of Beijing Tongren Hospital (approval number: MR-11-26-084745, approval date: September 30, 2026). All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Due to the retrospective and anonymized nature of the study, with no involvement of patient intervention, the requirement for informed consent was waived by the committee.

Consent for publication

As this is a retrospective study using anonymized imaging data, the requirement for consent to publish individual images was waived by the Ethics Committee of Hospital, approval number: MR-11-26-084745, approval date: September 30, 2026.

Availability of data and materials

The data used to support the findings of this study are available from the corresponding author upon request.

Competing interests

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. The surgical implications discussed in this manuscript are based on anatomical relationships, published literature, and the authors' clinical experience; no commercial entity, implant manufacturer, or external sponsor influenced the classification or interpretations.

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Authors' contributions

MJX contributed to conception and design and drafting of the manuscript. JHT contributed to acquisition of data, and analysis and interpretation of data. XXQ contributed to administrative, technical, or material support. JGT, BXB, and XKC

contributed to critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript.

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