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History

The historical evolution of the management of spinal cord injury

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ABSTRACT

The history of spinal cord injury (SCI) is long and fascinating. From Ancient Egypt to the current day, SCI has gradually shifted from being seen as an inevitably fatal condition, to one most amenable to treatment, albeit not yet cure. Several controversies have paved the path of this condition's history, from the question of whether to treat, to the optimal timing of surgical intervention, to the potential of recent novel therapies. This article traces the major developments in the management of SCI, in addition to many broader historical developments relating to SCI.

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Surgical intervention, coupled with rehabilitation and complication-prevention, remains the mainstay of treatment for spinal cord injury (SCI). Future decades hold promise that this may give way to an actual cure. As several promising avenues of SCI research are pursued, it is a prudent juncture to review the historical development of this field. Table 1 provides a timeline of important milestones.

The history of the treatment of SCI is marked, more than anything else, by controversy. The question of whether SCI was at all amenable to treatment was contentious for millennia, whereas for the past two centuries the issue of contention has shifted heavily to whether it should be treated with aggressive surgical intervention or non-surgical medical management. More recently, the focus has begun to shift more towards the question of the ideal timing of surgical intervention, a controversy that remains alive today.

The known history of SCI can be traced into antiquity, to the earliest known record of medicine and surgery – the Edwin Smith Papyrus – which is thought to have been written in Egypt around 2500–3000 Before Common Era (BCE).[1–3] Although it describes techniques of spinal surgery, the document expressly labels SCI as an "ailment not to be treated", a dogma that predominated for many centuries.

The first references to SCI in classical antiquity come from the works of Homer.[4,5] The Greeks appear to have pioneered the treatment of SCI, with Hippocrates performing external reduction for the condition.[1,2,6,7] Hippocrates was also the first to raise the issue of preventing SCI-associated complications, describing techniques for ulcer prevention. SCI research had its genesis in Roman times, with Galen's pioneering experiments into spinal cord levels.[5,8] However, it was not until the time of the Byzantine Empire that surgical intervention for the condition was introduced, with Paul of Aegina first performing surgical decompression in the 7th Century Common Era (CE).[2,4,6,9] He also introduced a forerunner to spinal fixation in the form of splinting. Despite these advances, many remained resigned to the sentiments of the Edwin Smith Papyrus with regards to the ultimately fatal nature of SCI, including the great Persian physician Avicenna, as well as the Frenchman Ambroise Pare much later in the 16th Century.[2,4,6,9,10]

The issue of the timing of intervention for SCI, one that dominates in the present context, first appears in the work of Roland of Parma, Italy, who identified the importance of prompt intervention in 1210 CE.[6] The idea of open reduction of spinal fracture dislocation did not come until the 16th Century.[5,11] By the time of the late renaissance, knowledge of the spinal cord and SCI had advanced considerably, with Blasius publishing the first work with the spinal cord as its sole subject in 1666.[12,13] Surgery for patients with SCI became more widespread in the 18th Century, particularly in France,[5,6] although the hopeless prognosis still prevailed. This attitude came to prominence at the Battle of Trafalgar, in 1805, with the resigned death of Lord Admiral Horatio Nelson after suffering a SCI.[1]

Not long after the Napoleonic age, arguably the most fierce and foundational debate in the treatment of SCI arose. From 1824, British surgeons Sirs Astley Cooper and Charles Bell bitterly argued over the merits of laminectomy for SCI.[1,7,9,14,15] Cooper boldly reasoned that, given the fatal nature of the condition, nothing could be lost by attempting surgery. However, Bell contended that such intervention unnecessarily risked death and further spinal cord damage, believing that continued pressure on the spinal cord was not a mediating factor in the nature of the injury, and his views were more in line with the mainstream.

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Table 1
A timeline of important events in the history of spinal cord injury (SCI)

Date	Location	Person(s)	Event [ref]
c. 3000–2500 BCE	Egypt	Unknown	The first known record of SCI (and indeed medicine and surgery), the Edwin Smith Papyrus, described SCI and paraplegia in detail. Describes surgery for spinal trauma without SCI, although advises against surgery for SCI, describing it as an 'ailment not be treated'.[1–3]
c. 700–800 BCE	Greece (?)	Homer	The *Iliad* described two incidences of SCI caused in battle, the first caused by Achilles. The *Odyssey* described a character who broke his neck after falling from a roof inebriated, and died as a result.[4,5]
c. 460–370 BCE	Greece	Hippocrates	Performed traction in order to reduce SCIs, describing the method in detail, and arguing against open reduction. Also described the anatomy of the spine, and recommended techniques to prevent and treat ulcers.[1,2,6,7]
c. 25 BCE–50 CE	Rome	Aulus Cornelius Celsus	Was the first to recognise that injury to the spinal cord was the mediating factor in the effects of spinal injury. Distinguished between cervical and lower SCI. Advocated Hippocrates' traction technique for vertebral dislocations with incomplete injuries.[4–8]
c. 129–210 CE	Rome	Galen	Pioneered spinal cord research and experimentation. Demonstrated that transection of the cord at a particular level caused particular patterns of paralysis and anaesthesia below that level, and first described what is now known as Brown-Séquard syndrome. Recommended reduction by traction for SCI.[5,8]
c. 625–690	Greece	Paul of Aegina	Described and performed the use of a windlass for reduction of dislocation, along with splinting of the spine. Pioneered decompression techniques, particularly laminectomy, and was the first to perform this as a routine procedure.[2,4,6,9]
c. 980–1037	Persia	Avicenna	Advocated stabilisation and reduction in less serious SCI cases, but essentially maintained that SCI with paralysis was inevitably fatal and did not recommend surgical intervention.[2,4,9]
1210	Italy	Roland of Parma	Published his book on surgery (at one of the first re-established medical schools at the time), encouraging the use of manual extension for spinal fractures. Was the first to emphasise the importance of early intervention for SCI.[2,6,9]
1267	Italy	Theodoric of Cervia	Published a surgical work advocating meticulous techniques. Pioneered a primitive form of aseptic technique, and described conditions for good wound healing.[4]
1564	France	Ambroise Paré	Wrote the *Ten Books of Surgery*, recommending laminectomy for spinal cord compression, and detailing methods of reducing dislocation, namely manual reduction and splinting. Was still resigned to the injury being ultimately fatal.[2,6,10]
c. 1533–1619	Germany	Hieronymus Gabricius ab Aquapendente	Suggested open reduction of spinal fracture dislocation. Devised a technique for arresting associated haemorrhage.[2]
c. 1560–1634	Germany	Fabricius Hildanus	Developed a novel method for closed reduction of cervical fracture dislocations, involving forceps. Introduced the idea of performing open reduction in cases of failed closed reduction.[5,11]
1666	Netherlands	Gerard Blasius	Published *Anatome medullae spinalis, et nervorum inde proventium*, the first work written solely about the spinal cord. First distinguished between grey and white matter.[12,13]
1750s–1760s	France	Geraud and Louis	Two cases were reported where projectiles were removed from the spines of injured patients, causing at least partial recovery from paraplegia.[6]
1796	France	Pierre-Joseph Desault	Advocated surgical decompression for SCI, even in cases without vertebral fractures.[5]
1800	United Kingdom	Humphrey Davy	Discovered nitrous oxide's anaesthetic properties, and recommended its use in surgical procedures.[19]
1805	Cape Trafalgar	Lord Admiral Nelson	Suffered a SCI from a sniper's bullet, and his ship's surgeon told him "nothing can be done for you".[1]
1815	United Kingdom	Henry Cline	Performed and recommended laminectomy for fracture dislocations.[6]
1823	United Kingdom	Sir Astley Cooper	Identified the effects of SCI at different levels and corresponding prognoses, he recorded SCI patients living as long as 2 years and being rehabilitated. Promoted laminectomy as treatment, reasoning that nothing was to be lost by attempting surgical intervention given the fatal nature of the condition.[1,2,14]
1824	United Kingdom	Sir Charles Bell	Vehemently opposed Cooper's views on laminectomy, arguing that continued pressure was not the cause of damage to the spinal cord, and that intervention unnecessarily increased the risk of death while potentially further damaging the spinal cord (his assessments received wide acceptance). Identified different types of paralysis, and described renal complications as the cause of death in paraplegia.[7,9,15]
1828	United Kingdom	James Blundell	Performed the first successful human-to-human blood transfusion to treat haemorrhage.[16]
1829	United States	Alban Gilpin Smith	Performed the first successful lumbar laminectomy.[5]
1841	United Kingdom	Marshall Hall	Introduced the term 'spinal shock'.[72,73]
1846	United States	William Morton	First used ether as a surgical anaesthetic.[17]
1847	United Kingdom	James Simpson	Discovered advantages of chloroform as an anaesthetic and introduced it into clinical practice.[18]
1847	Hungary	Ignas Semmelweis	Encouraged hand-washing and clean technique as methods of reducing rates of infection and demonstrated their effectiveness.[1,22]
1852	Netherlands	Antoninius Mathijseu	First immobilised a spinal fracture using a plaster cast.[11]
1856	France	Pierre Marie Edouard Chassaignac	Introduced wound drainage using rubber tubes.[7,23]
1867	United Kingdom	Joseph Lister	Promoted disinfection to reduce rates of surgical infections, publishing *On the Antiseptic Principle in the Practice of Surgery*[21]
1876	France	Just Marcellin Lucas-Championniére	Published *Antiseptic Surgery*, the first authoritative text on the topic.[74]
1878	Germany	Robert Koch	Established the role of bacteria in wound infection.[20]
1881	United States	James Garfield (US President)	Died 80 days after being shot in the spinal cord.[1]

(*continued on next page*)

Table 1 (*continued*)

Date	Location	Person(s)	Event [ref]
1881	United Kingdom	Sir William Gull	Coined the term quadriplegia for what was previously called cervical paraplegia.[6]
1887	United Kingdom	Herbert Burrell	Pioneered the use of fixation by a plaster jacket following traction or laminectomy.[6,11,25,26]
1890	United States	William Halsted	Introduced rubber gloves in surgical procedures.[24]
1891	United States	Bethold Hadra	Achieved the first surgical immobilisation and fusion of the spine, using wires attached to the spinous processes.[27,28]
c. 1848–1900	Germany	Wilhelm Wagner	Pioneered practical treatment of spinal injuries, publishing a seminal book on the subject, which included indications for surgery and many measures for minimising complications, although opposed surgical intervention. Described a technique of reducing spinal fractures involving continued extension for many weeks. This was conducted systematically on a large patient cohort. Was able to rehabilitate and mobilise many patients.[2,7,9,75]
1895	Germany	Wilhelm Rontgen	Discovered the x-ray.[33]
1902	Italy	Lorenzo Bonomo	Introduced hemilaminectomy.[6,29]
1905	United States	Harvey Cushing	Described indications and contraindications for surgery for various types of spinal injury.[6]
1908	Germany	Fritz Lange	Used internal fixation to return spinal function. Steel wires coated with tin were placed on either side of the spinous processes, were fastened to them with silk, and were found to result in faster healing.[30–32]
1911	United States	Alfred Reginald Allen	Developed a standardised model for experimentally producing SCI, using a system of graded weights that were dropped. Postulated the concept of secondary injury in SCI. Promoted the concept of early decompression following SCI.[5,42]
1913	United States	Henry Ford	Began mass production of the automobile, which would become one of the main causes of SCI.[76]
1914–1918	Europe	–	The First World War saw a dramatic increase in SCI cases, with *de facto* multidisciplinary spinal units being established by the UK, Germany, and France, although high mortality was reported (these closed down following the war).[9]
1915–1916	United Kingdom	George Riddoch	Developed a system of medical care for SCI patients in a new Royal Army unit that dramatically improved the survival rate (from less than 10% to almost 90%).[77]
1918	United States	Charles Frazier	Published the book *Surgery of the spine and the spinal cord*, providing a detailed statistical analysis of the outcomes of surgical intervention, to which he was opposed.[2,9,78]
1921	France	Jean-Athanase Sicard and Jacques Forestier	Introduced the technique of myelography with lipiodol.[34]
1924	United States	Von Lackum and DeForest-Smith	Performed the first anterior spinal surgery.[45,79]
1929	United States	Alfred Taylor	First used the technique of halter traction, followed by immobilisation by a plaster cast then a neck brace.[11,80]
1929	United Kingdom	Alexander Fleming	Discovered penicillin and its growth-inhibiting effect on certain bacteria.[81]
1936	United States (Boston)	Donald Munro	Realised (essentially for the first time) that successful treatment of patients with spinal injuries was feasible and worthwhile. Started the first spinal cord unit, providing holistic care to prevent complications and facilitate rehabilitation to allow societal reintegration. Published extensively from this year onward. Despite being a neurosurgeon, believed that reduction of spinal fractures should be performed by gentle traction rather than surgical intervention (showed mortality to decrease by 30% in the absence of laminectomy).[1,2]
1940	United Kingdom	Chain, Florey, Gardner, *et al.*	Established the chemotherapeutic action of penicillin.[37]
1944	United Kingdom	Sir Ludwig Guttmann	Established the National Spinal Injuries Centre in Stoke Mandeville, introducing a multidisciplinary approach to treatment and rehabilitation.[2,9]
1937	United States	Donald Munro	Introduced tidal drainage (a mechanical method of filling the bladder with irrigating fluid), preventing many problems in SCI patients, most notably UTI.[35,36]
1945	Europe	General George Patton (US Third Army)	Sustained a cervical SCI in a motor vehicle accident, and refused all treatment, believing that there was no cure for SCI.[1]
1950	United States	Ernest Bors	After developing a paraplegia management program at a military hospital during the war, established a SCI centre at a veterans hospital in California, which became the leading centre of its kind.[2,9]
1954	United States	–	American Paraplegia Society established (now publishes the *Journal of Spinal Cord Medicine*).[6]
1954	United States	Isadore Tarlov	Used an experimental model in dogs to demonstrate that early decompression in SCI improves neurological outcome.[43]
1954	Australia	George Bedbrook	Established the first Australian spinal injury unit, in Perth.[1]
1958	United States	Paul Harrington	Presented his newly-developed Harrington instrumentation system of rods and hooks, which provided distraction and compression. Originally intended to treat scoliosis, as its popularity expanded, so did its applications, becoming used in traumatic spinal fractures.[1,32,44–46]
1961	United Kingdom	–	International Medical Society of Paraplegia established (now International Spinal Cord Society, and publishes the journal *Spinal Cord*).[40]
1964	Australia	Allen Dwyer	Designed the Dwyer anterior instrumentation system involving screws that would cross vertebral bodies, associated with plates.[32,45,47,48]
1966	United States	Paul Harrington	Designed a pedicle screw (for use in spondylolisthesis), which provided three-column support and greater biomechanical strength.[32,45]
1967	Australia	Patients at Prince Henry Hospital, Sydney	Australian Quadriplegic Association established (now Spinal Cord Injuries Australia).[41]
1969	United States	Thomas Ducker and Harold Hamit	Based on animal studies, proposed steroid administration for SCI patients within 3 hours of injury.[5,57]
1970	Australia	–	The government of the State of Victoria passed the first legislation worldwide making the wearing of seatbelts compulsory for drivers and front-seat passengers.[82]

Table 1 (*continued*)

Date	Location	Person(s)	Event [ref]
1973	United States	–	American Spinal Injury Association (ASIA) established.[83]
1973	United States	–	*Rehabilitation Act* introduced.
1974	Australia	–	*Handicapped Persons' Assistance Act* introduced.
1973	United Kingdom	Godfrey Hounsfield	Introduced computed tomography (CT) for medical imaging.[52]
1970s	United States	Erich Keueger	As National Director of the Veterans Administration, initiated physician traineeships in the field of SCI care.[6]
1970s	Germany	Klaus Zielke	Improved the Dwyer anterior system to produce the Zielke system, with the addition of a semi-rigid rod and an outrigger.[32,45,50]
1976	Mexico	Eduardo Luque	Introduced the Luque instrumentation system of sublaminar wiring for posterior segmental fixation of the spine, which became widely used in conjunction with Harrington rods.[32,49]
1977	United States	Peter Mansfield (and colleagues)	First magnetic resonance imaging (MRI) scan of *in vivo* human anatomy.[51]
1980s	United States	Emanuele Manerino	Established a fellowship program for training in SCI care.[6]
1980s	–	Various	Development of MRI technology for clinical applications.[51]
1981	–	–	International Year of the Disabled Person.
1983		Norman et al.	The first reported use of MRI for examination of spinal cord lesions, with mention that the modality would likely become the imaging procedure of choice.[53]
1980s	France	Yves Côtrel and Jean Dubousset	Developed the CD system of fixation, which involved cross-linked double rods and multiple hooks that could be placed in many sites along the rods. Allowed for segmental fixation and correction in three-dimensions.[7,32,45,84]
1990	United States	Bracken et al.	First randomised control trial of pharmacological intervention in the management of SCI, namely methylprednisolone and naloxene.[1,58]
1990	United States	Flanders et al.	Findings on MRI found to correlate with degree of neurological deficit in SCI patients.[85]
1990	United States	–	*Americans with Disabilities Act* introduced.
1992	Australia	–	*Disability Discrimination Act* introduced.
1995	United States	Christopher Reeve	Became a quadriplegic after a horse accident, becoming a strong lobbyist for spinal cord injured patients.[86]
2005	United States	Keirstead et al.	Demonstrated that transplanted human embryonic stem cell-derived oligodendrocyte progenitor cells enhanced remyelination and improved neurological function in the context of spinal cord injury in a rat model.[87]
2008	Australia	Mackay-Sim et al.	Phase I/IIa trial of transplantation of autologous olfactory ensheathing cells into spinal cord injured patients concluded that the procedure is safe.[64]
2009	United States	–	United States Food and Drug Administration gave approval to trial of human embryonic stem cells therapy for spinal cord injury.[63]

BCE = Before Common Era, c. = circa, CE = Common Era.

During the 19th Century, numerous advances in fields related to surgery would eventually render surgery for SCI a more appropriate treatment modality. These included blood transfusion,[16] anaesthesia,[17–19] antiseptic technique,[20–22] wound drainage,[23] and surgical gloves.[24] The end of the century also saw several developments in spinal fixation. In the United Kingdom, Burrell used a plaster jacket following surgery for SCI,[6,11,25,26] while in the United States, Hadra pioneered internal fixation.[27,28] The major spinal surgical advances were in the introduction of hemilaminectomy by Bonomo,[6,29] and the improvement of fixation technique by Lange[30–32] in the first decade of the 20th Century. Around this time, medical imaging had its genesis, with the discovery of X-rays in 1895.[33] Imaging would soon become pivotal in SCI diagnosis, particularly after the technique of myelography was developed in 1921.[34]

Although spinal units arose transiently during the First World War along with the skyrocketing of patients with SCI at that time, it was not until 1936 that Donald Munro established the first permanent spinal cord unit in the United States. Ludwig Guttman did the equivalent in the United Kingdom as the Second World War drew to a close. On opposite sides of the Atlantic, these two men did much to revolutionise the treatment of, and attitude toward, SCI, developing multidisciplinary programs focused on holistic care and rehabilitation.[1,2,9] Novel techniques were developed to prevent SCI complications, such as tidal drainage to prevent urinary tract infection.[35,36] Also, by the end of the Second World War, antibiotics were available,[37] allowing this new breed of SCI physician to deal with the many infections associated with the condition. As well as revolutionising medical management, the advent of antibiotics meant that the prospects of surgical intervention were greatly improved. However, such interventional was still not seen as worthwhile by those such as Munro.

Not until this point did SCI begin to leave behind its reputation as an ultimately fatal condition. Before the 1940s, most patients with SCI in the United States and United Kingdom died within a few weeks of injury; however, their average life expectancy increased to around 10 years by the late 1940s. This would double by the 1950s.[38] With these increases in life expectancy, the population of patients with SCI increased steadily, as did their expectations about quality of life.[38,39] Affected patients became increasingly well organised, and structures soon developed around SCI care, including the American Paraplegia Society in the 1950s, the Australian Quadraplegia Association (now Australian Spinal Cord Injuries Australia) and the International Medical Society of Paraplegia in the 1960s, and SCI care traineeships and the American Spinal Injury Association (ASIA) in the 1970s.[6,40,41] The focus of SCI advocacy would slowly shift from the medical aim of achieving survival to the political aim of achieving social equality.

The concept of ''secondary injury'' in SCI was postulated by Allen in 1911.[5,42] Since then, progress in elucidating the precise pathology of this phenomenon has been slow, and our understanding remains very incomplete even today. Nonetheless, treatment modalities to date have focused on the limitation of this secondary injury.

It was in 1954 that a pioneering animal study by Tarlov first established the benefit of early decompression in improving neurological outcome after SCI,[43] lending some evidence for early surgical intervention. Paul Harrington, the man who would lend his name to probably the most well-known and widely used spinal instrumentation system, first presented that system in

1958.[1,32,44–46] Over the following decades, advances in both anterior and posterior fixation systems came at a fast pace, with the Dwyer, Zielke, Luque, and CD systems being among the most prominent.[32,45,47–50] With these new systems, successful and secure biomechanical fixation became increasingly feasible. Alongside these developments came a revolution in medical imaging, in CT scanning in the 1970s, and MRI in the 1980s.[13,51–53] While CT imaging remains the preferred method for assessing fractures and compressive bony fragments associated with traumatic SCI, it was not until the development of MRI that pathology of the spinal cord itself could be effectively visualised.[54] With much improved resolution in recent decades, MRI remains the definitive imaging modality for evaluating SCI. Despite surgical and radiological advances, the most recent systematic review of spinal fixation and decompression surgery concluded that there is insufficient evidence about the benefits and harms of such intervention, given a lack of well-designed, prospective controlled trials.[55] However, recently published results of the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS) show that decompression within 24 hours is associated with a significantly improved neurological outcome.[56] Considering that surgery has been the mainstay of SCI treatment for many decades, it is surprising that the evidence for its effectiveness until now has been so limited. This is partly symptomatic of the condition's low incidence.

In 1969, Ducker and Hamit found that early pharmacological treatment with steroids in animals with SCI improved neurological outcome, presumably due to a limitation of secondary injury.[57] To the present, numerous animal and human studies have sought to confirm this phenomenon for both surgical and pharmacological interventions. The effect of methyprednisolone in humans was confirmed in a randomised trial by Bracken et al. in 1990.[58] However, methyprednisolone's merits have since been brought into question due to its complication profile and its use has diminished.[59]

Several advanced functional treatments have become available to SCI sufferers in recent years, including tendon transfer to improve hand grasp, and functional electric stimulation (FES) to allow reactivation of limb, bowel and bladder muscles.[59] Additionally, recent developments in assistive technologies, particularly in the area of computing, have provided the potential for much improved quality of life.[60,61]

As our understanding of the complicated pathophysiology of SCI has advanced exponentially in recent years, so the avenues for potential therapies have become numerous. These developments are the subject of a recent review,[62] and are beyond the scope of this article. Of particular interest are those therapies involving cell transplantation. Olfactory ensheathing cells and human embryonic stem cells currently hold the most promise for a therapy based on enhanced regeneration, and trials involving both are currently underway.[63,64] Extensive reviews of the numerous completed, ongoing and planned clinical trials into SCI therapies have been published.[65,66]

The epidemiology of SCI has only become well illuminated in recent decades. A recent review of international epidemiological studies since 1995 found reported incidences to range from 10.3 to 83 per million.[67] In the United States, this figure is estimated to be approximately 40 per million, with a prevalence of about 265,000 individuals.[68] In Australia, for the financial year 2007–2008, 362 new patients with SCI were admitted to the country's six spinal units, with 385 of these being traumatic. This equates to an age-standardised incidence of persisting traumatic SCI of approximately 15 new cases per million population, with an estimated SCI population of about 9000 individuals.[69,70] Despite these small rates, the debilitating nature of SCI renders it one of the most costly medical conditions, both in terms of its effects on the lives of sufferers, and its associated economic costs. In the United States, the estimated direct lifetime costs for a person who becomes a "high tetraplegic" at the age of 25 years is US$4,373,912.[68] In New South Wales, the estimated annual personal care and equipment costs for a ventilator-dependent SCI sufferer is estimated to be approximately AU$300,000, while the ongoing costs of caring for the Australian SCI population is around AU$500 million per annum.[71] The enormous personal, social and financial costs of SCI heighten the importance of achieving the next major advance in SCI treatment.

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