0022-5347/88/1406-1331$2.00/0
THE JOURNAL OF UROLOGY
Vol. 140, December
Printed in U.S.A.


# State of the Art

# ELECTRICAL STIMULATION IN THE CLINICAL MANAGEMENT OF THE NEUROGENIC BLADDER

EMIL A. TANAGHO* AND RICHARD A. SCHMIDT

*From the Department of Urology, University of California School of Medicine, San Francisco, California*

The neurogenic bladder is a major problem. By conservative estimates there are more than one million patients in the United States alone who need to regain bladder control. More than half have spinal cord injuries and an estimated 50,000 additional patients per year will sustain injury to the spinal cord. A successful bladder pacemaker not only would reduce the morbidity rate in these patients but would dramatically improve the quality of life and psychological outlook.

## BACKGROUND STUDIES

Genuine interest in the electrical control of bladder function began in the 1950s and was followed in the 1960s[1] by reports of attempts to initiate voiding through implantable electrodes. Most of these reports concerned the stimulation of either the spinal cord[2-6] or the detrusor directly,[2, 7-10] while a few discussed the use of the pelvic[2, 10, 11] or sacral nerves[12-14] as a means to stimulate the bladder.

*Direct detrusor stimulation.* The advantages of this method are easy placement of electrodes, high specificity of target organ and direct application in lower motor neuron lesions. Disadvantages are occasional electrode malfunction from movement during voiding, production of fibrosis, erosion into the bladder and the need for current densities above physiological levels.[8, 9]

*Direct pelvic nerve stimulation.* This method was reported initially to have produced encouraging results.[10, 11] However, it has been shown that pelvic nerves do not tolerate stimulation for long periods, the pudendal nerves are activated and, therefore, outflow resistance is augmented, patients have increased pain via the hypogastric nerves and the bladder nerves may be damaged permanently. Additionally, in humans the parasympathetic innervation of the bladder is split early in its course through the pelvis, forming a broad plexus unsuitable for direct electrode application.[10, 11]

## ANIMAL EXPERIMENTS—CANINE MODEL

About 15 years ago we were asked to explore the possibility of inducing micturition via stimulation of the spinal cord. Several electrodes were developed.[5, 6] We first tried surface electrodes to stimulate the spinal cord externally but this did not achieve voiding.[6] We then explored implantable electrodes, attempting to localize stimulation to the centers for bladder evacuation and sphincteric function separately. This also failed for several reasons: a low stimulus will activate the sphincter first and an increased stimulus will initiate bladder activity but sphincteric activity will increase; thus, bladder contractions are outstripped by strong sphincteric contractions. An electrically initiated void clearly lacks the normal coordination between detrusor and sphincter, emphasizing the complexity of the micturition phenomenon.

*Requests for reprints: Department of Urology, U-518, University of California, San Francisco, California 94143.

Our next attempt,[6] a more sophisticated, coaxial electrode designed to limit stimulation to a small sphere, was likewise a failure. However, this attempt demonstrated that the characteristics of the striated muscles cause sphincteric relaxation to be much faster than bladder relaxation; at the end of stimulation bladder pressure remains a little higher and some spurts of urine can be emitted. If intermittent stimulation could be timed to maintain bladder contractions continuous voiding could be achieved (post-stimulus voiding).[5] However, the unphysiological, extremely high intravesical pressures so generated made this unacceptable.

To overcome the deleterious effect of simultaneous contraction of the striated sphincter and bladder, we next attempted to locate and differentiate the principal neuronal cells in the spinal cord. We concentrated on the autonomic and somatic systems, injecting horseradish peroxidase into various locations and tracing it back to the spinal cord (fig. 1, *a*).[15, 16] By injections into the anal and urinary sphincters the somatic component could be traced into the pudendal nucleus, which is located easily in the spinal cord. Injections into other locations (bladder wall, bladder base, trigone, urethral meatus and urethra) likewise traced the autonomic component to the spinal cord. Thus, the existence of 2 nuclei—a parasympathetic nucleus and the pudendal nucleus—became clear.[17] When these 2 nuclei are mapped on the spinal cord the parasympathetic nucleus is within the confines of the somatic pudendal nucleus; the bladder cannot be driven separately from the sphincter by stimulation at the level of the spinal cord.

We then investigated the sacral roots,[14, 18, 19] hoping that these would carry different neuronal axons to different locations. Through an extensive laminectomy in the canine model we explored the sacral roots and tried to stimulate them, either intradurally or extradurally, but within the spinal canal. The following 5 modalities were developed (fig. 1, *b*): 1) unilateral stimulation of the intact sacral root at various levels, 2) simultaneous bilateral stimulation of the intact sacral root at various levels, 3) stimulation of the intact ventral or dorsal root separately, 4) stimulation of the proximal and distal ends of the divided sacral root, and 5) stimulation of the proximal and distal ends of the divided dorsal and ventral roots.

*Sacral nerve stimulation (acute studies).* Intact Nerves: Bladder and sphincter responses to sacral root stimulation were consistent.[14, 19] With stimulation of S2 alone the detrusor response was dominant; S1 and S2 exerted a significant influence on sphincter closure, while S3 induced a lesser response in the detrusor and sphincter (fig. 2). The simultaneous stimulation of groups of sacral nerves resulted in additive effects on the detrusor and sphincter, although the effect on sphincter closure was more apparent than on detrusor contraction.

Afferent Nerve Responses (Dorsal): Stimulation of the intact dorsal component of S2 produced responses in the bladder and sphincter that were similar to those induced by stimulation of

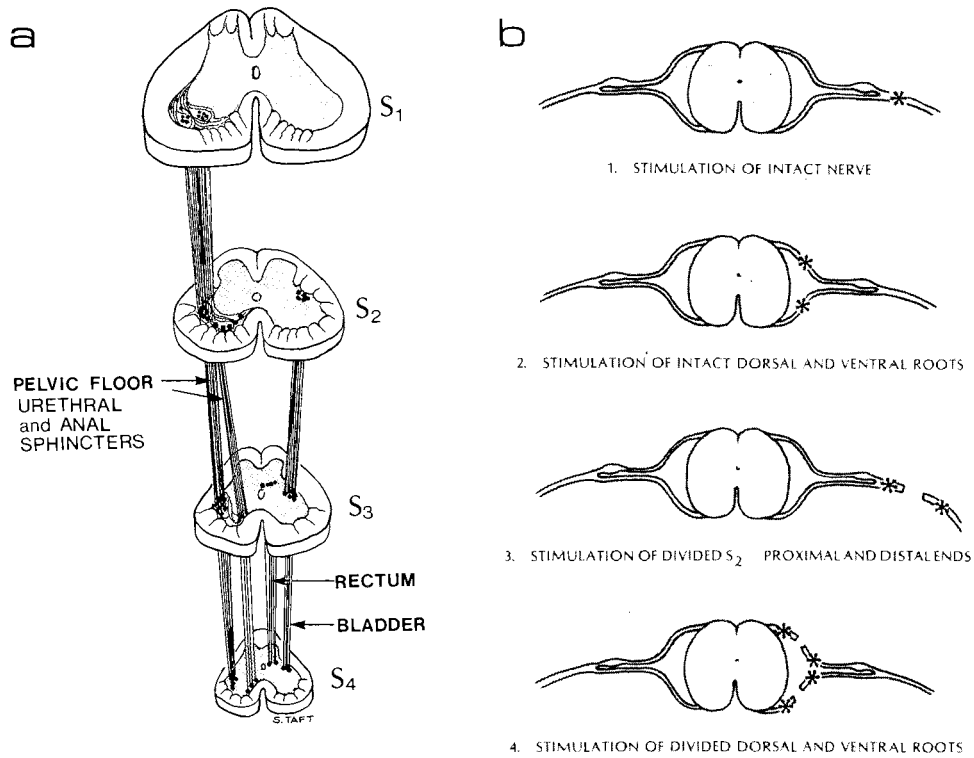


FIG. 1. *a*, by injection of horseradish peroxidase in canines, neurons controlling target organs were mapped on spinal cord. *b*, sites of stimulation and varieties of neurotomy in acute canine experiments. Reprinted with permission.[22]

the intact nerve and ventral root.[14, 18, 19] After division of the dorsal root and stimulation of its proximal and distal cut ends, the observed response with the intact root was primarily reflexive in nature, being mediated via monosynaptic and polysynaptic pathways within the spinal cord. The sphincter reflex contraction was extremely efficient and was eliminated only through subsequent successive division of all remaining sacral nerves. Most of the sphincter response was lost with division of S1 and S2 bilaterally (fig. 3).

Efferent Nerve Stimulation (Ventral): Stimulation of the ventral component of S2 resulted in a strong contraction of the detrusor and urethral sphincter (fig. 4, *a*).[14, 18, 19] Stimulation of the divided ends of this nerve proved this response to be of a primarily efferent nature, with a minimum of reflex activity being produced by stimulation of the proximal stump. After division of the somatic fibers peripherally, either selectively or by cutting the pudendal trunk unilaterally, stimulation of the ventral root resulted in purely autonomic responses (fig. 4, *b*). Voiding in these situations was accomplished with low bladder pressures due to the markedly reduced outlet resistance. In addition, the pattern of voiding was smooth (fig. 5).

*Development of the paraplegic animal model (chronic studies).*[20, 21] Animals selected for chronic study underwent transection of the spinal cord at the T11 to T12 level. Subsequently, the animals were housed in cages containing a generous flooring of saw dust to prevent decubitus ulcer. They were examined daily for reflex activity and studied urodynamically each week for return of bladder, urethral and anal reflexes.

Female Spinal Cord Injury Animals (fig. 6): After maturation of the neuropathic bladder in 4 female dogs an electrode was implanted around one of the sacral nerves. Chronic animal models were established that were similar to the aforementioned acute animal models: 1) stimulation of an intact S2, 2) stimulation proximal to dorsal rhizotomy and 3) stimulation distal to dorsal ganglionectomy.

After a minimum of 2 months the animals underwent division of somatic fibers as follows: 1) selective division of somatic fibers, 2) unilateral division of the pudendal nerve and 3) bilateral pudendal neurotomy. The dogs were stimulated daily and studied urodynamically at least twice a month for 5 to 12 months. After sacrifice, stimulated nerves were examined microscopically.

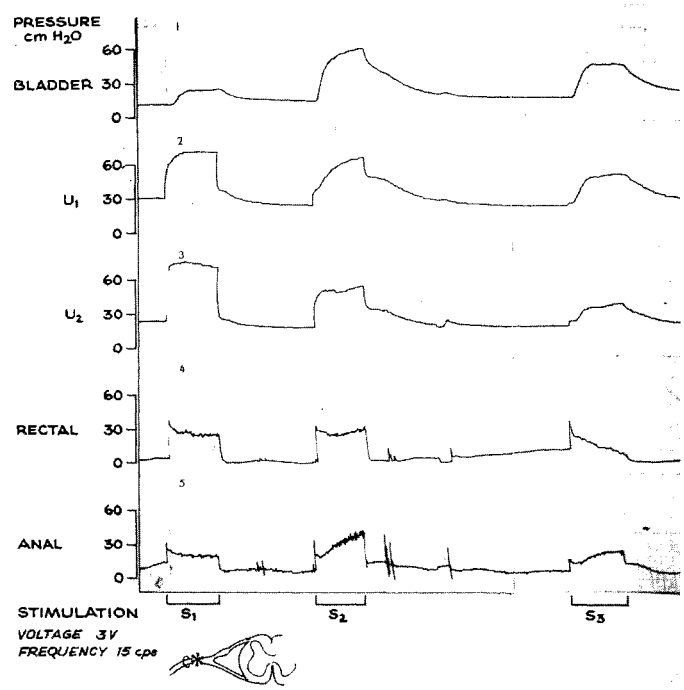


FIG. 2. Response to unilateral stimulation of various sacral roots in dogs. Stimulation of S2 consistently produced strongest detrusor contraction. $U_1$, proximal urethra. $U_2$, mid or distal urethra.

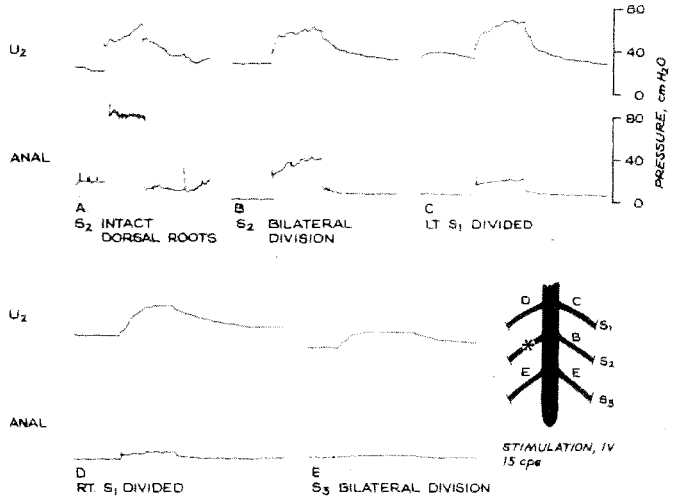


FIG. 3. Sphincteric responses in canines to sequential division of sacral nerves and stimulation of proximal end of divided S2 before each nerve section. Reprinted with permission.[22]

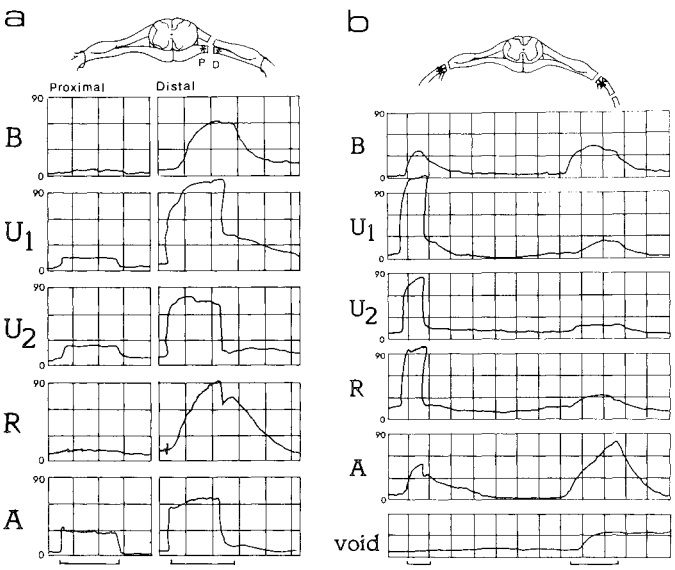


FIG. 4. *a*, responses to stimulation of divided ventral root of S2 in acute animal experiments: antidromic mild sphincteric response with stimulation of proximal end, and strong bladder, urethral, anal and rectal responses with stimulation of distal end. *b*, stimulation of distal end of divided S2 after selective division of somatic component unilaterally in dog. Urethral resistance was negligible with stimulation of S2 ipsilateral to neurotomy, while high resistance was present with stimulation in contralateral S2. Note differences in voiding. *B*, bladder. $U_1$, proximal urethra, $U_2$, mid urethra. *R*, rectum. *A*, anus.

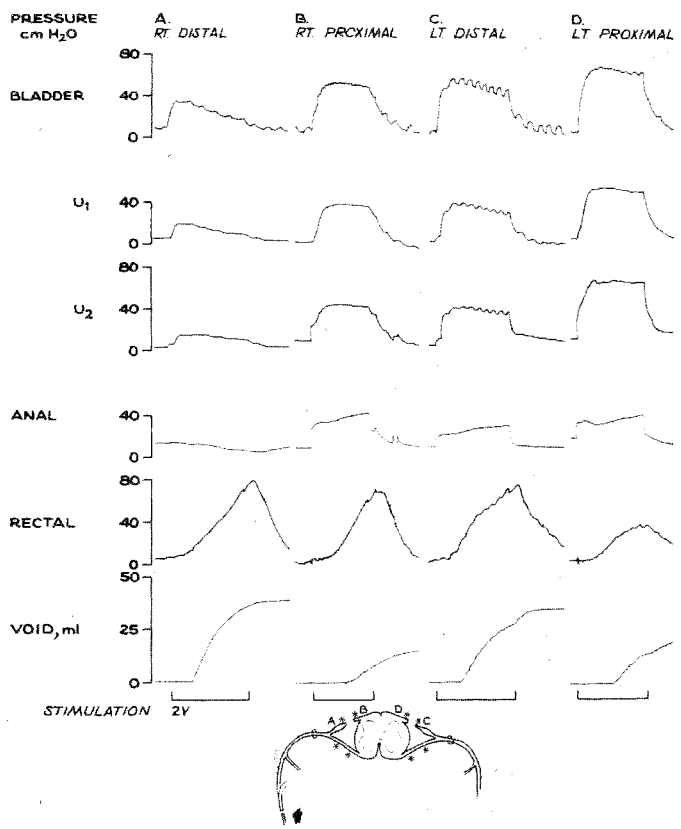


FIG. 5. Effect of combining dorsal rhizotomy with division of pudendal trunk in canines. Dorsal rhizotomy was performed on S2 bilaterally, while main pudendal trunk was divided unilaterally. Of 4 stimulus locations depicted *A* (distal to cut in dorsal root) provided best voiding response. Including dorsal root fibers with or without pudendal neurotomy increased outlet resistance (*C* and *D*).

Male Spinal Cord Injury Animals—Bladder Evacuation: Six paraplegic animals were studied in this group.[20,21] After inducement of spinal cord injury and maturation of the neuropathic bladder an electrode was implanted in each animal distal to a dorsal rhizotomy. For the first 2 animals the somatics were divided selectively but this proved to be inadequate for the elimination of sphincteric reflexes. In the remaining dogs dorsal rhizotomy of those sacral nerves with significant sphincteric influence (S1 and S2) was added to the implantation procedure. This method preserved sensory innervation to the pelvic floor as well as desired motor influence.

The animals were followed for a 3-month period with daily stimulation and weekly urodynamic assessment. Stimulated voiding was assessed radiographically shortly before sacrifice, with special attention to all levels of outlet resistance: the bladder neck because of its sphincteric function, prostatic urethra, membranous urethra and, due to erection, the anterior urethra.

Urodynamic studies demonstrated the unique ability of male dogs to use the urethral striated muscles to provide a pulsatile characteristic to the stream. In this way they establish territorial markings and can also void in limited amounts.

Radiographic study during bladder stimulation revealed an open bladder neck in all phases of emptying, as well as absence of closure or obstruction at the level of the prostate or membranous urethra (fig. 7). Pressure studies confirmed this finding in that they always reflected the low pressure within the bladder. Thus, it became clear that to succeed in evacuating the bladder we had first to eliminate the afferent fibers (the dorsal nerves) and also to divide the somatic fibers selectively. This became the final model (fig. 8). We separate the dorsal fibers, cut the dorsal component, stimulate the ventral component and perform selective neurotomy leaving some other somatic fibers coming down through the remaining arc of the pudendal nerve. In this model the stimulated sacral root becomes essentially a carrier of purely autonomic efferent fibers.

In chronic experiments with 3 consecutive colonies of 8 spinal cord injury dogs apiece[22-24] persistently good voiding was obtained with good bladder contraction and almost no sphincteric response, although some sphincteric relaxation occasionally was elicited similar to the normal voiding act associated with good detrusor contraction and evacuation of the bladder.

Satisfied with the ability to achieve consistently good detrusor contraction and complete bladder evacuation in the dog, we then concentrated on the ability to control sphincteric function.

Male Spinal Cord Injury Animals—Sphincteric Control: To be able to initiate detrusor contraction without exciting sphinc-

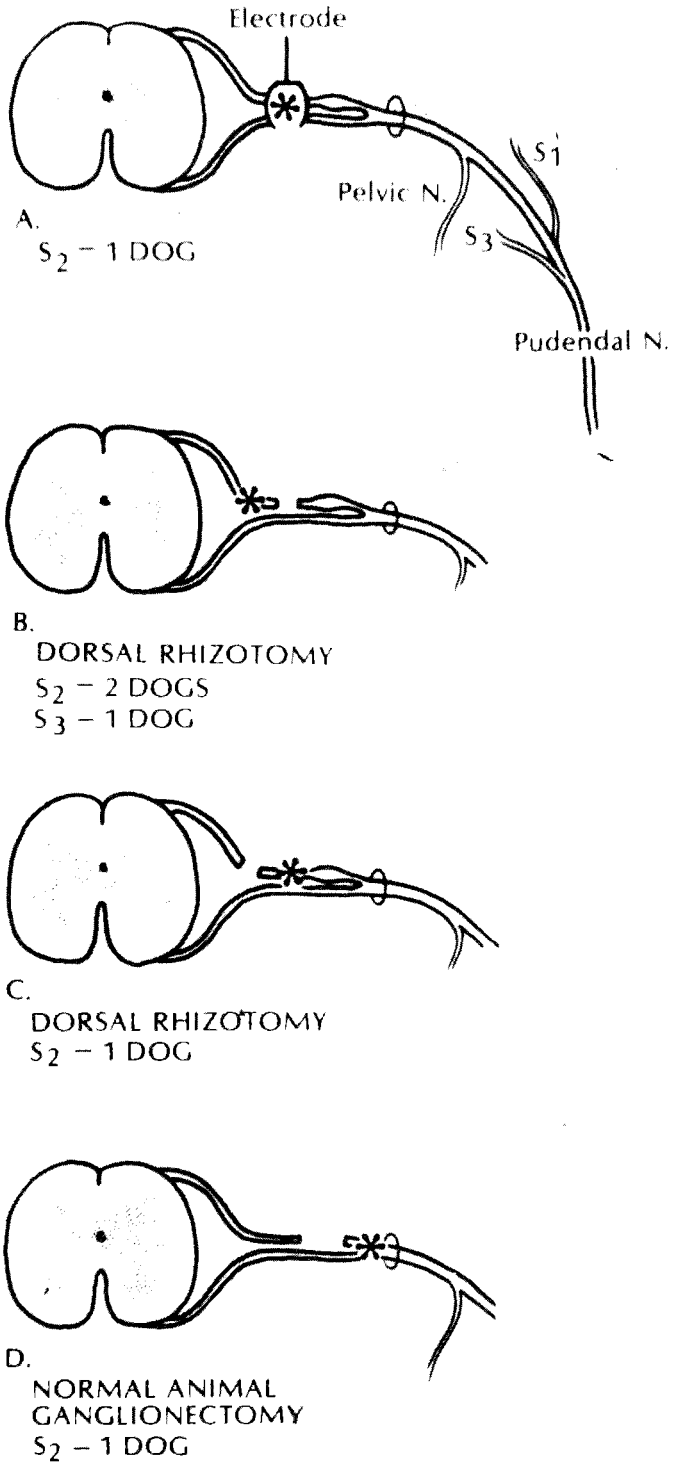


FIG. 6. Pattern of chronic stimulation in 5 paraplegic dogs and 1 normal dog. *A*, electrode implanted around intact sacral root. *B*, dorsal root fibers sectioned, electrode proximal to cut. *C*, same as *B* but electrode distal to cut. *D*, stimulation distal to site of ganglionectomy in normal animal. Reprinted with permission.[22]

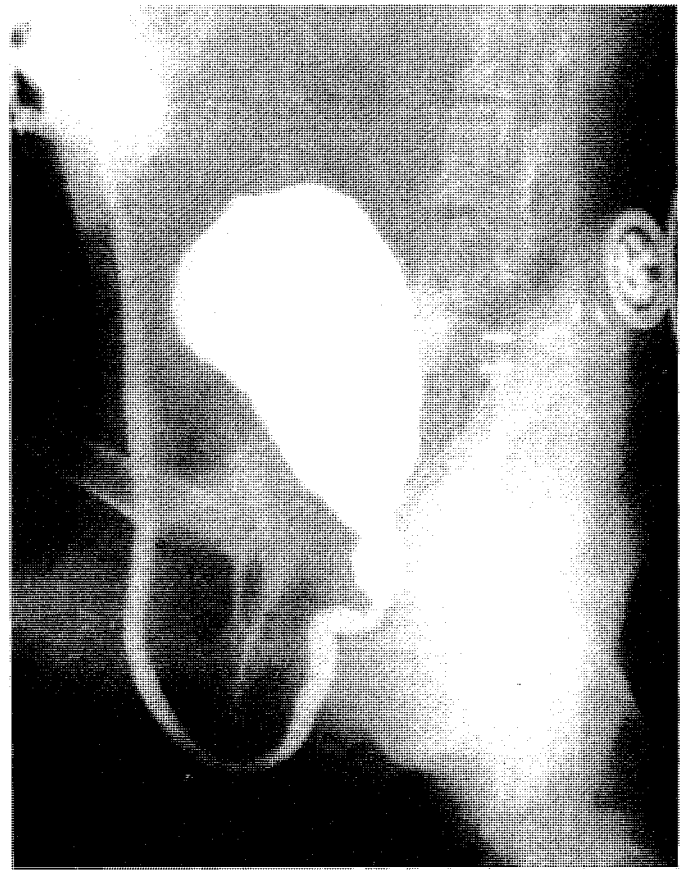

FIG. 7. Voiding in male paraplegic dog produced by stimulation of S2. Note patency of bladder neck. Reprinted with permission.[22]

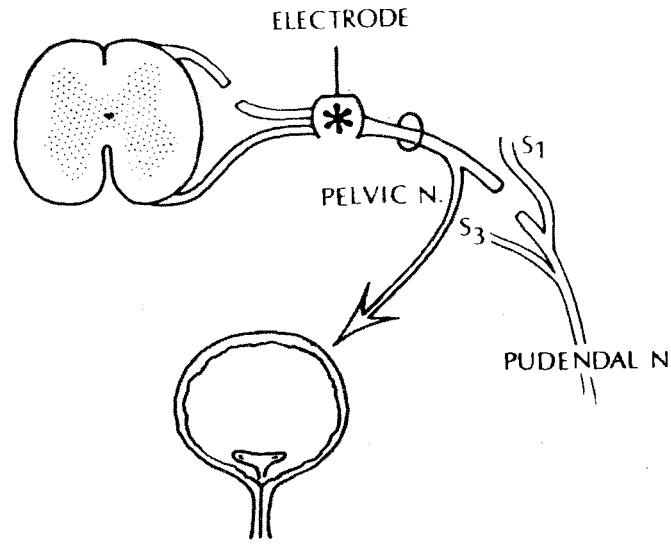


FIG. 8. Avenue of bladder stimulation. Electrode implanted on S2 distal to sectioning of dorsal root afferents elicits response in autonomic and somatic motor nerves. Somatic fibers are then divided in pelvis so that only response from stimulation of S2 autonomic fibers will be seen.

ter activity is a major achievement. Full control, however, would not be complete unless sphincteric activity could be governed and the closure mechanism strengthened. For this purpose electrical stimulation of sacral roots to improve urethral sphincter closure was attempted.[20, 21]

Ten dogs were used for these experiments. To induce and maintain urethral closure in long-standing stimulation, a variety of stimulation patterns were investigated systematically. With continuous stimulation, the induced sphincteric response faded with the increase in frequency of applied stimulation. However, in phasic stimulation with a stimulation-to-rest ratio of 1:2 strong sphincter contractions were reproducible after each rest interval. If the stimulation bursts were shortened to 30 to 60 msec. interrupted by an off-time of twice the duration of the stimulation unfused sphincteric tetani were induced, resulting in a sinusoidal oscillating closure pressure that did not decrease to the pre-stimulus baseline during the off-time.

Thus, sufficient sphincteric closure pressure could be sustained during 1 hour of uninterrupted stimulation.[21]

The quality of sphincteric contraction proved to be highly dependent on the frequency of stimulation: 1) the force of contraction increased with the stimulation frequency (with less than 20 Hz. unfused tetani were induced, providing a weak pressure response, fig. 9, *a*), 2) the speed of the urethral pressure increase was markedly accelerated at frequencies of 50 Hz. or more and 3) fatigue appeared earlier with an increase in frequency and was accentuated at frequencies greater than 50 Hz.

Nevertheless, in phasic stimulation with an off-time about twice as long as the stimulation phase a strong pressure response was reproducible indefinitely with minimal fatigue (fig. 9, *b*). In continuous stimulation the response faded if frequencies of greater than 10 Hz. were applied and the low frequencies provided a poor pressure response (fig. 9, *a* and *c*). From these data it was clear that in terms of force and speed of contraction a stimulation frequency of 20 to 30 Hz. was favorable. In terms of fatiguability in phasic stimulation an on/off ratio of roughly 1:2 provided sufficient closure pressure during the off-time, since the pressure did not decrease to the pre-stimulus baseline (fig. 9, *c*). Thus, our stimulation pattern was basically a hybrid of continuous and phasic stimulation types, producing unfused tetani with a sphincteric pressure oscillating sufficiently above the pre-stimulus baseline.

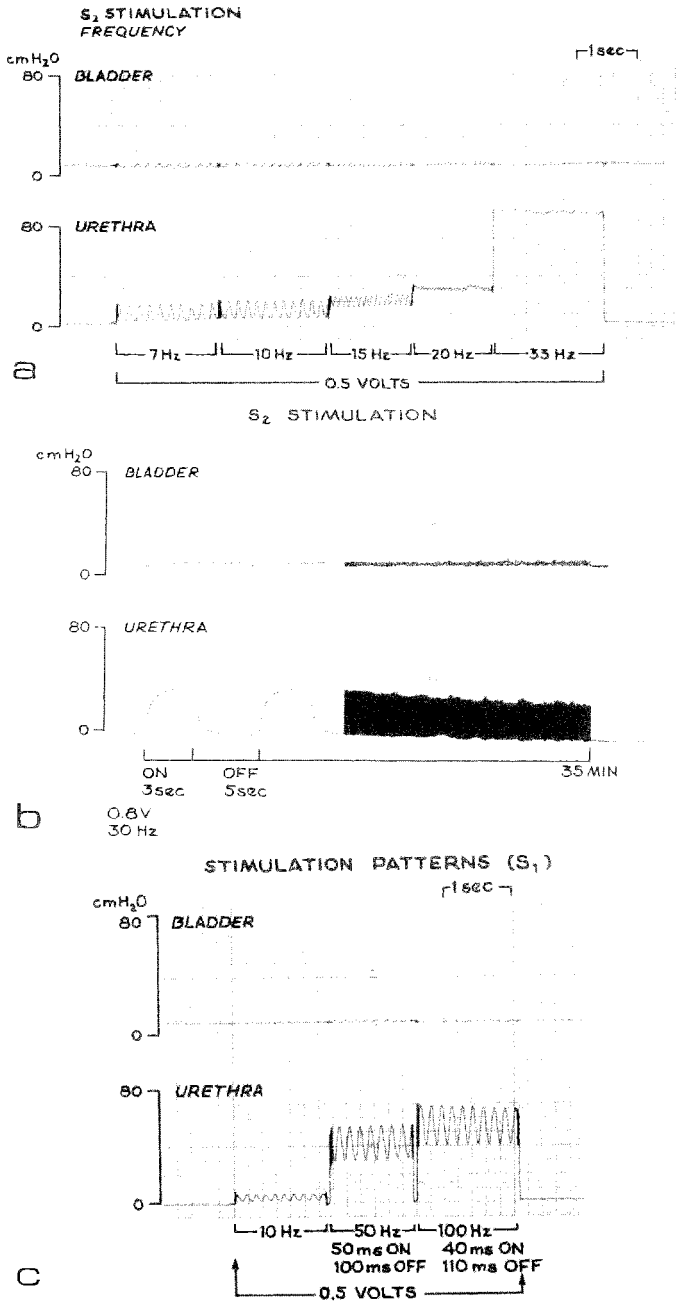


FIG. 9. Chronic canine experiments. *a*, force of sphincteric contraction increases at frequencies at which tetani fuse. *b*, phasic stimulation induces reproducible sphincteric contractions after each off-period with minimal fatigue. *c*, sphincteric pressure responses with phasic stimulation. Frequencies of 50 and 100 Hz. induced unfused tetani much above pre-stimulus baseline.

A major difference between most reported studies and ours is that we used a pulse width of 200 μsec., whereas generally a pulse width of 1 to 1.5 msec. was judged to be most appropriate for sphincteric contraction. The good sphincteric response with our short pulse width probably is related to the mode of direct nerve stimulation. The reduced charge per phase with a short pulse reduces the risk of nerve damage.

We learned that stimulation with low frequency and low voltage can maintain adequate sphincteric activity, stimulation with high frequency and low voltage will fatigue the external sphincter and block its activity, and when high frequency, low voltage stimulation is followed by high voltage stimulation bladder contraction will be induced and voiding will ensue.

The finding that detrusor contraction can be activated separately from sphincteric activity and that adequate sphincteric contraction can be sustained without exciting a detrusor reaction made it seem possible that a true bladder pacemaker could be achieved.

Effect of Chronic Neural Stimulation on the Striated Sphincter—Histochemical Analysis: During the course of our studies with the canine model[14, 18, 19, 22-24] we found it essential to investigate the histochemical characterization of the urethral striated musculature. Two main groups of muscle fibers could be identified: type 1—slow-twitch oxidative fibers, which are resistant to fatigue and type 2—fast-twitch fibers. The fast-twitch fibers were subdivided into glycolytic (fatiguable) and oxidative glycolytic (fatigue-resistant) fibers; the latter constitute 15 per cent of all fast-twitch fibers. Type 1 constitutes 35 per cent of the entire musculature and its proportion tends to decrease toward the distal end of the external urethral sphincter. From these observations we infer that type 1 fibers are likely responsible for continence at rest and that type 2 fibers are recruited in stress conditions, for example during coughing or sneezing. The fast-twitch glycolytic fibers are strongly reactive to alkaline adenosine triphosphatase and strongly reactive to phosphorylase. These fibers are easily fatiguable because of their low oxidative enzyme content and dependence on anaerobic energy. However, we found that in the striated urethral sphincter 15 per cent of fast-twitch fibers are oxidative glycolytic, which are resistant to fatigue because they can use anaerobic and aerobic energy. Some investigators believe that both types of fast-twitch fibers, the fatiguable (glycolytic) and the fatigue-resistant (oxidative glycolytic), are the expression of a dynamic range of properties of these fibers that are interchangable, depending on the demand for their use.[25] Further studies are needed to ascertain whether there exist different states (glycolytic versus oxidative-glycolytic) within the same population of fast-twitch fibers or whether there are 3 distinctly different fiber types.

We theorize that slow-twitch oxidative fibers are an integral part of the continence mechanism during rest because they are resistant to fatigue and can contract for a long interval at a low amplitude. The fact that fast-twitch fibers are recruited during stress conditions may explain the significance of their increase toward the distal end of the urethral sphincter.

Ten dogs with chronically implanted electrodes at the S2 root were subjected to prolonged stimulation for 2 to 5 months, after which we detected hypertrophy of the striated muscle

fibers of the urethra, anal sphincter and stimulated side of the tail.[26, 27] The stimulated muscle fibers of intact and spinal cord injury animals showed a higher over-all oxidative activity than the controls. Stimulated fibers also had increased glycolytic activity, as shown by the enhanced intermyofibrillar deposition, especially in the fast-twitch fibers. The increased glycolytic activity also may increase fatigue resistance by producing energy during periods of low oxygen supply at the peak of muscular contraction. As a consequence of increased oxidative and glycolytic capacities and muscular hypertrophy, the striated musculature of the urethra will be not only more resistant to fatigue but also capable of generating higher tension. Both are important in achieving continence via electrostimulation of sacral nerve roots.

Approximately 3 months after the conclusion of the stimulation program these changes had reverted gradually to the normal pre-stimulation level. The implication is that electrical stimulation for a prolonged period will induce enough favorable histological changes and functional characteristics that marginally weak muscles might become competent after several weeks of stimulation and might require only occasional reactivation by stimulation for a shorter period to boost their responses (few hours per day, 1 day per week or 1 week per month).

Taking advantage of this information, 3 successive colonies of spinal cord injury dogs underwent implantation of sacral root electrodes on the ventral component with dorsal rhizotomy and ipsilateral selective neurotomy.[27] Animals were maintained for 6 to 12 months with repeated stimulation at frequent intervals. Several animals had electrical stimulation for a total of 150 hours. On sacrifice, histological and electron microscopic findings of the stimulated sacral roots were compared to those of the contralateral (control) roots. Neither the operation itself nor prolonged application of electrical stimulation damaged the stimulated ventral root. Neural responses remained reliable and stable even after 8 months and 150 hours of stimulation.

During development and refinement of the surgical technique the importance of some surgical principles became evident: whereas microsurgical separation of the dorsal and ventral roots was safe with sufficient experience, any mechanical stress to the nerve via the implanted electrode was deleterious. To avoid these problems stable fixation of the cables at the electrode site and sufficient subcutaneous play of the cables are necessary so that movements or tension of the cables is not transmitted to the electrode. Furthermore, the risk of mechanical stress is minimized by a refined electrode design using thin, flexible silicone in a spiral shape that secures the electrode surfaces to the nerve without compressing it. Also, minute and highly flexible electrical cables connecting the electrode and radiofrequency receiver lessen the risk of any kinking of the nerve at the implantation site. Another important surgical principle was the transplantation of a pedicle flap of fat around the exposed nerves to restore their natural environment and prevent intraspinal scarring.

Electrical energy can damage nerve tissue if the charge density per phase exceeds the safe limit of 30 $\mu$C./cm.$^2$. With our electrodes and the applied stimulation parameters the charge density per phase was calculated to be between 2 and 6 $\mu$C./cm.$^2$. That this was clearly within the safe limit proved to be true, since not even slight changes in threshold as an indicator of progressive nerve damage were observed during long-term stimulation, nor was nerve degeneration seen histologically.

With the successful and safe outcome of our canine studies we were encouraged to proceed to human experiments.

## HUMAN STUDIES

We began by staging the disease in every patient and performing different combinations of nerve root implantation. After the first 4 patients it became clear that for sacral root stimulation to be effective it must be associated with selective peripheral neurotomy. This prompted us to do detailed anatomical studies on cadavers to establish the exact anatomical distribution of the entire sacral plexus, following it from the sacral roots in the spinal cord through the sacral foramen and inside the pelvic cavity.[28] Emphasis was placed on the autonomic pelvic plexus as well as the somatic fibers and the subdivision into motor and sensory fibers with the intent to define the motor supply to the levator ani, transversus perinei, and urethral and anal external sphincters, and also the sensory supply to the penis (the dorsal nerve of the penis).

*Sacral nerve anatomy.* After the nerve fibers of S2 to S4 traverse the sacral foramen they divide into autonomic and somatic nerve fibers. The former primarily comprise the pelvic plexus, which innervates the bladder and smooth muscle wall of the urethra, and the latter fibers form the pudendal nerve. However, a few somatic branches emanate from S2 and S3 ventral roots and run close to the pelvic plexus to innervate the levator ani muscle and the striated rhabdosphincter around the membranous urethra. The levator ani, as one of the major muscular components of the pelvic floor as well as of the closure mechanism of the urethra, emerges from the fascia of the obturator internus muscle and runs down to the urethra to form the funnel-like muscle floor of the entire pelvis. Close to the urethra, its muscular thickness becomes more prominent, forming a 300-degree ring around the membranous urethra with both ventral levator branches connected by fibrous tissue (fig. 10). This muscular sling surrounds the external urethral rhabdosphincter, which is difficult to separate from the urethral smooth muscle wall in gross anatomical studies. However, both nerves derive their innervation primarily from S2 and S3 somatic fibers that branch proximally before the pudendal nerve reaches the ischial spine. Topographically, these nerve fibers are closely related to the autonomic fibers (the pelvic plexus) from which they run on the inner side of the levator ani down to the urethra to supply the levator ani muscle as well as the intrinsic striated rhabdosphincter. These somatic nerve fibers are identified by intraoperative neurostimulation. This sphincteric complex is essential for urinary continence because of its occlusive force on the urethra in addition to that provided by those muscles innervated via the pudendal nerve, particularly the transversus perinei muscle.

*Pudendal nerve anatomy.* The pudendal nerve is a mixed nerve carrying motor and sensory fibers. It is a part of the sacral plexus, yet its fibers are derived from S2 to S4 as these

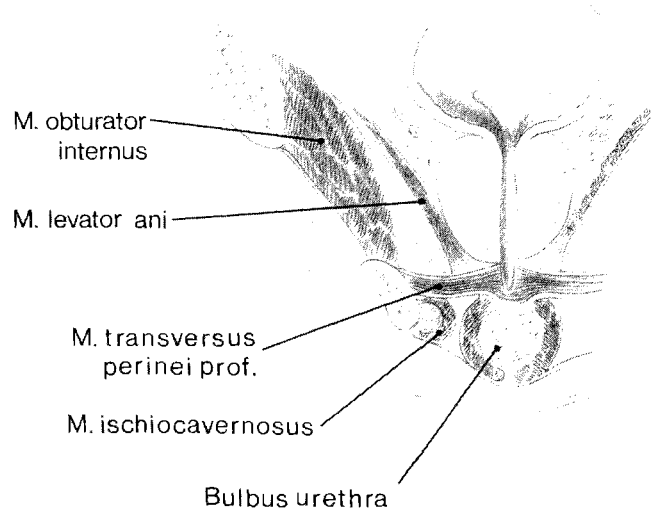


FIG. 10. Relationship of urogenital and pelvic diaphragms to membranous urethra in man (coronal section, ventral aspect).

sacral roots leave the spinal canal through the sacral foramen. Once the roots traverse the sacral foramen they divide first into somatic and autonomic components (S2 to S4).

Autonomic branches originating from S2 to S4 traverse more ventrally and form the pelvic plexus, which is primarily the parasympathetic autonomic supply to the pelvic region, especially the detrusor muscle and the urethral smooth musculature. From the somatic component of the S2 to S4 nerve roots, nerve branches combine to form 1 major trunk of the pudendal nerve superior to the sacrospinosus ligament on the coccygeus muscle and lateral to the coccygeal bone (fig. 11, *a*). Further caudal, the pudendal nerve enters laterally the ischiorectal fossa at the medial side in a fascial sheath (Alcock's canal) close to the obturator internus muscle where it is protected by an overhang of the gluteal musculature dorsally. The pudendal artery and vein, emanating from the internal iliac artery and vein respectively, join the pudendal nerve on its way into the ischiorectal fossa and create the landmark for the first pudendal nerve branch, the dorsal nerve of the penis. Directly inferior to the ischial spine, these blood vessels run between both nerves, thus, separating the underlying dorsal nerve of the penis from its overlying mother trunk, the pudendal nerve.

The penile branch travels dorsolaterally in relation to the main nerve trunk, above the obturator internus muscle and underneath the levator ani muscle; it perforates the transversus perinei muscle laterally to enter the dorsum of the penis ventromedially. The nerve runs lateral to the dorsal artery and deep dorsal vein of the penis to its final destination, the glans penis.

Further down in the ischiorectal fossa the pudendal nerve splits into several motor and sensory fibers. At the level of the anus the rectal nerve fibers take off medially to target the final

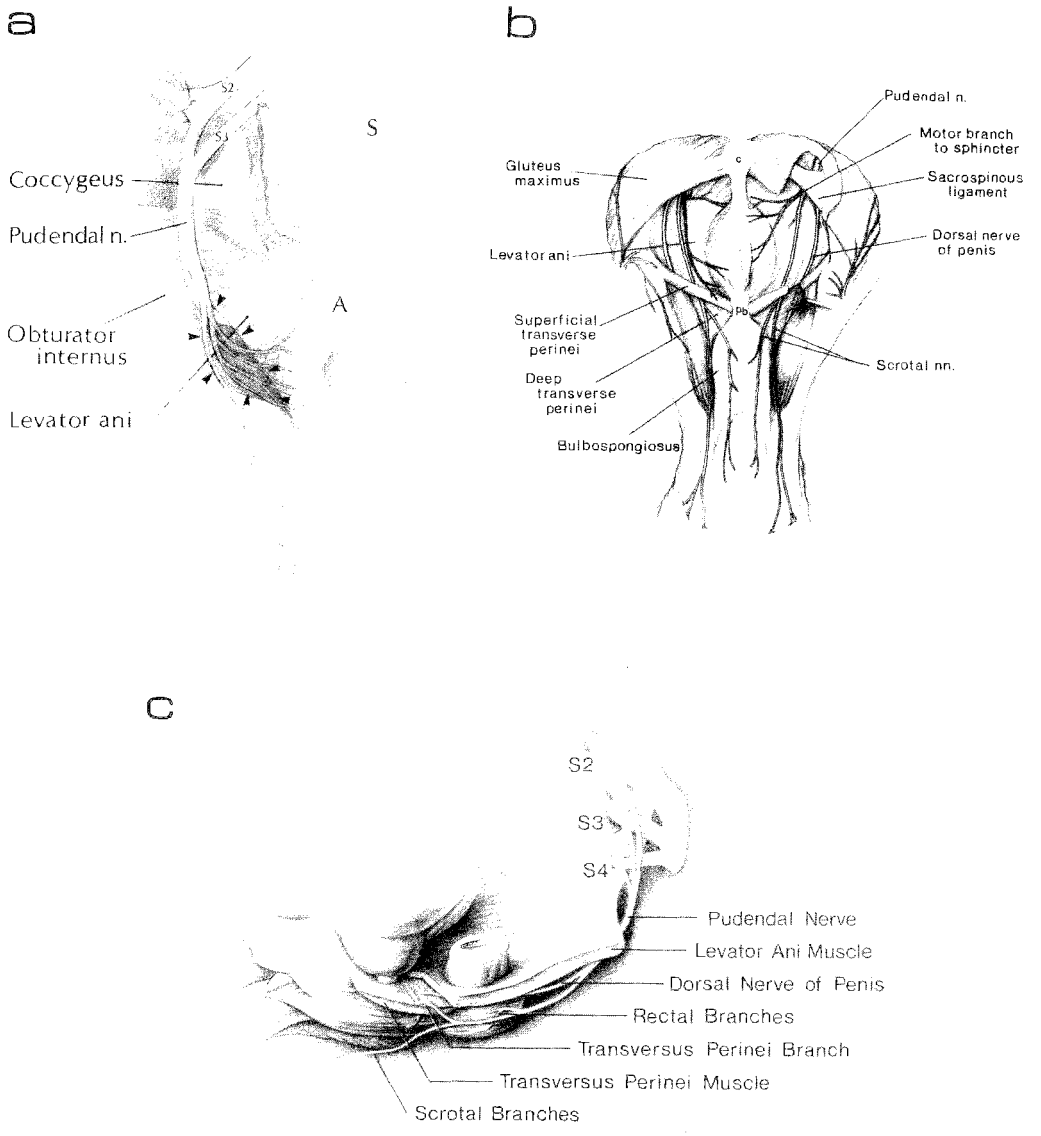


FIG. 11. *a*, origin and pathway of pudendal nerve as delineated by human cadaveric dissection. Arrowheads indicate ischiorectal fossa. *A*, anus. *S*, sacrum. *b*, urogenital diaphragm and external genital organs viewed from below. *C*, coccyx. *Pb*, pubic bone. *c*, innervation of pelvic floor muscles (sagittal section, left side, lateral aspect). Nerve fibers to transversus perinei and ischiocavernosus muscles branch off from main pudendal nerve trunk caudolaterally to rectal branches.

destination, the external anal sphincter (fig. 11, *a* and *b*). The remaining part of the pudendal nerve trunk, often called the perineal nerve, continues further caudally in an intermediate position between the penile dorsal nerve (which is deep at this level) and the more superficial anal sphincteric branches of the pudendal nerve (fig. 11, *b*). The most caudally located nerve branch supplies the bulbospongiosus muscle, and provides the ventral portion of the penis and the scrotum with sensory fibers (fig. 11, *b*).

Dorsolaterally, topographically at the level of the anal sphincteric branches another single branch emerges from the main pudendal nerve trunk; this branch to the pelvic floor provides the innervation of the transversus perinei and ischiocavernosus muscles. The nerve dives into the transversus muscle from the dorsomedial sidewall of the pelvis and some fibers perforate it to supply the underlying ischiocavernosus muscle also (fig. 11, *c*).

This neuroanatomical interrelationship becomes important for providing continence and an adequate urethral sphincteric mechanism (vide infra).

*Stimulation of human sacral roots.* The accumulated knowledge from our canine studies and human cadaveric dissections constituted the background for the human application of neural stimulation. This need not by any means be limited to the paraplegic but it can be used to modulate many types of voiding dysfunction. For sphincteric weakness it can initiate the activity of the sphincter and maintain it continuously without fatigue through intermittent pulses. Sphincteric function can be maximized; more of its fibers will be converted into fatigue-resistant fibers for good control. In cases of bladder hyperreflexia electrical stimulation can eliminate the sensory urge, aid the motor urge and modulate pelvic floor activity. The use can be tailored to each distinct indication.

To date we have treated 119 patients, 22 of whom have complete bladder pacemakers. The remaining 97 patients have voiding dysfunction of various causes (neurogenic, nonneurogenic and post-prostatectomy incontinence).

*Severe neuropathic voiding dysfunction.* In the 22 patients with neuropathic dysfunction resulting from suprasegmental spinal cord lesions a multiple array of sacral root electrodes was implanted. These electrodes were combined with a variable number of dorsal rhizotomies and peripheral neurotomies in the process of clinical trials. Our goals in these patients were to restore reservoir function, re-establish continence and obtain complete bladder evacuation in a synergistic voiding act with low voiding pressure. The first 2 goals were achieved in 70 per cent of 18 patients available for followup and the last goal was achieved in 50 per cent of those whose treatment had been completed.

Several observations have been made from the evaluation, implantation and followup of these patients. Exposure of the sacral nerves extradurally is uncomplicated. It is possible to separate the S2 and S3 ventral roots from the S2 and S3 dorsal roots with microdissection. Voiding is produced only when sphincter resistance is greatly minimized (that is with lidocaine blocks on the pudendal nerve preoperatively and subsequent severing of selective somatic nerve sections after electrode implants). Bladder responses to stimulation are better after than before pudendal nerve block. This observation suggests that sphincteric stimulation inhibits bladder contraction and argues against the success of post-stimulus voiding techniques. Bladder instability decreases with division of sphincter innervation. This results in a decrease in bladder pressure, decreased risk to the kidneys from back pressure and preservation of continence. Stimulus parameters that will accomplish bladder evacuation consistently range between 4 to 6 mA., and 15 to 20 Hz. with a pulse width of 200 $\mu$sec.

*Treatment of spasticity.* It is well established that neurostimulation minimizes or decreases spastic behavior. Used properly, it becomes a useful way to modulate spastic voiding dysfunction.

*Results of neuroprosthetic implantation in 97 patients*

| Diagnosis | Success No. (%) | Improved No. (%) | Failures No. (%) | No. Not Evaluable | Total No. |
|---|---|---|---|---|---|
| Urge incontinence | 13 (68) | 1 (5) | 5 (24) | 2 | 21 |
| Post-prostatectomy incontinence | 8 (40) | — | 12 (60) | — | 20 |
| Pelvic dysfunction syndromes: | | | | | |
| Male pts. | 6 (40) | 4 (27) | 5 (33) | 2 | 17 |
| Female pts. | 19 (63) | 3 (10) | 8 (27) | 9 | 39 |

Detrusor activity is suppressed by sphincter contractions. Thus, enhancing tone within the external sphincter will have a suppressive effect upon the detrusor and improve storage. This inhibitory effect of the sphincter contraction can be used therapeutically when the goal is to achieve continence through suppression of an unstable bladder. Many patients rendered incontinent because of unstable bladder or rectal behavior may be made continent by applying a continuous or intermittent train of pulses that cause sphincter muscles to contract. The stronger the muscle contractions the greater the inhibition or stabilization of detrusor activity. Fortunately, there is a pain-free window that allows application of these techniques to patients with intact sensory pathways.

Patients have presented with other categories of bladder dysfunction (severe urge and frequency, pelvic pain, urinary retention, post-prostatectomy incontinence or mild stool incontinence) but these problems all have had as the common denominator a form of sphincteric spasticity. The response to stimulation often was dramatic (see table). What is clear to date is that technical access to the motor pathways of the bladder is possible and that some form of neural stimulation can be applied beneficially to restore some or all of lost bladder and sphincteric function.

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