Advanced Posterior Strategies for Upper Cervical Spine Surgery

PhD thesis

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Budapest, 2026

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1 Introduction

The upper cervical spine is a highly complex region housing the brainstem, vertebral arteries and upper cranial nerves with many anatomical variations of bony and vascular structures further increasing the complexity of this region.
Its intricate anatomy and biomechanics demand precise surgical planning to minimize risks. This dissertation explores two key techniques and their applied anatomy: atlantoaxial fusion and the posterolateral extradural suboccipital approach for retro-odontoid access.

Atlantoaxial fusion is performed in cases of instability caused by congenital anomalies, trauma, tumors, degenerative diseases, infections or rheumatoid arthritis. While early fusion techniques involved posterior wiring, modern advancements introduced screw-rod fixation systems, significantly improving stability. However, traditional posterior approaches often require extensive muscle dissection, leading to postoperative pain and muscular dysfunction. To address these limitations, minimally invasive techniques have been developed, such as the muscle-splitting approach.

Surgical access to the retro-odontoid region has traditionally been achieved through anterior approaches like the transoral or high cervical retropharyngeal routes. These methods provide direct access but often necessitate a second-stage posterior fusion, increasing surgical risks. As an alternative, posterior approaches, such as the posterolateral extradural suboccipital approach, offer safer access without direct spinal cord manipulation while enabling decompression and stabilization within a single procedure.

A thorough understanding of the craniocervical junction anatomy is essential for safe and effective surgery. This region consists of the occipital bone, atlas (C1) and axis (C2), these bony structures together facilitate head movement, load bearing, spinal alignment and protection of the neural structures.

Stability is reinforced by various ligamentous structures, including the transverse atlantal ligament, which secures the dens against the anterior arch of C1, the alar ligaments, limiting excessive rotation, and the tectorial membrane, providing additional cranial support. The suboccipital muscles contribute to fine motor control and postural adjustments, while the vertebral arteries and cervical nerve roots, which traverse this region, must be carefully preserved to prevent vascular compromise and neurological injury. Given the anatomical complexity and the proximity to vital structures, precision in surgical planning and execution is needed to ensure optimal patient outcomes while minimizing risks.

2 Objectives

The upper cervical spine is crucial for stability and movement, housing several vital structures. Due to its complexity, surgical interventions require precision to minimize complications.

Traditional posterior C1-C2 approaches involve bone removal and extensive muscle dissection, leading to higher morbidity and prolonged recovery. The research presented here focuses on a minimally invasive muscle preserving technique and targeted bone removal allowing for tailored surgical technique.

The first study evaluates a muscle-splitting approach for posterior C1-C2 fusion, assessing its feasibility for precise screw placement with minimal muscle disruption. The second study examines the extent of bone removal needed for a posterior far-lateral suboccipital approach to the retroodontoid region and the odontoid process.

Both studies aim to balance surgical access with structural preservation, refining minimally invasive techniques for improved patient outcomes. This PhD research advances C1-C2 fusion strategies, providing anatomically guided techniques designed to minimize morbidity, enhance surgical accuracy and optimize patient outcomes.

3 Methods

The upper cervical spine and craniocervical region were investigated using macerated dry bone specimens and Thiel-fixed cadavers.

Dry bone specimens, including the occipital bone, atlas, and axis vertebrae, were examined to describe and visualize bony structures and landmarks. Specimens incorporating the third cervical vertebra were used to demonstrate bone removal steps for the posterolateral extradural suboccipital approach.

To further explore the applied anatomy of the craniocervical junction, three Thiel-embalmed cadavers were dissected. For the anatomical experimental study on the posterolateral extradural suboccipital approach, five Thiel-fixed cadaveric specimens (mean age: 83.7 years) were analyzed. Bilateral measurements were taken using an electric caliper. The vertebral arteries were filled with red-colored silicone to enhance visualization. The head was secured in a modified Halo-fixation system to maintain a neutral cervical spine position during the measurements.

A feasibility study on the muscle-splitting approach to posterior C1-C2 fusion was conducted on one formalin-fixed and one fresh cadaver. The steps of the operation were performed, proving if adequate visualization of the key bony landmarks for screw placement into the C1 and C2 vertebras were possible. The approach was tested bilaterally on 12 fresh human cadavers, with screw insertion performed in four cases using the described technique.

Anatomical dissections were aided by loupe magnification (Zeiss, 3.4x) and detailed photo documentation was conducted using a Canon 5D digital camera.

4 Results

The present thesis evaluated two key surgical approaches for the upper cervical spine: the muscle-splitting approach for C1-C2 fusion and the far-lateral suboccipital approach to the retro-odontoid region. The findings provided anatomical validation, technical feasibility, and potential clinical benefits for optimizing surgical access while preserving structural integrity.

The muscle-splitting approach for posterior C1-C2 fusion confirmed that this minimally invasive technique allowed for safe and precise screw placement while reducing soft tissue trauma. By splitting rather than detaching muscles, the approach preserved the posterior musculature, potentially leading to reduced postoperative pain and faster recovery. This approach allowed for direct visualization of the bony landmarks and the screw starting points needed for screw placement into the C1 lateral mass and C2 pars interaricularis. The greater occipital nerve was consistently identified and preserved, minimizing the risk of postoperative neuropathic pain. Fluoroscopy confirmed accurate screw placement, reinforcing the safety and effectiveness of the technique.

The far-lateral suboccipital approach to the retro-odontoid region study focused on quantifying the extent of bone removal needed to optimize surgical exposure. Stepwise resection of the C1 posterior arch and lateral mass significantly increased access to the retro-odontoid space. The study identified three key stages of bone removal: partial resection of the posterior arch (inferior laminotomy), complete removal of the posterior hemi arch and medial removal of the C1 lateral mass. The surgical window was increased from 6mm * 10mm – without bone removal - to a maximum of 10mm * 17mm after the complete removal of the posterior hemi arch and the medial aspect of the lateral mass. Without bone removal, the anterior epidural space and the base of the odontoid process could be reached. Using the laminotomy of C1 and the resection of the posterior C1 arch resulted in an increase of the vertical surgical window with which the base of the odontoid (laminotomy) or also the tip of the odontoid process could be reached (removal of the posterior arch). Partly removal of the C1 lateral mass widened the horizontal surgical window making the anterior epidural space and the odontoid – from base to its tip – accessible. This approach significantly expanded the surgical window while protecting the vertebral artery, demonstrating that posterior access could serve as a viable alternative to anterior and transoral approaches also eliminating the need for staged surgeries.

These findings highlight the benefits of minimally invasive techniques in upper cervical spine surgery. The muscle-splitting approach offers improved postoperative recovery by preserving musculature, while the far-lateral suboccipital approach optimizes exposure with minimal bone removal. Both techniques reduce surgical morbidity and enhance precision. However, further clinical validation is needed to assess their long-term efficacy and safety in live surgical settings. This research contributes to the advancement of upper cervical spine procedures, refining surgical strategies to improve patient outcomes.

5 Conclusions

This thesis explores two key advancements in upper cervical spine surgery: the far-lateral suboccipital approach to the retro-odontoid region and a muscle-splitting technique for C1–C2 fusion. The relevant anatomy was described for both studies, followed by an anatomical feasibility study. Our goal was to improve surgical access and preserve soft tissue integrity.

The stepwise classification of C1 bone resection enhances surgical exposure and allows for tailoring the amount of bone removal to the goal of the surgery. It reduces the reliance on high-risk anterior approaches and also avoids staged surgery. The muscle-splitting fusion method provides safe and effective screw placement with less muscle trauma, potentially leading to reduced pain and faster recovery.

While these approaches show promise, clinical validation is needed. Future integration of navigation-assisted surgery and 3D modeling could further improve precision. Overall, this research supports minimally invasive techniques to optimize surgical outcomes and refine C1–C2 procedures.

6 Bibliography of the Candidate´s Publications

Publications related to this dissertation:

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