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Computer-Assisted C1 Pedicle Screw Fixation in the Treatment of Atlantoaxial Instability: Anatomical Considerations and Radiological Outcomes

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Abstract

Background

C1 pedicle screw (CPS) fixation provides superior stability over C1 lateral mass screws (LMS) for atlantoaxial instability but is limited by anatomical variability and vascular risk. We propose a novel planning strategy that uses a patient-specific instrument (PSI) by 3D printing to improve the safety and accuracy of C1 CPS placement.

Methods

In this retrospective study, 22 patients underwent C1 CPS fixation using PSI between August 2015 and August 2025, with 44 screws implanted. Pedicles were classified according to the morphological classification proposed by Abhishek Srivastava et al. Screw trajectories were preoperatively planned, and PSIs were fabricated accordingly. Postoperative CT assessed screw placement accuracy using Gertzbein–Robbins (GR) grading.

Results

Twenty-two patients (9 males, 13 females; mean age 68.7 ± 13.1 years) were included. Morphological analysis of the C1 pedicles demonstrated a mean right-sided

extramedullary height (EMH) of 3.81 ± 1.06 mm and intramedullary height (IMH) of 1.20 ± 1.05 mm, while the left-sided EMH and IMH were 3.92 ± 1.20 mm and 1.30 ± 1.11 mm, respectively. The 44 pedicles were classified as 16 Type 1A, 4 Type 1B, 1 Type 2, and 23 Type 3.

Postoperative evaluation demonstrated that 42 (95.5%), 1 (2.3%), and 1 (2.3%) screws were classified as GR Grades 0, 1, and 2, respectively. No Grade 3 breaches were identified. One postoperative wound infection was successfully managed with medication; no major complications or revision surgeries occurred.

Conclusions

PSI-assisted C1 CPS fixation demonstrated high radiological placement accuracy, including in patients with challenging pedicle anatomy, and may expand the clinical applicability of C1 pedicle screw fixation.

Keywords: C1 pedicle screws; atlantoaxial instability; 3D patient-specific instrument; Computer-assisted surgery

Background

Posterior fixation with fusion is a common treatment modality for atlantoaxial instability (AAI). Traditionally, C1 fixation uses C1 lateral mass screws (LMS).[1,2]

However, C1 pedicle screw (CPS) fixation represents an alternative fixation technique that stabilizes through the C1 posterior arch and pedicle–laminar complex, providing superior biomechanical strength while avoiding the potential risks of injury to the paravertebral venous plexus and the C2 nerve root.[1-3] This study aimed to analyze the anatomical considerations of C1 CPS placement and use our novel refinement method to improve surgical safety and accuracy.

Methods

Between August 2015 and August 2025, 22 patients underwent C1 CPS fixation using a novel screw-trajectory planning and 3D-printed patient-specific instrument (PSI) guiding templates, with 44 screws implanted in total. The Institutional Review Board of Cathay General Hospital approved this study (CGH-P113062) and waived individual informed consent due to its retrospective design. The PSI devices, YIDING Medical Imaging Stereotaxic System, used in this study were approved by the Taiwan Food and Drug Administration, numbered 008297, and manufacturing number QMS2281. This study adhered to the ethical standards of the Declaration of Helsinki and the PROCESS guidelines. Continuous variables are presented as mean ± standard deviation. Because the craniocaudal height of the atlas pedicle is the primary limiting factor for pedicle screw placement, detailed morphological evaluation is essential. Based on the C1

pedicle morphological classification by Abhishek Srivastava et al,[4] preoperative 1-mm slice-thickness computed tomography angiography (CTA) was performed to reconstruct the C1 vertebra and evaluate bone and vascular anatomy. We measured extramedullary height (EMH) and intramedullary height (IMH) at the narrowest pedicle segment beneath the vertebral artery groove. C1 pedicles were classified as:

- **Type 1A:** EMH > 4 mm, IMH > 1 mm
- **Type 1B:** EMH > 4 mm, IMH < 1 mm
- **Type 2:** EMH > 4 mm, no IMH
- **Type 3:** EMH < 4 mm, IMH < 1 mm

Although Srivastava et al. advised against C1 CPS placement in type 2 and 3 pedicles because of the high risk, our novel preoperative trajectory planning and custom PSI design overcame this limitation. Screw trajectories were planned using in-house surgical planning software. To ensure the screw path remained centered within the narrowest portion of the pedicle and avoid cortical breach, we established distinct entry-point strategies based on pedicle morphology. For types 1A and 1B, we positioned the entry point at the lateral midpoint of the posterior arch. For types 2 and 3, we positioned it slightly inferior to the lateral midpoint (Figure 1).

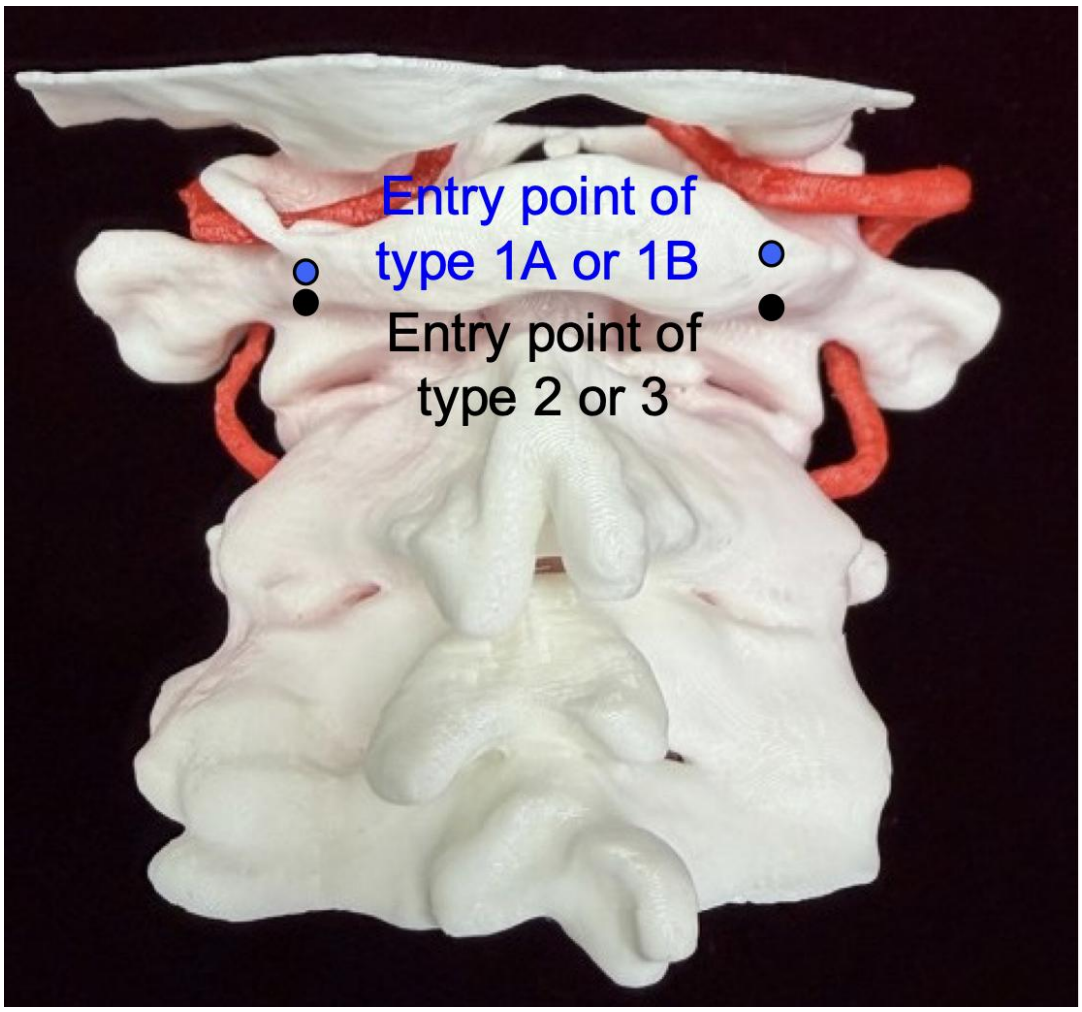


Figure 1. C1 pedicle screw entry points for Types 1A–3. Blue marks (Types 1A/1B) are slightly higher than black marks (Types 2/3)

Our software enables 3D visualization of the cervical spine and adjacent carotid arteries, detailed examination of comprehensive segmentations (Figure 2), and path adjustments based on preset screw diameters. Using these planned trajectories, customized PSIs were designed.[5,6] Each PSI featured two sleeves, upper/lower hooks for secure attachment to the posterior arch, and a holder. PSIs were fabricated via stereolithography (Form 3, Formlabs, USA) using biocompatible resin, while cervical

models were fabricated using standard PLA. PSIs were preoperatively fitted onto 3D-printed models to rehearse screw insertion.[6] Postoperative CT was performed to evaluate screw placement accuracy using the Gertzbein-Robbins (GR) scale (Grade 0: entirely within pedicle; Grade 1: cortical breach < 25% screw diameter; Grade 2: breach 25–50%; Grade 3: breach > 50%). Two neurosurgeons and a PhD researcher responsible for fabricating the PSI jointly performed the postoperative evaluations.

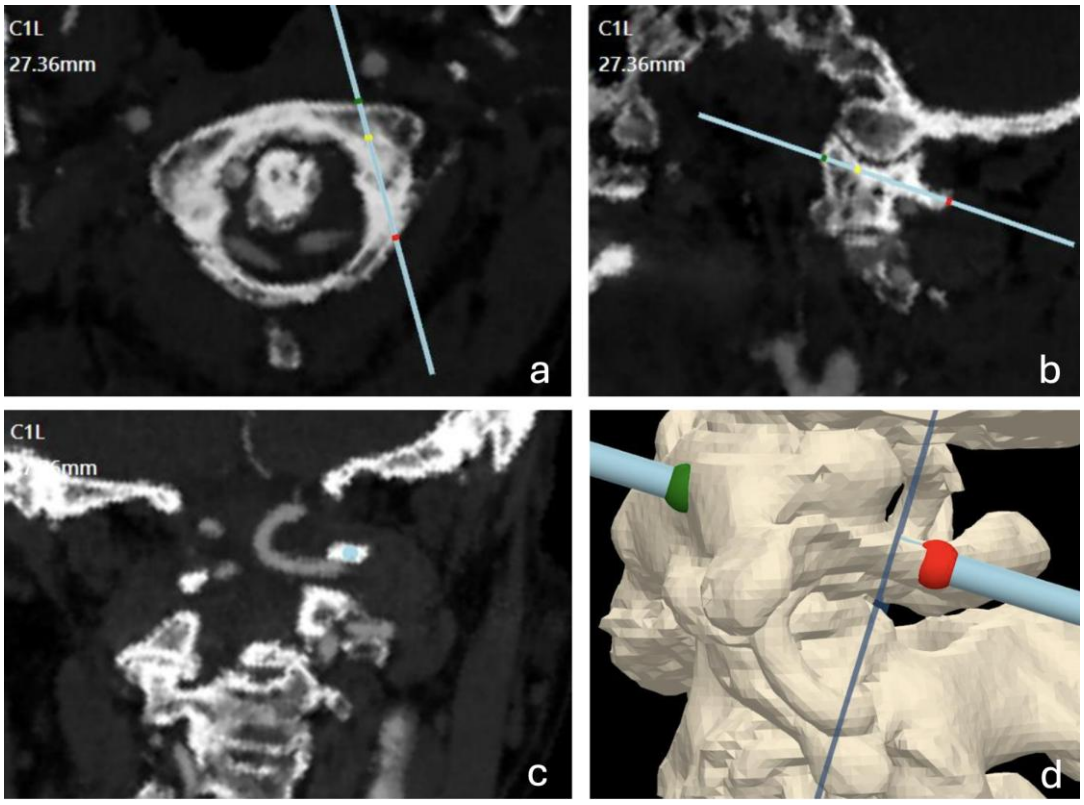


Figure 2. Using our advanced planning software, 3D cervical spine anatomy, including the carotid arteries, can be clearly visualized.

(a) Axial view of the screw pathway.

(b) Sagittal view of the screw pathway.

(c) Coronal view of the screw pathway and the adjacent vertebral artery.

(d) Simulated 3D surgical view

Results

A total of 22 patients were included in the analysis, comprising 9 males and 13 females, with a mean age of 68.7 ± 13.1 years. Morphological analysis of the C1 pedicles demonstrated a mean right-sided EMH of 3.81 ± 1.06 mm and IMH of 1.20 ± 1.05 mm, while the left-sided EMH and IMH were 3.92 ± 1.20 mm and 1.30 ± 1.11 mm, respectively.

Table 1 shows the distribution of pedicle types and C1 CPS (GR) grading for the 22 patients. Types 1A, 1B, 2, and 3 account for 16, 4, 1, and 23 screws, respectively, in the 44 pedicles. Postoperative assessment of screw placement revealed that the 42, 1, 1, and 0 screws were Grades 0, 1, 2, and 3, respectively. No Grade 3 breaches were observed. During follow-up, no significant complications, neurological deficits, or revision surgeries were required, except for one patient who developed a postoperative wound infection that was successfully managed with medication.

Table 1. Patient demographics, pedicle types, and GR grading for C1 CPS insertion.

Case	Gender	Age	Type of C1R	Type of C1L	GR of C1R	GR of C1L
1	F	64	1A	1A	0	0
2	F	76	3	3	0	0
3	F	55	3	2	0	0
4	F	78	1A	1A	0	0

Case	Gender	Age	Type of C1R	Type of C1L	GR of C1R	GR of C1L
5	F	52	1A	1A	0	0
6	M	64	1A	1A	0	0
7	F	62	3	3	0	0
8	F	69	3	1B	0	0
9	M	70	1A	1A	0	0
10	F	85	1A	3	0	0
11	F	54	1A	3	0	0
12	F	82	3	3	0	0
13	F	78	3	1A	0	2
14	F	78	3	3	0	0
15	M	71	1A	1A	0	0
16	M	77	3	3	0	1
17	M	28	3	3	0	0
18	M	73	3	3	0	0
19	M	76	1A	3	0	0
20	M	76	1B	3	0	0
21	F	75	1B	1B	0	0
22	M	69	3	3	0	0

Discussion

Posterior fixation and fusion for AAI constitute the cornerstone of surgical management for upper cervical spine pathology. C1 screw fixation does not require an intact posterior arch and is compatible with modular systems used for occipitocervical or subaxial cervical fusion. Therefore, it is particularly well-suited for patients who require a C1 laminectomy for decompression.[7] Traditionally, the C1 fixation is performed using C1 LMS. However, the C1 CPS have gained increasing attention because of their superior biomechanical strength and lower incidence of neurovascular complications.[1-3] A major technical challenge in C1 CPS placement is the lack of consistent anatomical

143 landmarks for identifying the optimal screw entry point. Although previous studies
144 have provided statistical guidelines,[8] anatomical variability limits their clinical
145 applicability, particularly regarding inclination angles. Therefore, achieving safe and
146 accurate C1 CPS insertion has become a critical clinical objective.
147
148 *Comparison of the Advantages and Disadvantages of C1 CPS and LMS*
149 Compared with C1 LMS, C1 CPS offers superior clinical and biomechanical
150 performance. In fatigue-loading evaluations, C1 CPS demonstrated significantly higher
151 initial (24.6 ± 3.9 N/mm vs. 19.9 ± 3.2 N/mm) and terminal stiffness ($16.6 \pm$
152 2.7 N/mm vs. 11.6 ± 3.6 N/mm).[1] C1 CPS also exhibited superior fatigue resistance
153 ($1{,}083 \pm 166$ vs. 689 ± 240 cycles to failure) and a markedly lower loosening rate
154 (33% vs. 100%).[1,9] Biomechanically, the trajectory of C1 CPS optimizes bone
155 volume engagement and cortical contact length, enhancing resistance to pullout and
156 fatigue. Consequently, monocortical and bicortical C1 CPS fixations achieve
157 comparable ultimate stability.[10]
158
159 *Comparison of Clinical Efficacy and Safety*
160 In a prospective, randomized controlled trial of 140 patients with AAI and C1 posterior
161 arch thickness > 4 mm. Yan et al. demonstrated that C1 CPS fixation significantly

reduced operative time and intraoperative blood loss compared with C1 LMS ($p < 0.01$), reflecting a less invasive and technically streamlined procedure.[3] Furthermore, C1 CPS completely avoided C2 nerve root irritation and C1–C2 venous plexus injury, whereas 13 patients in the C1 LMS group experienced venous bleeding and 9 developed C2 neuralgia/numbness.[3] Both groups achieved comparable 12-month fusion rates (100%) and neurological recovery (JOA recovery rate: 87.2% vs. 86.5%), as well as similar VAS score improvements. Overall, C1 CPS provides superior clinical safety primarily by minimizing perioperative complications.

Anatomical Limitations and Morphometric Variability

Despite its biomechanical superiority, C1 CPS placement is constrained by anatomical variations. Precise preoperative CT-based morphometric evaluation is essential to determine feasibility.[8,11] Small pedicle dimensions and insufficient C1 posterior arch thickness < 4 mm are primary contraindications, as narrow boundaries significantly increase the risk of cortical breach.[4,11,12] Reported mean C1 pedicle height (PH) is 4.3mm (range: 3.8-5.7 mm), and mean pedicle width is 5.3 mm (range: 2.8-8.7 mm).[8,12] However, a C1 PH < 4mm is common, occurring in 26.5%to 31.6% of patients across different cohorts.[8,11] Female patients consistently present with significantly smaller morphometric parameters than males ($p < 0.05$).[8,11] In an Indian population

study, approximately one-third of C1 pedicles were deemed unsuitable for CPS insertion. [4] Based on a novel radiological classification, pedicles with insufficient osseous thickness (Types 1B and 2) require extreme caution, whereas Type 3 pedicles (38% lacking an intramedullary canal; 49% with canal height $<$ 1mm) are generally unsuitable for CPS insertion.[4]

Anomalous Vascular Anatomy and Compared with other Image-Guided Navigation

Anomalous courses of the vertebral artery also pose major technical challenges and contraindications, underscoring the necessity of preoperative CTA or MR angiography (MRA).[13] Although clinical studies suggest C1 CPS fixation is technically simpler than LMS fixation, upper cervical instrumentation inherently involves a steep learning curve. While intraoperative O-arm-based navigation enhances placement accuracy and efficiency, it cannot completely eliminate the risk of cortical breach given the proximity to the spinal canal and neurovascular structures.[14] Meticulous preoperative planning and a thorough understanding of regional vascular anatomy remain indispensable.

Alternative Fixation Strategies for Anatomically Constrained Cases

In cases with severe anatomical constraints—such as pedicle/posterior arch hypoplasia, dysplasia, fractured trajectories, or congenital abnormalities—consider alternative

fixation techniques.[15,16] Titanium Cable & Rod Constructs: Posterior atlantoaxial fixation using C1 titanium cables combined with a C2 CPS–rod system offers a safe and effective alternative.[15] Unilateral Constructs: Unilateral C1 posterior arch screws (PAS) and C2 laminar screws (LS) combined with ipsilateral crossing C1–C2 CPS–rod fixation provide biomechanical stability comparable to bilateral constructs while lowering neurovascular risk.[17] C1 Lateral Pedicle Screw (LPS): For patients with a relatively thin atlas posterior arch, the C1 LPS serves as a safer alternative, reducing the risk of inferior cortical breach into the spinal canal associated with traditional medially directed trajectories.[18] Our novel planning strategy using a 3D-printed PSI also enables easy and accurate placement of C1 LPS.

In our study, 22 patients underwent placement of 44 C1 CPS. Preoperative assessment of the C1 pedicles revealed the following distribution: types 1A, 1B, 2, and 3 were present in 16, 4, 1, and 23 pedicles, respectively. According to conventional surgical criteria, only type 1A and type 1B pedicles—traditionally considered suitable for safe C1 CPS placement—accounted for 45.5% (20/44) of cases. In other words, based on previous concepts, more than half of the pedicles would have been deemed too thin to permit C1 CPS insertion.

Before introducing this technique, our previous study (conducted from August 2006 to May 2017) included 13 patients requiring C1–C2 fixation. Due to uncertainties

219 regarding C1 CPS placement, two patients underwent Halifax interlaminar clamping,
220 and five underwent occipitocervical fusion (OCF). Only six patients—all
221 preoperatively evaluated as having Type 1 C1 pedicles—received C1 CPS placement.
222 Postoperative follow-up of these 12 screws revealed 6 Grade 0 and 6 Grade 1
223 placements[6]. These findings clearly demonstrate that PSI-guided technology
224 significantly improves pedicle screw placement accuracy. Moreover, this approach
225 expands the surgical indications for C1 CPS placement; although over half of the
226 pedicles in our cohort were classified as Type 3 (52.3%, 23/44)—an anatomical type
227 historically considered unsuitable for C1 CPS insertion—accurate screw placement was
228 still successfully achieved in these patients using our technique.
229 Only one patient had a single screw classified as Grade 2 on postoperative evaluation.
230 A retrospective review demonstrated that although the patient-specific template
231 accurately guided the intended trajectory, partial collapse of the outer cortex occurred
232 during screw insertion, resulting in deviation. This issue was more likely to occur in
233 patients with a relatively low posterior arch height or underlying osteoporosis.
234 After encountering similar cases, we refined our technique. Once the pilot hole was
235 confirmed, we deliberately directed the tap toward the thicker cortex clockwise. For
236 example, if the superior cortex was thinner, we applied force toward the inferior cortex,
237 and vice versa. After this modification, we observed no further similar deviations.

In the Grade 1 case, the screw trajectory precisely followed the preoperative plan and passed through the center of the pedicle's narrowest portion. However, because of the extremely limited pedicle width, the cortex expanded slightly after screw insertion. This did not affect the clinical outcome or the biomechanical strength of the screw construct. Figure 3 illustrates cases from five patients with type 3 C1 pedicles; the preoperative and postoperative CT scans clearly confirm optimal screw placement. We believe the high accuracy in our series is primarily attributable to our method, which ensures the screw trajectory passes through the center of the narrowest, middle portion of the pedicle. This requires meticulous preoperative morphometric analysis of the C1 pedicle anatomy and thorough surgical planning, both of which our technique reliably accomplishes.

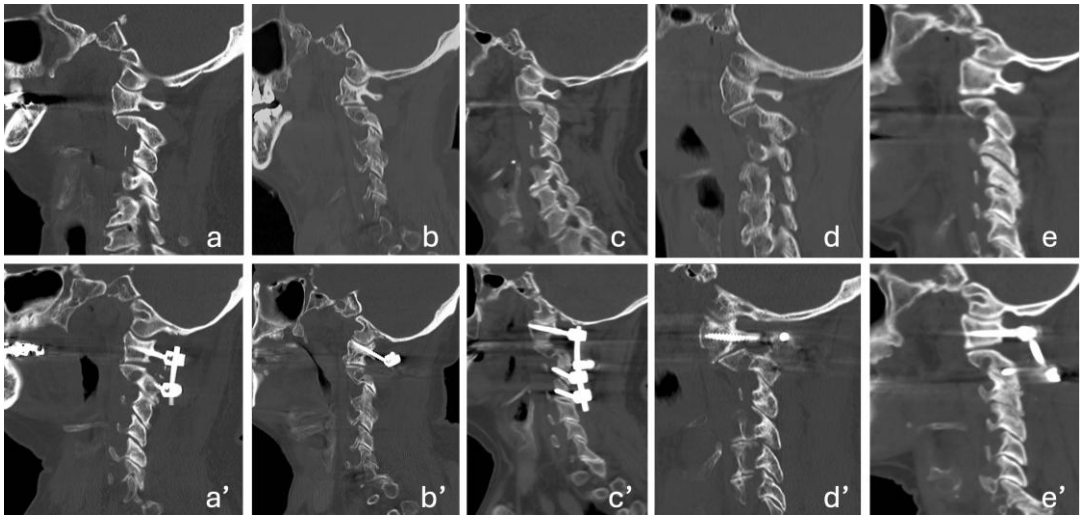


Figure 3. The five patients whose C1 pedicles were all classified as Type 3. The lowercase letters denote the preoperative CT images, and the corresponding lowercase letters with apostrophe represent the

252 postoperative CT images. All C1 pedicle screws (CPS) images were in optimal positions and were graded

253 0 according to the GR grading system

254

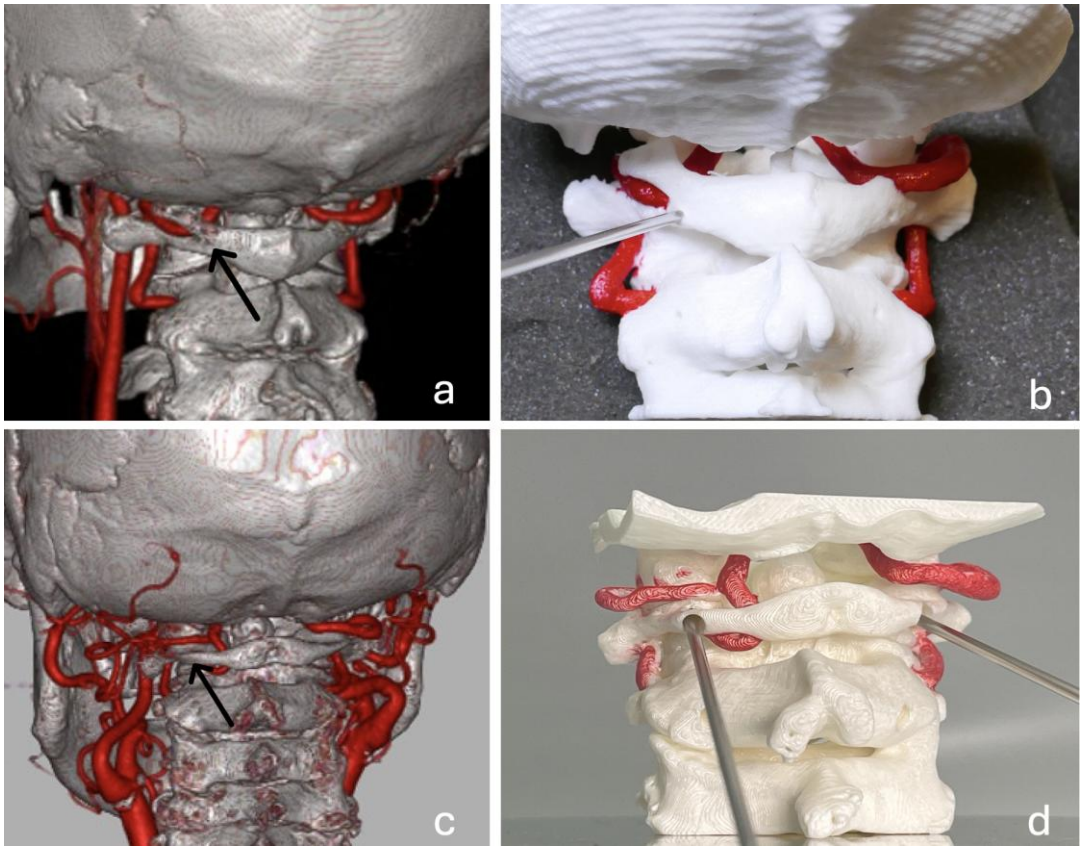
255 An additional major advantage of our approach is that our model enables not only 3D

256 printing of the osseous vertebral structures, but also reconstruction of the vascular

257 anatomy. This allows precise preoperative visualization of the vertebral artery location,

258 facilitating surgical simulation and reducing the risk of intraoperative vascular injury,

259 as illustrated in Figure 4.



260

261 **Figure 4.** Two patients with vertebral artery (VA) anatomical variations are presented. Preoperative CTA,

262 combined with our patient-specific 3D models, clearly delineated the spatial relationship between the C1

pedicle screw entry point and the VA. This approach allowed for accurate preoperative simulation and facilitated intraoperative strategies to minimize the risk of VA injury

(a) Case 16 CTA

(b) 3D model of Case 16

(c) Case 19 CTA

(d) 3D model of Case 19

We believe that improving the safety and accuracy of C1 pedicle screw insertion can reduce the necessity for OC fixation, thereby preserving patients' quality of life and cervical range of motion.

Below is a representative case: a 69-year-old male who presented with severe C1–C2 subluxation, severe kyphotic change, and bilateral type 3 C1 pedicles (Figure 5). Historically, without this technology, OC fixation might have been the only feasible approach. However, using our PSI design and guiding technique, we successfully performed C1–C6 pedicle fixation. The patient demonstrated an excellent postoperative outcome while preserving a functional range of motion in neck flexion and extension (Figure 6).

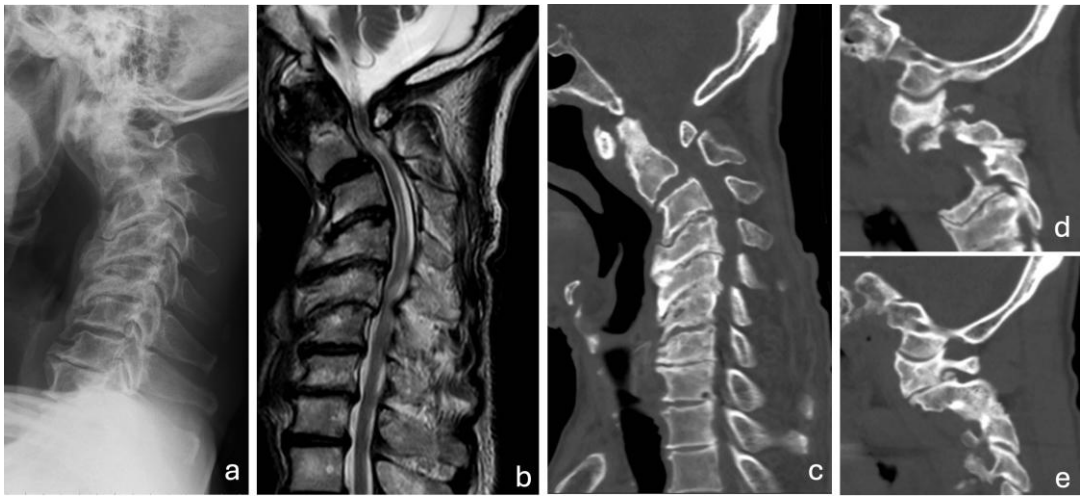


Figure 5. A 69-year-old male presenting with severe C1–C2 subluxation, severe kyphotic changes, and bilateral type 3 C1 pedicles.

(a) Pre-operative C-spine plain film

(b) Pre-operative C-spine CT

(c) Pre-operative C-spine MRI

(d) Sagittal CT view of the left C1 pedicle

(e) Sagittal CT view of the right C1 pedicle

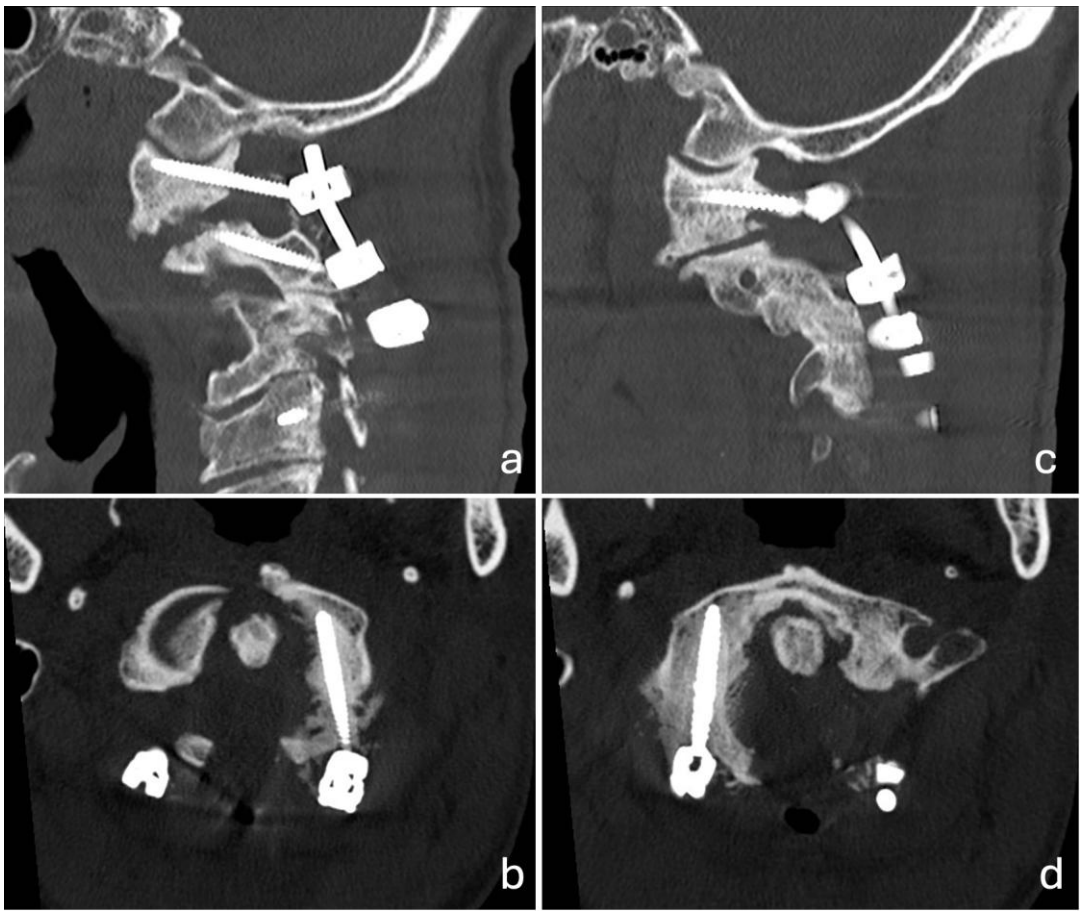


Figure 6. Postoperative CT images demonstrating satisfactory positioning of the C1 CPS

(a) Left C1 Sagittal view

(b) Left C1 Axial view

(c) Right C1 Sagittal view

(d) Right C1 Axial view

This study has several limitations. First, its retrospective, single-center design and small sample size may limit the generalizability of our findings. Second, the absence of a direct control group—such as cohorts undergoing computer-assisted navigation or

augmented reality-guided surgery—precludes direct comparative analysis. Future large-scale, prospective comparative studies are warranted to validate these results.

Conclusions

For patients with AAI, OCF should be avoided, when possible, by prioritizing C1 CPS placement over C1 LMS placement. Historically, narrow pedicle anatomy and limited reliable surgical guidance have constrained C1 CPS placement. Our optimized PSI design and guiding system enable safe CPS application across nearly all C1 pedicle morphologies, including previously unsuitable type 2 and type 3 pedicles. By offering precise 3D visualization of adjacent vascular structures for detailed preoperative simulation, this approach significantly enhances surgical safety and should be considered during preoperative planning for these patients.

List of abbreviations

CPS: cervical pedicle screw

C1: first cervical spine

LMS: lateral mass screw

AAI: atlantoaxial instability

PSI: patient-specific instrument

3D: three-dimensional

CTA: computed tomography angiography

EMH: extramedullary height

IMH: intramedullary height

GR: Gertzbein-Robbins

LPS: lateral pedicle screw

OCF: occipitocervical fusion

Declarations

Ethics approval and consent to participate

The Institutional Review Board of Cathay General Hospital approved this study (CGH-IRB No. CGH-P113062), and it was conducted in accordance with the ethical standards of the Declaration of Helsinki. The Institutional Review Board approved a waiver of individual informed consent because of the study's retrospective nature (CGH-IRB No. CGH-P113062).

Consent for publication

Not applicable (no individual patient’s identifying information or images are included in this article).

Availability of data and materials

All data generated during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

Funding

No funding was received for conducting this study.

Authors' contributions

CJC: Conceptualization, methodology, formal analysis, and writing—original draft. KYC: Data collection and investigation. MHH: Data collection and investigation. JJF: Methodology, formal analysis, and supervision. All authors contributed to manuscript review and editing. All authors read and approved the final manuscript.

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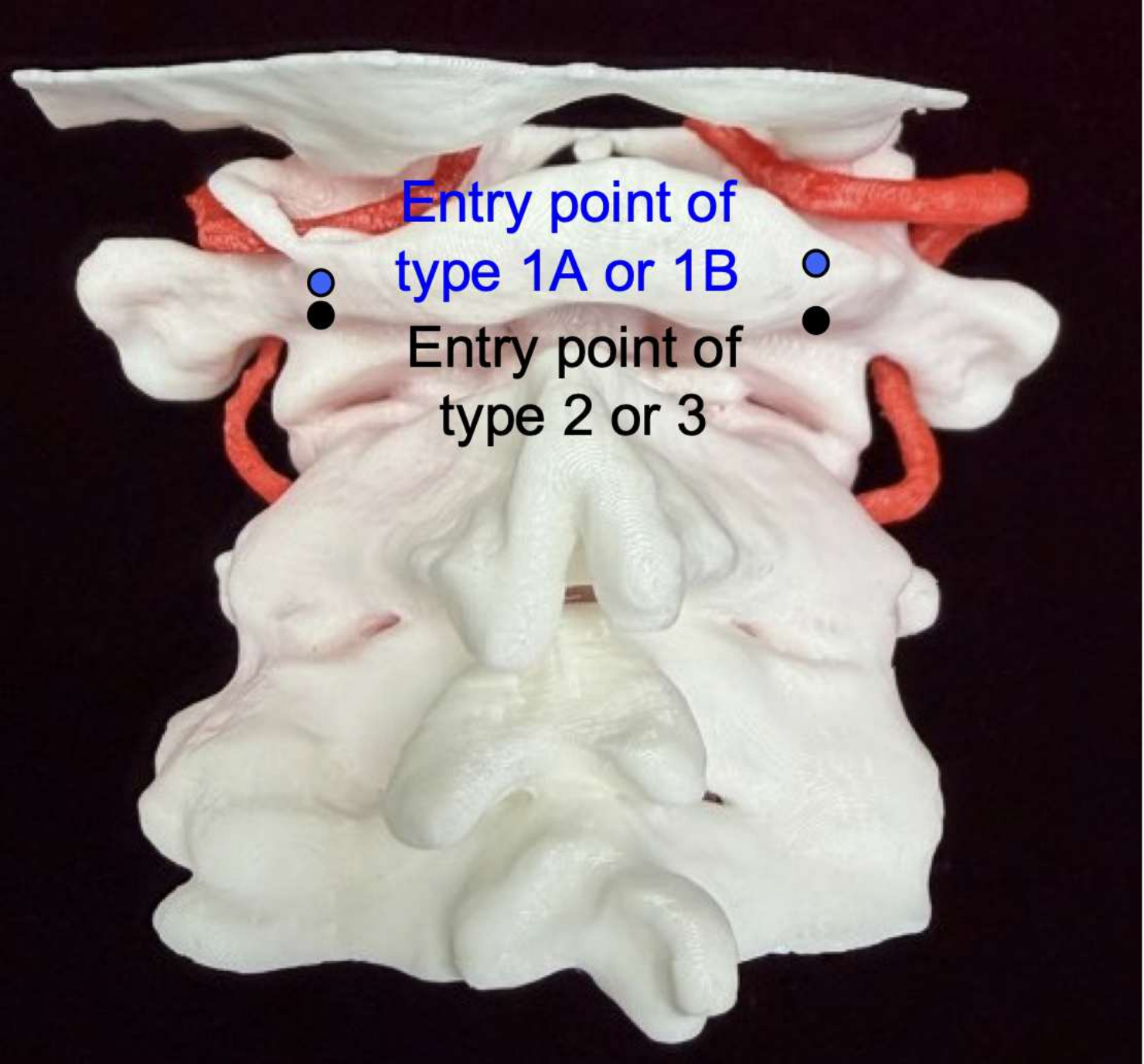
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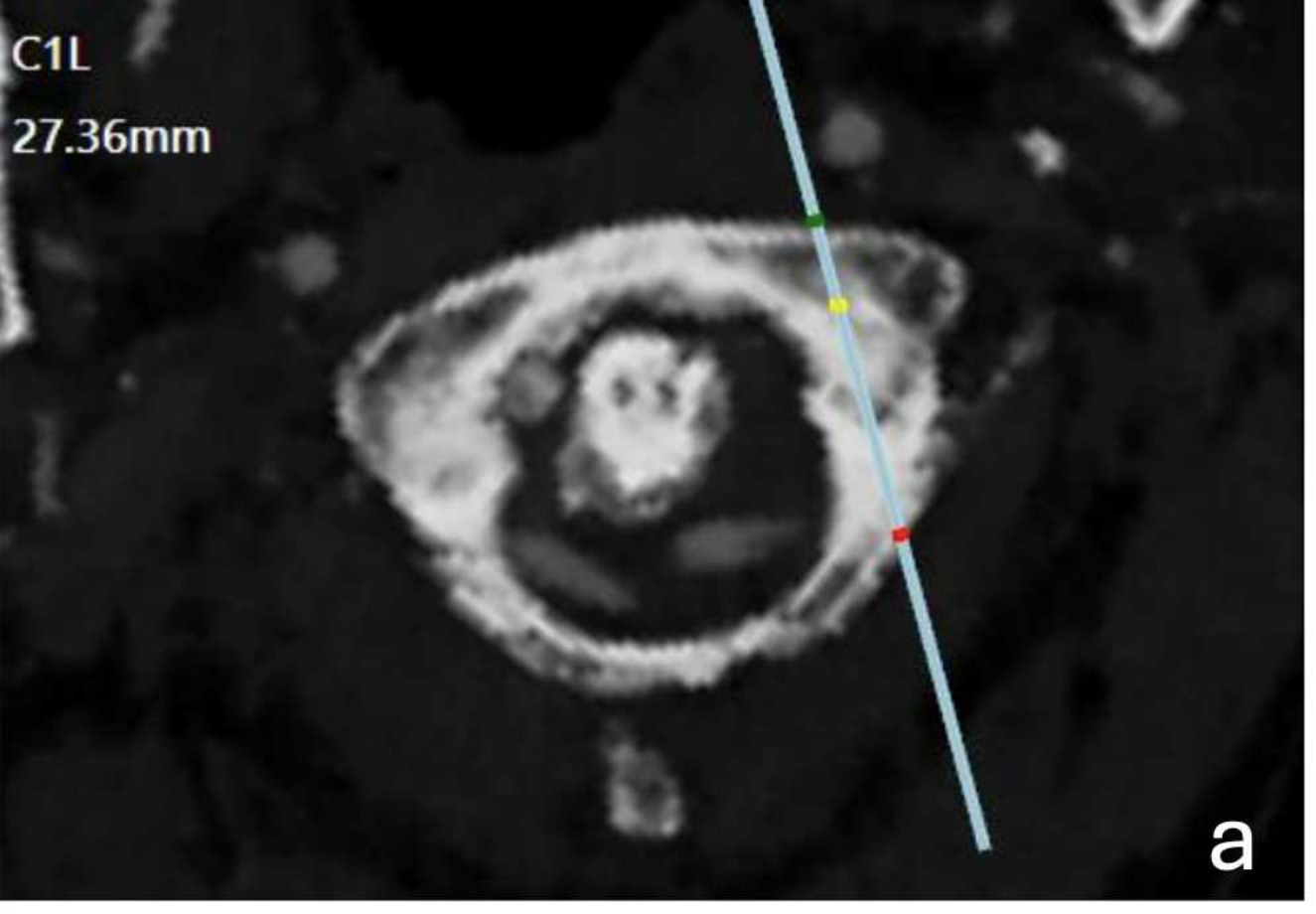
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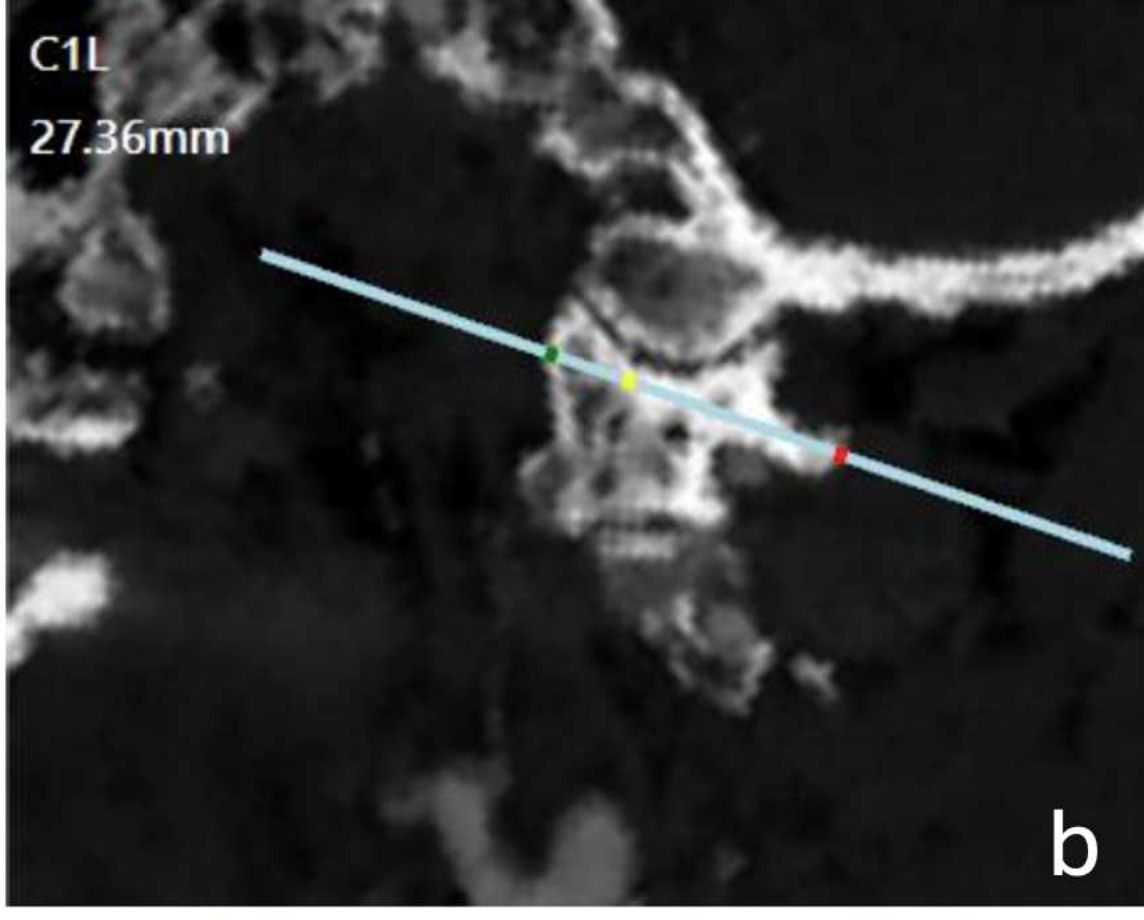
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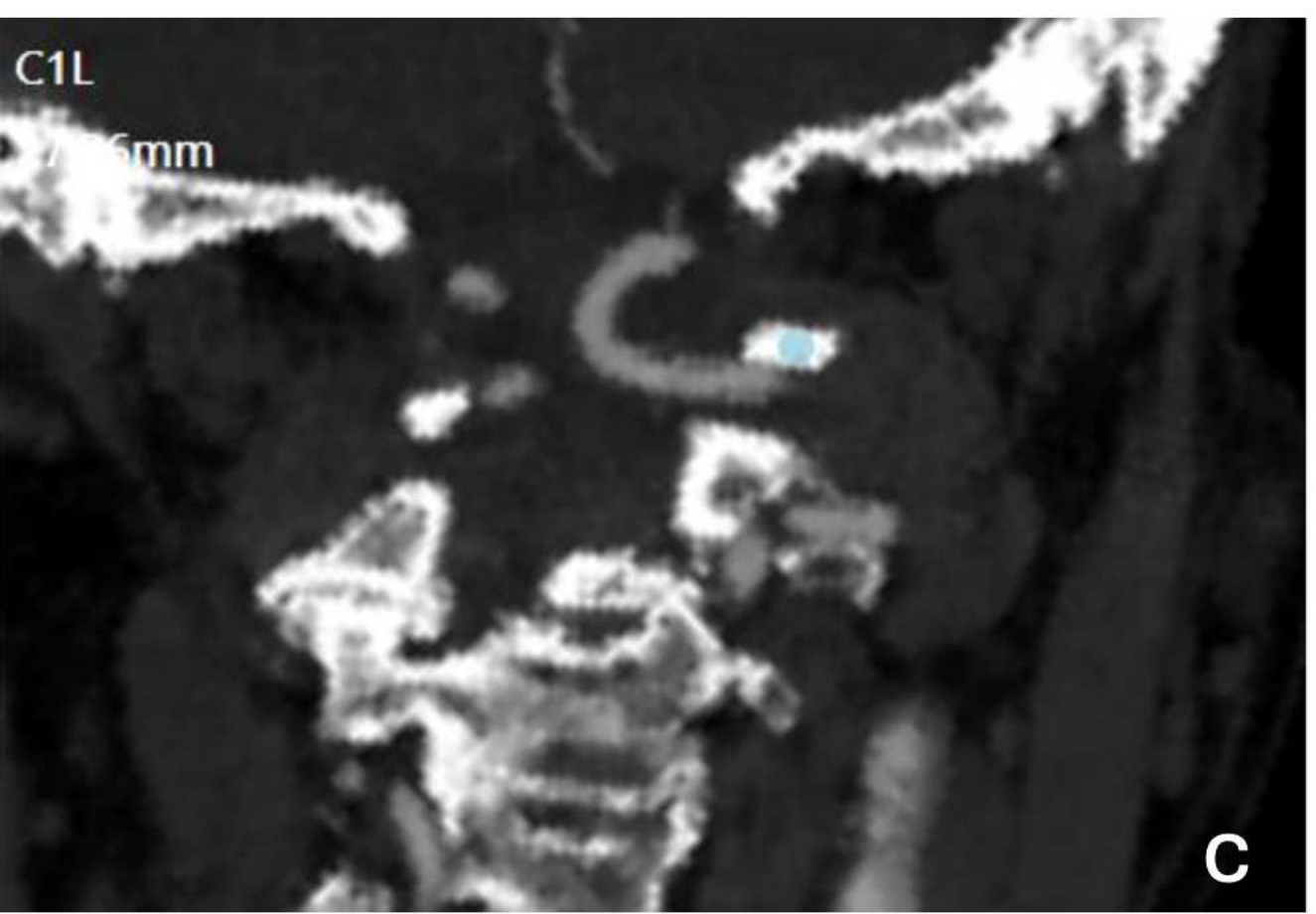
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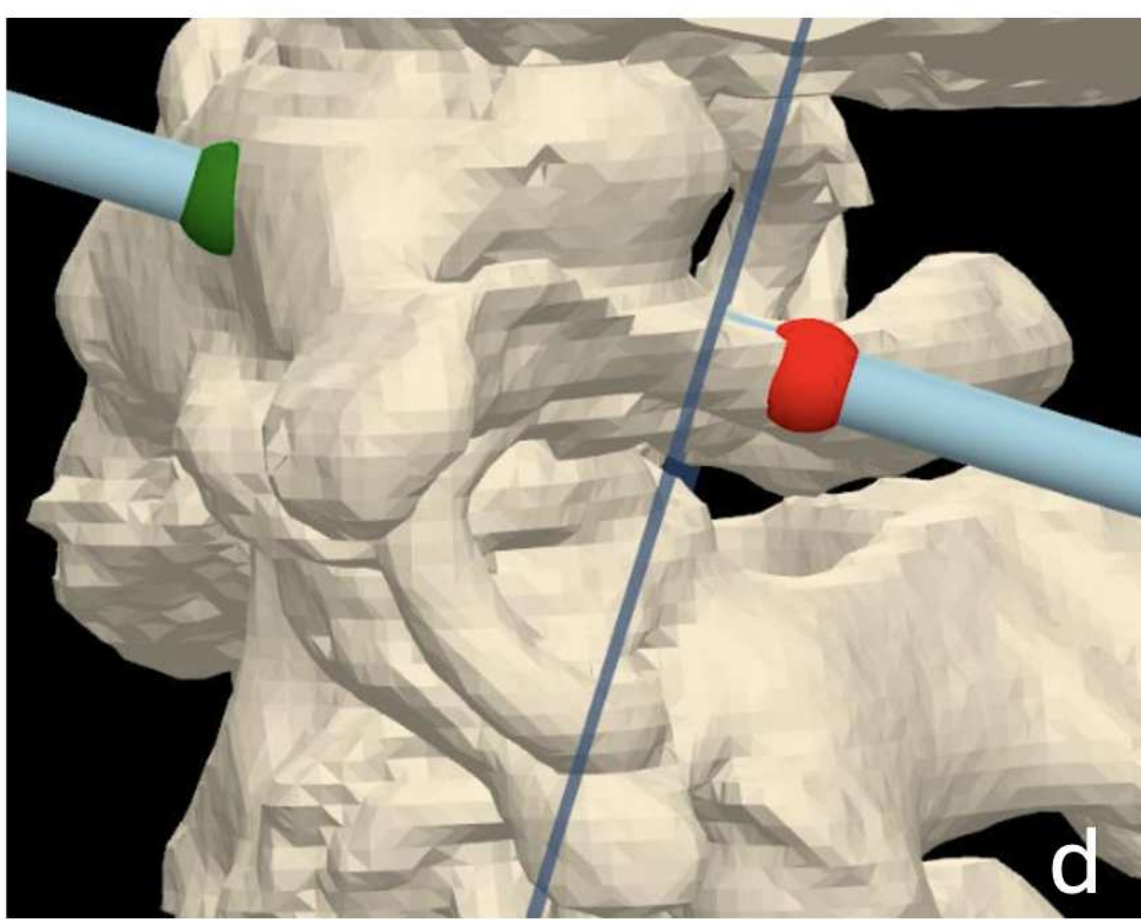
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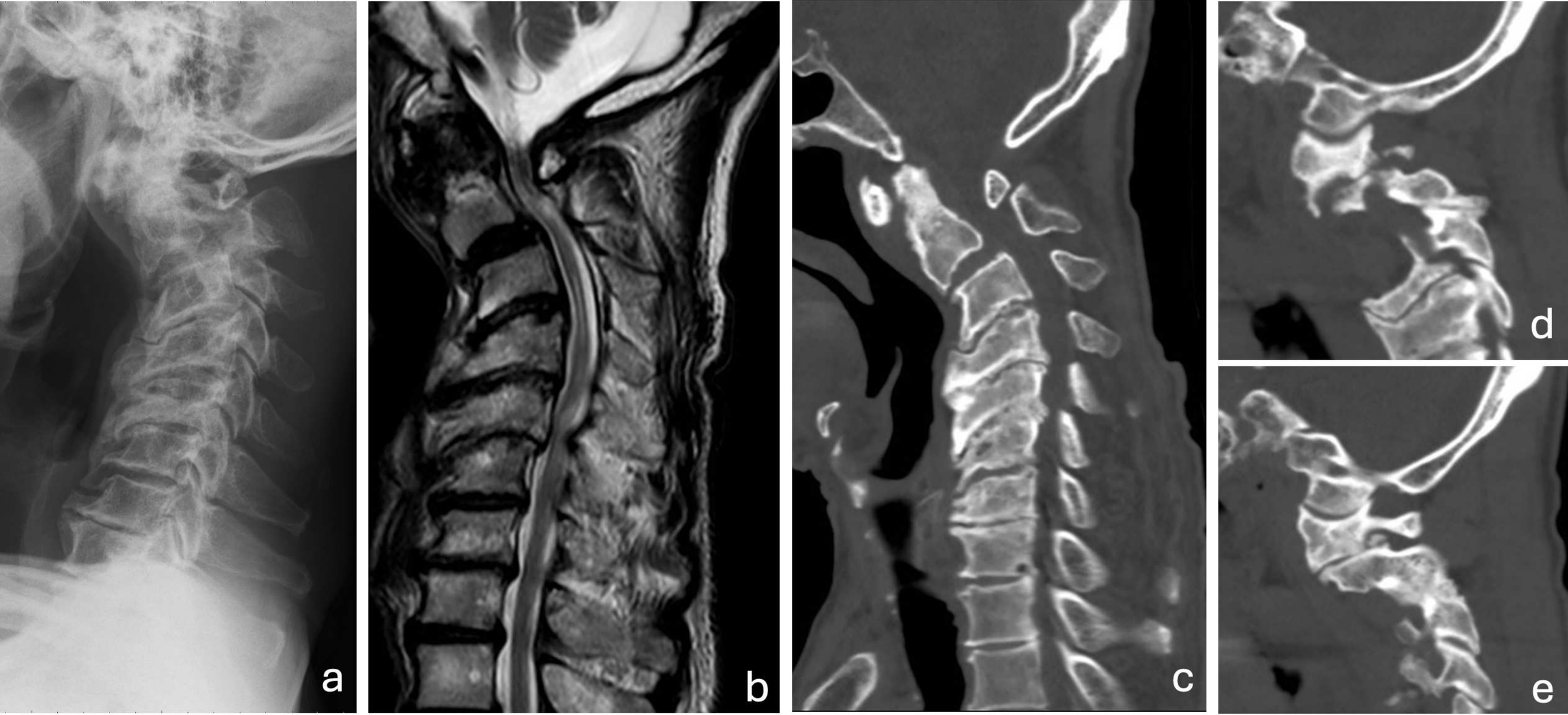

Entry point of
type 1A or 1B
Entry point of
type 2 or 3

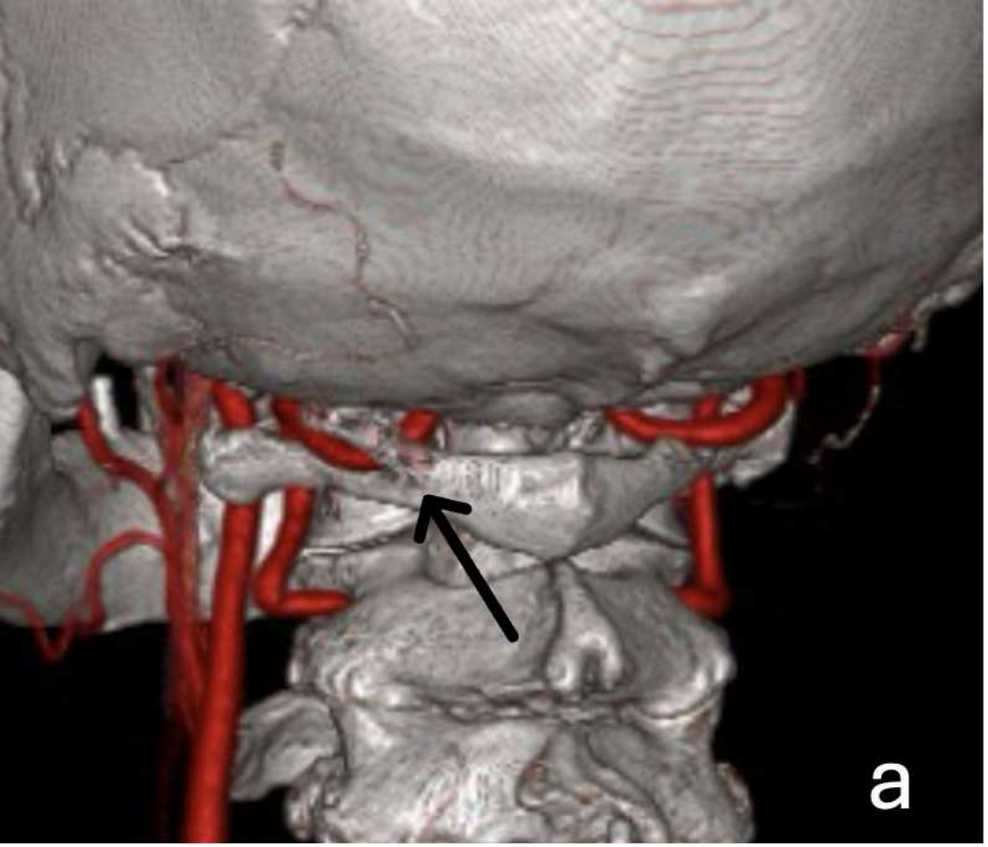

C1L
27.36mm
a


C1L
27.36mm
b

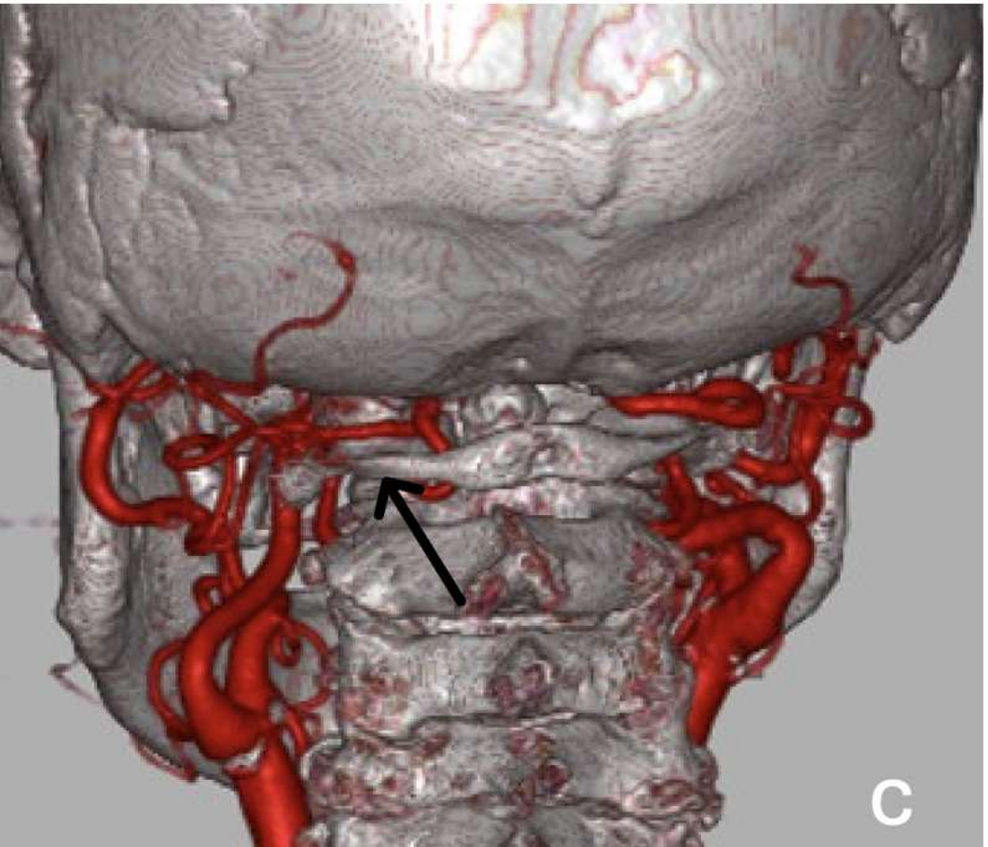

C1L
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d

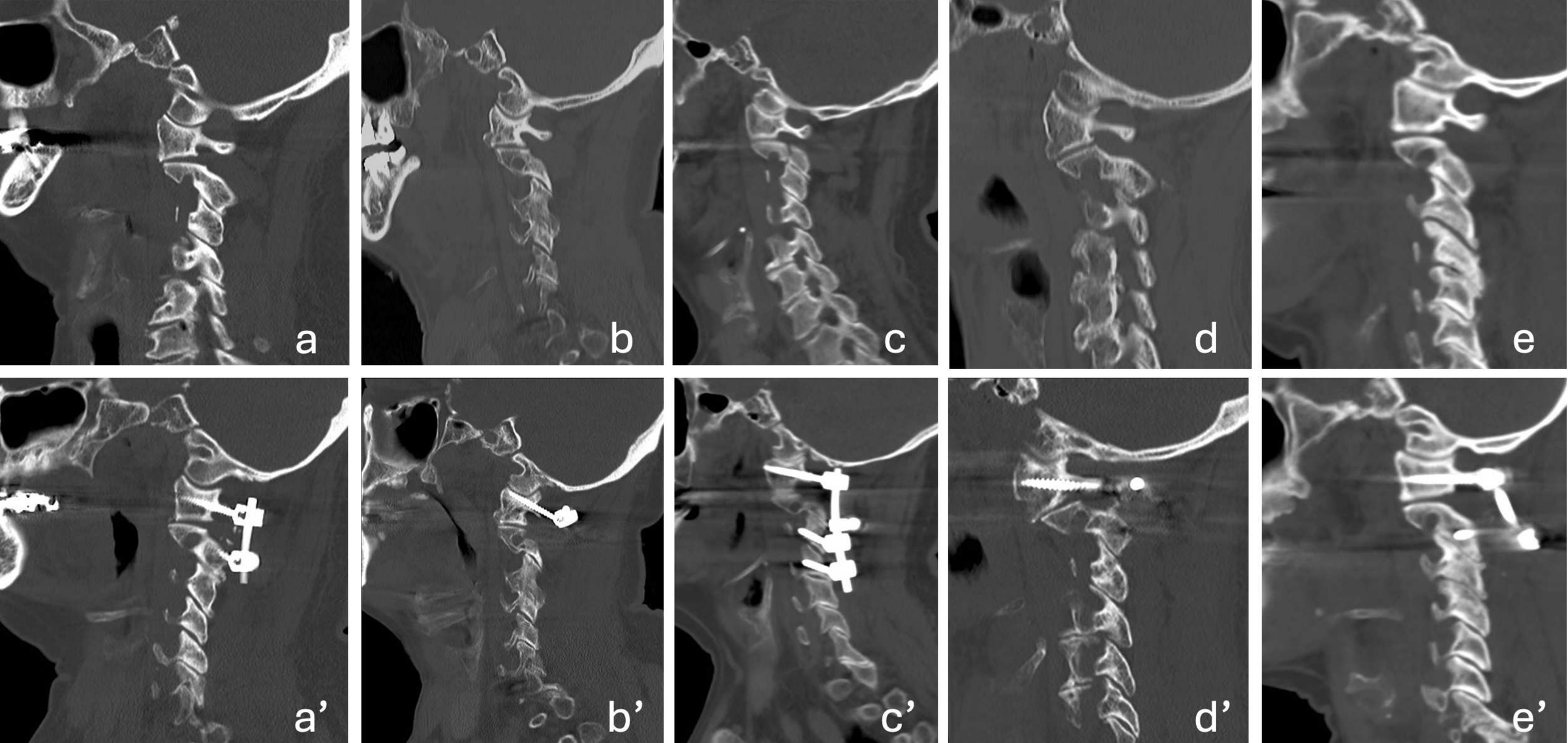

a
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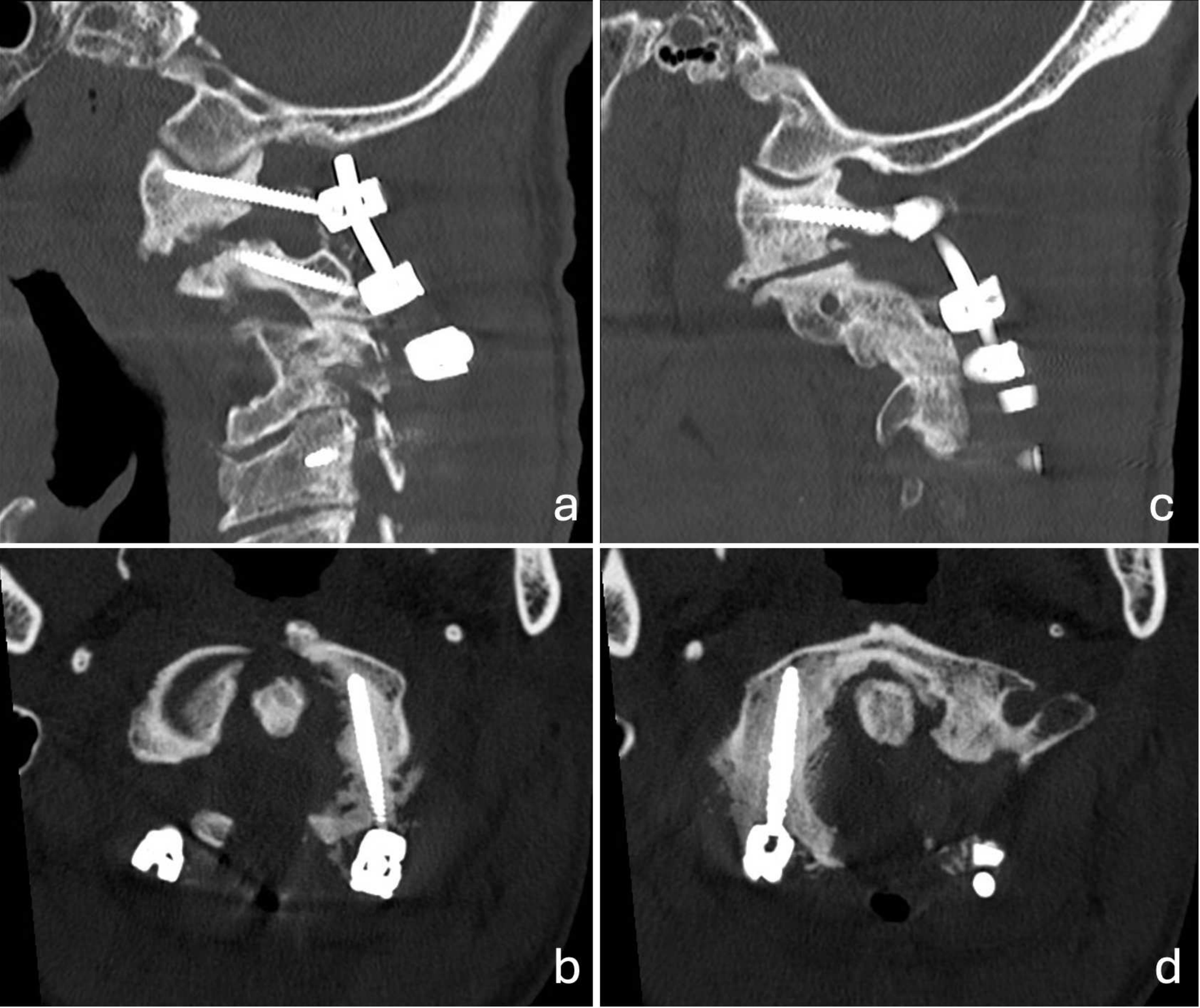

a


b


c


d


a
b
c
d
e
a’
b’
c’
d’
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a
c
b
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- Table20261116.docx