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Under pressure - A historical vignette on surgical timing in traumatic spinal cord injury

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ABSTRACT

Introduction: It was not even a century ago when a spinal cord injury (SCI) would inevitably result in a fatal outcome, particularly for those with complete SCI. Throughout history, there have been extensive endeavours to change the prospects for SCI patients by performing surgery, even though many believed that there was no way to alter the catastrophic course of SCI. To this day, the debate regarding the efficacy of surgery in improving the neurological outcome for SCI patients persists, along with discussions about the timing of surgical intervention.
Research question: How have the historical surgical results shaped our perspective on the surgical treatment of SCI?
Material and methods: Narrative literature review.
Results: Throughout history there have been multiple surgical attempts to alter the course of SCI, with conflicting results. While studies suggest a potential link between timing of surgery and neurological recovery, the exact impact of immediate surgery on individual cases remains ambiguous. It is becoming more evident that, alongside surgical intervention, factors specific to both the patient and their surgical treatment will significantly influence neurological recovery.
Conclusion: Although a growing number of studies indicates a potential correlation of surgical timing and neurological outcome, the precise influence of urgent surgery on an individual basis remains uncertain. It is increasingly apparent that, despite surgery, patient- and treatment-specific factors will also play a role in determining the neurological outcome. Notably, these very factors have influenced the results in previous studies and our views concerning surgical timing.

1. Introduction

More than a century ago, patients suffering from traumatic spinal cord injury (SCI), would primarily die from secondary complications, such as infection, within the first week after injury. The high case fatality rate led many to believe that nothing could be done to change the disastrous course of SCI. Nevertheless, since early history there have been multiple attempts to change a patient's fate by decompressing the spinal cord. Despite significant advancements throughout history, the indications and timing of surgery in SCI have long since been the subject of much controversy. This paper outlines the historical sequence of events that have led to ever-changing paradigm shifts regarding the surgical management of SCI.

2. Antiquity – first endeavours

The first written record on spinal injuries can be found in the Edwin Smith Surgical Papyrus (Hughes, 1988). Dating back to 2500–1900 BC, the document features six patients with spinal injuries, of whom two sustained a SCI. The author suggested that patients without SCI should

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receive conservative treatment by wrapping the injury with fresh meat, a mineral substance and honey. Complete SCI was considered untreatable. For incomplete SCI, the author was willing to provide treatment. However, the exact treatment was unclear as the document ended abruptly. There are no other written records about spinal injuries between these ancient Egyptian descriptions and the writings attributed to Hippocrates (460–377 BC). In his Corpus Hippocraticum, he describes one of the customary methods to treat displaced fractures, where the patient was fastened to a ladder and shaken in mid-air (Adams, 1886). Hippocrates was very sceptical about this procedure: *"Shaking on a ladder has never straightened anybody as far as I know, but it is principally practiced by those physicians who seek to astonish the mob … The physicians who follow such practices, as far as I have known them, are all stupid."* This is probably the first written controversy in the treatment of spinal injuries, but despite his critique, the procedure continued to be widely used. It wasn't until a couple of centuries later, that the Greek physician Paul of Aegina (625–690), also opposed this technique and instead recommended 'early' surgical decompression in order to prevent SCI (Er and Naderi, 2013). Likewise, the Arab-Andalusian physician Albucasis (936–1013) recommended urgent surgery, but only for thoracic injuries, since he considered cervical SCI hopeless (Goodrich, 2004).

Despite recommendations from these early pioneers advocating for surgical treatment of SCI, only a few anecdotal cases were described in the following centuries. The majority of physicians continued to favour a conservative approach, given the ultimately fatal course of SCI at that time. It was only until the eighteenth and beginning of the nineteenth century that more attention was directed to the surgical treatment of SCI and its secondary complications, resulting in more favourable outcomes. Furthermore, with the progress of antiseptic techniques, anesthesia and imaging in the nineteenth century, surgery in itself became a safer treatment, introducing the beginning of a more successful era in spine surgery.

3. Eighteenth century (1700–1800) – *from 'an ailment not to be treated' to propagation of surgery*

In 1762, Antoine Louis (1723–1792) was one of the first surgeons in France to perform a laminectomy in a SCI patient (Brown-Sequard, 1861). Captain de Villedon, sustained a gunshot injury to his back resulting in paraplegia. Four days later, he developed a high fever and Louis noticed movable fractured bones in his back, which he decided to remove operatively. In the following days the patient regained sensation and eventually some motor function, making him able to walk with the use of a cane. Louis, who from then on favoured surgery, stated *"this patient was a victim, from which art had saved him from a certain death"*. In the following years, French surgeons François Chopart (1743–1795) and Pierre-Joseph Desault (1738–1795) also started advocating surgical decompression of the spinal cord, (Goodrich, 2004) as well as Benjamin Bell (1749–1806), a Scottish surgeon. In his book, Bell described that *"Wherever we find that the spinal marrow is compressed, as the immediate effect of an injury … and where there is reason to think that the compression is produced by a fracture and depression of a portion of bone, as we know from experience that every such case will terminate fatally if the cause of compression be not removed, it would surely be better to endeavour to raise it than to leave the patient under an absolute certainty of suffering."*.

4. Nineteenth century (1800–1900) – *The era of controversies*

Despite the propagation and optimism towards surgery at the end of the eighteenth century, it later became more controversial. Surgical mortality was still high, and most SCI patients would die within days after their injury. During the beginning of the nineteenth century, Astley Cooper (1768–1841) and Charles Bell (1774–1842), an English and a Scottish surgeon, recognized there was a knowledge gap on the optimal management and started describing consecutive cases. They would often heavily criticize each other's management.

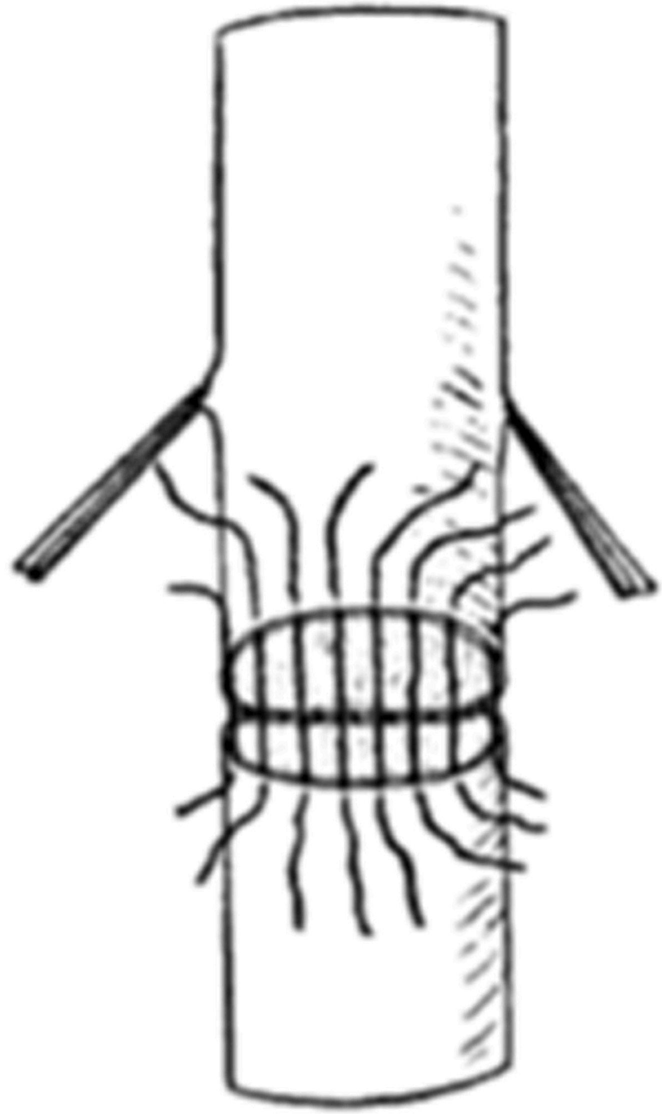

Fig. 1. From Chipault. *Etudes de Chirurgie Medullaire*, 1894 (Chipault, 1894). Pial sutures in case of a transection of the spinal cord with complete SCI.

Bell considered that the greatest danger to the spinal cord was inflammation instead of compression (Brown-Sequard, 1861). He opined that surgery would put a patient to unnecessary risk by promoting inflammation, thereby aggravating the risk of neurological injury and death. Therefore, he was highly averse to surgery (Goodrich, 2004). Instead, he emphasized the need to prevent secondary complications, particularly infections. He recommended that it was best to preserve the spine at rest in order to prevent further injury.

Conversely, Cooper often used the analogy of trepanation in case of traumatic brain injury and believed 'salvage' surgery could potentially alter the course of SCI, thereby preventing death (Jang et al., 2020). Henry Cline, a teacher of Cooper, performed the first laminectomy in England in 1814 on a young man who fell from a roof, resulting in sensory loss, paraplegia and midthoracic fractures (Brown-Sequard, 1861). Despite several attempts, he was not able to reduce the subluxated spine because the patient got exhausted. No neurological recovery occurred and three days later the patient had convulsions and subsequently died. Autopsy revealed a near total spinal cord transection. Cline only performed this one laminectomy. In 1822 and 1827, Cooper supervised his nephew Frederick Tyrell in performing laminectomies in two patients with complete SCI, resulting in some sensory recovery,

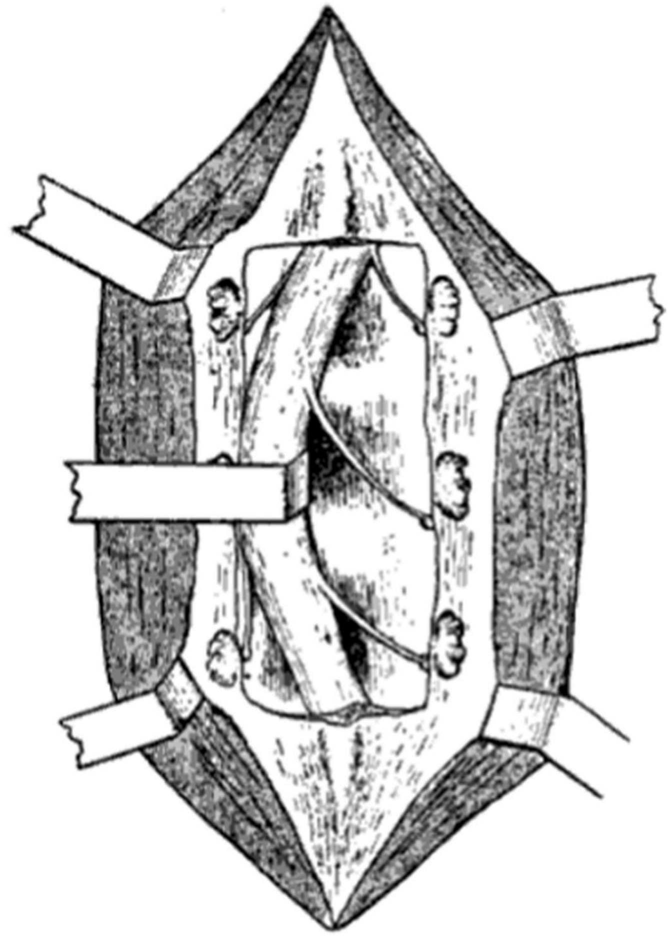

Fig. 2. From Chipault. *Etudes de Chirurgie Medullaire*, 1894 (Chipault, 1894). Exploration of the anterior dura by retracting the spinal cord.

however, both developed fatal infections.

In the following years, the negative attitude of Bell towards surgery prevailed, leading to conservative treatment over the following decades (Brown-Sequard, 1861). Surgery was limited to cases with a bullet or open wound, requiring debridement. Nonetheless, some still investigated whether surgery could lead to better outcomes. In 1894, William Thorburn (1861–1923) published his series on surgical approach and timing for SCI, including Antony Chipault's proposition to suture the spinal cord in case of transection and to remove any ventral compression of the spinal cord besides laminectomy (Figs. 1 and 2). (Brown-Sequard, 1861; Chipault, 1894) At the end of his case series, he found no clear neurological benefit from surgery, despite a lower mortality in surgically compared to conservatively treated patients. Since some patients with incomplete SCI exhibited spontaneous recovery, he only suggested surgery for incomplete SCI, but only when neurological recovery had plateaued after several weeks (Thorburn, 1894).

In contrast, U.S. surgeon Herbert Burrell (1856–1910) explored early surgery (<48 h) to prevent spinal cord damage from ongoing compression (Burrell, 1905). He based this timeframe on autopsy findings of a patient with damage of the spinal cord within 38 h of injury due to an impression fracture. Meanwhile, Samuel Lloyd (1860–1926) investigated the outcome of immediate versus delayed surgery. He observed higher mortality with immediate surgery and concluded that surgery should only be performed when it was certain that the patient would not die from the direct effects of injury.

5. Twentieth century (1900–2000) – a time for major advancements

5.1. (1900–1950) The influence of World Wars

By the late nineteenth century, advances in anaesthesiology and antisepsis made surgery safer. Moreover, the discovery in 1895 of X-rays by Conrad Röntgen revolutionized SCI diagnosis and management. Despite these advances there was still reluctancy to treat patients suffering from SCI surgically.

In 1902, George Walton, a Harvard neurologist, advocated surgical decompression, even in complete SCI (Walton, 1902). He thereby challenged the belief that complete SCI was a condition beyond repair, citing a case with complete SCI that recovered over time. He concluded that the prognosis without intervention was already poor, and surgery could hopefully reverse this. Therefore, Walton thought surgery within days could be warranted in these patients. Moreover, he advocated opening the dura to decompress the spinal cord. In the following years, Alfred Allen, who was somewhat sceptical about the benefits of laminectomy for neurological recovery, promoted additional myelotomy to the injured spinal cord in order to relieve pressure and drain haemorrhage, preferably immediately after injury (Allen, 1914). Subsequently, he performed a myelotomy in three complete SCI patients. One patient had temporary recovery of sensation but returned to complete SCI within 48 h and died shortly after; the second showed sensory recovery but developed a large pressure-sore and died days after; the third patient, operated within 4 h after injury, showed gradual recovery. After analysing his results, he deemed his work experimental (Allen, 1914). Meanwhile, Harvey Cushing (1869–1939), a pioneer in neurosurgery, managed several SCI patients in the early 20th century. Initially, around 1905, he advocated immediate surgery (<24 h) for both incomplete and complete SCI (Dasenbrock et al., 2011). Later, reviewing his cases and outcomes, he believed that complete lesions were irreparable, advising non-operative management for these patients. Cushing was sent to France during World War (WW) I to treat battlefield injuries. He noticed that the majority of SCI patients passing within one week and only some with incomplete SCI would survive, leading him towards a more conservative approach.

The focus of SCI management shifted towards preventing secondary complications, since spontaneous recovery could occur with conservative treatment. In 1936, neurosurgeon Donald Munro (1898–1978) established the first spinal cord unit in the U.S. (Bodner, 1983) Meanwhile in Europe, Ludwig Guttman (1899–1980), a German neurosurgeon, founded the first spinal unit after fleeing to England because of WW II (Guttmann, 1949). While surgery was generally accepted for open or bullet wounds, debate persisted over its indication in closed wounds. Guttman strongly opposed surgery in complete SCI, deeming it ineffective, especially if no recovery occurred within 48 h. For incomplete SCI, he favoured a conservative approach, with exceptions for patients deteriorating neurologically, or patients with radiculopathy, making them potential candidates for 'early' surgery, between 72 h and 2–3 weeks after injury. In absence of advanced diagnostics, surgeons would often perform spinal manometric examinations (Queckenstedt test) to diagnose a 'spinal block'. The test involved a spinal puncture and manual compression of the jugular veins. If case of spinal obstruction, the intraspinal pressure would not increase with compression of the jugular veins. In patients with incomplete SCI and ongoing manometric block without evidence of fracture, Guttman believed exploratory surgery could be performed.

The transition from conservatism to a more progressive attitude in the following years was exemplified by Walter Haynes, a neurosurgeon in the U.S. army during WW II (Haynes, 1946). At that time, surgery was rarely utilized due to the prior experiences of Cushing and Guttman. However, when certain surgeons began performing surgeries on SCI patients who had been brought to England with delays and achieved promising outcomes, this inspired Haynes to consider surgery for incomplete SCI and cases of progressive neurological deterioration. During the war, he expanded his indication for early surgery to patients with complete SCI with a 'spinal block'. Haynes operated on 76 patients, of whom 17 had incomplete and 57 had complete SCI and two with unknown neurological injuries. Within six weeks, 30 patients showed some neurological recovery. Haynes suggested that it would be better, or humane, to operate on many patients, where neurological improvement was unlikely, to at least save one. Nevertheless, Haynes' approach was not collectively adopted. Wilder Penfield (1891–1976), a Canadian neurosurgeon, only considered surgery for incomplete SCI with a 'spinal block'.

5.2. (1950–2000) - The post-War era

During WW II, surgery for SCI gained acceptance and internal stabilization of spinal fractures became part of standard care. Hence, the discussion shifted towards patient selection and timing. Tarlov and Klinger (1954) were among those studying time limits for SCI recovery, using experiments in dogs (Tarlov and Klinger, 1954). They found that shorter compression duration as well reduced force and incomplete SCI, were related to functional recovery. Tator et al. performed several animal studies on surgical timing, showing similar results (Tator and Rowed, 1979). These findings and other preclinical research provided a strong rationale for early decompression in SCI in humans. Nevertheless, surgeons remained divided on the benefit of surgery.

In 1987, Tator et al. published patient outcomes from their spinal cord unit, (Tator et al., 1987) revealing no significant difference in neurological recovery between operative and conservative treatments. By then, the indications for surgery included neurological deterioration or lack of improvement in case of spinal cord compression. In their study, 55.8% underwent surgery, but only 34.7% underwent spinal decompression. Incomplete SCI patients were considerably more likely to undergo decompression compared to complete injuries. Although this study did not find a superior outcome with surgery, other preclinical studies by Tator and Fehlings (1991) suggested potential benefits of surgery (Tator and Fehlings, 1991). They explored the concept of secondary injury from disturbances in the spinal cord microcirculation causing posttraumatic ischemia. Its potential reversibility supported the idea for early surgical intervention. Moreover, advances in techniques and instrumentation increased the safety and practicability of surgery in spinal trauma.

In 1992, the STASCIS group (Surgical Timing in Acute Spinal Cord Injury Study) was formed by the Spinal Cord Injury Committee of the Joint Section on Neurotrauma and Critical Care of The American Association of Neurological Surgeons (AANS) and Congress of Neurological Surgeons (CNS). The group performed a large retrospective cohort study between 1994 and 1995 on the use and timing of surgery in SCI patients in North America (Tator et al., 1999). They observed that 65.4% underwent surgery, of whom 23.5% < 24 h, 15.8% from 24 to 48 h, 19% from 48 to 96 h and 41.7% > 5 days after injury. Due to the ongoing discussion on the effectiveness of early surgery, Vaccaro et al. performed a prospective randomized controlled study between 1992 and 1995 in cervical SCI patients, randomizing them into 'early' (<72 h, n = 34) versus 'late' (>5days, n = 28) surgery (Vaccaro et al., 1997). No significant differences in recovery were found between both groups. The authors questioned whether their 'early' timeframe had been early enough. Subsequent studies favoured early surgery for improved neurological outcomes in SCI (Mirza et al., 1999; Papadopoulos et al., 2002). However, high-class evidence was still lacking with great heterogeneity in study groups, and a clear definition of 'early' surgery remained ambiguous. By this time, there was still a prevailing skepticism regarding the use of surgery, leading to large differences in surgical management between, and even within, centers. In general, patients with complete injuries were often still not considered candidates for surgery, due to their poor neurological prognosis.

6. Twenty-first century (2000+) – *The need for speed*

In a meta-analysis by La Rosa et al., early surgical intervention (<24 h) was linked to improved neurological recovery compared to late surgery (>24 h), or non-operative management in SCI (La Rosa et al., 2004). In patients with complete SCI, 42% improved with surgery <24 h, compared to 8.3% and 24.6% in the late surgical and conservative group respectively. In incomplete SCI, early surgery resulted in 89.7% recovery, as opposed to 58.5% and 59.3% in the late and conservative groups. However, due to significant heterogeneity in the included studies, the authors could merely propose early surgery <24 h as a potential option for patients with SCI. Subsequently, the focus on identifying the optimal surgical timeframe intensified.

In 2002, the Spine Trauma Study Group (STSG) was formed (Fehlings et al., 2010). Under the guidance of Fehlings, Vaccaro and Dvorak, 50 neurosurgical and orthopedic spine surgeons developed novel methods to uniformly classify spinal injuries and set up the definition of 'early' as surgery <24 h.

Between 2002 and 2009, Fehlings et al. conducted the STASCIS study, (Fehlings et al., 2012) a large, prospective multicenter cohort study on the effect of early surgery (<24 h) on neurological outcome in cervical SCI patients. The study found early surgery to be safe and potentially beneficial for neurological recovery, reshaping the general perceptions on surgery. Still, due to the significant differences observed between the early and late cohorts in the STASCIS study and the variable effects reported in subsequent studies, (Rahimi-Movaghar et al., 2014; Wilson et al., 2012; Biglari et al., 2016; Liu et al., 2015) some continued to express skepticism, (Ter et al., 2018; van and Middendorp, 2012) especially in complete SCI.[53] Recent studies, however, have shown a significant beneficial effect of early surgery in complete SCI (Wengel et al., 2020; Ter et al., 2019; Bourassa-Moreau et al., 2016; ter et al., 2022). Moreover, a recent study combining data from four major prospective SCI multicenter cohorts demonstrated that surgery <24 h led to an improvement of 23.7 motor points compared to 19.7 in the late cohort ($p = 0.0006$) (Badhiwala et al., 2021). Subsequent smaller studies yielded similar positive results from early surgery; however, high-quality evidence remained lacking. Not all patients will recover neurologically despite early surgery, raising questions about patient-specific factors and treatment variability. The SCI-POEM group performed a large European prospective cohort study on the impact of surgical intervention <12 h versus late (12 h–14 d) on the recovery of lower extremity motor score (LEMS) at 12 months, (Hosman et al., 2023) but found no significant differences. Unfortunately, significant baseline differences in age, severity and level of the injury between the cohorts may have affected interpretation. Nevertheless, such imbalances are to some extent almost inevitable in prospective observational studies. Interestingly in this cohort, patients with severe neurological injuries (i.e. AIS A) more frequently underwent surgery in the "early" timeframe than patients with less severe injuries (i.e. AIS D). Such imbalance was also observed in the STASCIS trial, where more patients with severe injuries underwent surgery <24 h of injury (57.7% were AIS A/B in the early surgery group while only 38.2% were AIS A/B in the late surgery group). Consequently, this again sparked debates and controversy regarding the influence of surgical timing on neurological recovery.

Apart from investigating more urgent timeframes (Jug et al., 2019; Wutte et al., 2020; Mattiassich et al., 2017)–(Jug et al., 2019; Wutte et al., 2020; Mattiassich et al., 2017), the significance of adequate decompression is being reconsidered, emphasized by Aarabi et al., who analyzed neurological recovery, based on the extent of decompression, by assessing the presence of cerebrospinal fluid around the spinal cord on post-operative MRI scans (Aarabi et al., 2017). This study showed that in patients with "complete decompression", 58.9% improved compared to only 18.5% when complete decompression was not achieved on MRI. Performing a posterior laminectomy, in addition to an anterior approach, increased the rate of successful spinal cord

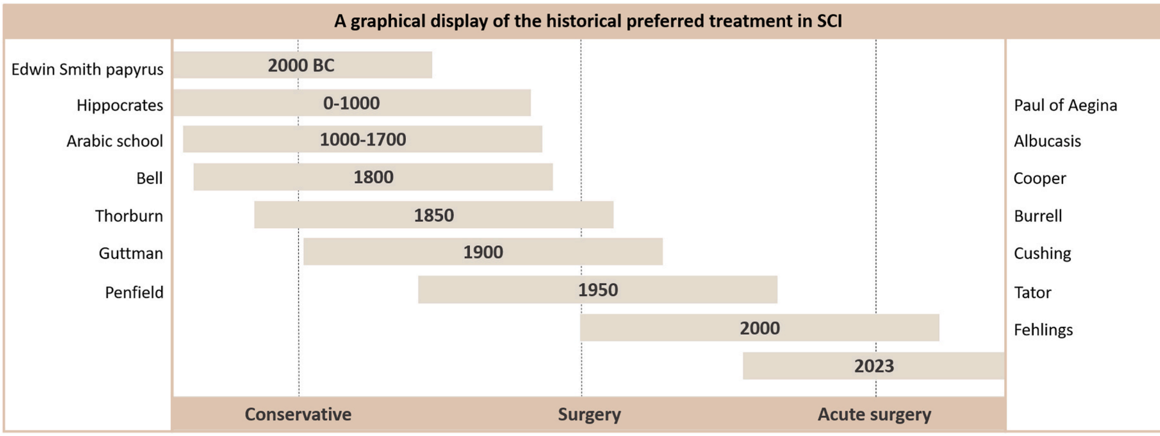

Fig. 3. A historical graphical display of the preferred treatment in SCI.

decompression from 46.8 to 72%, with more levels of laminectomy increasing the likelihood of a complete decompression (Aarabi et al., 2019). However, the role of sufficient decompression remains unclear. Currently, the DISCUS (Duroplasty for Injured cervical Spinal Cord with Uncontrolled Swelling) trial is reexploring whether ongoing compression of the spinal cord by the dura affects neurological recovery (Phang et al., 2015). In this prospective multicenter randomized controlled trial in severe cervical SCI at major UK spinal injury centers, patients are randomly assigned for a laminectomy and expansion duroplasty or laminectomy alone. The preliminary reports show that expansion duroplasty can enhance spinal cord perfusion pressure in severe SCI (Phang et al., 2015). However, thus far it remains unclear whether this intervention impacts neurological outcome. These studies underscore the ongoing need to identify the optimal individualized treatment for each SCI patient.

7. Reflection on the past

The substantial impact of SCI on patients lives, as well as their families, has driven many physicians to explore ways to improve clinical outcomes (Fig. 3). In the past, SCI was considered fatal, leading many to believe that treatment was futile. Due to the endless efforts of many pioneers, significant advancements have been made in reducing case fatality, primarily by addressing secondary complications. As survival improved, the focus shifted to enhancing neurologic function, particularly through surgical intervention. Historically, surgical outcomes were frequently disappointing, but advances in anesthesia and antisepsis improved surgical safety. Moreover, a better understanding of SCI led to more precise surgical indications, such as suturing a transected spinal cord being ineffective, and decompression without fusion in an unstable spine resulting in severe secondary deformities. Due to unfavorable outcomes in complete SCI, many surgeons avoided performing any surgery, let alone expeditious decompression. Recent studies have changed this paradigm, at least for cervical injuries. Advances in imaging have revolutionized the diagnosis of SCI, allowing for precise localization and assessments of the effects of trauma and continuous compression on the spinal cord. This has formed the basis for a time-sensitive approach in SCI, supported by experimental animal studies. Unfortunately, these findings have not yet translated into clinical practice, prompting further investigation to bridge this discrepancy.

Over the years, our understanding has evolved due to the effort of many surgeons analyzing their SCI patient cohorts, mostly retrospectively. It became apparent that the severity of initial neurological injury is linked to neurological recovery. While recovery without surgery is possible, a mounting body of evidence suggests that surgical decompression may improve recovery more compared to a conservative approach. The impact of surgical timing on neurological recovery remains a debated topic, with an increasing number of studies suggesting a clear relation, although high-quality evidence is still lacking. This raises similar questions surgeons have asked before: Is our definition of 'early' sufficiently early? Is the definition of a positive outcome sensitive enough? Is there necessity to decompress the injured spinal cord at all? Through advancements in identifying patient- and treatment-specific factors and collaboration in prospective international registries, we hope to address these longstanding questions, which have remained unanswered over the past centuries.

Author contribution

PVTW was responsible for the study conceptualization, literature search and analysis, writing of the paper and final approval of the manuscript. FR contributed to the study conceptualization, literature search and analysis, writing of the paper and final approval of the manuscript. CYA was responsible for the literature analysis, critical revision of the paper and final approval of the manuscript. MGF was responsible for the study conceptualization, critical revision of the paper and final approval of the manuscript. BKK was responsible for the study conceptualization, critical revision of the paper and final approval of the manuscript. WPV contributed to study conceptualization and critical revision of the paper and final approval of the manuscript. FCO was responsible for the study conceptualization, literature search and analysis, writing of the paper and final approval of the manuscript.

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Declaration of competing interest

None.

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