History and evolution of surgical treatment for spasticity: a journey from neurotomy to selective dorsal rhizotomy

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The evolution of neurosurgical approaches to spasticity spans centuries, marked by key milestones and innovative practitioners. Probable ancient descriptions of spasmodic conditions were first classified as spasticity in the 19th century through the interventions of Dr. William John Little on patients with cerebral palsy. The late 19th century witnessed pioneering efforts by surgeons such as Dr. Charles Loomis Dana, who explored neurotomies, and Dr. Charles Sherrington, who proposed dorsal rhizotomy to address spasticity. Dorsal rhizotomy rose to prominence under the expertise of Dr. Otfrid Foerster but saw a decline in the 1920s due to emerging alternative procedures and associated complications. The mid-20th century saw a shift toward myelotomy but the revival of dorsal rhizotomy under Dr. Claude Gros’ selective approach and Dr. Marc Sindou's dorsal root entry zone (DREZ) lesioning. In the late 1970s, Dr. Victor Fasano introduced functional dorsal rhizotomy, incorporating electrophysiological evaluations. Dr. Warwick Peacock and Dr. Leila Arens further modified selective dorsal rhizotomy, focusing on approaches at the cauda equina level. Later, baclofen delivered intrathecally via an implanted programmable pump emerged as a promising alternative around the late 1980s, pioneered by Richard Penn and Jeffrey Kroin and then led by A. Leland Albright. Moreover, intraventricular baclofen has also been tried in this matter. The evolution of these neurosurgical interventions highlights the dynamic nature of medical progress, with each era building upon and refining the work of significant individuals, ultimately contributing to successful outcomes in the management of spasticity.

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Spasticity has been an observed phenomenon for much of recorded history, and its origins and treatments have puzzled physicians for just as long. In the modern era of medicine, neurosurgical techniques have consistently provided the most reliable progression of treatment for spasticity and alleviation of its painful effects. The first breakthroughs came in the late 19th century, when neurosurgery began emerging as a standalone discipline. The first neurosurgical procedures to control spasticity were aimed at the peripheral nerves (neurotomy), followed by lesioning of spinal roots (dorsal rhizotomy) and the spinal cord (myelotomy). The general success of these procedures was sometimes eclipsed by the complications and adverse effects of loss of function in unaffected areas of the body. By the mid-20th century, neurosurgical treatments for spasticity included more selective lesioning processes based on patient selection and spasticity symptoms. Greater understandings in physiology and spasticity allowed the dorsal root entry zone (DREZ) to become a focal point for selective surgical procedures. The resulting procedure, called DREZotomy, interrupted all tonogenic fibers and was able to control spasticity (Fig. 1). Likewise, neurosurgeons worked to mitigate the adverse effects of earlier dorsal rhizotomies by selectively sectioning and preserving various rootlets. The techniques made use of new technologies, which reduced some of the historic complications associated with this type of neurosurgical intervention. The process of selective dorsal rhizotomy has been modernized not just through these technologies, but also by changes in sectioning with a focus on operat-
ing in the cauda equina over the traditional conus medullaris.

Besides these novel techniques, baclofen delivered intrathecally via an implanted programmable pump emerged as a promising alternative around the late 1980s, pioneered by Richard Penn and Jeffrey Kroin and then led by A. Leland Albright. The indications for intrathecal baclofen (ITB) include severe spasticity with a positive baclofen test and association with spinal cord injury, multiple sclerosis, and cerebral causes such as cerebral palsy or traumatic brain injury in patients older than 4 years. Moreover, intraventricular baclofen has also been tried in this matter. Stereotactic lesioning techniques and neurostimulation, on the contrary, have failed to prove some consistent benefit.

This historic accounting of the evolution of neurosurgical treatment of spasticity acknowledges both key innovators and milestones in the surgical management of spasticity, culminating in the effectiveness of the most up-to-date procedures.

Ancient Descriptions of Spasticity

Spasmodic conditions were an observed phenomena throughout medical history. Looking as far back as Classical Greece, obscure descriptions such as Hippocrates’ “a stiff and painful neck” (traxhlos sklhos) or Pliny the Elder’s rigor cervicis may in fact be descriptors of neuropathologies such as torticollis. Movement disorders have been continuously referenced through the Middle Ages and Renaissance in various other disciplines such as history, art, and literature, but without much distinction due to a lack of unified nomenclature and the underdevelopment
of the field of neuroanatomy at the time. One of the great leaps forward in understanding spasticity and its associated pain came during the 19th century with an initial classification of the condition. It would still require the better part of that century for neurosurgery to diverge from both neurology and psychiatry to produce effective treatments, but the collection and categorization of clinical information early on was an essential step for future interventions.

### 19th-Century Classifications and Interventions of Spasticity

One of the best initial attempts to understand spasticity comes from the work of orthopedic surgeon Dr. William John Little (1810–1894). In 1861 he became the first physician to describe cerebral palsy (although the term would be later coined by Dr. William Osler in 1888). Early in his career, Little had failed to qualify for the Royal College of Surgeons in London, but in a twist of fate, this rejection led him to Berlin where he encountered many pediatric patients and mastered surgical procedures such as tenotomy. His professional experiences led to a unique nexus between bone, joint, and muscle deformities along with disorders of the pediatric neurological system. In retrospect, Little’s unique combination of surgical practice and neurological research can be seen as a first step in a theoretical neurological approach to management of spasticity.

By the middle of the 19th century both British and American surgeons were engaged in a series of trial-and-error interventions to neutralize affected neural pathways in the alleviation of spasticity. Some of the more noteworthy names of the time included the American doctor William Alexander Hammond (1828–1900) and the British doctor Victor Horsley (1857–1916). Prevailing theories at the time prioritized external methods such as pharmacological and shock treatment modalities (such as galvanism). The poor results of such methods inspired surgeons such as Hammond and Horsley to seek out novel invasive therapies that destroyed neural pathways, thus substituting paralysis for abnormal spontaneous movements. Chief among these methods was a process known as “therapeutic nerve stretching.” This sometimes resulted in symptomatic improvement but fell out of favor by the turn of the century. The high morbidity rate and overall poor outcomes of this procedure led to controversy that ultimately helped to usher in stricter protocols for study controls in the Progressive Era.

The groundwork for understanding the pathophysiology of spasticity came via the work of Dr. Charles Sherrington (1857–1952) (Fig. 2). As a neurophysiologist, he had been experimenting on cats since the 1880s in order to understand the associations between hyperexcitability of the stretch reflex and the subsequent loss of inhibitory influences from the descending supraspinal structures. Dr. Sherrington’s description of decerebrate rigidity would lay the foundation for later dorsal rhizotomies.

### The Emergence of Neurotomy and Dorsal Rhizotomy

Surgeons seeking to treat spasticity were concentrated mostly in Western Europe and North America in the latter half of the 19th century. While therapeutic nerve stretching was showing poor results, new methods of sectioning nerves were being implemented. In 1887, Austrian surgeon Dr. Adolf Lorenz (1854–1946) published details of the first neurotomy performed to reduce hip adductor spasticity. In some cases hypertonicity was relieved, however loss of function remained as a major adverse effect. At the same time, Dr. Charles Loomis Dana (1852–1935), an American neurosurgeon (Fig. 3), proposed the first posterior rhizotomy procedure to address spasticity and intractable chronic pain in a letter to his friend Dr. Robert Abbe (1851–1928). Dr. Dana’s reasons for not performing the procedure himself are unknown, although his bibliography shows that he was a prolific researcher and writer having composed classic books such as Diseases of the Nervous System and The Peaks of Medical History. Perhaps due to these commitments, Dr. Dana did not have the time and resources to implement the posterior rhizotomy himself, but he found a capable specialist in his friend Dr. Abbe. Abbe went on to treat a wide range of spasticity using posterior rhizotomy while giving due credit to the original source, always referring to the method as “Dana’s operation.” Dana’s first proposal of the procedure came in 1886, and Abbe’s first operation occurred in 1889. Abbe’s success with the procedure was immediate and well documented over the course of his career. One noteworthy complex case involved posterior rhizotomy at C5–8 and anterior rhizotomy at C7–8 to help control pain and “incessant spasm” (Fig. 4). The results were a great diminishment of pain and spasms in the patient whom Abbe continued to follow up for 16 years after the procedure with a good quality of life. The practice of dorsal rhi-
zotomy rapidly demonstrated to other neurologists and neurosurgeons the efficacy of cutting sensory rootlets to control spasticity and treat pain. The indications for surgical neurotomy in this period were mostly treatments of spasticity of the lower limbs. Tibial neurotomy for spastic foot in hemiplegic patients was able to reduce some spasticity as well as improve motor function by balancing the tone between and against antagonist muscles.14

Simultaneously, in the United Kingdom Dr. William Bennett (1852–1931), citing directly from the work of the aforementioned Horsley, was the first to divide the posterior spinal nerve roots in a patient with uncontrollable spasms in 1888.15 What is significant about these dorsal rhizotomies is that they were the first neurosurgical interventions to yield consistently effective results in the management of spasticity.16 The surgeon who arguably took the practice to its zenith during this time was the German neurologist and neurosurgeon Otfrid Foerster (1873–1941). He improved upon the dorsal rhizotomies of his contemporaries with even higher success rates. In one accounting of dorsal rhizotomies for spasticity, he tabulated 28 cases in which he operated, of whom only 3 patients died, 15 had no relapse at all, and 8 cases relapsed.17,18 Even though rhizotomy flourished under Foerster’s supervision, the practice was no longer the pivotal treatment for spasticity by the 1920s. The sudden decline in retrospect has been explained medically as the procedure being “eclipsed by the spinothalamic cordotomy, then by the stereotactic procedures on encephalic targets, and finally by neurostimulation of the pain inhibitory pathways.”19 Foerster’s career also lost standing among many Western surgeons politically when he became the caretaker of Lenin in the wake of his stroke (in 1922). Other historians cite complications such as major sensory loss, bladder denervation, trophic changes, and proprioception difficulties as undermining dorsal rhizotomy’s otherwise functional treatment for spasticity, which up until then lacked any therapeutic solution.16

The Rise of Myelotomy and the Revival of Dorsal Rhizotomy

During the 50-year period (1920s–1970s) between the peak of dorsal rhizotomy and the emergence of DREZotomy as favored treatments for spasticity, surgery on the spinal cord (myelotomy) came into the forefront. In 1951, Dr. W. Bischof first described the longitudinal myelotomy procedure for the treatment of intractable spastic parapale-
The Innovation of DREZotomy

The resurgence rhizotomy in tandem with Dr. Gros’ innovations reintroduced it into the canon of French neurosurgery. One of his students in particular, Dr. Marc Sindou, would incorporate this exposure into his own practice and eventual thesis at the Neurological Institute Pierre Wertheimer in Lyon (Fig. 5). In addition to the rejuvenation of rhizotomy, a newly proposed theory of pain localization called “gate control” was described in 1965. This theory stated that in each dorsal horn there exists a “gate” responsible for inhibiting or facilitating afferent impulses. One of the authors of the theory, Dr. Patrick Wall (1925–2001), mentored Dr. Sindou and encouraged his interest in the neuroanatomy of the dorsal horn. Sindou was keen to explore pain modulation in this part of the body, particularly by sectioning nerves at the DREZ. Dr. Sindou trained as a doctor in neurophysiology, which also primed him for the innovation of these elements in his inquiry. In Sindou’s thesis, the DREZ region was defined as the central portion of the dorsal rootlet, including the medial part of the tract of Lissauer and layers I to V of the dorsal horn where the afferent fibers terminate and synapse (Fig. 6).

In March 1972, when Dr. Sindou was treating a case of Pancoast-Tobias syndrome, he found an opportunity to implement the DREZ lesioning he had practiced in the laboratory when the patient’s refractory pain required treatment. It was the radiculometameric distribution of the symptoms that led Sindou to consider sectioning at the DREZ, thus giving rise to the first recorded DREZotomy on a living patient. A positive outcome of the first procedure soon led to its replication. In December of that same year, DREZotomy was also performed in a patient with neuropathic pain due to a spinal cord injury. It soon became apparent to Sindou that pain management was not the only benefit of DREZotomy because one of the adverse effects of this surgery was hypotonia, but that such an effect was actually an answer to the management of another serious problem, that of spasticity.

In July 1973 and January 1974, 2 further patients with spasticity successfully underwent DREZotomy procedures (Fig. 7). These original cases and further interventions demonstrated that DREZotomy could be used to control spasticity for the following indications: paraplegia, hemiplegia, and focal dystonia of the limb due to spasticity. Sindou’s original DREZotomy technique utilized a microknife to make a dorsolateral sulcus opening. For DREZotomy to be effective, special care is taken during this procedure to section deeply (5–6 mm) from the dorsal horn to the ventral horn within the spinal cord.

Approaches to Spasticity Through Conus-Level Interventions

Modifying Foerster’s technique, Dr. Gros and his surgeons at the Montpellier school preserved 1 rootlet out of 5, resulting in a notable 75% reduction in spasticity among the monitored 25 patients. Coining this technique as “sectorial posterior rhizotomy,” Gros and his team aimed to selectively retain maximal functional innervation through their topographical rootlet selection.
In the late 1970s, the Italian neurosurgeon Dr. Victor Fasano (1920–1991), hailing from Turin, innovated a fresh approach based on muscle response intensity during dorsal root stimulation. He labeled this technique “functional dorsal rhizotomy.” Responses exhibiting after-discharge contraction patterns or expansive spatial diffusion to muscles beyond the conventional myotome were deemed part of the uninhibited spinal circuits responsible for spasticity. Soon, Fasano began incorporating detailed electrophysiological evaluations during rhizotomy procedures. This was a conus-level approach in the same tradition of Foerster and Gros, wherein he was selectively sectioning fascicles. The new technology allowed him to target only those fascicles contributing to abnormal muscular tone. By using electrophysiological principles, Fasano asserted that patients experienced reduced sensory deficits, diminished weakness, and improved functionality.

The Modern Revival of Selective Dorsal Rhizotomy

While Fasano’s combination of intraoperative electrophysiological stimulation and partial resection of the dorsal root both improved the success rate of dorsal rhizotomies, the selective dorsal rhizotomy site remained almost exclusively in the conus medullaris region. It was the pioneering work of Drs. Warwick Peacock and Leila Arens, neurosurgeons at the University of Cape Town, who revitalized selective dorsal rhizotomy for managing spasticity by modifying it to a cauda equina–level approach. Peacock and Arens opted for a long-segment exposure (L2–5 laminectomy), deviating from short-segment lumbar laminectomy. This was inspired by concerns about the high incidence rates of bladder and bowel deficits associated with the previously favored conus-level approach of others such as Gros and Fasano. The revival of selective dorsal rhizotomy in the lumbosacral region soon became the industry standard for treating spasticity in children with cerebral palsy. By 1986, Peacock was hired by UCLA, to both lead the pediatric neurosurgery program and to introduce lumbar selective dorsal rhizotomy to major clinical centers across the United States. Dr. Sindou endorsed the technique of cauda equina exposure to identify the nerve at the exit foramina but was concerned about the long-segment exposure required by the Peacock technique (L2–S2). Sindou and Georgoulis then developed the keyhole interlaminar dorsal rhizotomy (KIDr) technique in 2014, which results in minimal spinal ligamentous injury and still allows accurate nerve root identification at the exit foraminae. The indications for the modern surgical management of
spasticity are reserved for candidates whose spasticity is harmful and refractory to medications and physical therapy. This includes adult patients who are para-, hemi-, or tetraplegic or who may have severe focalized dystonic components. Children affected with cerebral palsy experiencing progressive deformities in spastic di- or quadriplegia—specifically when botulinum toxin injections or treatments with a cast or orthosis are rendered insufficient—are potential candidates as well.\textsuperscript{14}

**ITB and Intraventricular Baclofen as Promising Alternatives**

Baclofen, a gamma-aminobutyric acid type B receptor

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**FIG. 7.** Operative report of a patient with a left brachial plexus avulsion who underwent a DREZotomy from C7 to T1. The procedure was performed on January 22, 1974. © Marc Sindou, published with permission.
agonist, improves spasticity by inhibiting reflex transmission at the spinal cord. However, oral baclofen’s limited ability to cross the blood-brain barrier results in the need to administer high doses, which yield systemic adverse effects. ITB overcomes this limitation, allowing higher concentrations to reach the spinal cord with fewer adverse effects. Introduced in 1984, ITB demonstrated efficacy in reducing spasticity in patients with multiple sclerosis, leading to its widespread adoption in the late 1980s.

Studies in the late 1980s showcased ITB’s benefits in treating spinal and cerebral spasticity with a spinal and cerebrospinal origin through continuous infusion of 50–800 µg/day, 21–500 µg/day, 10–900 µg/day, or single doses. In 1992, ITB was proposed as an alternative for moderate to severe cases of spastic quadriparesis in children, reserving selective dorsal rhizotomy for mild cases. Subsequent research validated ITB’s effectiveness in treating cerebral spasticity, with mean dosages ranging from 110.6 to 486.5 µg/day, and spinal spasticity. While ITB systems present complications, including catheter, pump, and wound issues, the search for alternatives has led to the exploration of intraventricular baclofen since 2005.

The Brief Rise and Fall of Stereotactic Lesioning Techniques

The history of stereotactic lesioning techniques for spasticity treatment has seen various proposed targets, such as the cerebral cortex, basal ganglia, and cerebellum. Early attempts, such as dentatotomy in 1935, electrocoagulation of the ipsilateral nucleus fastigii in 1960, and pulvinectomy in 1971, showed mixed results. However, these techniques were largely abandoned due to complexity, risks, and limited long-term effectiveness compared to other surgical options.

Neurostimulation Methods: Is There Hope?

As for stereotactic lesioning, basal ganglia structures and the cerebellum have been proposed as targets for deep brain stimulation techniques. Cerebellar stimulation in the 1970s and 1980s demonstrated improvement in spasticity, but hardware malfunctions led to spasticity reappearance. Despite concerns, recent successful series suggest a renewed interest in cerebellar stimulation. Additionally, spinal cord stimulation has proven effective for spasticity secondary to multiple sclerosis. As ITB remains a promising solution for spasticity, exploration into intraventricular baclofen and the revival of cerebellar stimulation highlight ongoing efforts to refine and expand treatment options for spasticity.

Conclusions

The neurosurgical history of the management of spasticity demonstrates that significant physicians have employed crucial methods in physiology and technology for the treatment of spasticity. Initial classifications of spasticity in the early 19th century allowed for the categorization of clinical information, laying the groundwork for future interventions. A series of trial-and-error methods defined much of the remainder of the century, with experiments consisting mainly of external approaches such as pharmaceuticals and shock treatments. However, the limited success of these methods led to a shift toward novel invasive therapies. The groundwork for understanding the pathophysiology of spasticity eventually emerged through the work of Dr. Charles Sherrington, whose contributions laid the foundation for later dorsal rhizotomies. The posterior approach with surgical sectioning was a new foundation on which neurosurgeons began to operate, first with neurotomies, that culminated in arguably the most successful surgeon at the time, Dr. Otfrid Foerster, who achieved high success rates for dorsal rhizotomy. Although myelotomy replaced dorsal rhizotomy in popularity during the early 20th century, dorsal rhizotomy made a comeback thanks to the innovative approaches of Dr. Claude Gros who argued for greater selectivity in the procedure. His work combined with new understandings in physiology and pain led to Dr. Marc Sindou’s evolution of the DREZotomy technique. At the same time, Dr. Victor Fasan-no’s utilization of electrophysiological stimulation assisted in lessening the historic adverse effects associated with dorsal rhizotomy. The modern revival of selective dorsal rhizotomy owes much to Drs. Peacock and Arens, who modified the procedure from a conus medullaris–level approach to a cauda equina–level approach. This approach, with a long-segment exposure, became the industry standard for treating spasticity in children with cerebral palsy. Dr. Sindou’s endorsement of cauda equina exposure and the subsequent development of the KIDr technique by Sindou and Georgoulis have further refined the procedure to higher effectiveness. Simultaneously, ITB has proved to be a solid alternative for spastic quadriparesis, and intraventricular baclofen could overcome the complications related to intrathecal administration. Moreover, cerebellum stimulation seems to be a valid option, but more studies are needed on this matter. It is clear from tracing the trends in medical history related to spasticity that successful outcomes are part of a process of building upon and refining the work of significant individuals over time. From ancient observations to contemporary innovations in neurosurgery, each era has contributed to our understanding and treatment of spasticity, demonstrating the dynamic nature of medical progress.

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