Functional variability of sacral roots in bladder control

Clinical article

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Object. Sacral roots are involved in sensory, autonomic, and motor innervation of the lower limbs and perineum. Theoretically, it can be assumed that the S-3 root level innervates the bladder; however, clinical practice shows that this distribution can vary. Few researchers have studied this variability.

Methods. The authors conducted a retrospective study involving 40 patients who underwent surgery requiring an electrophysiological exploration of the sacral roots. They performed stimulations for the monitoring of muscular (3 Hz, 1 V) and bladder responses under cystomanometry (30 Hz, 10 V).

Results. Although the S-3 roots were involved in bladder innervation in all cases, they were exclusively involved (i.e., the only nerve roots involved) in only 8 of 40 cases. In the remaining 32 cases, other sacral nerve roots were involved. The most common association was S-3+S-4 (12 cases), followed by S-2+S-3 (6 cases), S-2+S-3+S-4 (5 cases), and S-3+S-4+S-5 (2 cases). Stimulation of S-2 could sometimes induce bladder contraction (15 cases, 40%); however, the amplitude was often low. S-4 nerve roots were involved in 24 of 40 cases (60%) in the bladder motor function, whereas S-5 roots were only involved 7 times (17%). Occasionally, we noticed a horizontal asymmetry in the response, with a predominant response from the right side in 6 of 7 cases, always with a major S-3 response.

Conclusions. This is the first study showing a significant horizontal and vertical variability in the functional distribution of sacral roots in bladder innervation. These results show the variability of cauda equina syndromes and their forensic implications. These data should help with the monitoring of sacral roots and the performance of several tasks during surgery, including neurostimulation and neuromodulation.

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Key Words • sacral roots • neurogenic bladder • sacral neuromodulation • sacral neurostimulation

Sacral roots consist of 5 pairs of mixed sensory-motor roots. From an anatomical point of view, the last 4 lumbar spinal nerves and the sacral spinal nerves gather below the terminal part of the spinal cord and form the cauda equina. Intrathecally, the organization of nerve roots is not random, but their distribution is similar to the laminar pattern of nerve fibers in the spinal cord. The roots are held in place by arachnoid invaginations, which are located between the roots. Within the spinal nerves, the motor constituent is ventral or ventromedial relative to the sensory constituent.20 Extrathecally, the nerve root angle when exiting the dural sac decreases in the craniocaudal direction. The size of the dorsal root ganglion increases in length and width from L-1 to S-1 and then decreases gradually to the lower sacral roots. The dorsal ganglion is strictly inferior to the vertebral pedicle in 90% of cases, whereas in the remaining cases, it is inferior-lateral to the pedicle and very rarely medial to the lateral recess. Laterally, it covers a portion of the intervertebral disc in 32% of cases, unrelated to the vertebral level. This is interesting in the pathophysiology of pain and in some surgical techniques.2 Understanding the anatomy involved in bladder innervation has aided in the development of new therapeutic strategies. Habib5 described the effects of sacral root electrical stimulation on micturition. Later, with the work of Brindley,2 electrical stimulation of the sacral roots became a clinical reality, producing an effective micturition in spinal cord injury patients. More
recently, continuous stimulation of the sacral roots has been suggested for overactive bladder.\textsuperscript{1,10} Thus, thanks to the development of these procedures, the role of clinical neurophysiology has expanded, contributing to a better understanding of the nervous control mechanisms involved in visceral functions and in the lower urinary tract.\textsuperscript{1,14} The 5 pairs of sacral roots are involved in sensory, autonomic, and motor innervations of the lower limbs and perineum. We usually assume that the S-3 root level innervates the bladder, but clinical practice reveals some variations regarding this distribution. Studying the leading role of sacral roots from a somatic (musculoskeletal) and especially autonomic (bladder contraction) point of view could provide useful information.

**Methods**

**Patient Inclusion/Exclusion**

We included 40 consecutive patients in this physiological study. Inclusion criteria included complete paraplegia or tetraplegia with a spinal injury above the sacral voiding centers; an unstable, overactive bladder (central neurogenic bladder); and failure of rehabilitation techniques. Sacral anterior root stimulation (SARS, or Brindley technique) was indicated to restore bladder function. Patients with incomplete lesions or with trauma of the conus medullaris or lumbosacral roots were excluded.

**Technique**

Surgery was performed with the patients in a state of general anesthesia without the use of products that interfere with bladder contraction, including curare and anticholinergic drugs such as atropine, which decrease bladder responses to stimulation. The patients’ body temperature was maintained between 36°C and 37°C to avoid the effects of hypothermia on the autonomic nervous system. Recently, a specific noninvasive marker of the autonomic nervous system (electrocardiogram spectral analysis) was suggested for early detection of autonomous hyperreflexia in reaction to any invasive procedures.\textsuperscript{19}

The patients were placed in a prone position, in a genu-pectoral posture, to clear the perineum and lower limbs. This optimized the perioperative monitoring and limited the increase in abdominal pressure to avoid bias in bladder contractions. A transurethral catheter was used to perform cystomanometry (Dantec, Medtronic) for each sacral root stimulation. This cystomanometry estimated a pressure differential from the baseline to the maximum contraction under stimulation. The roots of the cauda equina were intradurally exposed after a laminectomy up to L-3 and extending along the sacral roof. Along with systematic radiography of the region, this technique ensured the anatomical location.

Identification of the sacral roots was performed under an operating microscope. Electrical stimulation (Nimbus stimulator, Newmedic) was applied by means of a tripo- lar electrode (Newmedic) to the S-1, S-2, S-3, S-4, and S-5 sacral roots to identify the motor and sensory components and the roots involved in bladder function, and the response was measured with cystomanometry.

Thus, all the sacral roots were studied bilaterally, from S-1 to S-5. We monitored muscular (3 Hz stimulation, 1 V) and bladder responses under cystomanometry (30 Hz stimulation, 10 V). An observer other than the surgeon (rehabilitation physician) collected data regarding responses to stimulation. A positive response to bladder contraction was defined arbitrarily as an increase in bladder pressure of at least 10 cm H\textsubscript{2}O, and muscular contraction was defined as direct visualization or tactile perception of contraction of the anal sphincter.

**Validation and Reliability of the Technique**

Perioperative modalities of identifying the sacral roots by electrical stimulation allowed us to predict that 80% of our patients reached complete electrically induced micturition. This result is reliable and reproducible when roots associated with bladder function are strictly select- ed.\textsuperscript{19} Tripolar electrodes guarantee selective stimulation of each root, without any electrical diffusion. Each root was stimulated twice, once for global root stimulation to identify the level and bladder response and a second time to determine the anterior and posterior parts of the root. Finding that the same bladder response was associated with the same root stimulation was remarkable.

**Results**

Sixteen women and 24 men (range age 25–58 years) were recruited over a 15-year period. In all, 30% were tetraplegic, and 70% were paraplegic; they all had complete sensory and motor impairment.

Electrical stimulation of the S-1 roots did not induce a bladder response. Stimulation of S-2 induced a bladder contraction in 15 cases (40%), often with a low amplitude (less than 20 cm H\textsubscript{2}O). This may be due to indirect contractions. However, in 2 of the 15 cases, a high contraction (greater than 20 cm H\textsubscript{2}O) was observed, undoubtedly a bladder response. S-3 roots are strongly involved in bladder contraction (intrabladder pressure differential greater than 50 cm H\textsubscript{2}O); however, they were only exclusively involved in 8 of 40 cases. S-4 roots were involved (60%) in the motor function of the bladder in 24 of 40 cases, whereas S-5 roots were involved only 7 cases (17%) (Fig. 1).

The combination of the S-3 and S-4 root levels (S-3+S-4) was the most common (12 cases, 30%), followed by S-2+S-3 (6 cases, 15%). We also found a combination of S-2+S-3+S-4 (5 cases, 12.5%) and, rarely, S-3+S-4+S-5 (2 cases, 5%) (Fig. 2). Finally, in 7 cases, we noticed a horizontal right/left asymmetry of the response, with a predominance for the right side at 6 of 7 responses; all 7 were S-3 predominant.

Muscle response corresponds to a conventional distribution. The contraction of the leg and foot flexors is associated with the S-1 level, while S-2 involves the gluteus and soleus, S-3 the pelvic floor and the toe flexors, and S-4 the anal sphincter and perineum.

**Discussion**

Few studies have focused on changes in the distribu-
Sacral root variability in bladder control

![Bar graph showing sacral root variability](image1)

**Fig. 1.** Bladder response to individual stimulation of sacral roots (positive response was defined by an increase in bladder pressure of at least 10 cm H$_2$O).

Sacral root variability in bladder control is a key consideration in understanding bladder control. The variability among sacral roots affects bladder function, with significant implications for clinical management.

Sacral root variability is demonstrated through the distribution of nerve fibers in the sacral nerve roots. These fibers are categorized into three types: A$\alpha$, A$\gamma$, and B. A$\alpha$ fibers are the largest and are characterized by a large diameter surrounded by a thick myelin sheath; A$\gamma$ fibers have an intermediate diameter; and B fibers have a small diameter with virtually no myelin sheath. The frequency of A$\alpha$ fibers decreases as the sacral roots increase in number, from S-1 to S-5. B fibers are predominant in S-3 (17%), abundant in S-4 and S-5, but are only occasionally found in S-2 (7.3%) and S-1 (< 1%) fascicles. These data correlate with those of Light et al., who showed that patients with detrusor areflexia had a great variability in bladder neck incompetence.

In sacral neuromodulation, a low-intensity electrical stimulation is applied continuously at the level of theafferent sacral nerve, which innervates the bladder to restore function to an impaired bladder (bladder hypoper- or hypoactivity), which does not usually have an identifiable injury. This stimulation is thought to result in spinal circuitry rearrangements causing better regulation of bladder control. The initial electrical signal most likely travels through the large fibers of the somatic system. Actually, the visceral nerve fibers cannot be activated by the current intensities normally used with this technique. The supraspinal centers must play an important role.

Sacral neuromodulation takes place in 3 main stages. In the first stage (acute test), an electrode is placed. A percutaneous stimulation test of the afferent sacral roots is then performed through the sacral foramina with an external neurostimulator. Thus, we can observe if there is a symptomatic improvement over a period of 3 to 7 days (subchronic test). In the third step, if the test is positive, a final implementation of a neurostimulator is recommended. In this situation, our study indicates that the right S-3 root should be chosen initially for the therapeutic test. Some have conducted multi-staged testing to optimize the stimulation of the root targets. A negative test does not necessarily mean that the technique has failed; in some cases, repeating the procedure is recommended, or a dual stimulation system could be used. Designing a device for the simultaneous stimulation of S-3 and S-4 on a unilateral or bilateral basis would be of value.

The interesting results from our study were sufficient to show the functional variability of sacral roots. Some limitations could be avoided with a larger number of patients. Over the years, the Brindley technique has not significantly changed, and the patient population has remained the same. Bladder monitoring could be limited due to the requirements of the device and the need for the presence of a physician who can interpret the results, but we strongly believe that this monitoring is useful for some lumbosacral surgeries.

Sacral anterior root stimulation (SARS) is offered to patients with complete spinal cord injury, and a neurogenic bladder can have several complications, including upper urinary infections and decreased quality of life from incontinence. Described by Brindley, the pro-
procedure consists of performing rhizotomies on posterior components and implementing stimulation electrodes on anterior components of the sacral roots with intermittent stimulation, especially on the sacral roots generating bladder motor function. As previously observed, the intervention must preferentially focus on the S-3 and S-4 roots, but we must also take into account individual variations; an evaluation of all sacral roots may be required. This is particularly important for reducing urinary incontinence, which is directly related to the number of posterior rhizotomies performed for bladder control, and for the efficacy of electrical micturition, which is directly related to the number of stimulated sacral roots.

Predicting these results before surgery may be possible without laminectomy using transcutaneous magnetic stimulation for each sacral root. Gilling et al. described the use of this technique to stimulate S-3 nerve roots bilaterally via their sacral foramina to reduce idiopathic bladder hyperactivity. However, no study has determined the functional variability of sacral roots.

Other clinical situations, such as tethered spinal cord, tumors of the sacral region, or lumbosacral defects, sometimes require identification of the sacral roots. Pouratian et al. evaluated the intraoperative usefulness of electrophysiological monitoring, either continuously or by a threshold system. This technique results in a reduction in the rate of iatrogenic injuries. Such electrophysiological monitoring would also allow a more aggressive dissection in electrophysiologically silent areas, which significantly reduces recurrence of certain diseases. Intraoperative electrophysiological monitoring seems increasingly important for early detection, the avoidance of sacral nerve root damage, and quick anatomical identification of the sacral roots to distinguish tumors or fibrous tissue. In the operating room, by using this monitoring method, testing sacral root responses at the beginning of the surgery is easy and can be regularly performed during the surgery as needed.

Conclusions

To our knowledge, this is the first electrophysiological study involving the complete in vivo mapping of human sacral roots. Our study found a significant horizontal and vertical variability in the functional distribution of sacral roots for bladder innervation. These findings help us to understand the variability of cauda equina syndromes and their forensic implications. These data are important for monitoring sacral roots in situations involving conditions such as a tethered spinal cord and tumors. A bi-radiculatus stimulation device could improve sacral neuromodulation. This monitoring, including urodynamic measurement and physician assistance, is easy to implement in the operating room and provides information to prevent radicular injuries. Thus, medical and surgical advances will provide for better control of neurogenic bladder dysfunctions.

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Disclosure

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