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Posterior Atlantoaxial Fixation in a Single-Center Consecutive Series: Anatomy-Driven C2 Anchorage Selection

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ABSTRACT

AIM: To present a single-center experience with posterior C1–C2 fixation for atlantoaxial instability, emphasizing an anatomy-driven approach to C2 anchorage selection, construct strategy, complications, and clinical outcomes.

MATERIAL and METHODS: We retrospectively reviewed 45 patients who underwent posterior C1–C2 fixation between June 2020 and January 2026. Constructs were categorized as pedicle, hybrid, bilateral laminar, planned C2 omission (C1–C3 extension), or transarticular fixation. Demographics, etiology, operative variables, complications, reoperations, mechanical failure, and fusion were analyzed. Exploratory categorical comparisons were performed using Fisher's exact test. Fusion was evaluated using postoperative computed tomography (CT) obtained ≥6 months postoperatively and was defined as osseous bridging without implant loosening.

RESULTS: The mean patient age was 47.8 ± 20.1 years, and 25 patients (55.6%) were women. Etiologies included trauma (31.1%), basilar invagination (22.2%), Chiari malformation (15.6%), os odontoideum (8.9%), atlantoaxial subluxation (8.9%), tumor (8.9%), and other causes (4.4%). Construct types included pedicle fixation in 31 patients (68.9%), hybrid constructs in 5 (11.1%), bilateral laminar fixation in 5 (11.1%), planned C2 omission in 3 (6.7%), and transarticular fixation in 1 patient (2.2%). The median follow-up duration was 6.3 months (IQR, 1.2–22.3 months). CT-based fusion assessment was available for 26 patients at a median follow-up of 19.5 months, and fusion was observed in 20 patients (76.9%). Radiographic mechanical abnormalities were identified in 7 patients (15.6%), including 6 (13.3%) who underwent revision surgery. Construct strategy was not significantly associated with either mechanical abnormalities or CT-confirmed fusion. Mechanical abnormalities were significantly more frequent in patients with os odontoideum or nontraumatic atlantoaxial subluxation than in those with other etiologies ($p < 0.001$).

CONCLUSION: An anatomy-driven escalation strategy for C2 anchorage selection provided a practical framework for managing variable craniovertebral anatomy during freehand posterior atlantoaxial fixation. Hybrid constructs, bilateral laminar fixation, and planned C2 omission served as feasible alternatives when pedicle fixation was limited by anatomical constraints or pathology.

KEYWORDS: Atlantoaxial instability, C1–C2 fixation, C2 pedicle screw, C2 laminar screw, Craniovertebral junction

ABBREVIATIONS: BI: Basilar invagination, **CT:** Computed tomography, **CTA:** Computed tomography angiography, **HRVA:** High-riding vertebral artery, **IQR:** Interquartile range, **MRI:** Magnetic resonance imaging, **POD1:** Postoperative day 1, **STIR:** Short tau inversion recover, **VA:** Vertebral artery

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INTRODUCTION

Atlantoaxial instability may result from trauma, congenital malformations, inflammatory disorders, neoplasms, as well as iatrogenic and degenerative conditions (3, 6). Because of the unique biomechanics of the craniovertebral junction, rigid stabilization is often required once stability is compromised (13).

Magerl and Seemann first described transarticular screw fixation as a reliable technique for posterior atlantoaxial stabilization (20). Subsequently, Harms and Melcher introduced C1 lateral mass–C2 pedicle screw fixation, which improved intraoperative flexibility and expanded the applicability of posterior fixation techniques (13). Goel and Laheri further demonstrated the biomechanical superiority of segmental screw constructs compared with traditional wiring techniques (10).

Wright later introduced C2 laminar screw fixation as a vertebral artery–sparing alternative for cases with unfavorable pedicle anatomy (26). Subsequent clinical studies have confirmed the safety and biomechanical reliability of laminar screw fixation when appropriately indicated, including in Turkish populations (14,22).

In the present study, we evaluate a consecutive series of posterior C1–C2 instrumentation procedures performed at a tertiary referral center for traumatic, congenital, deformity-related, neoplastic, iatrogenic, and degenerative pathologies. The primary objective was not to compare fixation techniques directly, but rather to describe a pragmatic, anatomy-driven framework for selecting C2 anchorage strategies in routine clinical practice. In addition, we aimed to evaluate operative indications, early clinical and radiographic outcomes, complication patterns, reoperation rates, and interim CT-based fusion outcomes in patients with adequate follow-up.

MATERIAL and METHODS

Study Design and Patient Population

This retrospective study included 45 consecutive patients who underwent posterior C1–C2 instrumentation at a tertiary neurosurgical center between June 2020 and January 2026. Demographic characteristics, indications, operative details, and postoperative outcomes were extracted from institutional records. Institutional ethics approval was granted by the Başakşehir Çam and Sakura City Hospital Clinical Research Ethics Committee (18.02.2026/107), and the requirement for informed consent was waived owing to the retrospective design and anonymized use of patient data.

Etiology Classification

Etiologies were categorized as trauma, basilar invagination, Chiari malformation, os odontoideum, nontraumatic atlantoaxial subluxation, tumor, and spondylosis.

Traumatic subtypes were classified using thin-slice cervical CT (1-mm sections) and magnetic resonance imaging (MRI), including short tau inversion recovery (STIR) sequences.

Imaging and Preoperative Planning

All patients underwent preoperative CT and CT angiography (CTA) to evaluate vascular anatomy relevant to screw placement planning. Imaging findings were reviewed to assess the feasibility of C2 pedicle screw placement, identify vertebral artery constraints, and guide the selection of pedicle or alternative C2 anchorage techniques.

Surgical Technique

All procedures were performed with the patient in the prone position using a posterior midline approach. Subperiosteal dissection was carried out to expose the C1 posterior arch and lateral masses, as well as the C2 lamina and pars/pedicle region. The integrity of the C2 spinous process and the muscles attached to its inferior aspect was preserved in all cases, except in procedures involving C3 fixation.

Bone grafting was performed at the surgeon's discretion. When an autograft was used, graft material was harvested from the occipital bone, C1 posterior arch, and/or iliac crest. Allograft material was also used depending on availability and surgeon preference. All screws were inserted freehand using anatomical landmarks and preoperative imaging guidance; intraoperative navigation was not used.

C1 lateral mass screws were placed according to standard trajectories. C2 pedicle screws were used when morphometric evaluation permitted a safe trajectory. In cases with unfavorable anatomy, alternative C2 anchoring techniques, including laminar or pars fixation, were selected according to the predefined construct strategy.

The C2 nerve root was preserved whenever feasible. When necessary to achieve adequate exposure or facilitate safe implant placement, limited mobilization of the C2 nerve root was performed; routine sacrifice of the root was not part of the standard surgical technique.

C1–C2 facet preparation, including cartilage removal and decortication, as well as graft placement, was performed at the surgeon's discretion according to intraoperative exposure and feasibility. A standardized facet preparation protocol was not applied uniformly across all patients.

Construct Strategy Classification

Construct strategies were classified a priori according to the type of C2 anchorage into the following categories:

1. Pedicle: bilateral C2 pedicle screws (primary option).
2. Hybrid: unilateral C2 pedicle screw + contralateral laminar or pars anchor.
3. Bilateral laminar: bilateral C2 laminar screws due to bilateral unfavorable anatomy (e.g., thin pedicles and/or high-riding vertebral artery).
4. Planned C2 omission (C1–C3): at least one side planned omission of C2 anchoring with intentional extension to C3 for secure distal fixation in select cases where C2 anchoring was not feasible or safe.

C1 lateral mass screws were used in all cases whenever feasible. A single transarticular fixation case was analyzed separately.

Decision framework for C2 anchor selection

Bilateral C2 pedicle screw fixation was preferred when preoperative CT/CTA demonstrated adequate pedicle morphometry and a safe vertebral artery corridor. Unfavorable pedicle anatomy was defined as the presence of a high-riding vertebral artery (HRVA), characterized by a C2 isthmus height ≤5 mm and/or C2 internal height ≤2 mm measured 3 mm lateral to the spinal canal, or a narrow C2 pedicle (<4 mm). These anatomical features increase the risk of vertebral artery injury and limit safe pedicle screw placement (17,29).

When unilateral pedicle fixation remained feasible, a hybrid construct consisting of a unilateral pedicle screw and a contralateral laminar or pars anchor was used. Bilateral laminar fixation was selected in cases with bilateral anatomical constraints. Planned omission of C2 fixation with extension to C3 was reserved for cases in which secure C2 fixation was not feasible on at least one side. The proposed anatomy-driven construct selection algorithm is illustrated in Figure 1.

Fusion Assessment

Fusion was assessed using postoperative CT obtained at least 6 months after surgery and independently evaluated by two neurosurgeons (23,25). Fusion was defined as osseous bridging across the intended C1–C2 fusion site, including one or more of the following: bridging between the C1 anterior arch and the odontoid process, across the C1–C2 lateral mass/facet complex, or through the interlaminar region, in the absence of radiographic evidence of implant loosening. Implant loosening was defined as halo formation or radiolucency surrounding the screws, rod or screw breakage, or implant pullout.

Disagreements between reviewers were resolved by consensus. Patients without postoperative CT follow-up beyond 6 months were excluded from fusion rate analysis. Consequently, the absence of adequate radiographic surveillance in some patients may have introduced selection bias into the CT-based fusion assessment.

Outcomes

Recorded outcomes included operative duration, construct type, screw strategy, vertebral artery injury, neurological complications, wound infection, C2 neuralgia, 30-day reoperation, overall reoperation, mechanical failure, and fusion.

Neurological complication was defined as newly developed postoperative motor weakness. C2 neuralgia was defined as neuropathic occipital pain, such as lightning-like or shock-like pain, documented in the clinical records.

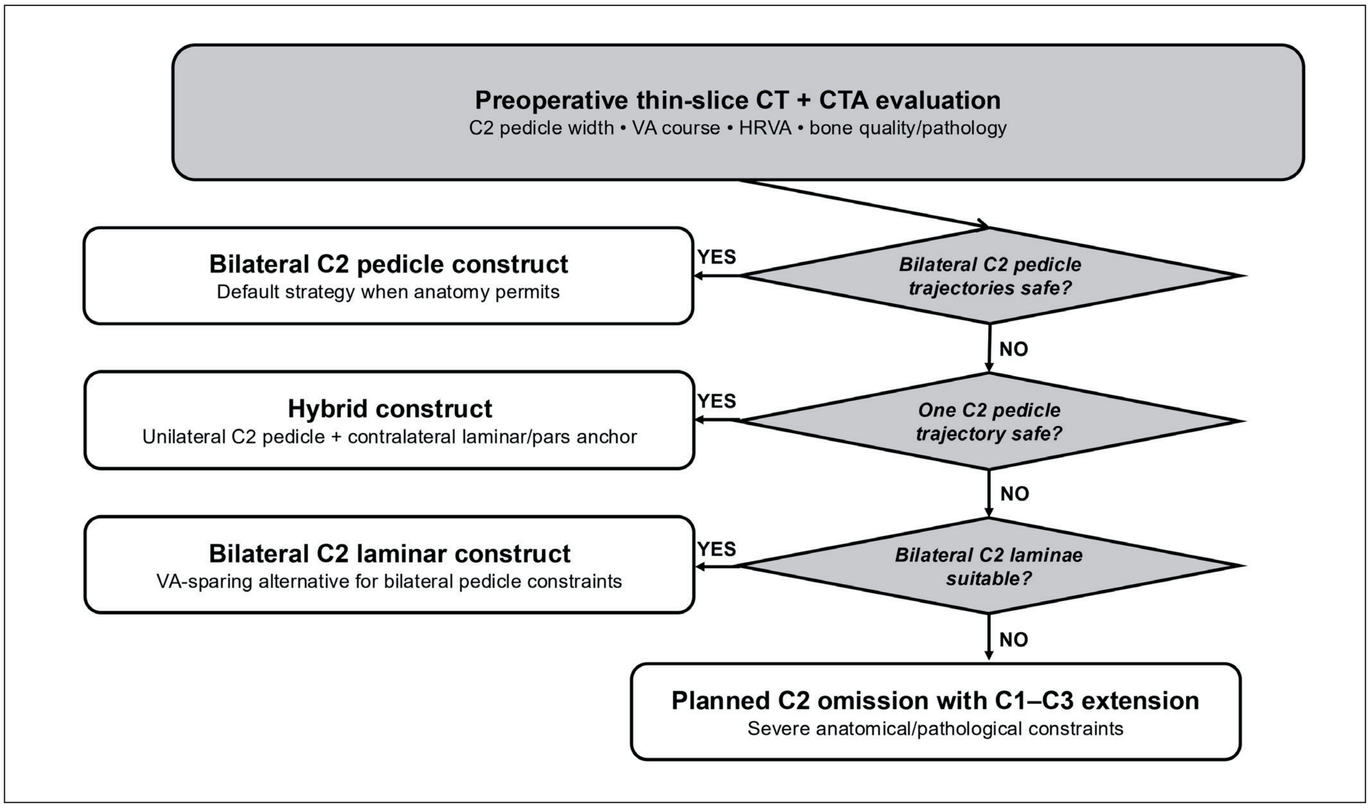

Figure 1: Anatomy-driven framework for C2 anchorage selection during posterior atlantoaxial fixation. Bilateral C2 pedicle fixation was preferred when pedicle morphology and vertebral artery anatomy permitted safe trajectories. Hybrid constructs were used for unilateral pedicle constraints, bilateral laminar fixation for bilateral unfavorable pedicle anatomy, and planned C2 omission with C1–C3 extension for severe anatomical or pathological constraints. HRVA: high-riding vertebral artery; VA: vertebral artery.

Mechanical failure was categorized as follows:

1. Radiographic mechanical findings: Asymptomatic construct-related abnormalities, including screw loosening, rod or screw breakage, pseudoarthrosis, or implant pull-out.
2. Clinically significant mechanical failure: Mechanical instability requiring revision surgery because of symptomatic instability, progressive deformity, or construct failure.

Because of the limited subgroup sizes and low number of events, exploratory categorical comparisons were performed using Fisher's exact test. These analyses included comparisons between construct strategy and radiographic mechanical findings, construct strategy and CT-confirmed fusion as well as selected etiology-based comparisons. Multivariable analysis was not performed because the number of events was insufficient to permit reliable statistical adjustment.

RESULTS

Baseline Characteristics

A total of 45 patients were included in the study. The mean age was 47.8 ± 20.1 years, and 20 patients (44.4%) were male. The mean operative duration was 261.9 ± 69.5 minutes, with a median duration of 265 minutes (IQR, 215–300 minutes). The median length of hospital stay was 3 days (IQR, 3–5 days). Median follow-up for the overall cohort was 6.3 months (IQR, 1.2–22.3 months). Baseline demographic and perioperative characteristics are summarized in Table I.

Etiologies

The distribution of surgical indications was as follows: trauma in 14 patients (31.1%), basilar invagination in 10 (22.2%), Chiari malformation in 7 (15.6%), os odontoideum in 4 (8.9%), nontraumatic atlantoaxial subluxation in 4 (8.9%), tumor in 4 (8.9%), and spondylosis in 2 patients (4.4%). The relationship between etiology and construct strategy is presented in Table II.

Table I: Baseline and Perioperative Characteristics

Variable	Value
Age, mean±SD (years)	47.8±20.1
Sex, n (%)	Female 25 (55.6); Male 20 (44.4)
Etiology, n (%)	Trauma 14 (31.1); Basilar invagination 10 (22.2); Chiari malformation 7 (15.6); Os odontoideum 4 (8.9); Atlantoaxial subluxation 4 (8.9); Tumor 4 (8.9); Spondylosis 2 (4.4)
Operative duration, mean±SD (minutes)	261.9±69.5; median 265 (IQR 215–300)
Length of stay (days)	median 3 (IQR 3–5)
Follow-up, full cohort (months)	median 6.3 (IQR 1.2–22.3)
Follow-up, fusion-assessed subgroup (n=26) (months)	median 19.5 (IQR 10.5–41.2)

Values are presented as mean ± SD, median (IQR), or n (%), as appropriate. Fusion was assessed on thin-slice (1 mm) CT scans obtained ≥6 months postoperatively when available and defined as osseous bridging across C1–C2 (anterior arch–dens, lateral mass/facet region, interlaminar space) without radiographic loosening.

Table II: Etiology by Construct Strategy

Etiology	n	Pedicle	Hybrid	Bilateral laminar	Planned C2 omission	Transarticular
Trauma	14	12	0	1	1	0
Basilar invagination	10	5	1	2	1	1
Chiari malformation	7	6	1	0	0	0
Os odontoideum	4	1	2	1	0	0
Atlantoaxial subluxation	4	2	1	1	0	0
Tumor	4	3	0	0	1	0
Spondylosis	2	2	0	0	0	0
Total	**45**	**31**	**5**	**5**	**3**	**1**

Pedicle = bilateral C2 pedicle screws (primary option). Hybrid = unilateral C2 pedicle screw with contralateral alternative anchor (laminar or pars). Bilateral laminar = bilateral C2 laminar screws due to bilaterally unfavorable anatomy (e.g., thin pedicles and/or high-riding vertebral artery). Planned C2 omission = at least one side planned omission of C2 fixation with intentional C1–C3 construct. Transarticular reported separately.

Within the trauma subgroup (n = 14), the most common injury pattern was odontoid fracture. Anderson–D'Alonzo type II odontoid fractures accounted for 7 patients (50.0%), whereas type III fractures accounted for 4 patients (28.6%) (2). The remaining traumatic indications included C1 ring fractures associated with transverse atlantal ligament injury in 2 patients (14.3%) and a dislocated Hangman fracture in 1 patient (7.1%).

Notably, five odontoid fracture cases represented delayed or complex presentations. These included four cases of type III odontoid fracture with nonunion or progressive displacement following an initial period of conservative management and one salvage case involving loosening of a previously placed anterior odontoid screw for a type II fracture, which ultimately required posterior C1–C2 stabilization.

Construct Strategy Distribution

Construct strategies included pedicle fixation in 31 patients (68.9%), hybrid constructs in 5 (11.1%), bilateral laminar fixation in 5 (11.1%), planned C2 omission with C1–C3 extension in 3 (6.7%), and transarticular fixation in 1 patient (2.2%). A representative standard pedicle construct using bilateral C2 pedicle screws (Harms technique) is shown in Figure 2.

Figure 3 illustrates a representative anatomy-driven hybrid construct strategy, including preoperative CTA demonstrating narrow pedicle morphology and postoperative axial CT confirming hybrid fixation. In two patients (4.4%), C1 lateral mass screws were not used, and either occiput–C2 fixation or transarticular C1–C2 fixation was preferred.

Outcomes Stratified by Construct Strategy

Reoperations included one wound revision procedure; all remaining reoperations were performed because of mechanical failure, including screw loosening or breakage, rod breakage, pseudoarthrosis, and implant pullout.

Safety events, complications, and reoperation outcomes stratified according to construct strategy are summarized in

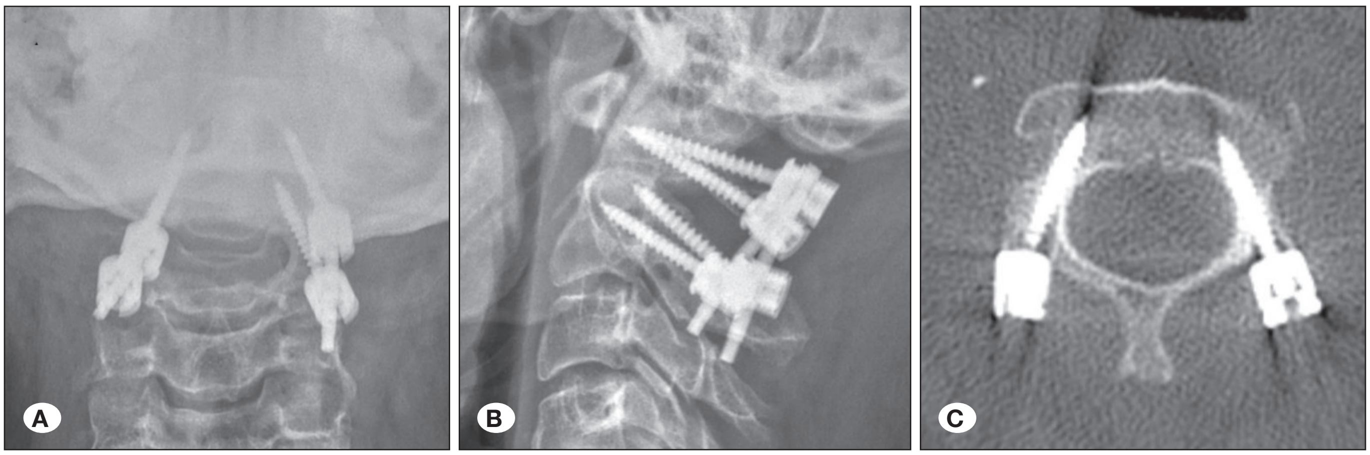

Figure 2: Posterior C1–C2 fixation in basilar invagination associated with Chiari malformation. A 31-year-old female underwent posterior fossa decompression with duraplasty and C1–C2 fixation. **A)** Postoperative anteroposterior radiograph. **B)** Lateral radiograph. **C)** Axial computed tomography confirming bilateral C2 pedicle screw positioning.

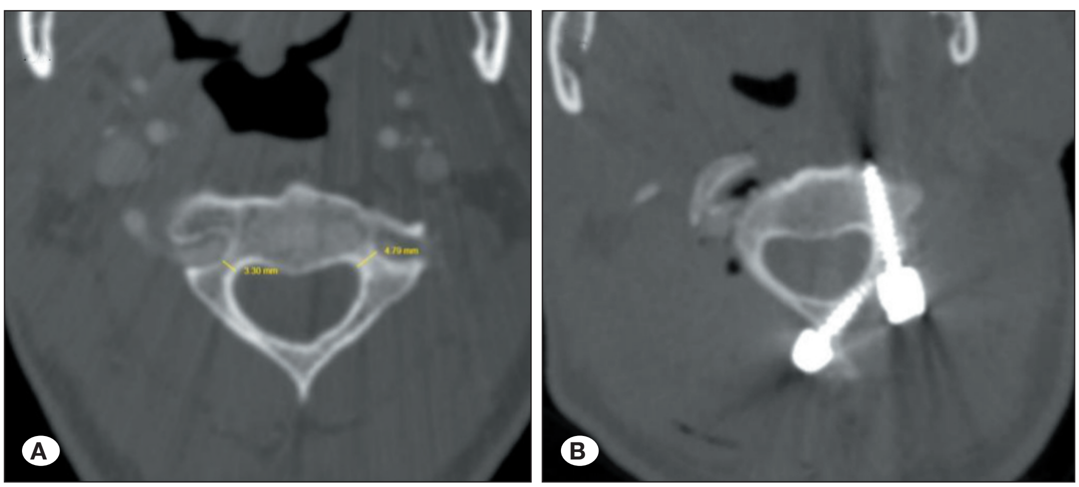

Figure 3: Hybrid C1–C2 construct in os odontoideum with narrow C2 pedicle. A 50-year-old male underwent C1–C2 fusion. **A)** Preoperative computed tomography angiography (CTA) demonstrating narrow right C2 pedicle (3.30 mm) compared with the left (4.79 mm). **B)** Postoperative axial CT showing hybrid construct with the right C2 laminar screw and left C2 pedicle screw.

Table III. Mechanical failure and CT-based fusion outcomes in the fusion-assessed subgroup are summarized in Table IV.

Because of the limited subgroup sizes and low event rates, exploratory categorical analyses were performed using Fisher's exact test. Construct strategy was not significantly associated with radiographic mechanical findings ($p = 0.287$) or CT-confirmed fusion among patients with evaluable postoperative CT follow-up ($p = 1.000$).

Radiographic mechanical findings were not observed in trauma cases (0/14) and occurred in 7 of 31 nontraumatic cases (22.6%); however, this difference did not reach statistical significance ($p = 0.081$). In contrast, radiographic mechanical findings were significantly more common among patients with os odontoideum or nontraumatic atlantoaxial subluxation than among patients with other etiologies (5/8 [62.5%] vs. 2/37 [5.4%], $p < 0.001$). These analyses were exploratory in nature and underpowered for definitive comparative conclusions.

Radiological progression in a representative trauma case, from preoperative displacement to postoperative day 1 reduction and one-year fusion, is illustrated in Figure 4.

Fusion Outcomes

CT-based fusion assessment was available for 26 of 45 patients (57.8%). Nineteen patients (42.2%) did not undergo postoperative CT evaluation beyond 6 months and were therefore excluded from the fusion analysis denominator. Fusion was observed in 20 of 26 patients (76.9%). Fusion outcomes according to the construct strategy are summarized in Table IV.

Complications

Overall, 17 of 45 patients (37.8%) experienced at least one complication. The most common complication was C2 neuralgia, which occurred in 8 patients (17.8%) and was characterized by neuropathic occipital pain with lightning-like or shock-like features.

Radiographic mechanical abnormalities occurred in 7 patients (15.6%) and included screw loosening, pseudoarthrosis, implant pullout, and construct-related hardware failure. Six patients (13.3%) developed clinically significant mechanical failure requiring revision surgery.

Table III: Complication and Reoperation Outcomes by Construct Strategy

Construct strategy	n	VA Injury	Neural Complication	Wound Infection	C2 Neuralgia	Reop 30d	Reop any
Pedicle	31	0 (0.0)	0 (0.0)	0 (0.0)	5 (16.1)	1 (3.2)	4 (12.9)
Hybrid	5	0 (0.0)	0 (0.0)	0 (0.0)	1 (20.0)	0 (0.0)	1 (20.0)
Bilateral laminar	5	0 (0.0)	0 (0.0)	0 (0.0)	1 (20.0)	1 (20.0)	1 (20.0)
Planned C2 omission (C1–C3)	3	0 (0.0)	1 (33.3)	2 (66.7)	1 (33.3)	0 (0.0)	1* (33.3)
Transarticular	1	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)

Values are presented as n (% within construct strategy), unless otherwise indicated. "Reop 30d" denotes return to the operating room within 30 postoperative days; "Reop any" denotes return to the operating room at any time during available follow-up. The asterisk denotes reoperation for wound revision; remaining reoperations were performed for mechanical failure. C2 neuralgia/occipital neuralgia was defined as neuropathic-character occipital pain, such as lightning or shocking occipital pain, documented in routine clinical records; incidence and severity may be underestimated because standardized pain instruments were not used. "Neural Complication" denotes postoperative neurological deterioration; the single neurological complication occurred in a patient with an intramedullary tumor and was attributed to the intramedullary tumor procedure rather than the fixation construct. VA, vertebral artery.

Table IV: Mechanical and Fusion Outcomes by Construct Strategy

Construct strategy	n	Radiographic Mechanical Failure	Revision Requiring Mechanical Failure	Fusion Assessed (n)	Fused n (%)
Pedicle	31	4 (12.9)	4 (12.9)	15	13 (86.7)
Hybrid	5	2 (40.0)	1 (20.0)	5	3 (60.0)
Bilateral laminar	5	1 (20.0)	1 (20.0)	3	2 (66.7)
Planned C2 omission	3	0 (0.0)	0 (0.0)	3	2 (66.7)
Transarticular	1	0 (0.0)	0 (0.0)	0	—

Values are presented as n (% within construct strategy), unless otherwise indicated. Radiographic mechanical failure included screw loosening, pseudoarthrosis, implant pullout, or construct-related hardware failure. Revision-requiring mechanical failure was defined as clinically significant mechanical failure requiring revision surgery because of symptomatic instability, progressive deformity, or construct failure. Fusion assessment was restricted to patients with available postoperative CT obtained ≥6 months after surgery. "Fusion assessed" indicates the number of evaluable patients within each construct strategy; fused percentages were calculated only among patients with evaluable CT follow-up. Exploratory Fisher exact testing did not demonstrate statistically significant associations between construct strategy and radiographic mechanical failure (p=0.287) or CT-assessed fusion (p=1.000). These analyses were exploratory and underpowered for definitive comparative inference; no multivariable modeling was performed.

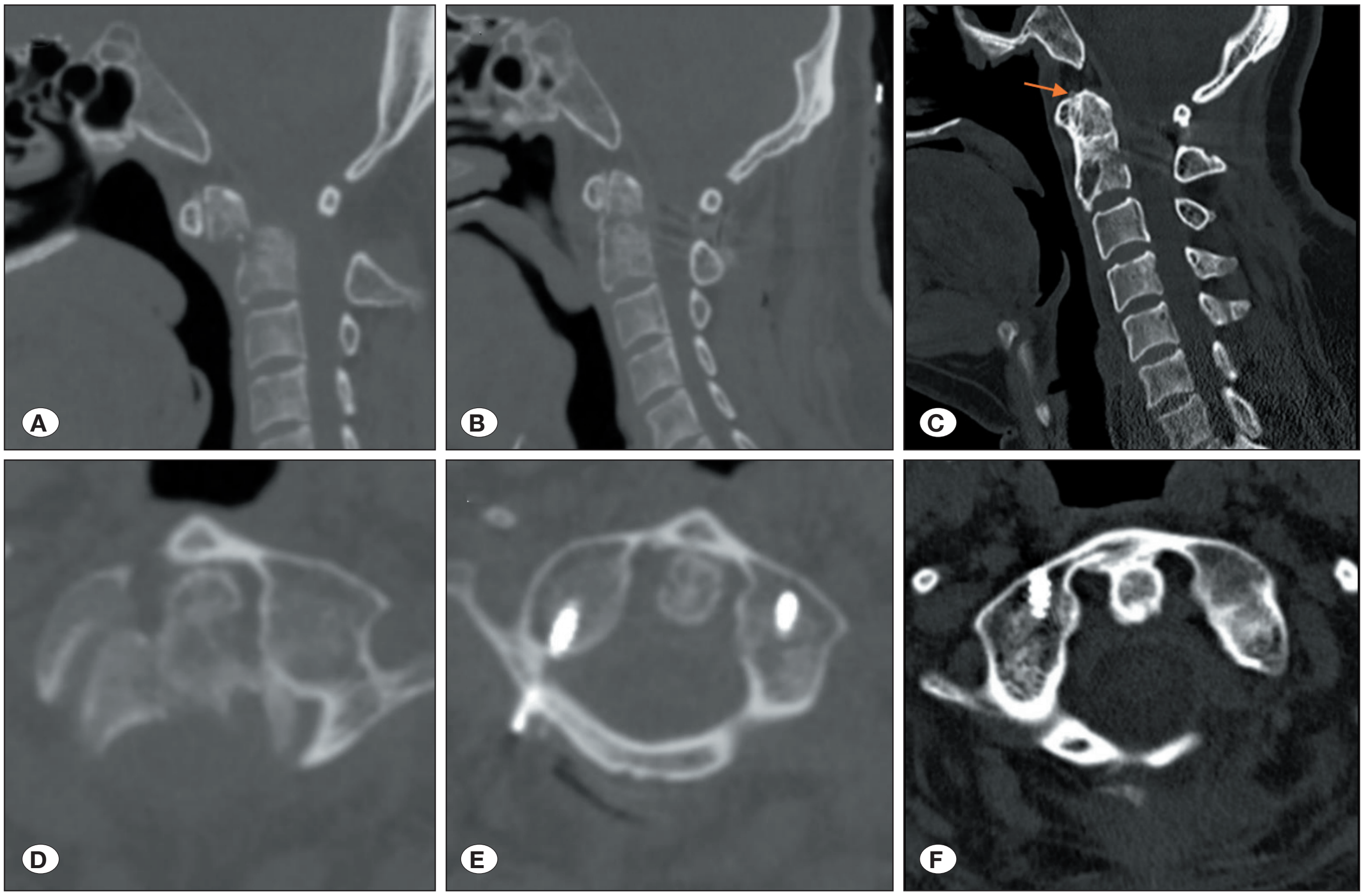

Figure 4: Radiologic evaluations following posterior C1–C2 fixation for Anderson–D'Alonzo type II odontoid fracture. A 55-year-old male underwent reduction and fixation. **A, D)** Preoperative sagittal and axial computed tomography (CT) scans. **B, E)** Postoperative day 1 CT demonstrating reduction and construct positioning. **C, F)** One-year follow-up CT demonstrating maintained alignment and solid fusion. Arrow indicates fusion between the C1 anterior arch and C2 dens.

Wound infection occurred in 2 patients (4.4%); one of these patients required surgical wound revision. One patient (2.2%) developed new postoperative motor weakness in the setting of surgery for a C1–C2 intramedullary tumor. This neurological deficit was attributed to the intramedullary tumor procedure rather than to the instrumentation itself.

No vertebral artery injury occurred in this series (0/45, 0%).

DISCUSSION

Posterior C1–C2 fixation has evolved from transarticular constructs to segmental screw–rod techniques that provide greater intraoperative flexibility and broader anatomical applicability (5,20). Magerl's transarticular approach and the subsequent segmental construct described by Harms and Melcher established the foundation of modern screw-based atlantoaxial stabilization, supported by biomechanical and clinical evidence favoring rigid fixation over posterior wiring techniques (6,10,13,20). These advances allow fixation strategies to be tailored to patient-specific anatomy while maintaining the reduction capability and fusion potential required for atlantoaxial instability (7,10).

In this consecutive series, the predominance of bilateral C2 pedicle anchorage reflects current practice in anatomically favorable cases (7), whereas the use of hybrid, bilateral laminar, and planned C2 omission constructs reflects deliberate escalation when C2 morphology and/or vertebral artery anatomy limited safe pedicle trajectories. The etiologic heterogeneity of our cohort mirrors real-world management of atlantoaxial instability, with trauma representing the most common indication, followed by craniovertebral junction deformity and other causes. Trauma remains a common indication for atlantoaxial surgery, particularly Anderson–D'Alonzo type II odontoid fractures, in which posterior segmental fixation is frequently selected when instability is substantial, reduction is required, or anterior odontoid screw fixation is unsuitable (2,12). Conversely, basilar invagination and Chiari malformation represent craniovertebral junction deformity paradigms in which posterior stabilization is commonly used in selected patients to facilitate reduction and decompression (9,11). Across this spectrum, maintaining construct rigidity while adapting to patient-specific anatomy remains a central practical requirement (7,26).

Accordingly, our institutional approach may be summarized as a structured construct-selection framework focused on C2 anchorage. Bilateral C2 pedicle screw fixation served as the preferred option when morphometric assessment permitted safe trajectories (30). When unilateral anatomical constraints existed, such as a narrow pedicle, HRVA, or unfavorable vascular anatomy, a hybrid strategy preserved pedicle fixation on the feasible side while using a contralateral alternative anchor (laminar or pars) to maintain stability while reducing vascular risk (21,30). When bilateral constraints precluded safe pedicle placement, bilateral C2 laminar fixation provided a vertebral artery–sparing alternative supported by morphometric and clinical evidence (15). In selected cases in which secure C2 fixation was not feasible or safe on at least one side, planned omission of C2 fixation with intentional extension to C3 provided reliable distal fixation (24). In our series, this escalation strategy was used for destructive unilateral C2 pathology (neoplastic or traumatic) and complex congenital anatomy, including C2–C3 Klippel–Feil anomaly with bilaterally thin pedicles and high-riding vertebral arteries, in which fixation was achieved with bilateral C3 pedicle screws. The single transarticular case reflects that transarticular fixation remains an option in selected anatomical situations but is used less frequently in modern practice because of reduction requirements and vascular considerations (20,30). A separate radiographic analysis from this cohort evaluated arcuate foramen and congenital anomalies affecting C1 screw entry; however, those anatomy-focused findings are outside the scope of the present outcomes- and C2 anchorage-focused report.

All screws in this cohort were placed freehand. Although navigation systems and patient-specific guides have gained increasing interest, freehand atlantoaxial fixation is safe when meticulous preoperative imaging assessment and anatomical landmarks are used (16,27). Vertebral artery injury remains a recognized risk during C2 pedicle and transarticular screw placement; therefore, preoperative three-dimensional vascular assessment is critical for selecting the safest anchor strategy and supports escalation toward hybrid or laminar fixation when high-risk anatomy is identified (1,30). Importantly, no vertebral artery injuries occurred in this series, supporting the practical value of a predefined escalation framework rather than attempting pedicle placement in high-risk corridors.

Comparison with published series should consider differences in indication profiles, construct-selection philosophy, imaging modalities, and follow-up protocols. A large series by Isik et al. reported favorable outcomes after posterior atlantoaxial screw–rod fixation and emphasized the importance of preoperative radiologic planning and surgical experience. The authors also described C2 laminar screws as a successful alternative in anatomically constrained cases (14). Additional Turkish studies have reported alternative anchorage strategies in the setting of vertebral artery anomalies or complex C2 anatomy, highlighting that a single construct strategy may not apply to all patients (24). Our findings are consistent with these reports, emphasizing the importance of anatomy-driven anchor selection in safe posterior atlantoaxial fixation (14,24).

Fusion assessment warrants cautious interpretation. In this study, fusion was evaluated by two independent neurosurgeons using postoperative CT scans obtained at ≥6 months. CT is widely regarded as the most specific modality for assessing osseous bridging (23), and CT-based criteria have been evaluated against surgical exploration in cervical fusion and nonunion assessment (25). However, fusion rates may appear lower when strict CT-based bridging criteria are applied, particularly in studies with heterogeneous pathology and nonstandardized follow-up. Published atlantoaxial fixation studies vary considerably with respect to pathology, follow-up duration, grafting strategy, fusion biology, and methods of fusion assessment, including dynamic radiographs, clinical stability, CT, or combined criteria (6,18,23). Meta-analyses have generally reported high fusion rates for screw–rod constructs. Elliott et al. reported a pooled fusion rate of 97.5% for screw–rod constructs, whereas Lvov et al. reported a nonunion rate of 4.2% for the Goel–Harms technique (6,18). Our CT-confirmed fusion rate of 76.9% was therefore lower than many published technique-specific estimates, but this finding should be interpreted in the context of strict CT-based criteria, heterogeneous pathology and follow-up, variable fusion biology, and incomplete CT availability for the full cohort. Standardized CT follow-up protocols would improve benchmarking in future studies (23).

In our cohort, the complication profile consisted primarily of C2 neuralgia (17.8%), radiographic mechanical findings (15.6%), wound infection (4.4%), and a single neurological complication, with no vertebral artery injuries observed. The absence of vertebral artery injury compares favorably with pooled estimates in the literature. Ghaith et al. reported vertebral artery injury rates of approximately 2% per operated patient and 1% per screw placed, whereas Lvov et al. reported a vertebral artery injury rate of 2.8% in a meta-analysis of the Goel–Harms technique (8,18). Our C2 neuralgia rate was higher than the 6.1% rate of clinically significant C2 nerve root irritation reported by Lvov et al.; however, comparisons remain difficult because studies differ in C2 root handling techniques, reporting definitions, and patient-reported outcome assessment (18,28). Yeom et al. demonstrated that postoperative occipital neuralgia may be clinically significant and technique-dependent, particularly with respect to C2 nerve root management (28). The wound infection rate of 4.4% and wound revision rate of 2.2% in our series were within the low single-digit range reported in contemporary posterior atlantoaxial datasets, although definitions and follow-up periods vary across studies (19). The single neurological complication occurred in a patient undergoing resection of a C1–C2 intramedullary tumor and was therefore attributed to the intramedullary procedure rather than the fixation construct itself.

Our relatively broad definition of radiographic mechanical findings likely contributed to rates that appear higher than those reported in some indication-specific series and technique-focused meta-analyses (4,18). This likely reflects both the inclusive radiographic definition and the heterogeneous nature of our cohort, which included acute trauma, chronic instability/

deformity, tumor-related instability, and degenerative pathology. Differences in bone quality, reducibility, chronic deformity, and fusion biology may increase implant stress and pseudarthrosis risk compared with more homogeneous cohorts. Exploratory Fisher's exact analyses did not demonstrate statistically significant associations between construct strategy and either radiographic mechanical findings or CT-confirmed fusion. Although radiographic abnormalities appeared descriptively more common in hybrid constructs, this should be interpreted cautiously because hybrid fixation was preferentially selected in anatomically constrained and often chronic instability cases, resulting in likely confounding by indication. Instead, mechanical findings clustered more prominently in chronic instability phenotypes, particularly os odontoideum and nontraumatic atlantoaxial subluxation. These observations suggest that underlying pathology, chronic deformity, reducibility, and fusion biology may influence mechanical outcomes more strongly than construct category alone; however, these findings remain exploratory because of the limited subgroup sizes. Nevertheless, the observed pattern is consistent with the concept that chronic deformity and altered biomechanics may impose greater demands on fixation constructs than acute traumatic instability (6).

C2 neuralgia remains a clinically relevant outcome after C1–C2 fixation (18). In this study, neuralgia was identified from routine clinical documentation rather than standardized patient-reported instruments; therefore, both incidence and severity may have been underestimated. We intentionally avoided formal risk-factor analysis and instead reported this outcome descriptively, reserving definitive evaluation for future studies incorporating standardized pain instruments and detailed operative variables, including C2 root management.

Stratified analyses suggested that mechanical failure and reoperation clustered in chronic instability phenotypes, particularly os odontoideum and nontraumatic atlantoaxial subluxation, whereas traumatic cases demonstrated no mechanical failures or reoperations in this cohort. These findings should be considered hypothesis-generating because of the small subgroup sizes and variable follow-up duration. In addition, shorter follow-up in recently operated patients may have limited the detection of delayed failure or late nonunion.

Overall, this consecutive series supports the practical feasibility of freehand posterior atlantoaxial fixation across heterogeneous indications using a structured, anatomy-driven construct-selection strategy focused on C2 anchorage (6,26). Prospective follow-up with standardized CT fusion assessment and patient-reported outcome measures would improve benchmarking and enable more robust risk-factor analyses across construct categories.

This study has several limitations. First, the retrospective single-center design introduces inherent selection and information biases, and the heterogeneous etiologic spectrum limits direct subgroup comparisons. Second, construct-strategy subgroups were small; therefore, analyses stratified by strategy or etiology should be considered descriptive and hypothesis-generating rather than confirmatory. Statistical analyses were intentionally limited because subgroup sizes were insufficient for robust multivariable modeling. Third, radiologic fusion was assessed by CT in only 26 of 45 patients (57.8%), whereas 19 patients (42.2%) lacked postoperative CT at ≥6 months. This may have introduced selection bias and limited definitive benchmarking for the entire cohort. Imaging intervals were not standardized, and interobserver reliability for fusion assessment was not formally evaluated. Fourth, important patient-centered outcomes, particularly occipital pain and C2 neuralgia, were derived from routine clinical documentation rather than standardized patient-reported instruments, potentially underestimating symptom burden and severity. Finally, follow-up duration was variable, and shorter follow-up in recently operated patients may have limited the detection of delayed mechanical complications or late nonunion.

CONCLUSION

In this consecutive single-center series, an anatomy-driven construct-selection strategy demonstrated the practical feasibility of safe freehand posterior atlantoaxial fixation across a heterogeneous spectrum of C1–C2 instability. Bilateral pedicle fixation served as the preferred strategy when anatomically feasible, whereas hybrid constructs, bilateral laminar fixation, and planned C2 omission with C1–C3 extension provided practical preplanned alternatives in the setting of predictable anatomical or pathological constraints. CT-confirmed fusion was achieved in most evaluable patients, with acceptable complication and reoperation profiles. Prospective studies with standardized CT-based fusion assessment and patient-reported outcome measures are needed to improve benchmarking and better define strategy-specific risks and long-term outcomes.

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AUTHORSHIP CONTRIBUTION

Study conception and design: ATB

Data collection: ATB, BT

Analysis and interpretation of results: ATB, BT

Draft manuscript preparation: ATB

Critical revision of the article: ATB, BT

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REFERENCES

1. Abumi K, Shono Y, Ito M, Taneichi H, Kotani Y, Kaneda K: Complications of pedicle screw fixation in reconstructive surgery of the cervical spine. Spine 25:962-969, 2000. https://doi.org/10.1097/00007632-200004150-00011
2. Anderson LD, D'Alonzo RT: Fractures of the odontoid process of the axis. JBJS 56:1663-1674, 1974.
3. Bahadur R, Goyal T, Dhatt SS, Tripathy SK: Transarticular screw fixation for atlantoaxial instability-modified Magerl's technique in 38 patients. J Orthop Surg Res 5:87, 2010. https://doi.org/10.1186/1749-799x-5-87
4. Buchmann N, Schweizer C, Kirschke JS, Rienmüller A, Gempt J, Ringel F, Meyer B, Ryang YM: C1-C2 posterior screw fixation in atlantoaxial fractures revisited: Technical update based on 127 cases. Eur Spine J 29:1036-1042, 2020. https://doi.org/10.1007/s00586-019-06244-2
5. Chen Q, Brahimaj BC, Khanna R, Kerolus MG, Tan LA, David BT, Fessler RG: Posterior atlantoaxial fusion: A comprehensive review of surgical techniques and relevant vascular anomalies. J Spine Surg 6:164-180, 2020. https://doi.org/10.21037/jss.2020.03.05
6. Elliott RE, Tanweer O, Boah A, Morsi A, Ma T, Smith ML, Frempong-Boadu A: Atlantoaxial fusion with screw-rod constructs: Meta-analysis and review of literature. World Neurosurg 81:411-421, 2014. https://doi.org/10.1016/j.wneu.2012.03.013
7. Elliott RE, Tanweer O, Boah A, Smith ML, Frempong-Boadu A: Comparison of safety and stability of C-2 pars and pedicle screws for atlantoaxial fusion: Meta-analysis and review of the literature. J Neurosurg Spine 17:577-593, 2012. https://doi.org/10.3171/2012.9.Spine111021
8. Ghaith AK, Yolcu YU, Alvi MA, Bhandarkar AR, Sebastian AS, Freedman BA, Bydon M: Rate and characteristics of vertebral artery injury following C1-C2 posterior cervical fusion: A systematic review and meta-analysis. World Neurosurg 148:118-126, 2021. https://doi.org/10.1016/j.wneu.2020.12.165
9. Goel A: Treatment of basilar invagination by atlantoaxial joint distraction and direct lateral mass fixation. J Neurosurg Spine 1:281-286, 2004. https://doi.org/10.3171/spi.2004.1.3.0281
10. Goel A, Laheri V: Plate and screw fixation for atlanto-axial subluxation. Acta Neurochir 129:47-53, 1994. https://doi.org/10.1007/bf01400872
11. Goel A, Sathe P, Shah A: Atlantoaxial fixation for basilar invagination without obvious atlantoaxial instability (group B basilar invagination): Outcome analysis of 63 surgically treated cases. World Neurosurg 99:164-170, 2017. https://doi.org/10.1016/j.wneu.2016.11.093
12. Grauer JN, Shafi B, Hilibrand AS, Harrop JS, Kwon BK, Beiner JM, Albert TJ, Fehlings MG, Vaccaro AR: Proposal of a modified, treatment-oriented classification of odontoid fractures. Spine J 5:123-129, 2005. https://doi.org/10.1016/j.spinee.2004.09.014
13. Harms J, Melcher RP: Posterior C1-C2 fusion with polyaxial screw and rod fixation. Spine 26:2467-2471, 2001. https://doi.org/10.1097/00007632-200111150-00014
14. Isik HS, Sandal E, Cagli S: Clinical outcomes of posterior C1 and C2 screw-rod fixation for atlantoaxial instability. Turk Neurosurg 28:602-609, 2018. https://doi.org/10.5137/1019-5149.Jtn.20525-17.1
15. Jea A, Sheth RN, Vanni S, Green BA, Levi AD: Modification of Wright's technique for placement of bilateral crossing C2 translaminar screws: Technical note. Spine J 8:656-660, 2008. https://doi.org/10.1016/j.spinee.2007.06.008
16. Jo DJ, Seo EM, Kim KT, Kim SM, Lee SH: Cervical pedicle screw insertion using the technique with direct exposure of the pedicle by laminoforaminotomy. J Korean Neurosurg Soc 52:459-465, 2012. https://doi.org/10.3340/jkns.2012.52.5.459
17. Klepinowski T, Żyłka N, Pettersson SD, Hanaya J, Pala B, Łątka K, Taterra D, Poncyljusz W, Ogilvy CS, Sagan L: Types of high-riding vertebral artery: A classification system for preoperative planning of C2 instrumentation based on 908 potential screw insertion sites. Spine J 25:59-68, 2025. https://doi.org/10.1016/j.spinee.2024.08.021
18. Lvov I, Grin A, Talypov A, Smirnov V, Kordonskiy A, Barbakadze Z, Abdrafiev R, Krylov V: Efficacy and safety of Goel-Harms technique in upper cervical spine surgery: A systematic review and meta-analysis. World Neurosurg 167:e1169-e1184, 2022. https://doi.org/10.1016/j.wneu.2022.09.016
19. Macki M, Basheer A, Lee I, Kather R, Rubinfeld I, Abdulhak MM: Surgical site infection after transoral versus posterior approach for atlantoaxial fusion: A matched cohort study. J Neurosurg Spine 28:33-39, 2018. https://doi.org/10.3171/2017.5.Spine161064
20. Magerl F, Seemann PS: Stable posterior fusion of the atlas and axis by transarticular screw fixation. In: Kehr P, Weidner A (eds), Cervical spine I: Strasbourg 1985. 1987:322-327. https://doi.org/10.1007/978-3-7091-8882-8_59
21. Neo M, Fujibayashi S, Miyata M, Takemoto M, Nakamura T: Vertebral artery injury during cervical spine surgery: A survey of more than 5600 operations. Spine 33:779-785, 2008. https://doi.org/10.1097/BRS.0b013e31816957a7
22. Park JS, Cho DC, Sung JK: Feasibility of C2 translaminar screw as an alternative or salvage of C2 pedicle screws in atlantoaxial instability. J Spinal Disord Tech 25:254-258, 2012. https://doi.org/10.1097/BSD.0b013e318218a4f7
23. Rhee JM, Chapman JR, Norvell DC, Smith J, Sherry NA, Riew KD: Radiological determination of postoperative cervical fusion: A systematic review. Spine 40:974-991, 2015. https://doi.org/10.1097/brs.0000000000000940
24. Senturk S, Akyoldas G, Yaman O, Ozer AF: A new technique for the surgical treatment of atlantoaxial instability: C1 lateral mass and C2-3 transfacet screwing. Turk Neurosurg 28:843-846, 2018. https://doi.org/10.5137/1019-5149.Jtn.20022-17.1
25. van Bilsen MWT, Ullrich C, Ferraris L, Hempfing A, Hitzl W, Mayer M, Koller H: Diagnostic accuracy of CT scan-based criteria compared with surgical exploration for the analysis of cervical fusion and nonunion. J Neurosurg Spine 33:51-57, 2020. https://doi.org/10.3171/2019.12.Spine191011
26. Wright NM: Posterior C2 fixation using bilateral, crossing C2 laminar screws: Case series and technical note. J Spinal Disord Tech 17:158-162, 2004. https://doi.org/10.1097/00024720-200404000-00014
27. Xu RM, Ma WH, Wang Q, Zhao LJ, Hu Y, Sun SH: A free-hand technique for pedicle screw placement in the lower cervical spine. Orthop Surg 1:107-112, 2009. https://doi.org/10.1111/j.1757-7861.2009.00023.x

28. Yeom JS, Buchowski JM, Kim HJ, Chang BS, Lee CK, Riew KD: Postoperative occipital neuralgia with and without C2 nerve root transection during atlantoaxial screw fixation: A post-hoc comparative outcome study of prospectively collected data. Spine J 13:786-795, 2013. https://doi.org/10.1016/j.spinee.2013.04.006
29. Yeom JS, Buchowski JM, Kim HJ, Chang BS, Lee CK, Riew KD: Risk of vertebral artery injury: Comparison between C1-C2 transarticular and C2 pedicle screws. Spine J 13:775-785, 2013. https://doi.org/10.1016/j.spinee.2013.04.005
30. Yoshida M, Neo M, Fujibayashi S, Nakamura T: Comparison of the anatomical risk for vertebral artery injury associated with the C2-pedicle screw and atlantoaxial transarticular screw. Spine 31:E513-517, 2006. https://doi.org/10.1097/01.brs.0000224516.29747.52