Cerebral palsy is a major neurological problem in children; it occurs in 1 of 500 live births and inflicts lifelong disabilities on those with the disorder. Among several factors contributing to the disabilities of patients with CP is spasticity. This condition affects nearly 80% of patients with CP; and once fully developed, it never resolves spontaneously. It hinders motor tasks in activities of daily living and also causes muscle contractures and orthopedic deformities in growing children. Selective dorsal rhizotomy reduces spasticity in patients with CP; this reduction facilitates the patients’ motor performance and alleviates orthopedic deformities. Several surgical techniques for SDR are currently used. The following is a description of an operation that includes an L1-laminectomy, use of ultrasonography for localization of the conus medullaris, and partial deafferentation of L1–S2 roots with the aid of an operating microscope after EMG examination. We have performed this SDR in more than 1500 children and young adults since 1991.

Patient Selection

The primary beneficiaries of SDR are children with spastic diplegia (the most prevalent subtype of CP in which the lower extremities are affected) in which there is minimal or no involvement of the upper extremities (Table 1). Children with spastic quadriplegic CP, in whom all extremities and the trunk are involved, also benefit from SDR. In spastic hemiplegic CP, spasticity is not a predominant cause of motor impairments, and reduction of spasticity does not greatly improve motor function. Some adults younger than 40 years of age who have relatively mild spastic diplegia and can walk independently are also able to benefit from SDR.

When evaluating a patient, one should first be certain that the motor impairment dates back to infancy and has followed a course of steady improvement rather than progressive deterioration during the preschool years. A careful review of the patient’s perinatal and medical history provided by physicians and therapists is invaluable. A premature birth is considered a positive factor in the selection of candidates for SDR. Findings on neurological examination determine whether spasticity is a major cause or the only cause of muscle hypertonia and whether it significantly hinders motor activities (for example, sitting, crawling, standing, and walking). In addition, the severity of orthopedic deformities and their effects on a patient’s motor performance should be assessed in detail. A thorough understanding of orthopedic problems by the neurosurgeons performing SDR is desirable, although orthopedists and therapists can assist in evaluation.

Radiological evaluation includes x-ray films of the lumbarosacral spine and hips. The spine films may show the presence of lumbar hyperlordosis, scoliosis, spondylolisthesis, and congenital anomalies, whereas the x-ray films of the hips may reveal subluxation and dislocation, deformities that influence the timing of surgical interventions. In children who were delivered at term, an MR image of the head is obtained because diverse abnormalities underlie the diagnosis of spastic diplegia or quadriplegia. In
adults with back pain, an MR image of the spine is obtained to rule out herniated discs and other intraspinal disorders. A gait analysis is not routinely obtained, but it helps to confirm the presence of spasticity before SDR and also to assess changes in motor performance after SDR.

Selective dorsal rhizotomy is not considered appropriate for children younger than 2 years of age because CP cannot be diagnosed with certainty in young children. Dystonia that is concomitant with spasticity is not a contraindication for SDR. Dystonia is exceedingly rare in patients with spastic diplegia but is common in nonambulatory children with whole-body involvement. Dystonia becomes clinically evident by the age of 5 years. In patients with this condition, SDR can improve motor function, and this improvement does not worsen the dystonia. Rigidity, which is also rare in spastic diplegia, cannot be ascertained in the presence of concomitant spasticity. Severe damage to the basal ganglia, as revealed by MR imaging, is considered a contraindication because of the possibility of concomitant rigidity.

A history of multiple orthopedic operations is generally a contraindication for rhizotomy, mainly because of severe muscle weakness and fixed deformities. Patients with severe fixed joint deformities are excluded from SDR because their deformities limit the potential for gains in motor function after rhizotomy. The best example is severe crouch knees due to overstretched or lengthened heel cords after heel cord release procedures. Severe scoliosis is only a relative contraindication for SDR through a single-level laminectomy. Children with increased muscle tone due to severe hydrocephalus, intrauterine and neonatal infections, and head trauma are not candidates for SDR. In general, neuronal migration disorders are contraindications for rhizotomy, but children with typical clinical features of spastic diplegia due to schizencephaly can benefit from the operation.

Preoperative Preparation

Oral midazolam is administered, if deemed necessary. Intubation is performed while the patient is in a state of deep halothane-induced anesthesia; sometimes intubation is facilitated by short-lasting muscle relaxants (for example, atracurium or vecuronium). Anesthesia is induced with thiopental, halothane, and nitrous oxide, and is maintained with fentanyl (10 μg/kg), 1% halothane, and 70% nitrous oxide. Propofol is avoided because it alters EMG activity. The patient receives a dose of an antibiotic agent before a skin incision is made. A bladder catheter is inserted.

Operative Procedure

The patient is placed prone on the operating table so that CSF is pooled rostrally and CSF loss from the intracranial compartment is minimized (Fig. 1). Needle electrodes are placed bilaterally in the adductor longus, vastus lateralis, anterior tibialis, medial hamstrings, and medial gastrocnemius muscles in preparation for intraoperative EMG examinations.

Localization of the Conus Medullaris and a Single-Level Laminectomy

Normally the conus medullaris terminates between the T-12 and L-3 spinal levels. For a laminectomy to be limited to a single level, the conus medullaris must be localized
Surgical techniques of selective dorsal rhizotomy for spastic CP

in several steps with ultrasound before a laminectomy is completed.

In children younger than 10 years of age, the conus medullaris and cauda equina are localized using axial views of the spinal cord on ultrasonography studies obtained through the skin and paraspinal muscles. An ultrasound probe is placed lateral to the spinous process to get axial views of intradural structures at a few levels (Fig. 2A). On axial views, the conus medullaris appears hypoechogenic and circular. The ventral and dorsal roots are attached to the lateral aspects of the conus. Pulsatile movements of the conus are always present. The cauda equina appears as a hyperechogenic mass that also has pulsatile movements (Fig. 2B).

In this age group (< 10 years), the skin incision is made over the interlaminar space where the conus has been localized with ultrasonography. The paraspinal muscles are injected bilaterally with saline solution that contains epinephrine in a concentration of 1:400,000. The interlaminar space is exposed, and the interspinous ligament and ligamentum flavum are removed. The conus is localized on axial and sagittal views obtained using ultrasonography. If ultrasonography reveals that the spinal cord on ultrasonography studies obtained is too tight for the examination, the interlaminar space is enlarged with a Kerrison punch. Two levels of interlaminar space are examined to localize both the conus and cauda equina.

If the conus medullaris and cauda equina are localized, a single-level laminectomy is performed using a craniotome (Fig. 3A) equipped with a B5 attachment (Midas Rex Pneumatic Tools, Inc., Fort Worth, TX). After the lamina is removed, another ultrasonography examination of the laminectomy site is performed to confirm that the conus and cauda equina are situated at the laminectomy site. On this examination, the conus is distinguished from the cauda equina as follows (Fig. 2B): a sagittal examination reveals the conus as a hypodense triangle tapering caudally. The ventral and dorsal spinal roots appear hyperdense. When only a caudal end of the conus is present in the laminectomy area, the sagittal view does not clearly delineate this structure, and an axial view is required. On the axial view, a hypoechogenic circular structure is sought at the center of the dural tube; it is most reliable in localizing the conus. Also, on axial views one can notice a small cleft between the dorsal and ventral spinal roots on the lateral aspect of the conus. This cleft is an important anatomical landmark because it guides the surgeon in separating the dorsal from the ventral roots. Sometimes the patent central canal appears hyperechogenic within the conus.

Even in 2-year-old children, only a single-level laminectomy is needed for SDR. The laminectomy should cover at least 5 mm of the conus so that the dorsal roots are safely separated from the ventral roots at a later stage of the operation. If it is needed for adequate exposure of the conus, one third of the lamina that is immediately rostral to the laminectomy is removed. A wide laminectomy is necessary to expose the spinal nerve roots for EMG testing.

Other neurosurgeons perform SDR through L2–S1 or L1–S1 laminectomy or laminoplasty. The multilevel laminectomy makes SDR easy. Nevertheless, the multilevel laminectomy or laminoplasty, when performed in children with spastic diplegia or quadriplegia, can lead to late spinal deformities, including spondylolisthesis and increased lumbar lordosis or scoliosis. The multilevel laminectomy may carry a higher risk of spinal deformities after SDR in older children and adults than in young children.

Separation of Dorsal From Ventral Roots

After bleeding from the epidural veins and bone is con-
trolled, a dural incision is made. Saline irrigation is not used after the dura mater is opened because it alters EMG responses. An operating microscope is then brought into the field and used during EMG testing and sectioning of dorsal root fascicles. The operating table may be slightly rotated away from the surgeon as the contralateral spinal roots are dissected. The arachnoid membrane is removed, and the conus and filum terminale are identified. At this point, EMG activities are continuously monitored to examine if they are evoked by any movement of the nerve roots. Stretching and pressure on the ventral but not on the dorsal roots evoke EMG activities and often movement of the patient’s lower extremity.

Next, the L-2 spinal roots are identified at the neural foramen, and the L-2 dorsal root is separated from the ventral root (Fig. 3B). The L-2 ventral and dorsal roots are traced back to the conus medullaris until the cleft between these roots is identified. Then the L-2 and adjacent dorsal roots are gently retracted medially, and a cotton patty is placed over the ventral roots (Fig. 3C). The L-1 root is left untouched at this point. Next, the conus and the filum terminale are examined, and the S2–5 sacral roots that exit the conus are identified. The S-2 dorsal root can be bulky, especially in patients with the postfixed lumbosacral plexus, but there is always an abrupt and marked decrease in size of the S-2 root. The individual S3–5 spinal roots appear as thin threads. The dorsal and ventral roots at this level are close together with no intervening space between them, so all of the S3–5 spinal roots are left intact. The lower sacral roots can be identified with a gentle lift at the dorsal roots from the entry zone on the dorsal aspect of the conus. Whenever the surgeon is unsure of the exact identification of the S3–5 spinal roots, then sparing the S-2 dorsal root is prudent.

Once the L2–S2 dorsal roots are identified, a 5-mm-wide blue Silastic sheet (Medtronic Xomed, Jacksonville, FL) is placed around all of the dorsal roots and distant from the conus medullaris (Fig. 3D); the Silastic sheet keeps the L2–S2 dorsal roots safely separate from the ventral and lower sacral roots during the rest of the operation. Before starting EMG testing, the surgeon reexamines three structures to ensure that no ventral root or lower sacral root is on top of the Silastic material: the L-2 foraminal exit; the cleft lateral to the conus between the ventral and dorsal roots; and the S3–5 roots.

**Identification of Individual Dorsal Roots**

A shortcoming of this technique, compared with alternative methods, is difficulty in the identification of individual dorsal roots with certainty. Precise identification of the roots, however, is not critical for SDR because all major lower-extremity muscles in children with spastic CP receive motor innervation from several segments. As had been shown in animal experiments, significant somatotopic organization and sprouting may occur in the spinal cord and brain after deafferentation.

The L-2 dorsal root is readily identified at the neural foramen. The L3–S2 dorsal roots below the conus are close together without a natural separation, so unequivocal identification of the individual root is difficult. Nevertheless, dorsal root fibers of individual segments are roughly identified as follows. First, the dorsal roots are spread on top of the Silastic sheet. The L-3 and L-4 dorsal roots, which are located medial to the L-2 root, are identified; each of the roots consists of two or three naturally separated rootlets. The L-5 and S-1 roots are medial to the L-4 root and are the largest of all the lumbosacral roots. The L-5 and S-1 dorsal roots consist of three or four rootlets with natural separation. The S-2 root has a single fascicle. Second, an innervation pattern of each root is examined using EMG testing. An individual dorsal root is...
placed over two hooks of the rhizotomy probes (Fig. 4A; Aesculap Instrument Co., Burlingame, CA), and responses to electrical stimulation with a threshold voltage are recorded from the lower-extremity muscles. The entire dorsal root is tested at each level immediately before subdividing the dorsal root into rootlets.

**The EMG Examination and Sectioning of Dorsal Roots**

After the innervation of a dorsal root is determined, the root is sharply subdivided with a Scheer needle (Storz Instruments, St. Louis, MO; Fig. 4B) into three to five rootlet fascicles of equal size. The rootlet fascicles are suspended over two hooks of the rhizotomy probes (Fig. 4C). Single constant square-wave pulses of 0.1-msec duration are applied to the rootlet at a rate of 0.5 Hz. The stimulus intensity is increased stepwise until a reflex response appears from the ipsilateral muscles. After the reflex threshold is determined, a 50-Hz train of tetanic stimulation is applied to the rootlet for 1 second. The re-
The intradural space is irrigated with saline solution. Clonidine (2 µg/kg in children up to 7 years old and 1 µg/kg in children older than 8 years) mixed with morphine at 15 µg/kg of body weight is injected intradurally. The Trendelenburg position is reversed. A strip of Gelfoam is left over the laminectomy defect, and the wound is closed in layers.

**Postoperative Care**

Patients stay overnight in the intensive care unit, where they receive an intravenous infusion of fentanyl (1–3 µg/hr/kg body weight), and diazepam, as needed. Patients are transferred to the ward the next day, and the fentanyl drip is continued for another for 24 to 48 hours. On the 3rd postoperative day patients are allowed to sit, and physical therapy is started. The patients are discharged home on the 5th postoperative day and receive outpatient physical therapy from local providers.

**Postoperative Course and Complications**

With spastic diplegia the operation invariably reduces spasticity, whereas with spastic quadriplegia there is a small chance of recurrent spasticity. Most patients who were independent walkers preoperatively resume independent walking within 2 weeks after undergoing the SDR technique previously described. Patients who walked with assistance preoperatively follow a slower postoperative course. Within 2 months, however, all patients show motor performance exceeding preoperative levels.

The major complications of SDR include paraplegia, sensory loss, bladder and bowel incontinence, CSF leakage, and infection. There has been only one case of CSF leak requiring operative repair in more than 1500 children and adult patients who have undergone single-laminectomy SDR at our institution, clear evidence of the safety of the procedure. Also, no patient had late spinal deformities that required medical or surgical intervention. Many patients, however, did experience hyperesthesia in the legs for several months.

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**Table 2**

Criteria for grading EMG responses in SDR for spastic CP

<table>
<thead>
<tr>
<th>Grade</th>
<th>EMG Response</th>
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<tbody>
<tr>
<td>0</td>
<td>unsustained or single discharge to a train of stimuli</td>
</tr>
<tr>
<td>1+</td>
<td>sustained discharges from muscles innervated through the segment stimulated in the ipsilateral lower extremity</td>
</tr>
<tr>
<td>2+</td>
<td>sustained discharges from muscles innervated through the stimulated &amp; immediately adjacent segments</td>
</tr>
<tr>
<td>3+</td>
<td>sustained discharges from segmentally innervated muscles &amp; muscles innervated through segments distant from the one stimulated</td>
</tr>
<tr>
<td>4+</td>
<td>sustained discharges from contralateral muscles w/ or w/o sustained discharges from the ipsilateral muscles</td>
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