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MODERN DIAGNOSTIC AND SURGICAL MANAGEMENT OF CRANIOVERTEBRAL JUNCTION INSTABILITY

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Abstract

Objective: Craniovertebral junction (CVJ) anomalies with functional instability represent a complex pathology in neurosurgical practice, often leading to spinal cord compression, vascular compromise, and significant neurological deficits. This study aims to improve surgical outcomes by developing a diagnostic algorithm based on neuroimaging criteria to guide the selection of surgical intervention.

Methods: A retrospective analysis of prospectively collected data was performed for 35 patients with CVJ anomalies treated between January 2021 and December 2025. A diagnostic algorithm was developed, incorporating 3D-CT assessment of posterior cranial fossa (PCF) volume and functional MSCT. Patients were classified into three subtypes (A, B, C) based on PCF morphology. Surgical tactics were tailored accordingly: Goel-Harms stabilization for Type A (instability-dominant), foramen magnum decompression (FMD) or expanded suboccipital cranioplasty (ESCP) for Types B and C (compression-dominant), and combined decompression-stabilization for mixed pathologies.

Results: The cohort had a median age of 30.5 years. Postoperatively, a significant reduction in pain (Visual Analog Scale, VAS) and improvement in functional status (Neck Disability Index, NDI) were observed at all follow-up points ($p < 0.001$). According to the Macnab criteria, 94.2% of outcomes were rated as excellent or good at 24 months. One complication (2.85%) related to screw malposition was successfully revised.

Conclusion: A differentiated approach to CVJ anomalies, guided by a diagnostic algorithm utilizing PCF volumetry and functional MSCT, allows for optimal selection of surgical strategy. This methodology results in significant and sustained clinical improvement with a low complication rate, proving to be both clinically effective and safe.

Keywords: Craniovertebral junction, CVJ instability, Occipitocervical fusion, Foramen magnum decompression, Goel-Harms technique, Posterior cranial fossa volume.

Introduction

The craniovertebral junction (CVJ) is a complex region whose integrity is critical for neurological function. Anomalies in this area can disrupt the normal anatomical relationship between the skull base and the upper cervical spine, leading to neural compression, impaired cerebrospinal fluid dynamics, and a spectrum of neurological symptoms, including headache, imbalance, spinal disorders, and progressive neurological dysfunction [1, 2].

Diagnosing CVJ anomalies requires a comprehensive approach, including neurological examination, neuroimaging (MRI, CT), neurophysiological studies, and functional tests. Early and accurate detection is crucial for timely intervention and preventing the progression of neurological deficits [3, 4]. Surgical management aims to decompress neural structures, restore normal CSF flow, and stabilize the spinal column. The choice of surgical strategy depends on the specific anomaly, the degree of compression, and the patient's overall condition. While various anterior, posterior, and combined approaches exist [5-7], selecting the optimal strategy remains challenging and requires an individualized patient approach [8-10].

Current limitations include the lack of universal diagnostic protocols for functional instability and varying outcomes of stabilization techniques, often due to anatomical variations and insufficiently personalized treatment plans [11, 12]. This study introduces a diagnostic algorithm based on 3D-CT volumetry of the posterior cranial fossa (PCF) and functional MSCT. We propose a corresponding surgical decision-making protocol that differentiates between three primary pathologies: decompression alone, stabilization alone (Goel-Harms), and

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combined procedures. The objective of this study is to evaluate the clinical outcomes of this differentiated approach in improving pain, functional status, and stability in patients with CVJ anomalies.

Materials and Methods

Study Design and Patient Population

A retrospective analysis of prospectively collected data was conducted for 35 patients with developmental CVJ anomalies who underwent surgical treatment at our institution between January 2021 and December 2025. The study was approved by the local ethics committee. The follow-up period ranged from 12 to 24 months, with a median of 18 months.

Diagnostic Algorithm

All patients underwent a standardized diagnostic workup:

1. Computed Tomography (CT): Used for detailed assessment of bony structures, including osteophytes, fractures, stenosis, and congenital anomalies.
2. Magnetic Resonance Imaging (MRI): Employed for superior soft-tissue visualization to identify spinal cord compression, syrinx, tumors, and inflammatory processes.
3. 3D-Volumetric Analysis: 3D-CT reconstructions were used to measure the volume of the posterior cranial fossa (PCF). Based on PCF volume and the volume of brain structures within the PCF (VBPCF), patients were classified into three subtypes (Fig. 1):

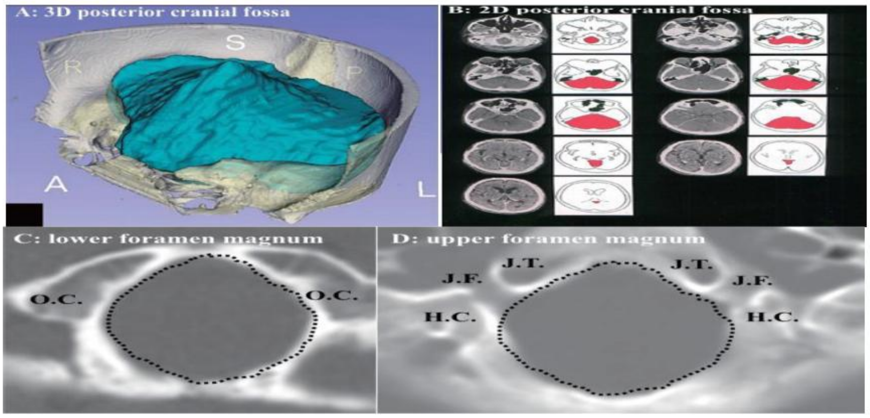

Figure 1: Volumetric analysis of the posterior cranial fossa (PCF). A: 3D-CT reconstruction. B: 2D-CT image with red areas indicating PCF volume (VPCF).

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C, D: 2D-CT images demonstrating the area of the foramen magnum outlets.
· Type A: Normal PCF and VBPCF volume, but evidence of brainstem ptosis due to CVJ instability.
· Type B: Normal PCF volume, but reduced VBPCF and undersized occipital bone, leading to compression of PCF structures.
· Type C: Significantly reduced PCF and VBPCF volumes, causing severe compression and low-lying brainstem.
4. Functional MSCT: Dynamic CT scans in flexion and extension were performed to assess articular instability. Instability was defined by established radiological criteria: Atlantodental Interval (ADI) >3 mm in adults, Basion-Dental Interval (BDI) >14 mm, and a change in ADI >1 mm during movement (Fig. 2).

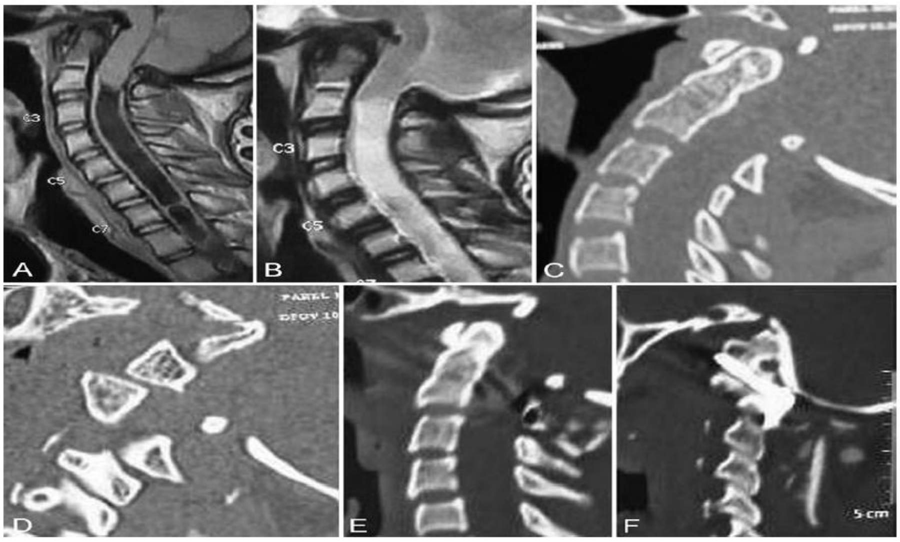

Figure 2: Types of atlantoaxial dislocations (I, II, III) and radiological parameters of instability.

Surgical Techniques

Surgical tactics were tailored based on the diagnostic classification:
1. Foramen Magnum Decompression (FMD) / Expanded Suboccipital Cranioplasty (ESCP): Indicated for patients with Types B and C (compression-dominant, e.g., Chiari I malformation with a small PCF) without evidence of instability on functional MSCT. The procedure involved suboccipital craniectomy, C1 laminectomy, and dural plasty (Fig. 3).

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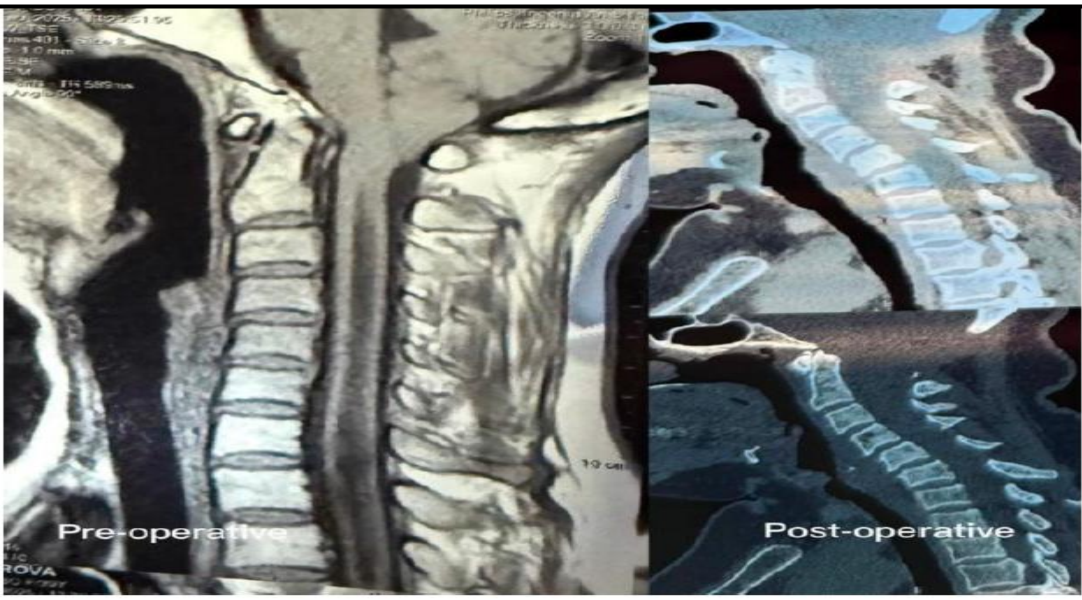

Figure 4: Schematic of C1-C2 stabilization using the Goel-Harms technique.

3. Combined Stabilization and Bony-Dural Decompression: A hybrid approach for cases with concurrent neural compression (especially with CSF flow obstruction) and instability. This involved posterior stabilization followed by dorsal decompression (laminectomy) and duroplasty (Fig. 5).

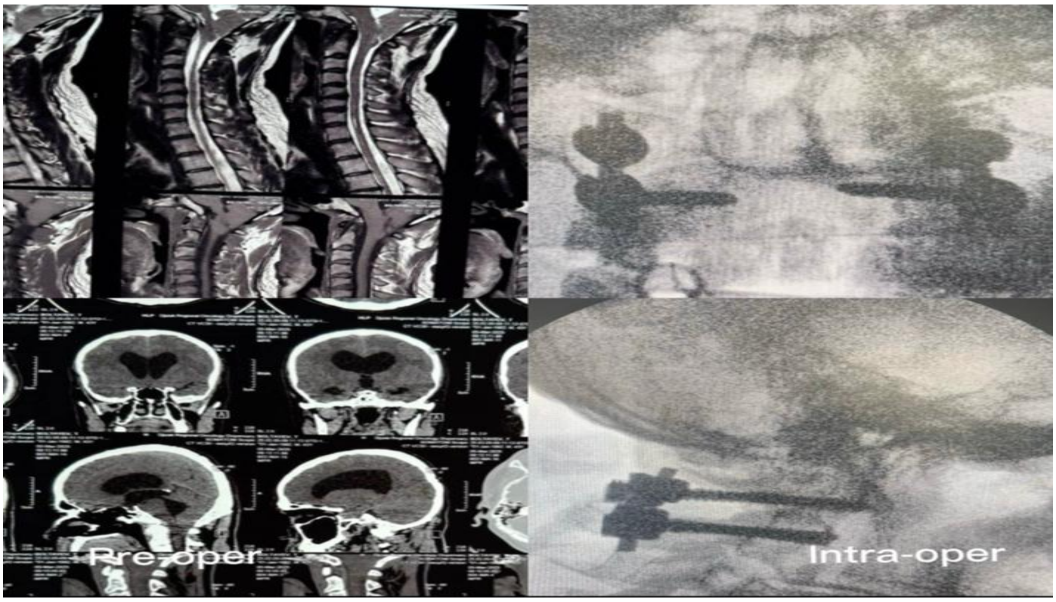

Figure 5: Postoperative radiograph showing posterior C1-C2 stabilization with bony-dural decompression

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Starting in 2023, the center implemented techniques for occipitocervical stabilization onto the lateral masses, and from 2024, C1-C2 stabilization using the Meddisay (Poseydon, Korea) transpedicular system.

Outcome Assessment

Clinical efficacy was evaluated based on:

·Pain Intensity: Measured using the Visual Analog Scale (VAS) for neck/occipital pain and upper limb pain.

· Functional Status: Assessed with the Neck Disability Index (NDI).

· Subjective Outcome: Rated via the Macnab criteria at 24 months.

·Surgical Parameters: Operative time, intraoperative blood loss, length of hospital stay, time to mobilization, and complication rates.

Assessments were performed preoperatively, at discharge, and at 6, 12, and 24-month follow-ups.

Statistical Analysis

Data are presented as medians with ranges. The Wilcoxon signed-rank test was used to compare pre- and postoperative VAS and NDI scores. A p-value of < 0.05 was considered statistically significant.

Results

Patient Demographics

The study included 35 patients with a male-to-female ratio of 1.5:1. The median age was 30.5 years (range: 8-53 years).

Surgical and Perioperative Outcomes The median operative time was 115 minutes (range: 100-130), and the median blood loss was 80 ml (range: 50-110). Patients began active mobilization on the second postoperative day. The median hospital stay was 10 days (range: 9-13).

Clinical Outcomes

Pain (VAS): A statistically significant reduction in pain intensity was observed in the cervical-occipital region and upper extremities at discharge and maintained throughout the 24-month follow-up period ($p < 0.001$) (Fig. 6).

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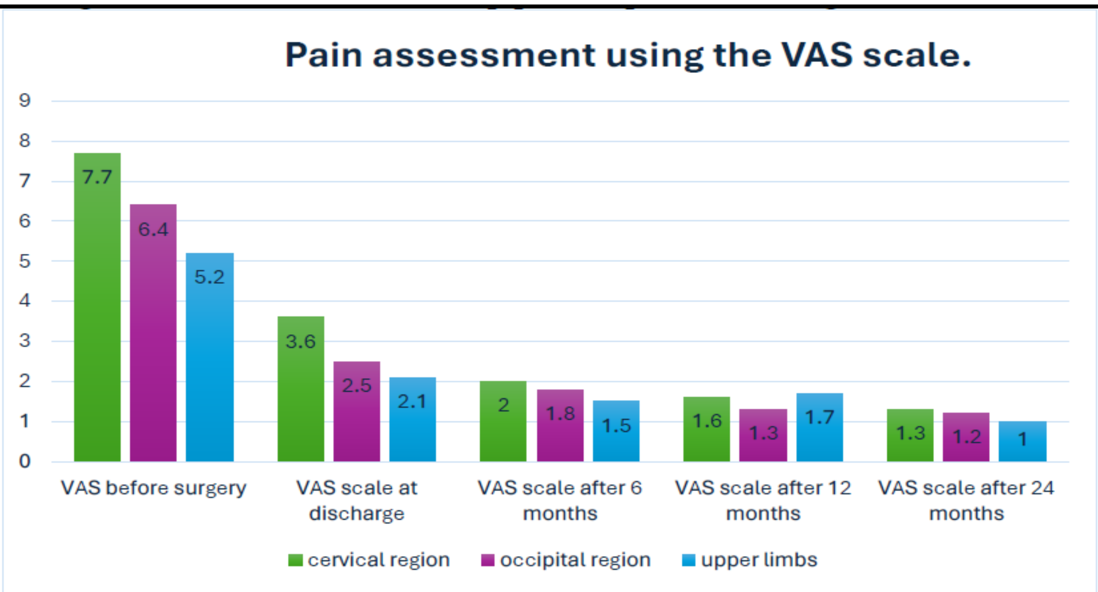

Figure 6: Dynamics of pain syndrome (VAS scores) in the study group.

Function (NDI): A significant improvement in functional status was noted compared to preoperative levels at all follow-up intervals ($p < 0.001$) (Fig. 7).

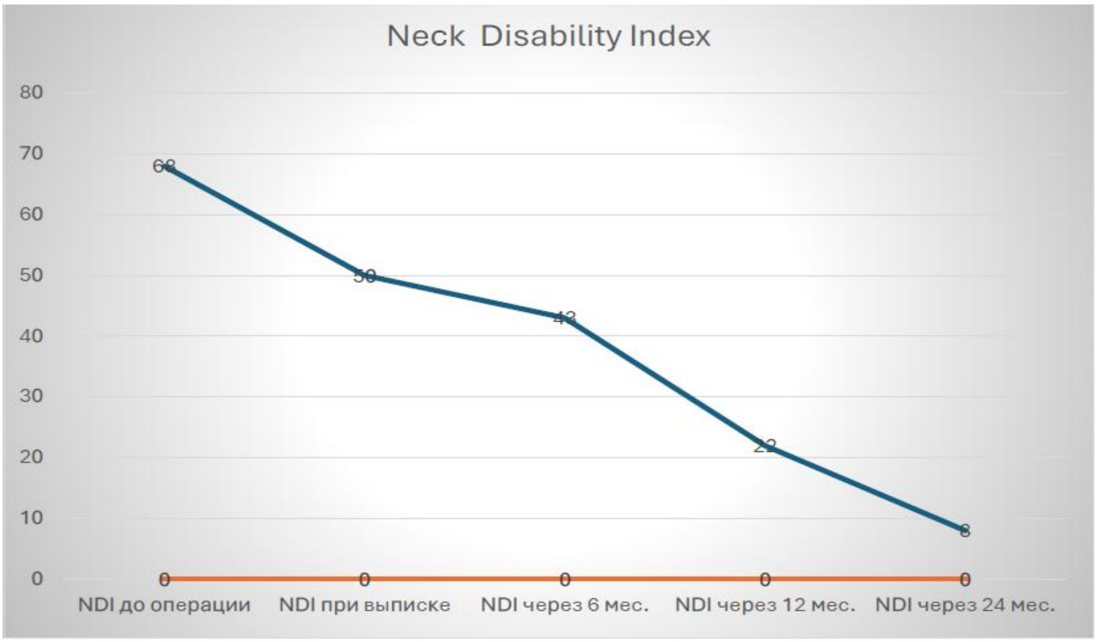

Figure 7: Dynamics of functional status (NDI scores) in the study group.

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Complications

One complication (2.85%) occurred, involving screw malposition, which was successfully revised. During the follow-up period (minimum 24 months), no signs of implant dislocation or migration were observed on control MSCT scans.

Discussion

This study demonstrates the efficacy of a structured, anatomy-based diagnostic algorithm for guiding surgical decision-making in complex CVJ anomalies. Our proposed classification system, rooted in the quantitative assessment of PCF volume, provides a reproducible framework for stratifying patients, directly addressing the need for standardized protocols highlighted in the literature [11, 12].

Our clinical outcomes align favorably with existing reports. The significant improvements in NDI and VAS scores we observed corroborate the findings of Goel et al. and other groups who have reported similar success with stabilization procedures [13, 14]. The high rate of excellent and good outcomes (94.2%) on the Macnab scale further underscores the effectiveness of a tailored approach. The core of our strategy lies in the nuanced selection between decompression and stabilization. We concur with earlier observations that decompression alone in the presence of instability carries a risk of symptom recurrence and progressive deformity [15]. Conversely, indiscriminate stabilization can unnecessarily limit cervical mobility. Our protocol offers a balanced solution: stabilization is reserved for confirmed instability (Type A), while decompression is prioritized in stable, compression-dominant pathologies (Types B and C). This aligns with the evolving consensus on individualized treatment protocols [16].

The three-pronged surgical approach allows for customization based on key factors:

·Pathoanatomy: The primary driver is the type of anomaly. Type A with instability is best served by Goel-Harms stabilization, which can simultaneously reduce basilar invagination via distraction. Types B and C require expansive decompression (FMD/ESCP) to address the constricted PCF.

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·Patient Age and Activity: In younger, active patients, C1-C2 stabilization is preferred to preserve motion segments, whereas occipitocervical fusion may be necessary in the presence of occipitoatlantal instability or in older patients, consistent with general spinal principles [17].
·Neurological Status: Severe brainstem compression with significant deficit warrants a more aggressive approach combining thorough decompression with robust stabilization.
An important finding is the socioeconomic benefit of this optimized pathway. The reduction in hospital stay and resource utilization demonstrates that improved clinical outcomes can be achieved cost-effectively, a critical consideration in any healthcare system.
Limitations and Future Directions
This study's limitations include its retrospective design and the relatively small sample size inherent to this rare pathology. Future prospective, multi-center studies with larger cohorts and longer follow-up are warranted to validate our classification and outcomes. Furthermore, advanced biomechanical modeling could provide deeper insights into the kinematic changes induced by these different surgical procedures.

Conclusion

The implementation of a differentiated surgical strategy for CVJ anomalies, guided by a diagnostic algorithm incorporating PCF volumetry and functional instability testing, leads to excellent and sustainable clinical outcomes. By accurately matching the surgical tactic—decompression, stabilization, or a combination thereof—to the underlying pathoanatomy, surgeons can achieve effective neural decompression and spinal stability while minimizing complications and preserving function where possible. This structured approach represents a significant advance in the management of these complex conditions.

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Figures Legend

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