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State of the art approaches for treating cervical spine pathologies

PhD thesis

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List of Abbreviations

CCJ - craniocervical junction

TO - transoral odontoidectomy

EE - endoscopic endonasal odontoidectomy

CSF - cerebrospinal fluid

AS - ankylosing spondylitis

PMMA - polymethyl methacrylate

MIS ASR - microscope-assisted minimally invasive anterior submandibular retropharyngeal keyhole approach

CT - computed tomography

MRI - magnetic resonance imaging

ASA - American Society of Anesthesiologists

ASIA - American Spinal Injury Association

1. Introduction

1.1 Key-hole surgery in neurosurgery

As is the case with the majority of surgical specialties, key-hole surgery is a common technique in the field of neurosurgery. The advent of microsurgical techniques and instruments, along with the introduction of endoscopes, has resulted in a growing prevalence of minimally invasive key-hole technology. Key-hole approaches, which utilise small incisions, have the potential to facilitate a faster recovery period compared to traditional techniques. The procedure has been extensively used for microdiscectomies worldwide. However, there have also been instances of its use in less common, innovative procedures. One such instance is Kaya's paper, in which he removed intradural tumours from a variety of localisations via a keyhole approach hemilaminectomy (1, 2). In their study, Takeuchi et al. employed a transvertebral keyhole approach to perform a cervical foraminotomy. This involved a ventral route through the vertebral body to the neuroforamen and the removal of a dislocated disc fragment (3). The potential of the endoscope is also evidenced by the findings of several studies which have demonstrated that percutaneous endoscopic lumbar discectomy can be as effective and safe as open discectomy (4).

1.2 Craniocervical junction pathologies and need for odontoidectomy

The craniocervical junction (CCJ) is a biomechanically intricate region where a variety of pathologies—ranging from congenital anomalies such as Chiari malformations and basilar invagination, to degenerative and inflammatory disorders exemplified by rheumatoid arthritis-induced instability, as well as traumatic injuries and neoplastic processes like chordomas and meningiomas—can compromise neural integrity and necessitate specialized neurosurgical and spinal surgical interventions (5-10).

Odontoidectomy is a specialized surgical procedure involving the resection of the odontoid process (dens) of the axis (C2) to alleviate ventral compression of the brainstem and upper cervical spinal cord. This operation is predominantly indicated for irreducible ventral compression arising from complex craniovertebral junction abnormalities, such as basilar invagination, irreducible atlantoaxial dislocation or rheumatoid pannus causing

severe anterior compression. As better disease control can be reached in rheumatoid arthritis patients, the incidence of pannus formation is decreasing. The improvements in posterior fixation systems and techniques are also narrowing the indications for ventral odontoidectomy. Considering this, anterior approach to the dens can be indicated in patients with persistent neurological symptoms after dorsal decompression, and in severe anterior compression, where a dorsal only approach is unsafe or inadequate (11). In addition, selected traumatic scenarios—particularly those involving complex fracture-dislocations or non-unions of the odontoid process that result in persistent ventral neural compression despite conventional posterior decompression and stabilization—may also necessitate an odontoidectomy. Advances in endoscopic techniques have fostered minimally invasive approaches, such as endoscopic transnasal odontoidectomy, which permit effective decompression while preserving vital structures like the anterior arch of C1 (5-7). Alternative transcervical and combined anterior-posterior strategies have further expanded the surgical possibilities for managing these complex pathologies (12, 13).

1.3 Traditional odontoidectomy approaches: transoral and transnasal

Transoral odontoidectomy (TO) is a well-established microsurgical procedure that accesses the ventral craniovertebral junction via the oral cavity to resect the odontoid process and decompress the brainstem. The technique is performed through a midline incision in the posterior pharyngeal wall, allowing direct visualization and microsurgical removal of the dens under high magnification (14). This direct approach provides the benefit of a straightforward anatomical route for treating basilar invagination and irreducible atlantoaxial dislocation. However, systematic reviews have noted a higher incidence of complications, such as postoperative dysphagia, velopharyngeal insufficiency, and an increased need for tracheostomy, compared to alternative methods (15-17).

Transnasal odontoidectomy, or endoscopic endonasal odontoidectomy (EE), is a minimally invasive, endoscopic procedure designed to decompress the ventral brainstem by resecting the odontoid process via the nasal cavity. The surgical technique begins with careful endoscopic navigation through the nasal passages to reach the nasopharynx, where

an incision in the posterior pharyngeal wall exposes the odontoid process; under high-definition visualization, the dens is meticulously drilled and removed to relieve anterior compression at the craniovertebral junction (6). This approach offers several advantages over the traditional transoral route, including avoidance of palatal splitting and a significantly lower incidence of postoperative airway complications such as tracheostomy and velopharyngeal insufficiency, as highlighted by comparative analyses (16). Nonetheless, the transnasal technique presents its own challenges, including a steep learning curve and potential complications such as cerebrospinal fluid (CSF) leakage, infection, and nasal morbidity, which have been discussed in comprehensive reviews and commentaries (15, 18).

1.4 Transcervical odontoidectomy

Anterior and lateral transcervical odontoidectomy are minimally invasive, endoscopic techniques that allow direct ventral decompression of the craniovertebral junction via a cervical approach, thereby avoiding the morbidity associated with transoral access. The anterior transcervical route typically involves a retropharyngeal dissection through a small neck incision, with endoscopic, image-guided navigation facilitating precise resection of the odontoid process and effective decompression (8, 12). In contrast, the lateral transcervical approach offers an alternative trajectory, particularly beneficial when anatomical constraints limit anterior access, by providing a favourable surgical corridor while minimizing soft tissue disruption, as outlined by Yakdan et al. (9). Recent navigated full-endoscopic techniques, such as those reported by Abaunza-Camacho et al. (10) and Ohara et al. (19), have further refined these approaches by enhancing visualization and surgical precision. Although these methods reduce risks like velopharyngeal insufficiency inherent to transoral procedures, they are not without complications—risks such as infection, dysphagia, and neurovascular injury remain significant (20, 21).

While each of these methods can be viable surgical options in both adult and pediatric cases, meticulous surgical technique and careful patient selection are essential to optimize outcomes (18, 20, 22, 23).

In this study, we demonstrate a technique that allows for the preservation of the hard and soft palates, similar to the traditional anterior retropharyngeal surgery. The procedure can be conducted through a 25 mm wide incision with the use of a single retractor.

1.5 Ankylosing spondylitis and cervical fracture instability

Ankylosing spondylitis (AS), also referred to as Bechterew's disease or Pierre-Marie's disease, is a chronic inflammatory disorder primarily affecting the spine, causing pain and spinal stiffness. This disease leads to eventual fusion of the vertebrae into a "bamboo-spine", reducing the patient's quality of life significantly, while also posing a higher risk for various spinal injuries, most frequently subaxial spinal fractures (24-26).

Among AS patients, acute spinal fractures most commonly occur in the subaxial cervical spine (26). Their clinical management can pose great challenges, as they are highly unstable fractures, posing elevated risk of neurological deficits ranging from 29% to 91%, accompanied by an increased mortality rate of 35% in different studies (27-30). Due to extensive degenerative structural remodelling of the vertebrae, unstable, three-column injuries are not uncommon in this population (31).

The management of severe cervical spine fractures in patients with AS necessitates a high level of expertise, given the presence of multiple comorbidities that render surgical intervention more challenging. This patient subgroup is characterised by a markedly elevated risk of cardiovascular disease, which is a significant contributor to mortality in individuals diagnosed with AS, accounting for approximately 60% of deaths (32).

The presence of contraindications to anaesthesia, such as increased cardiac risk and other comorbidities, may restrict the range of options available for surgical management. In cases of sub-axial unstable fractures, it is often necessary to use combined anterior and posterior instrumentation in order to restore adequate structural stability, due to the inherent poor biomechanical quality of the bone. Nevertheless, alternative approaches, such as a single posterior instrumentation or a multi-stage treatment plan, may be required due to the diminished surgical load-bearing capacity (31).

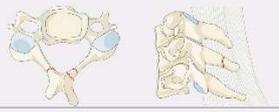
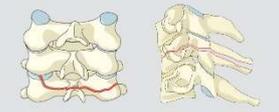
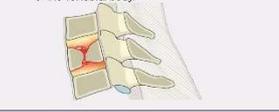
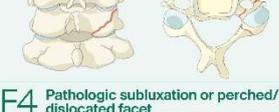
1.6 Bone cement and PMMA-based stabilization

Bone cement, particularly polymethyl methacrylate (PMMA), has been employed with increasing frequency in orthopaedic surgery over the past five decades. Its use has been documented in a range of procedures, including hip, knee, and other joint replacements, as well as in spinal surgery for vertebroplasty, kyphoplasty, and tumour surgery (33). Furthermore, it is employed in conjunction with screwed instrumentation. A substantial body of evidence indicates that cement augmentation can enhance pullout strength in individuals with low bone mineral density. Augmenting pedicle screws in the thoracolumbar region is a prevalent practice with a low complication rate among osteoporotic patients, as well as in instances of revision spinal surgery (34, 35).

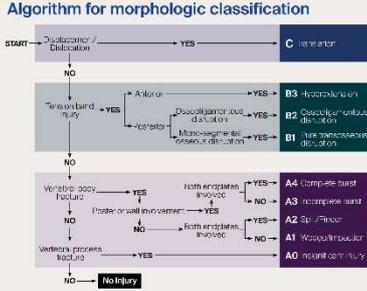
The combination of plate stabilisation and cement augmentation has demonstrated potential for restoring structural stability to the anterior column of the cervical spine. As evidenced by the cases presented by E. Bayley et al. (36) and Oppenlander et al., these methods have been shown to be effective, particularly in patients with osteoporosis and poor bone quality (37). In vitro studies provide further evidence that cement augmentation significantly improves screw stability during ventral fixation (38).

1.7 AO Spine Subaxial Classification System

The AO Spine Subaxial Injury Classification System was chosen as the morphological classification system for fractures in the study design. This classification system is renowned for its exceptional inter-observer and intra-observer reliability, accompanied by a high degree of transparency in the encodings of injury types. In addition to the morphological categories (A—compression, B—tension-band injury, C—translational injury, and F—facet injury), the classification system differentiates between various subcategories of injury (A1, A2, B1, B2, etc.) (39, 40). (Figure 1)

Type A Compression Injuries	Type B Tension Band Injuries	Type C Translation Injuries
<p>A0 Minor, nonstructural fractures No bony injury or minor injury such as an isolated lamina fracture or spinous process fracture.</p> 	<p>B1 Posterior tension band injury (bony) Physical separation through fractured bony structures only.</p> 	<p>C Translational injury in any axis-displacement or translation of one vertebral body relative to another in any direction</p> 
<p>A1 Wedge-compression Compression fracture involving a single endplate without involvement of the posterior wall of the vertebral body.</p> 	<p>B2 Posterior tension band injury (bony capsuloligamentous, ligamentous) Complete disruption of the posterior capsuloligamentous or bony capsuloligamentous structures together with a vertebral body disc, end/ or facet injury.</p> 	<p>Type F Facet Injuries</p>
<p>A2 Split Coronal split or pinbar fracture involving both endplates without involvement of the posterior wall of the vertebral body.</p> 	<p>B3 Anterior tension band injury Physical disruption or separation of the anterior structures (anterior disc) with tethering of the posterior elements.</p> 	<p>F1 Nondisplaced facet fracture With fragment <1cm in height, <40% of lateral mass.</p> 
<p>A3 Incomplete burst Burst fracture involving a single endplate with involvement of the posterior vertebral wall.</p> 	<p>BL Bilateral Injuries</p> <p>BL Bilateral injury</p> 	<p>F2 Facet fracture with potential for instability With fragment >1cm, > than 40% lateral mass, or displaced.</p> 
<p>A4 Complete burst Burst fracture or sagittal split involving both endplates.</p> 		<p>F3 Floating lateral mass</p> 
		<p>F4 Pathologic subluxation or perched/dislocated facet</p> 

Algorithm for morphologic classification



Neurology

Type	Neurological
N0	No neurologic
N1	Transient neurologic deficit
N2	Radicular symptoms
N3	Incomplete spinal cord injury or any degree of cauda equina injury
N4	Complete spinal cord injury
NX	Causes to be defined
+	Continued spinal cord compression

Modifiers

Type	Description
M1	Posterior Capsuloligamentous Complex injury without complete disruption
M2	Critical dislocation
M3	Stenomyelomalacia bone disease (e.g. A9, A8, O41, O41)
M4	Vertebral artery avulsion

Classification Nomenclature

C6-C7: C (C7: A1) → Primary injury → C6-C7: B2* → Secondary label injury → (F4; F2; N2, M3) → Neurologic status and modifiers

* If there are multiple injuries to the same facet - for example small fracture (F1) and dislocation (F4) - only the highest level facet injury is classified (F4).

** Only facet injuries are identified - no A, B, or C injury - they are listed first after the level of injury.

Figure 1: AO Spine Subaxial Injury Classification System – With the permission of the AO Foundation, accessed on 09.10.2025. from <https://www.aofoundation.org/spine/clinical-library-and-tools/aospine-classification-systems> - © AO Foundation, AO Spine, Switzerland

Type B injuries represent tension band failures affecting either the anterior or posterior stabilizing structures of the spinal column. B1 injuries describe monosegmental osseous failures of the posterior tension band extending into the vertebral body, involving only a single vertebra. B2 and B3 injuries involve a motion segment consisting of two vertebral bodies and the intervening intervertebral disc. B2 injuries involve disruption of the posterior tension band with or without bony involvement; this disruption may affect osseous, capsuloligamentous, ligamentous, or combined structures. B3 injuries, by contrast, involve the anterior tension band, with disruption or separation of the anterior bone or disc elements while the posterior structures remain tethered. These may traverse the intervertebral disc or vertebral body itself, as seen in ankylosed spines, with an intact posterior hinge preventing major displacement. Type C injuries denote displacement or translational injuries in any axis, characterized by the separation or translation of one vertebral body relative to another. All Type C patterns represent highly unstable injuries (39, 40).

The AO Spine Injury Classification Systems were developed and funded by AO Spine through the AO Spine Knowledge Forum Trauma, a focused group of international spine trauma experts. AO Spine is a clinical specialty of the AO Foundation, which is an independent medically-guided not-for-profit organization. Study support was provided directly through AO Network Clinical Research and AO ITC, Clinical Evidence (39, 40).

This single-stage plate stabilisation and ventral cement augmentation method of the subaxial spine prioritizes the restoration of structural stability while accounting for the altered biomechanical properties inherent to AS-affected spines. In a retrospective analysis of surgical outcomes, we aim to establish the procedural efficacy of the approach, assess the incidence of complications such as cement leakage, and study the potential long-term impact on patient morbidity and mortality. The integration of these findings should facilitate improvements and enhancements to surgical techniques for this high-risk patient population, thereby optimising surgical outcomes and patient quality of life.

2. Objectives

The objective of my study was to develop innovative procedures that enhance patient safety in the surgical management of cervical spine pathologies. I will present a range of surgical techniques that have been previously employed in other regions, including keyhole approaches, endoscopic procedures, and the utilisation of PMMA bone cement.

We introduce a novel surgical method, the microscope-assisted minimally invasive anterior submandibular retropharyngeal keyhole approach (MIS ASR), which we have employed for C1–C2 ventral decompression. This case series, comprising four patients, demonstrates the development, safety, and feasibility of this new surgical technique.

The other objective of this study was to evaluate the efficacy and safety of a single-stage plate stabilisation and ventral cement augmentation technique for treating subaxial cervical spine fractures in patients with ankylosing spondylitis (AS).

3. Methods

3.1 Submandibular retropharyngeal key-hole approach

The MIS ASR approach was performed at first in four carefully selected patients for whom the procedure was deemed technically feasible and safe (41). Since then, six more patient underwent surgery with the same approach. The surgeries were performed to relieve acute ventral compression at C1-C2 level, or in cases with acute or severe neurological symptoms, where the underlying pathology causing ventral compression would be at the C1-C2 levels. All cases had cervical spine computed tomography (CT) and magnetic resonance imaging (MRI) scans preoperatively, and postoperative CT scans were also performed.

From the postoperative CT, we calculated the mean depth of the operating field, the decompressed area of the dura, and a hypothetical decompression area, which could have been achieved using the transoral method. The decompressed area was measured in rectangular form on the postoperative CT scans, in the coronal plane, at the level of the ventral surface of the dura, also planning the surgery and the possible largest decompression via the transoral method. The hypothesized largest achievable decompression using the TO method was calculated by measuring the distance between the clivus and the upper third of the C3 vertebral body. The width of the decompression was calculated by the distance between the lateral masses of the C1 vertebra. (Figure 2) All patients were followed for a minimum of 4 months postoperatively.

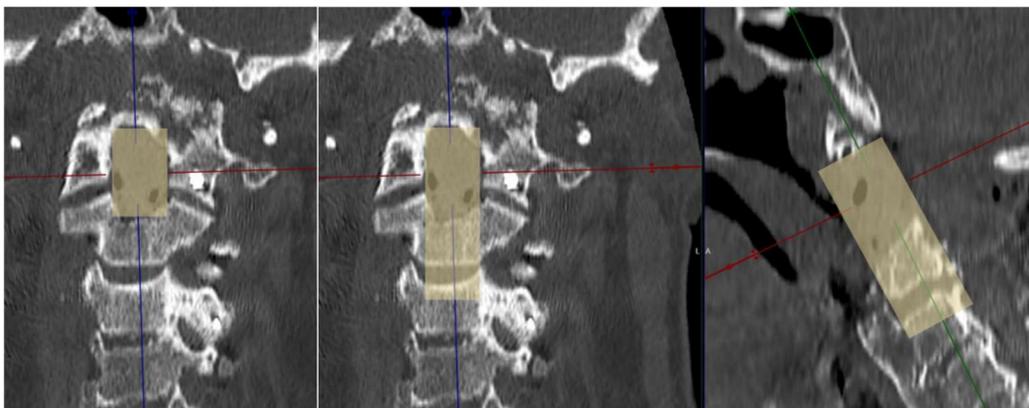


Figure 2: Measurement of the dural decompression area. Left: the achieved decompression with the MIS ASR method. Middle and right: The theoretical largest decompression using the TO method.

The mean operating depth was calculated by averaging the distance measured from the surface of the skin to the tubercle of the C1, the ventral surface of the C2, and the deepest point of the exposed dura in all cases. The hypothetical operating depth was measured between the same anatomical landmarks and the orifice. (Figure 3)

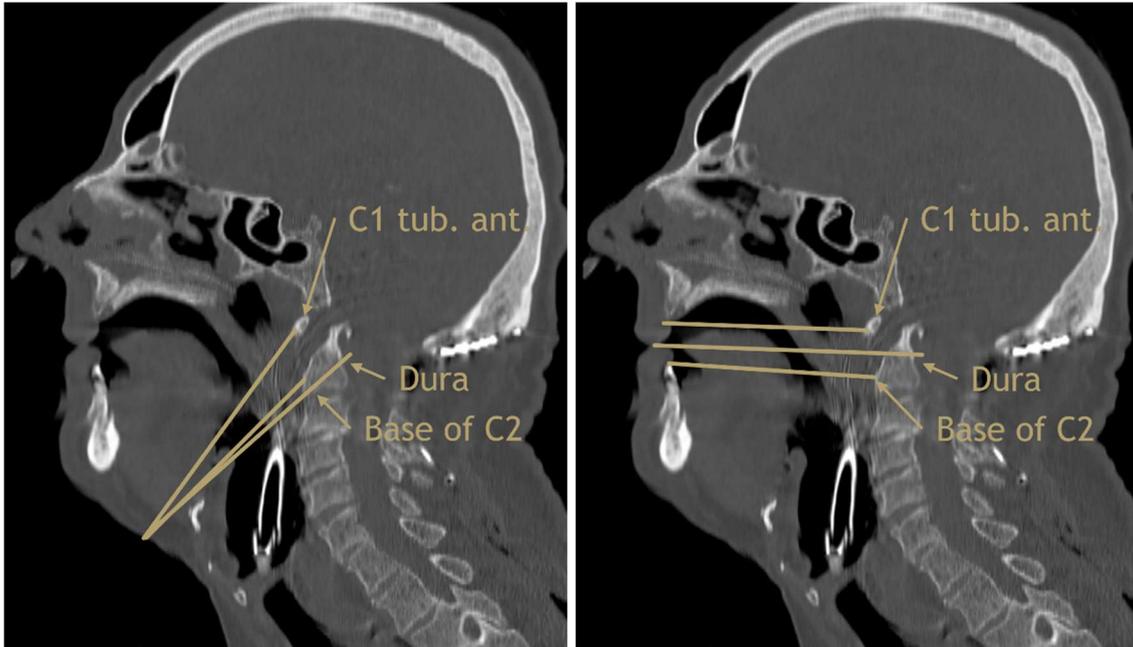


Figure 3: The measurement of the depth of the operating channel. Left: For the MIS ASR method. Right: for the TO method.

3.1.1. The development of the MIS ASR procedure

This technique was initially developed in response to a trauma case involving an odontoid fragment compressing the spinal cord, as confirmed on CT and MRI (Figure 4), resulting in compression of the spinal cord on the left side (42).

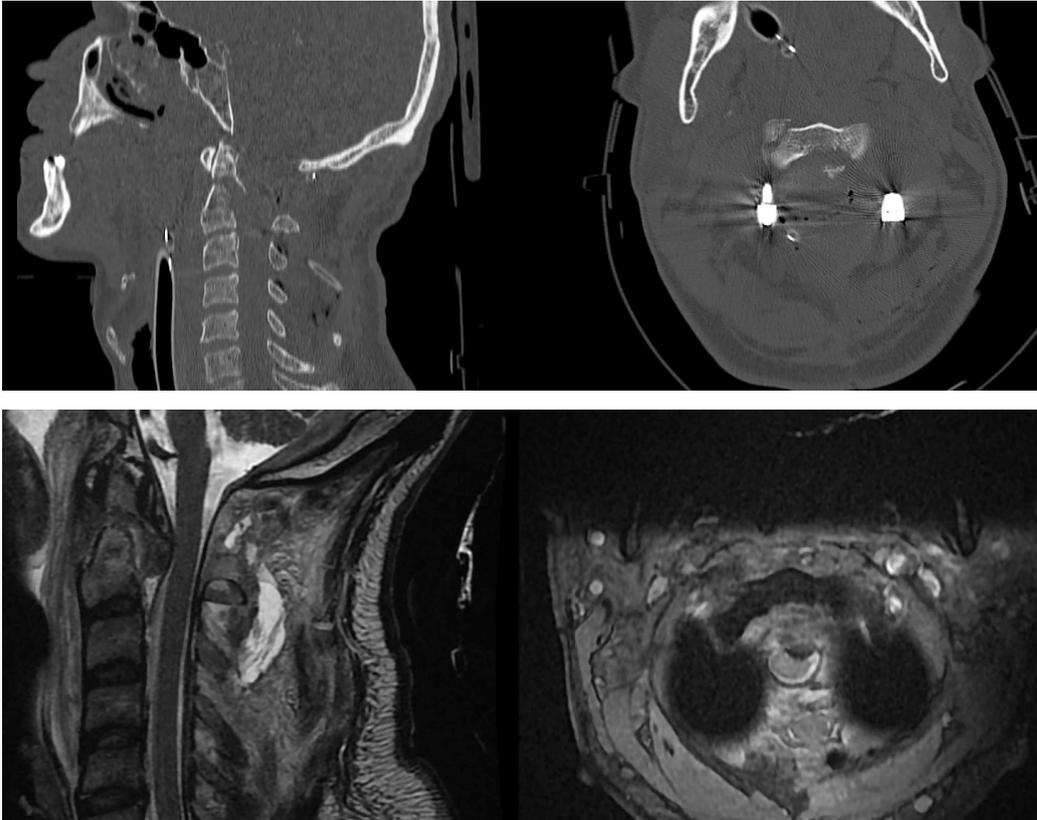


Figure 4: CT and MRI showing the bone fragment compressing the spinal cord (42)

The decision to utilise the MIS ASR was based on the MRI confirmation of a ventral dura injury, coupled with the elevated risk of velopharyngeal insufficiency associated with the transoral approach. This would have potentially elevated the likelihood of wound dehiscence and sepsis. In addition to the use of fibrin glue, the submandibular "keyhole" approach allowed for the tamponading of the dural injury with multiple layers of vital soft tissue. During the surgical procedure and in the postoperative period, there were no instances of CSF leakage or other complications.

3.1.2 Usability in other cases

Following the successful implementation of the MIS ASR key-hole method in the treatment of the trauma patient, an investigation was initiated to assess the feasibility of this approach in the context of rheumatoid arthritis and tumourous cases, which represent the two most prevalent etiologies of ventral compression. The surgical procedure was conducted on two patients in their 60s and 80s, both of whom presented with ventral spinal stenosis resulting from rheumatoid arthritis. Additionally, a patient in her 40s was operated on, with the underlying cause of her ventral spinal stenosis being a metastasis of a cervical squamous-cell carcinoma. Finally, the first, trauma patient in his 40s was treated for a traumatic odontoid fracture with dislocation, which had resulted in the compression of the medulla oblongata. Since then, six more patient underwent surgery with the same approach.

3.1.3. Technical steps of the MIS ASR procedure

In the initial phase of the procedure, three patients underwent occipito-cervical dorsal fusion surgery, while the fourth patient received a C1–C2 fusion, as described by Harms. A C1–C2 decompressive laminectomy was conducted in all four cases. In the second stage, ventral C1–C2 decompression was performed. All patients were placed in a supine position and secured within a Mayfield headrest. In order to perform the MIS ASR approach, a 25mm wide ventral and submandibular incision is made 30-40mm below the mental protuberance, but cranially from the hyoid bone. This incision begins on the right side and extends for 5mm to the left towards the midline. (Figure 5)

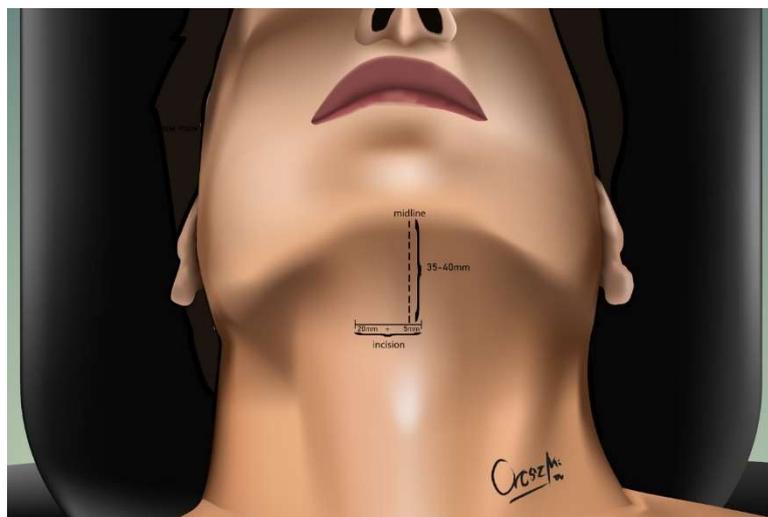


Figure 5: Location of skin incision (41)

Following the incision of the skin, the cervical fascia was visualised and subsequently opened with the use of surgical scissors. The platysma muscle was then dissected vertically in a blunt manner (Figure 6), after which the anterior belly of the right digastric muscle was retracted laterally. This procedure allows the mylohyoid muscle to be unfolded, and it enables the dissection to be carried out in a blunt, horizontal manner, corresponding to the fibres of the muscle. (Figure 7)

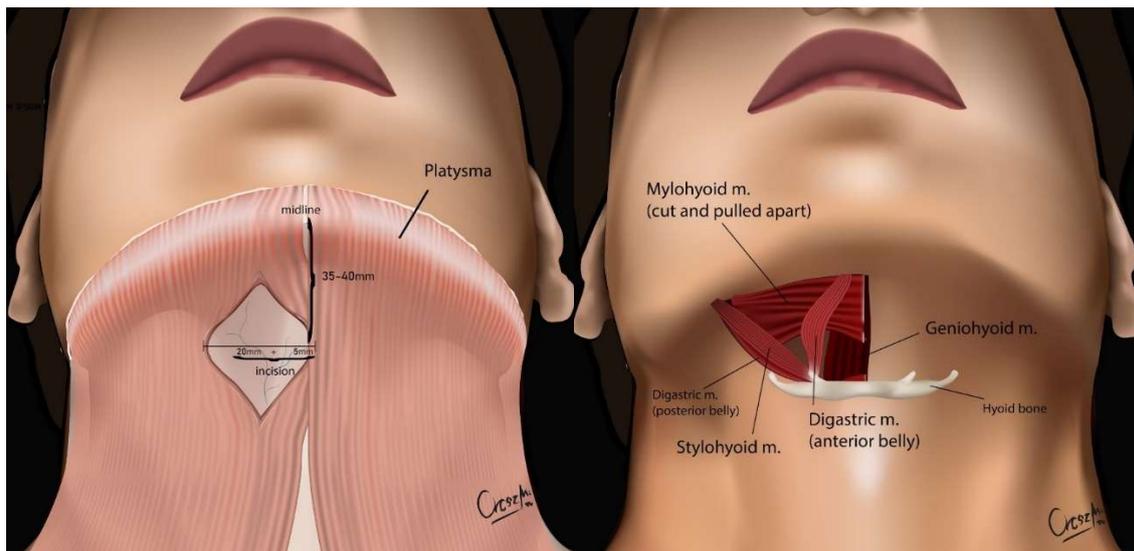


Figure 6: Vertical dissection of the platysma muscle (left) and **Figure 7:** Retracting and dissecting the deeper muscles of the neck to reach the spinal column (right) (41)

Below that, the geniohyoid muscle was dissected vertically between its fibers. At this point, we inserted a 15 mm wide–80 mm long carbon retractor (DePuy Synthes Synframe) reaching the ventral surface of C1 and C2 and secured it to the external holding ring. (Figure 8)

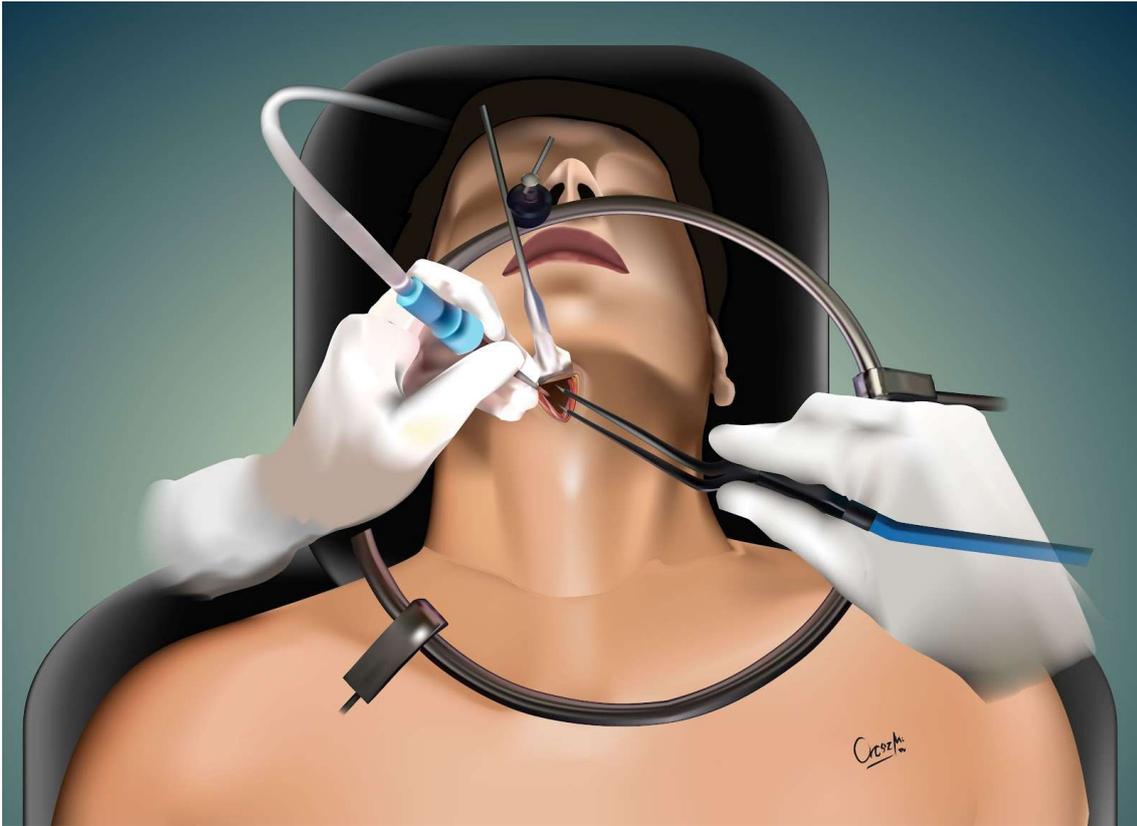


Figure 8: The carbon retractor attaches to an external holding ring (DePuy Synthes Synframe) (41)

With the aforementioned retractor in position, we proceeded to mobilise the upper portion of the oropharynx in a cranio-medial direction, thereby gaining access to the upper cervical spine. Subsequently, the insertion of the longus colli muscle was mobilised from the anterior tubercle of the atlas (Figure 9), allowing for the free resection of the C1 vertebra's anterior arch, the odontoid process, and the upper portion of the C2 vertebra. In accordance with the varying stages of the surgical procedure, the suction, bipolar diathermy, micro drill, and Kerrison rongeur were positioned in the surgeon's left and right hands in order to provide adequate retraction of the lateral and medial soft tissue. (Figure 10)

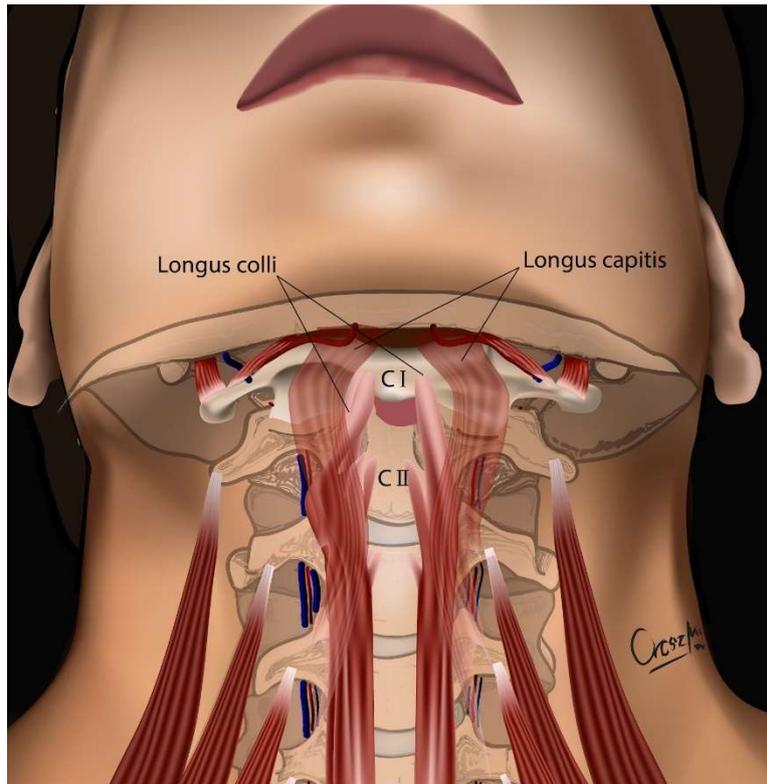


Figure 9: Insertion of longus colli muscle (41)

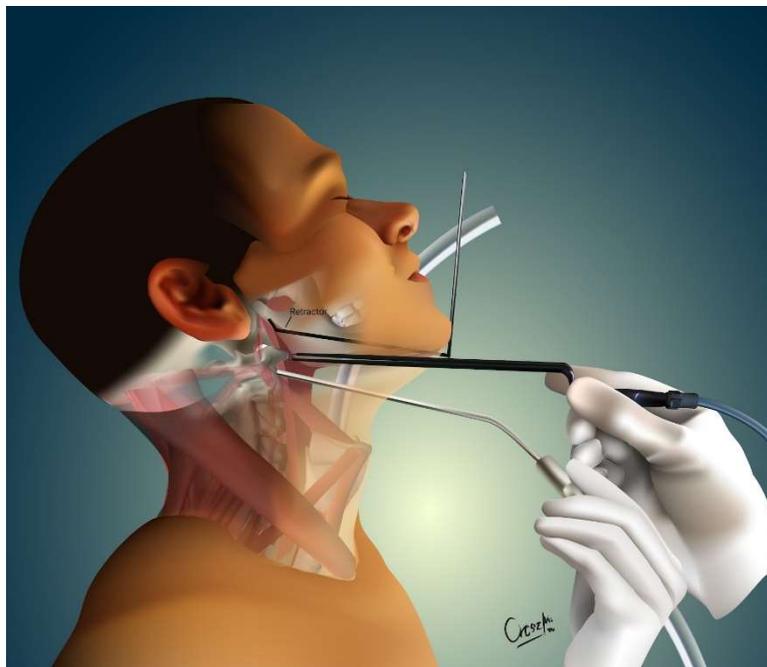


Figure 10: Mobilization of oropharynx with retractor and retraction of soft tissue with bipolar diathermy and suction (41)

3.2. Cervical stabilisation with PMMA augmentation

This study presents a single-stage plate stabilisation approach with ventral cement augmentation for the management of unstable subaxial cervical spine fractures in patients with AS, which eschews the use of posterior fixation (43). From November 2016 to December 2023, a total of 38 patients were treated with this procedure, with an age range from 52 to 87 and a mean age of 70.2 years. All surgeries were performed by a single senior surgeon using the Smith–Robinson anterolateral approach while the patients were in a supine position, and no additional dorsal stabilisation was applied (44).

The American Society of Anesthesiologists (ASA) Physical Status Classification System was used to determine the physiological status of the patients, which helps to predict operative risks (45). The AO Spine Cervical Classification was used to classify the patients' cervical spine injuries (46).

3.2.1. Technical steps of the cervical stabilisation with PMMA augmentation

The primary surgical procedure started with entailed the implantation of a cervical plate on the ventral aspect of the spinal column (Caspar plate), which was fixed in place with one screw per vertebra on the left side of the vertebral bodies using Caspar rescue screws. (Figure 11)

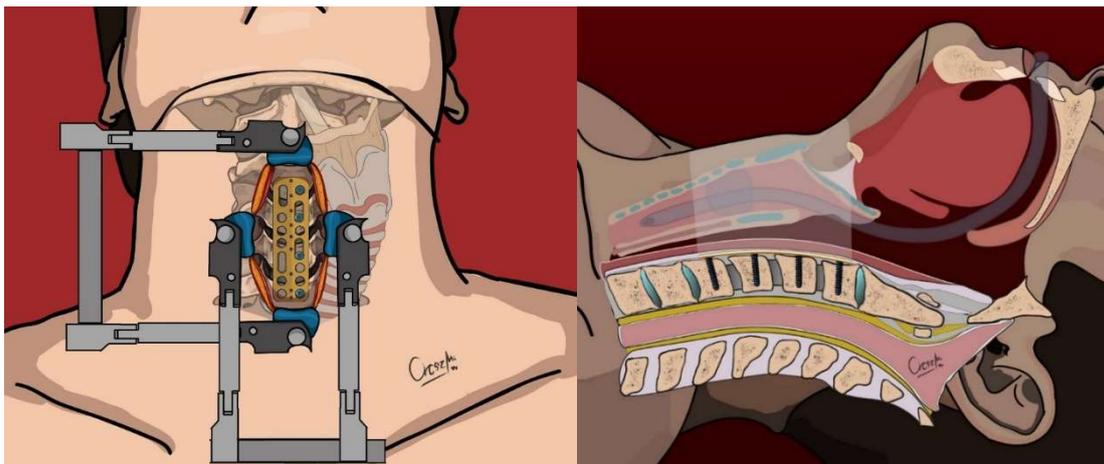


Figure 11: Positioning of the ventral cervical plate and insertion of screws to the left side—upper and sagittal view (43)

In all cases, the ventral stabilisation was aimed at connecting two healthy vertebral bodies above and below the fracture. In the eight patients who required discectomy due to calcified or injured discs, cervical interbody fusion cages (CeSPACE® PEEK, Aesculap, Hazelwood, MO, USA) were used to achieve fusion.

During the procedure, a 10G vertebroplasty needle (Diamond Tip, DePuy Synthes, Warsaw, IN, USA) was used to carefully inject Vertecem V+ PMMA into the right side of the vertebral bodies with the aim of injecting a maximum of 1.5ml of cement in a controlled manner under radiological control using the C-Arm. (Figure 12)

In six cases where the fracture lines involved one or more vertebrae, the involved vertebrae were not augmented to minimize the risk of cement leakage.

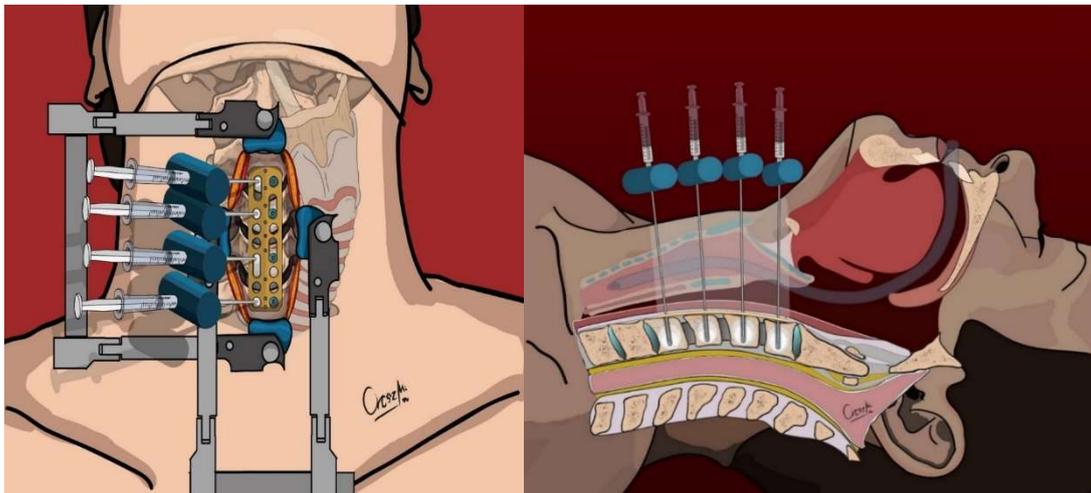


Figure 12: Cement augmentation through the right screwholes—upper and sagittal view (43)

Intraoperative lateral X-Ray fluoroscopy was used after each 0.2 mL cement injection to monitor for signs of leakage. If leakage was detected before the intended volume of 1.5 mL was reached, the injection was stopped immediately. After cement injection, 4.5 mm monocortical screws (Caspar rescue screws) were placed to secure the right side of the plate. Screw lengths varied from 15 to 21 mm depending on anatomical requirements. (Figure 13)

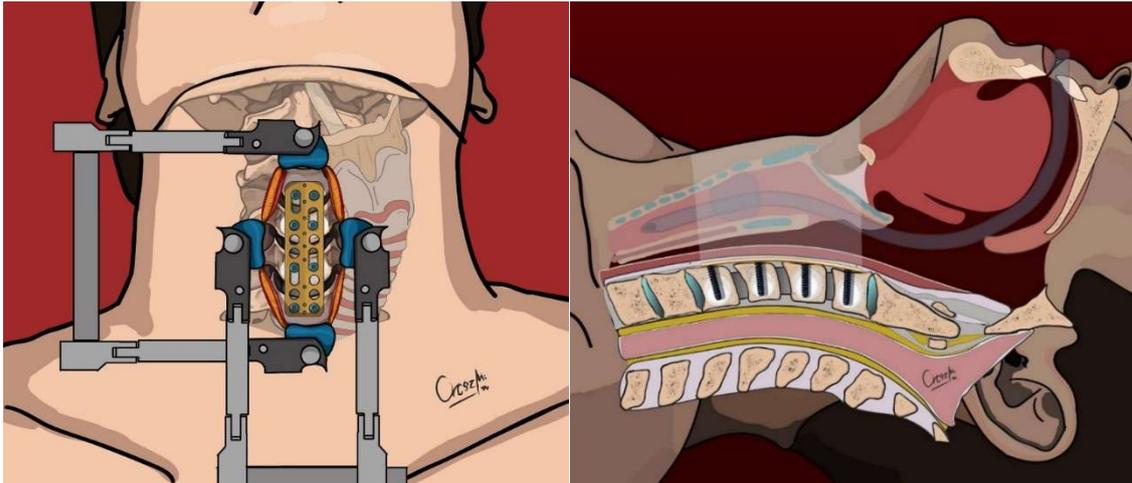


Figure 13: Final position of the cervical plate, screws, and cement—upper and sagittal view (43)

All patients were required to wear a rigid collar for six weeks, then a semi-rigid cervical collar for another six weeks postoperatively. The physical therapy started after six weeks postoperatively.

3.3. Ethical approval

Both of these studies were conducted in strict adherence to the Declaration of Helsinki. It was approved by the Institutional Ethics Committee of Péterfy Sándor Street Hospital Outpatient and Accident Center.

4. Results

4.1. Submandibular retropharyngeal key-hole approach

4.1.1. Summary of the cases

This MIS ASR approach can be used to perform C1-C2 ventral decompression. The average operative time in these ten cases 180 minutes, and the blood loss ranged from 80 to 120 ml. Tracheostomy was not required in any of the cases. Patients were extubated immediately after surgery. They were observed in the intensive care unit for 12 hours and started on an oral diet within 24 hours. Significant neurological improvement was seen in all cases with no intra- or post-operative complications. Mean follow-up was 8.25 months. The 83-year-old male operated on for rheumatoid pannus died of *Clostridium difficile* sepsis four months after surgery. The remaining three were ambulatory, independent, and neurologically intact at last follow-up.

4.1.2. The operating field

During the ten operations, we operated at an average depth of 89 mm measured from the skin incision. This was calculated by averaging the distance measured from the surface of the skin to the tubercle of the C1, the ventral surface of the C2, and the deepest point of the exposed dura in all cases. (Table 1) The decompressed area was 4.92 cm² on average. This area was measured in rectangular form on the postoperative CT scans, in the coronal plane, at the level of the ventral surface of the dura. The surgical procedures were planned with the TO method, utilising CT scans. In these cases, the mean length of the surgical channel would have been 89.1 mm, representing no major difference in comparison to the MIS ASR. The maximum possible area of decompression, as determined by measurement in the coronal plane on the CT scans, would have been 7.40 cm² on average.

Table 1: The length of the surgical channel with the MIS ASR and the TO method (41)

No. of patient	MIS ASR				TO			
	I-C1/ mm	I-C2/ mm	I-D/ mm	DS/ cm ²	O-C1/ mm	O-C2/ mm	O-D/ mm	DS/ cm ²
1.	78	70	101	4,84	74	86	91	5,61
2.	105	91	128	3,50	76	85	98	5,81
3.	98	79	110	4,83	89	96	111	7,35
4.	95	74	102	5,44	77	93	101	5,44
5.	91	80	96	1,82	84	87	101	8,40
6.	89	64	89	4,39	84	84	106	9,45
7.	81	60	85	5,93	62	66	801	8,46
8.	99	99	116	3,81	87	98	115	6,92
9.	77	76	98	8,24	84	95	116	9,46
10.	81	69	91	6,38	78	73	98	7,12

Legend: MIS ASR - minimally invasive anterior submandibular retropharyngeal key-hole approach

TO – transoral approach

I-C1 – distance between the incision and C1 vertebra’s anterior tubercle

I-C2 – distance between the incision and the ventral base of C2 vertebra

I-D – distance between the incision and the deepest point of the dura mater

DS – decompressed dura mater surface

O-C1 – distance between the orifice and C1 vertebra’s anterior tubercle

O-C2 – distance between the orifice and the ventral base of C2 vertebra

O-D – distance between the orifice and the deepest point of the dura mater

4.1.3. Case reports

The first four cases will be presented in more detail.

Patient one

The male in his 40s had a motorcycle accident, and subsequent CT imaging revealed an Anderson-D'Alonso type II odontoid fracture, wherein a 17 mm long cortical bone fragment from the process had broken off and punctured the dura, thereby exerting compression on the medulla oblongata.

The MRI scan confirmed the presence of cerebrospinal fluid leakage behind the odontoid process and demonstrated injury to the posterior ligamentous complex. Upon admission, the patient was found to be tetraplegic.

The initial surgical procedure entailed an emergency C1–2 fusion and the removal of the posterior arch of the C1 vertebra to decompress the medulla oblongata. Due to the patient's unstable circulatory system, it was not possible to perform the ventral decompressive surgery immediately; it was only possible to proceed seven days later. During the MIS ASR procedure, the middle third of the odontoid process, the haematoma, and the cortical bone fragment causing the compression were removed. In addition, the dural injury was explored and successfully tamponaded and tissue glued. The patient is now self-sufficient. (Figure 4 and Figure 14)



Figure 14: Postoperative CT (top) and MRI (bottom) after MIS ASR procedure.

Patient two

A male patient in his 80s was admitted from a neurological department with a two-month history of persistent symptoms and a slowly developing paraparesis. An MRI scan revealed the presence of a rheumatoid pannus, which was found to be causing ventral compression at the C1–2 level. Two days following the posterior C1–2 fixation and laminectomy, the MIS ASR surgery was performed without any complications. Following the procedure, the patient's paraparesis showed gradual improvement, leading to a full return of function and an ability to live a self-sufficient life. (Figure 15)



Figure 15: Preoperative MRI (left) and postoperative CT (right) of patient two.

Patient three

A male in his 60s presented with moderate tetraparesis, dysphagia, and a history of Bechterew's disease. From the MRI scans, it was evident that a rheumatoid pannus was compressing the medulla oblongata. The MIS ASR procedure was undertaken nine days following the dorsal C1–2 fusion and decompression. This involved the removal of the anterior arch of C1, the upper two-thirds of the odontoid process, and the pannus, causing the compression. (Figure 16) The surgical procedure was completed without any complications. The neurological deficit, dysphagia, and tetraparesis showed gradual resolution, and 10 days after the second surgical procedure, the patient was discharged to his home.

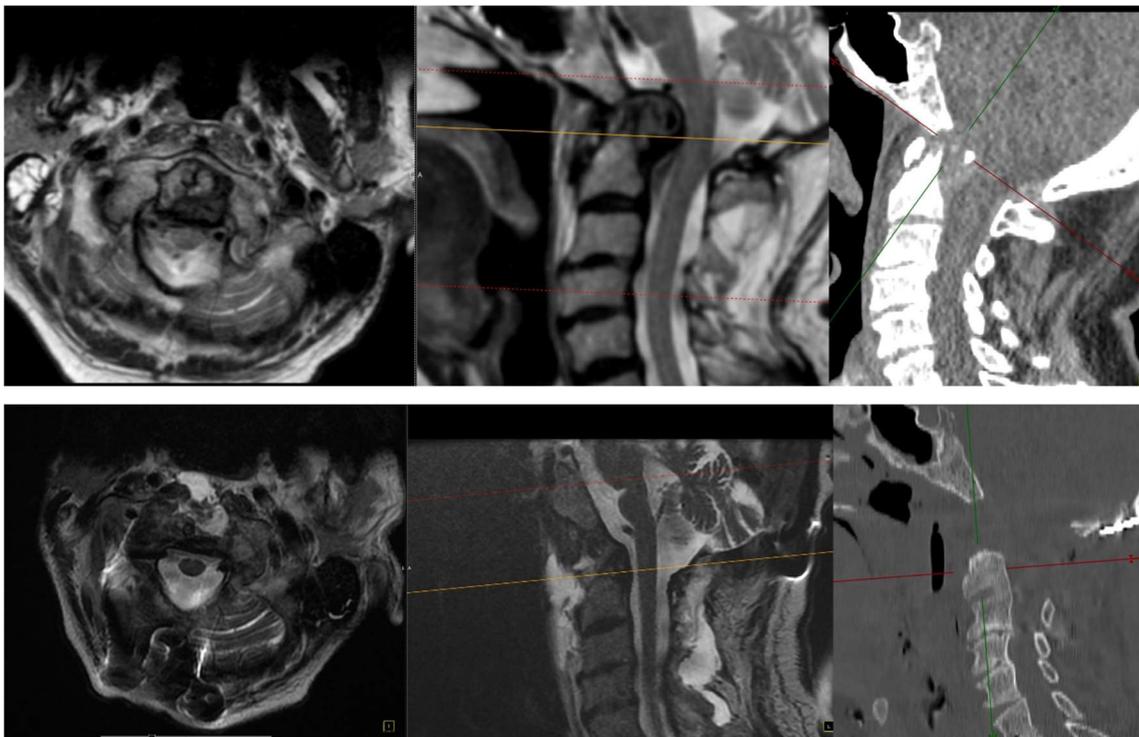


Figure 16: Pre- (top) and postoperative MRI (left, middle) and CT (right) of patient three.

Patient four

The female patient, in her fourth decade of life, exhibited evidence of tumorous infiltration of the C1 and C2 vertebrae on both CT and contrast MRI. This was attributed to a metastatic squamous cell carcinoma of the cervix, which had resulted in ventral compression of the spinal cord. The patient exhibited no neurological deficits; however, she did report pain in her nape, which radiated to the left shoulder. Two days following the occipitocervical (C0-C4) dorsal stabilisation procedure and C1-C2 laminectomy, the MIS ASR surgery was performed to remove the metastasis and to release the spinal cord. (Figure 17) On the fourth day following the second surgical procedure, the patient was discharged to their home with reduced pain levels.

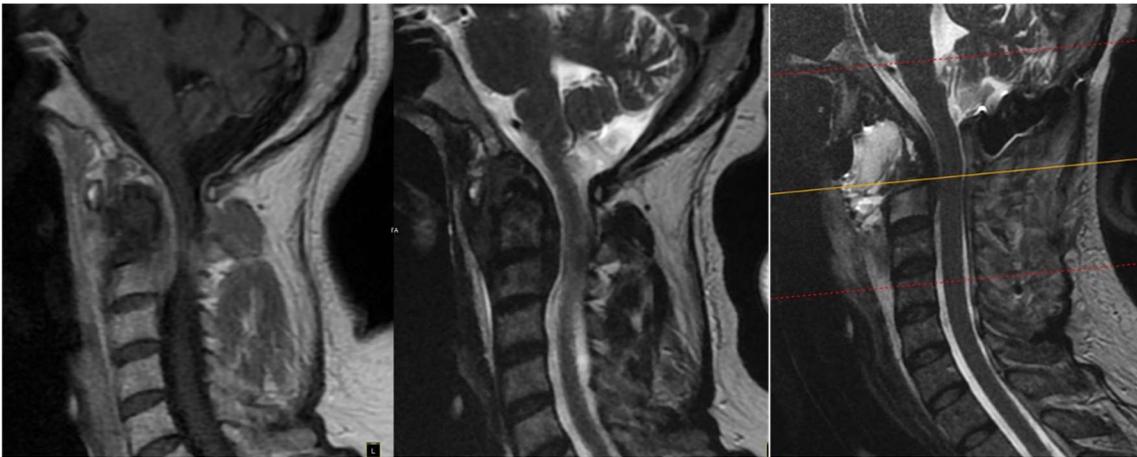


Figure 17: Pre- (left and middle) and postoperative (right) MRI of patient four.

4.2. Cervical stabilisation with PMMA augmentation

4.2.1 Patient demographics and comorbidities

From November 2016 to November 2023, 38 patients with AS who had sustained traumatic subaxial cervical spine injuries were treated using plate fixation with cement augmentation via a ventral approach. The mean age of the group was 70.7 years (standard deviation = 9.2 years), with 26 males (68.4%) and 12 females (31.6%) comprising the cohort. In terms of their general condition and anaesthetic risk, the distribution was as follows: one patient was classified as ASA I (2.6%), thirteen as ASA II (34.2%), twenty-two as ASA III (57.9%), and two as ASA IV (5.3%).

4.2.2. Mechanism of injury

Regarding the underlying mechanisms of injury, 14 patients sustained injuries from traffic accidents, representing 36.8% of the total cohort. A further 22 patients (57.9%) sustained injuries from low-energy trauma, including falls. Two cases (5.3%) exhibited no specific underlying traumatic event in their medical history.

4.2.3. Fracture classification

This study included five cases of revision surgery due to re-injury or screw loosening in previously untreated vertebral segments with cement augmentation (13.2%); the remaining 33 cases were primary. According to the AO Spine Cervical Classification, the most prevalent types are Type B3 (42.1%, N = 16) and Type C (34.2%, N = 13). Additionally, there were fewer Types B1, B2, and F4 instances. Notably, one patient exhibited a B2 fracture at the C4–C5 vertebra and a B3 fracture at the C6–C7 level. The majority of patients (94.7%; N = 36) exhibited three-column lesions, except for two cases where injuries affected the anterior two columns. (Table 2) Ten of the 38 patients (26.3%) exhibited neurological deficits.

Table 2: Injury classification and surgical details (43)

Injury Classification and Surgical Details		
Injury Type	Number of Cases	Percentage
Type B3 Fractures	16	42.1%
Type C Fractures	13	34.2%
Other Fractures	9	23.7%
3-Column Lesions	36	94.7%
Anterior 2-Column	2	5.3%

4.2.4. Surgical plans

In 23 cases (60.5%), plate stabilisation was extended to adjacent segments. This was not required in five instances (13.2%), while in a further ten cases (26.3%), the extent of plate stabilisation varied based on specific conditions. The basic rule was to start and end the cervical plates on intact vertebrae, as demonstrated on the case of a male in his 80s. He suffered a C6 AO Type B1 fracture, involving only the C6 vertebra. In this case, the plate started on the C5 and ended on the C7 vertebra, while the C6 was not augmented. (Figure 18)

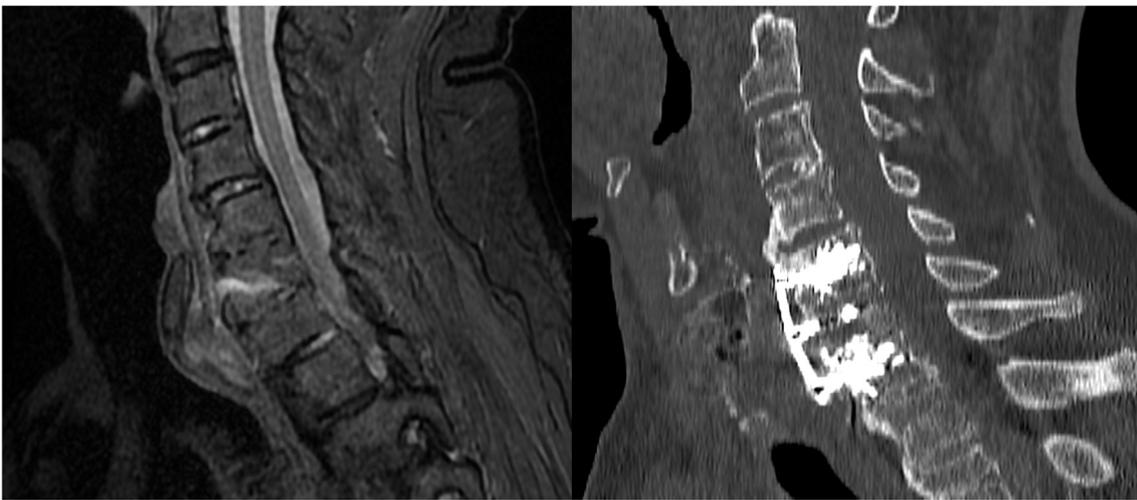


Figure 18: Preoperative MRI (left) and postoperative CT (right) of a male patient with C6 fracture.

In 32 cases (84.2%), cement was used to augment the segments undergoing stabilisation. In six cases, where vertebral body fractures were present, augmentation was limited solely to the intact vertebrae to minimise the risk of cement leakage (15.8%). In a case of a male in his 70s, who suffered a C4 AO A1 and C5 AO B3 fracture due to a traffic accident, a C3-C6 ventral plate fixation was performed. Only the intact vertebrae were augmented (C3 and C6) to decrease the risk of cement extravasation. (Figure 19) Postoperative imaging demonstrated the appropriate positioning of both plates and screws in all cases.

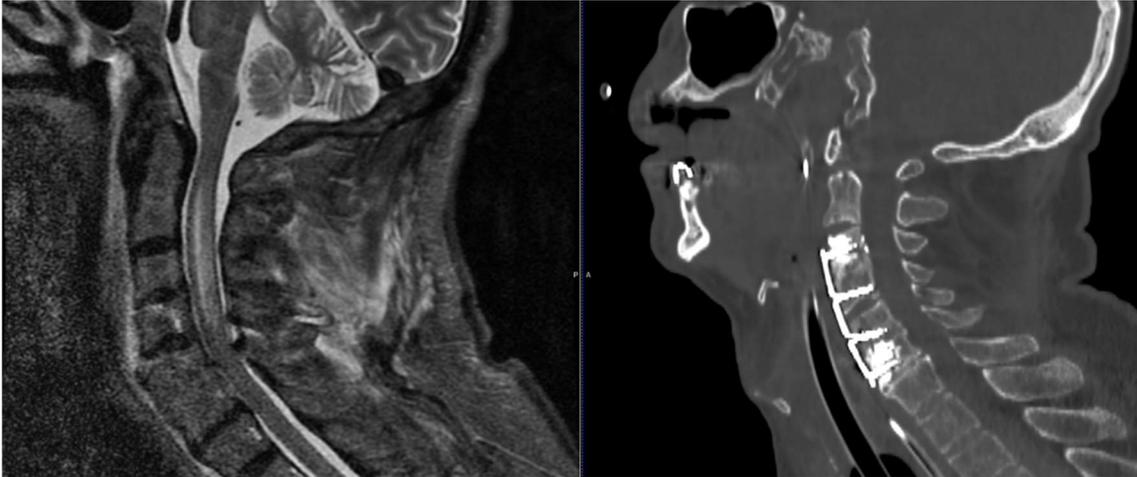


Figure 19: Preoperative MRI (left) and postoperative CT (right) of a male patient with C4 and C5 fracture.

4.2.5. Surgical complications and follow-up

No complications were observed as a result of cement leakage. Cement leakage was categorised into four groups based on postoperative CT scans: epidural to the spinal canal (71.1%, N = 27), near the vertebral artery (23.7%, N = 9), into the neuroforamen (7.9%, N = 3), and the paravertebral space (39.5%, N = 15). In four cases (10.5%), no evidence of cement leakage was observed on the postoperative CT scans. During the follow-up period, evidence of screw loosening and implant displacement was observed in two of the 38 cases. (Table 3)

Table 3: Surgical outcomes and complications (43)

Outcome	Details
Cement Leakage Location	
- Epidural Spinal Canal	27 cases (71.1%)
- Vertebral Artery Area	9 cases (23.7%)
- Neuroforamen	3 cases (7.9%)
- Paravertebral Space	15 cases (39.5%)
No Leakage	4 cases (10.5%)
Screw Loosening	2 cases
Postoperative Mortality	17 deaths (44.7%)
Survival Time Post-Surgery	Average 264 days

During the follow-up period, two out of 38 cases exhibited evidence of screw loosening and implant displacement.

At the time of data analysis, 17 of the patients who had undergone treatment had died, representing 44.7% of the total number of cases. The minimum follow-up period was 91 days, while the maximum was 2674 days. The mean survival period for the deceased patients following surgery was 264 days, with seven patients dying within one month, two within six months, four within one year, and four after more than one year. (Table 4)

Table 4: Follow-up and mortality rates (43)

Follow-up and Mortality Rates	
Timeframe	Number of Deaths
Within 1 month	7
Within 6 months	2
Within 1 year	4
After 1 year	4

5. Discussion

5.1. Anterior submandibular retropharyngeal dens resection

5.1.1. Complications of previous surgical methods

The most common complications associated with transoral and transnasal odontoidectomy are CSF leakage, velopharyngeal insufficiency, wound dehiscence, pulmonary issues, meningitis, and death (15). A review of the literature, encompassing 26 publications, revealed that the only statistically significant discrepancy in complication rates between the two methods pertains to the increased propensity for tracheostomy following transoral surgeries (15, 16). Despite the augmented access afforded by the lateral approaches, there is a heightened risk of injuries to the vertebral artery, jugular bulb, and hypoglossal nerve (47-50). Ponce-Gómez et al. also found a significant difference between the time duration of the TO and EE approaches. The mean duration of TO surgeries was 141 minutes, whereas the mean duration of EE surgeries was 238 minutes ($p \geq 0.02$). Patients who underwent the EE procedure could be extubated immediately after surgery, while those who underwent the TO method remained intubated for 24 hours. The time until oral feeding was significantly shorter in the EE group, $p \leq 0.009$ (51).

5.1.2. Complications of the MIS ASR method

The minimally invasive anterior submandibular retropharyngeal key-hole approach utilised in this study constitutes a novel method for decompression of ventral C1–C2 compressive lesions. The ten cases presented herein do not permit the drawing of long-term conclusions; however, it can be stated that during the MIS ASR, with the preservation of the hard and soft palates, the risk of velopharyngeal insufficiency associated with the TO method can be eliminated. The management of liquor leakage can also be easier using several layers of soft tissue. The blood loss is minimal, patients do not require tracheostomy, and can be commenced on an oral diet within 24 hours post-surgery.

5.1.3. Surgical field with the MIS ASR method

Compared to the TO method, the MIS ASR yielded an average dural decompression area 33.5% smaller (4.92 cm² / 7.40 cm²). It is hypothesised that this 2.48 cm² difference occurs due to the fact that during the MIS ASR surgery—compared to the TO method—the distance between the C1 anterior tubercle and the midline of the corpus of C2 is seen at a more obtuse angle, reducing the possible area of decompression by 2.48 cm². (Figure 20) However, it was possible to excise the entire pathology and achieve adequate decompression in all cases. (Figure 21) The small incision (25 mm wide), the deep surgical field (89 mm on average), and the narrow surgical channel require proficient microsurgical skills.

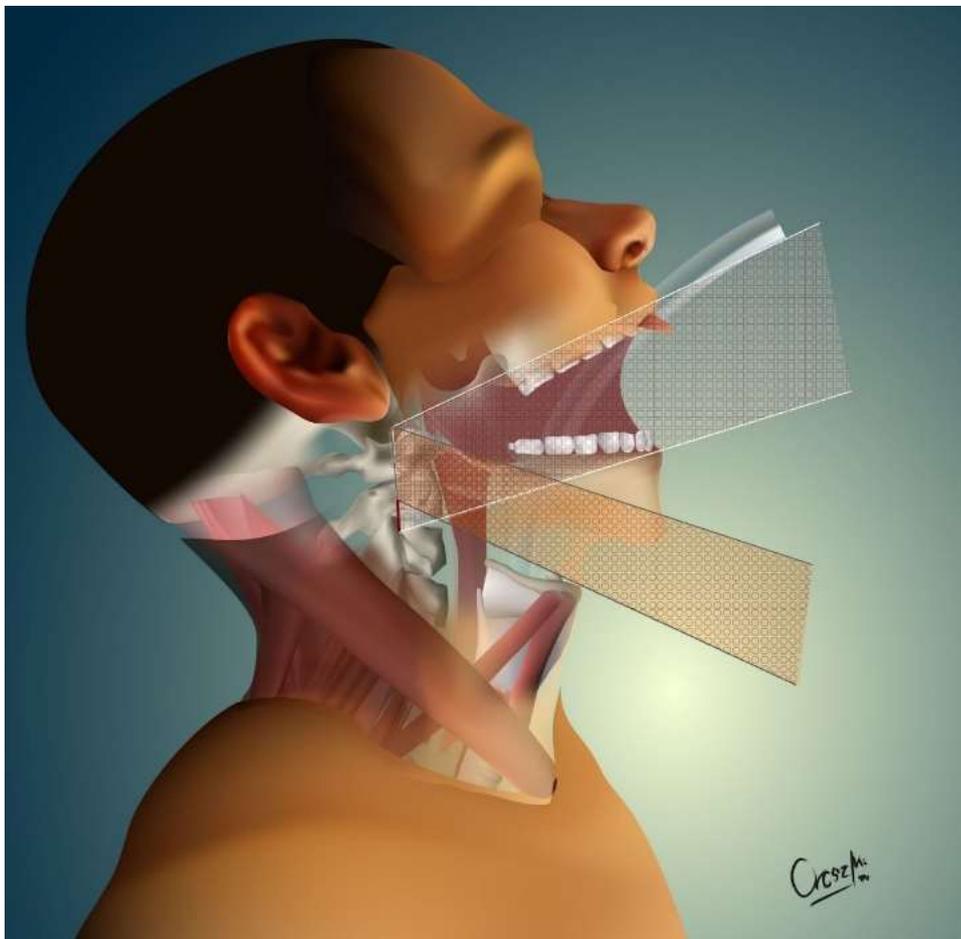


Figure 20: Schematic figure of different surgical interventions (41)

Legend: white line: maximum decompression area with the transoral method, black line: maximum decompression area with the anterior submandibular retropharyngeal method, red line: the difference between the two methods' decompression area



Figure 21: The preoperative (left) and postoperative (right) magnetic resonance (MRI-T2) imaging of the male patient in his 60s. (41)

5.2. Cervical stabilisation with PMMA augmentation

In this study, the efficacy of a treatment combining single-stage plate stabilisation with ventral cement augmentation for treating unstable subaxial cervical spine fractures in patients with AS was investigated.

5.2.1. Cervical cement augmentation in the past

The decision to employ a ventral approach without posterior fixation was made in light of the patient population's comorbidities and the complexity of the surgical demands. The technique, incorporating the ventral cervical plate and cement augmentation, is intended to restore structural integrity. The method under discussion aligns with the outcomes of previous studies, which demonstrated the efficacy of analogous procedures in stabilising the anterior cervical column (36, 37, 52, 53). For instance, as illustrated by Waschke et al., a standard cervical corpectomy of either one-level or two-level was performed in nine patients, utilising an expandable titanium cage, followed by anterior plating and

vertebroplasty (53). These techniques, which exhibited no instances of hardware failure, mirror our practice, wherein PMMA augmentation is applied through the screw pilot holes, a method comparable to that employed by Oppenlander et al. No significant complications were reported (37).

The objective of the approach was to inject a maximum of 1.5 millilitres of cement per vertebral body under radiological guidance using a C-arm, with the actual volume ranging from 0.8 to 1.5 millilitres. Augmenting only intact vertebrae adjacent to fractures minimizes the risk of cement leakage. Assessments of cement leakage revealed no adverse events, with leakage patterns typically occurring in the epidural and paravertebral spaces.

Reyes-Soto et al. utilised PMMA-filled mesh following odontoidectomy to perform a transoral clivus-cervical stabilisation in three cases. Following the excision of the tumorous odontoid, a PMMA-filled mesh was implanted as a replacement, with the clivus-cervical plate then being anchored to the mesh, yielding encouraging outcomes (54).

Bayley et al.'s treatment of seven patients with ventral vertebral augmentation entailed the introduction of 0.2–0.25 millilitres of Kyphon cement into the screw holes before the securing of the anterior plate, resulting in a seven-month follow-up period devoid of complications (36).

Oppenlander et al. presented encouraging results in their case study of an elderly osteoporotic patient (37). Following the performance of discectomies at the C3–C7 levels, an anterior cervical plate with PMMA augmentation into the vertebral bodies was inserted using the screw pilot holes. Despite an increase in the screw pullout strength, due to the severely compromised bone quality of the patients, a postoperative HALO was implanted for three months. This approach resulted in the successful healing of the interbody fusions, without the occurrence of screw pullout or implant displacement, as evidenced at the 6-month follow-up.

5.2.2. Patient demographics

The study encompassed 38 AS patients, predominantly male, with a mean age of 70.7 years and a high prevalence of comorbid conditions, as indicated by their ASA classifications. The injuries sustained were primarily the result of low-energy trauma or falls, predominantly affecting the C4-C5 and C5-C6 levels. It is noteworthy that 26.3% of these patients exhibited neurological deficits. In a comparative analysis, Caron et al. identified comparable injury patterns in a cohort of 67 patients, with a high prevalence of spinal cord injuries in conjunction with cervical fractures, predominantly at the C6–C7 levels (55).

5.2.3. Complications with the cervical stabilisation with PMMA augmentation

The postoperative mortality rate was 44.7%, with a one-year mortality of 34.2%. In contrast, Caron et al. reported a one-year mortality rate of 32% in conservatively treated patients and 23% in those who underwent surgery, emphasising that thoracolumbar fractures, which were included in their analysis, typically exhibit lower mortality rates compared to cervical fractures (55).

6. Conclusions

Neurosurgery remains a rapidly evolving and complex field, continually advancing to enhance patient safety and outcomes. This study underscores the promise of innovative surgical techniques in managing complex cervical spine conditions.

The microscope-assisted minimally invasive anterior submandibular retropharyngeal key-hole approach was feasible in these four cases for dens resection, reducing the risk of serious complications.

The cervical plate stabilisation with PMMA augmentation underscores the efficacy of ventral stabilisation techniques for managing complex spinal injuries in high-risk patients, offering insights into procedural effectiveness and patient outcomes. We demonstrated how a single-stage anterior screw and plate fixation of the cervical spine with cement augmentation could be a feasible and effective method to treat cervical spine fractures in patients with AS.

Whilst this study has certain advantages, it is essential to acknowledge its limitations, including its retrospective design and the relatively small cohort with both surgical methods. These factors thus limit the generalizability of the findings. On a positive note, the research provides valuable insights into the treatment of subaxial cervical spine fractures in patients with AS, as well as a novel method for ventral C2 decompression. To build on this foundation, it is recommended that future studies include larger sample sizes, prospective methodologies, and the inclusion of control groups. Including these elements would facilitate further substantiation of the efficacy and applicability of this surgical approach.

7. Summary

This dissertation presents innovative surgical methods aimed at enhancing patient safety and clinical outcomes in the management of complex cervical spine pathologies. Two novel surgical approaches are extensively discussed and evaluated.

The first approach, the microscope-assisted minimally invasive anterior submandibular retropharyngeal key-hole (MIS ASR) technique, was introduced to facilitate ventral decompression at the craniocervical junction. Avoiding a transmucosal pathway to the atlanto-axial region, this approach significantly reduces the risks associated with traditional decompression methods, such as cerebrospinal fluid leakage and velopharyngeal insufficiency, while enabling rapid postoperative recovery and avoiding the need for tracheostomy. Clinical outcomes from initial case series demonstrated that this minimally invasive approach was feasible, safe, and effective in carefully selected patients, with substantial neurological improvements observed postoperatively.

The second surgical method evaluated cervical plate stabilization combined with polymethyl methacrylate (PMMA) bone cement augmentation for treating unstable subaxial cervical spine fractures in patients with ankylosing spondylitis (AS). This technique successfully provided robust structural stability without the need for posterior fixation. Despite the complexity and the severe comorbidities of AS patients, the approach demonstrated favourable outcomes with respect to structural stability, improved or preserved neurology, and acceptable mortality rates when compared to traditional fixation methods.

Overall, while the initial findings from both approaches are promising, further prospective studies with larger patient populations are necessary to fully establish their long-term efficacy and safety, and to refine these surgical techniques.

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9. Bibliography of the candidate's publications

9.1. Publications in the topic of this dissertation

Süvegh, D., & Viola, Á. (2020). Fognyúlvány mikroszkóppal asszisztált reszekciója submandibularis retropharyngealis „key-hole” behatolásból, *Orvosi Hetilap* OH, 161(31), 1302-1306. doi: <https://doi.org/10.1556/650.2020.31784> IF: 0,540

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Süvegh D, Juhász Á, Viola R, Al-Smadi MW, Viola Á. Treatment of Ankylosing Spondylitis Patients with Cervical Spinal Injury with Anterior Single-Stage Fixation with Bone Cement Augmentation. *J Clin Med.* 2024 May 27;13(11):3131. doi: 10.3390/jcm13113131. IF: 3.000

9.2. Other publications

Süvegh D, Juhász Á, Veres DS, Viola Á. Impact of COVID-19 on neurotrauma cases, mortality rates, and rebound effect: a monocenter retrospective study. *Ideggyogy Sz.* 2023 Jul 30;76(7-8):253-260. English. doi: <https://doi.org/10.18071/isz.76.0253> IF: 0,8

Viola R, Aslan S, Al-Smadi MW, Süvegh D, Viola Á. From Detection to Decision: How STIR Sequence MRI Influences Treatment Strategies for Osteoporotic Vertebral Fractures. *J Clin Med.* 2024 Jun 6;13(11):3347. doi: 10.3390/jcm13113347. IF: 3.000

Viola, R.; Juhász, Á.; Süvegh, D.; Veres, D.S.; Gati, A.; Viola, Á.; Al-Smadi, M.W. Impact of Treatment Modalities and Fracture Stability on Survival in Thoracolumbar Fractures: A 5-Year Observational Study. *J. Clin. Med.* 2025, 14, 933. doi: 10.3390/jcm14030933. IF: 3.000

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