ABSTRACT: The bladder has only two essential functions. It stores and periodically empties liquid waste. Yet it is unique as a visceral organ, allowing integrated volitional and autonomous control of continence and voiding. Normal function tests the integrity of the nervous system at all levels, extending from the neuroepithelium of the bladder wall to the frontal cortex of the brain. Thus, dysfunction is common with impairment of either the central or peripheral nervous system. This monograph presents an overview of the neural control of the bladder as it is currently understood. A description of pertinent peripheral anatomy and neuroanatomy is provided, followed by an explanation of common neurophysiological tests of the lower urinary tract and associated structures, including both urodynamic and electrodagnostic approaches. Clinical applications are included to illustrate the impact of nervous system dysfunction on the bladder and to provide indications for testing.


NEUROPHYSIOLOGY IN NEUROUROLOGY

MARGARET M. ROBERTS, MD, PhD

AANEM, Illinois Urogynecology, LTD, Oak Lawn, Illinois, USA

Accepted 29 January 2008

The bladder has two essential functions: the storage and periodic elimination of liquid waste. It has a capacity in the range of 400–500 ml in an average adult but is typically emptied 5–7 times a day, often at much smaller volumes. With an average urine flow time of less than 30 s, the bladder is actively emptying less than 1% of the time. Thus, the predominant role of the bladder is that of a reservoir, storing urine at low pressures even during filling to capacity. When necessary, the bladder is also dynamic, responding to increased filling, infection, or even emotional stimuli with elimination at essentially any volume, any time, as many times as necessary.

The significance of normal bladder function may be more readily apparent if one considers the impact of dysfunction. Urinary incontinence is readily appreciated as a prevalent and costly problem, affecting 17 million Americans at an annual cost of more than 26 billion dollars. This is similar to the prevalence of diabetes in the United States and the total cost of health care for the entire country of Switzerland. Urinary retention, though less prevalent in the general population, is a common condition in patients with neurologic disorders. It has been identified in more than 27% of patients admitted for rehabilitation, with 20% of cases both asymptomatic and unsuspected at presentation. Retention may be equally burdensome to the individual, and untreated; it may result in devastating complications including renal failure and death. Until the 1970s, upper urinary tract disease was the leading cause of death in patients with spinal cord injury (SCI) and myelomeningocele.

While impressive for the sheer size of the numbers, statistics tend to be sterile and dry, failing to capture the human aspect of disease and impairment. Consider the stigmatization, isolation, loss of self esteem, depression, and risk of institutionalization that occurs in those with bladder dysfunction. Failure to maintain continence is a major factor for institutionalization, with more than half of those in nursing homes suffering from urinary incontinence. Following hemispheric stroke, urinary continence is the main determinant of discharge home within 6 months, independent of severity of hemiparesis.

The causes of storage and voiding dysfunction are myriad, diverse, and often multifactorial ranging from a simple and reversible urinary tract infection...
to prostatic hypertrophy or cancer, urethral hypermobility with or without associated pelvic organ prolapse, pharmacologic effects, and neurologic dysfunction, anywhere along the neuraxis from the brain to the spinal cord, or in the peripheral nerves or ganglia.36

Fortunately, neurourology, the study of the function of the bladder, is a rapidly expanding field. Since this monograph was originally written in 1977,35 more than 60,000 publications have appeared on human bladder function/dysfunction in the English language. The explosion of interest and research with the concomitant emergence of technology has provided new information on bladder function from the molecular level of the neuroepithelium of the bladder wall to the cellular interaction in the frontal cortex of the brain. It is the role of neurophysiologists to elicit symptoms and clinical findings which are sometimes nonspecific or silent; identify those patients in which neurological disease is potentially altering bladder function; and examine, diagnose, and ultimately ensure implementation of optimal treatment.

### BLADDER DYSFUNCTION

Urinary incontinence is defined by the International Continence Society as “the complaint of any involuntary leakage of urine.”4 It may be a symptom, a sign, or a condition,1 but it is a nonspecific diagnosis and fails to identify the underlying pathophysiologic process. It is sometimes categorized by the clinical presentation as stress incontinence (occurring with cough, laugh, sneeze, or other exertion which elevates the intraabdominal pressure); urge incontinence (which is accompanied by or immediately preceded by urgency); or continuous leakage. Mixed urinary incontinence has features of both stress and urge incontinence. While more descriptive, these categories still fail to define the underlying cause and any combination of these conditions may coexist. In addition, leakage may be insensible and patients may not be able to characterize their urine loss. Common conditions associated with these presentations are indicated in Table 1. Voiding dysfunction may result from impaired bladder contractility (due to sensory or motor defects), elevated outlet resistance, or a combination of the two. It is often identified after a patient presents with urinary retention and complaints of recurrent urinary tract infection, urinary frequency, nocturia, or even incontinence, but patients with chronic urinary retention may be asymptomatic in spite of large volume retention (1,000 ml) and associated upper urinary tract injury.53,160 Some causes of urinary retention are listed in Table 2.

#### Table 1. Urinary incontinence. Symptoms and associated conditions

<table>
<thead>
<tr>
<th>Stress</th>
<th>Urge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inadequate pelvic support with urethral hypermobility</td>
<td>Detrusor overactivity</td>
</tr>
<tr>
<td>Inadequate sphincter closure due to anatomic defect or functional impairment</td>
<td>Idiopathic</td>
</tr>
<tr>
<td>Lower motor neuron injury Retention (See text)</td>
<td>Neurogenic (upper motor neuron involvement)</td>
</tr>
<tr>
<td>Low compliance Pharmacologic agents (adrenergic antagonists, e.g.)</td>
<td>Continuous</td>
</tr>
<tr>
<td>Fistula</td>
<td>Ectopic ureter</td>
</tr>
<tr>
<td>Severe stress incontinence Unrecognized detrusor overactivity Retention (See below)</td>
<td>Fistula</td>
</tr>
<tr>
<td>Low compliance</td>
<td>Low compliance</td>
</tr>
</tbody>
</table>

#### Table 2. Causes of urinary retention.1,53

| Decreased contractility Lower motor neuron injury (cauda equina, radiculopathy including herpes zoster or simplex, neuropathy) Rapid overdistention such as with diuresis Pharmacologic agents (e.g., anticholinergic) Decreased afferent function Lower motor neuron injury (cauda equina, radiculopathy including herpes zoster or simplex, neuropathy) Analgesics (including alcohol) Outlet obstruction Prostatic hypertrophy (benign or malignant) Pelvic organ prolapse Stricture, stenosis, post-operative changes Stones Detrusor sphincter dyssynergia (upper motor neuron dysfunction) Non-neurogenic neurogenic bladder (Hinman syndrome) or pseudodyssynergia Pharmacologic agents (e.g., adrenergic agonists) Combined factors (e.g., diuresis and analgesia such as alcohol) |
supporting evidence drawn from experimentation in animals, monitoring of normal human function, and evidence drawn from clinical observation of patients with neurologic lesions.7

It is generally accepted that afferent information regarding bladder filling is conveyed via the visceral afferent fibers of the sympathetic and parasympathetic systems to neurons in the lumbar and sacral spinal cord, and then to the periaqueudctal gray (PAG).7,23,90 During urine storage the PAG maintains input to an area of the ventral pons known as the L (lateral) region,7,23 which results in contraction of the urethral sphincter and related musculature to increase urethral closure pressure and maintain continence.23,44 In contrast, at the appropriate level of filling and/or in the appropriate situation, the PAG activates a region of the dorsomedial pontine tegmentum known as the M (medial) region, analogous to the pontine micturition center (PMC) or Barrington’s nucleus.7,23,90 This activates descending pathways to excite parasympathetic neurons in the sacral spinal cord,90 resulting in increased intravesical pressure while concomitantly stimulating inhibitory interneurons which relax the urethral sphincter and facilitate flow.7,23,44 It is not clear what regulates the PAG.25,90

While the forebrain is not essential for the micturition reflex, multiple forebrain structures are involved in the initiation of micturition. In particular, the hypothalamus appears to have a role in activating the PMC when the situation is deemed “safe” to void. In addition, the cingulate gyrus and the prefrontal cortex are thought to be involved in attention and response selection.23,25

ANATOMY

While the following discussion focuses on the lower urinary tract, information regarding related systems is sometimes included due to common innervation and interrelated symptoms, function, and examination.

Peripheral Innervation. The bladder, the urethra, and the associated striated musculature of the urethra and pelvic floor are innervated by three sets of peripheral nerves, each with efferent and afferent components.

Autonomic. The sympathetic system supplies both somatic and visceral structures.118 In general, somatic structures are innervated in a segmental fashion, along with the somatic spinal nerves to the area, whereas visceral structures are innervated in conjunction with the vascular supply of the area. Pertinent effects of sympathetic stimulation include contraction of sphincter muscles, relaxation of smooth muscle in the wall of hollow viscera, and constriction of blood vessels. The parasympathetic system has a more limited distribution, with no innervation of somatic structures and no supply to blood vessels in general.118 Parasympathetic stimulation results in relaxation of sphincter muscles and contraction of smooth muscle in the wall of hollow viscera. In the single instance of parasympathetic innervation of blood vessels, stimulation results in vasodilation of vessels in the erectile tissue of the genitals and, hence, the pelvic splanchnic nerves may be referred to as nervi erigentes.

Visceral afferent fibers supply the visceral peritoneum, the pelvic organs, and the blood vessels. In general, sympathetic afferent fibers mediate dull, aching, poorly localized pain sensation, whereas parasympathetic afferent fibers convey visceral sensations including bladder distention, rectal fullness, urge to urinate or defecate, and sexual sensations.28 However, parasympathetic fibers have been implicated in mediating pain from all of the organs of the pelvis except the uterus.83,118 Both sympathetic and parasympathetic afferent fibers participate in visceral reflex activity.

Sympathetic. The sympathetic efferent fibers to the lower urinary tract originate in the intermediolateral cell column of the spinal cord at T10 to L2.1,2 They exit the spinal cord through the anterior root, intermingled with somatic efferent fibers forming the spinal nerve and synapse in one of the nearby paravertebral ganglia of the sympathetic chain which join the anterior rami and continue peripherally with associated somatic segmental fibers to reach the pelvic floor. Alternatively, those fibers destined for the bladder and urethra may pass directly through the paravertebral ganglia and exit as preganglionic visceral or splanchnic nerves. These fibers may synapse on one of the prevertebral or collateral ganglia on the anterior aspect of the aorta or internal iliac vessels such as the inferior mesenteric ganglia,2,118 before continuing inferiorly as the right and left hypogastric nerves which contribute to the pelvic plexus. Other fibers pass through both the paravertebral and prevertebral ganglia before reaching the pelvic plexus, resulting in a dense complex of pre- and postganglionic sympathetic and parasympathetic fibers and ganglia. The pelvic plexus gives rise to multiple named and unnamed subsidiary plexi and nerves including the vesical plexus to the bladder and the urethra38,118 and the cavernous nerves to
the urethral sphincter complex. The postganglionic fibers of the sympathetic nervous system produce excitation of the bladder base and urethra via α₁-adrenoceptors or inhibition of detrusor muscle via β-adrenoceptors. Further, these fibers may inhibit bladder parasympathetic ganglia via α₂-adrenoceptors, or facilitate bladder parasympathetic ganglia via α₁-adrenoreceptors. Based on findings in animal studies, it appears that inhibition and facilitation occur at different firing frequencies, thus allowing the same mechanism to facilitate storage and emptying as appropriate.

**Parasympathetic.** The parasympathetic effferent fibers to the lower urinary tract originate as preganglionic neurons in the intermediolateral cell column of the spinal cord at S2, S3, and S4. As with the sympathetic fibers, they exit the spinal cord through the anterior roots, intermingled with somatic efferent fibers forming the spinal nerves, continue in the anterior spinal rami, and finally travel via the pelvic splanchnic nerves to ganglion cells in the pelvic plexus, the subsidiary vesical plexus, cavernous nerves, and the wall of the bladder and urethra. (Fig. 1). Preganglionic synapses are nicotinic cholinergic, but they may be modulated by muscarinic, adrenergic, purinergic, and peptidergic input. The postganglionic fibers of the parasympathetic system are typically microscopic and are located intramurally in the detrusor. Cholinergic excitatory transmission in the bladder is mediated via muscarinic, primarily subtype M₃, receptors. In addition, noncholinergic excitatory transmission is mediated by adenosine triphosphate acting on purinergic receptors. Postganglionic neurons innervating the bladder also contain neuropeptides, such as vasoactive intestinal polypeptide and neuropeptide Y and may modulate neurotransmission. Parasympathetic nerve fibers release nitric oxide which is inhibitory to urethral smooth muscle.

**Sympathetic and parasympathetic afferent fibers** are found in the hypogastric and pelvic nerves, respectively, as well as the many autonomic plexi of the pelvis, after originating in the proximal urethra and bladder. As with all peripheral sensory nerves, the cell bodies are located in the spinal ganglia. The sympathetic fibers enter the spinal cord at T11 to L2 and the parasympathetic fibers enter at S2 to S4. Sensation from the bladder is carried predominantly in the sympathetic system but there are some afferent fibers that travel in the hypogastric nerves to the spinal cord. Sensation from the proximal urethra is also thought to be carried by both sympathetic and parasympathetic pathways.

**Somatic.** The somatic efferent fibers to the pelvis originate from motor neurons in the anterior cell column of the spinal cord at the lumbar, sacral, and coccygeal levels, with the sole purpose of innervating skeletal muscle. These fibers exit the spinal cord as the anterior root, form the spinal nerve with the posterior root, and contribute fibers through the anterior (or ventral) ramus to the lumbar and sacralplexuses. Anococcygeal nerves are formed from lower sacral and coccygeal anterior rami and spinal nerves. Somatic afferent fibers supply sensation to the parietal layer of the peritoneum, as well as the skin, muscles, tendons, and joints of the entire pelvis and perineum, including the outer urethra, vagina, anus, and genitalia. These fibers travel proximally along the same pathway to the posterior root and the spinal ganglion containing the cell body before entering the spinal cord through the lumbar, sacral, or coccygeal roots. These fibers convey pain, temperature, touch, vibration, and proprioception.

**Onuf’s Nucleus.** A subgroup of closely packed, atypical alpha motor neurons, collectively known as Onuf’s nucleus (after the original description by Onufrowicz) is located ventrolaterally within the anterior horns at S1 to S3 and provides innervation to the urethral and anal sphincters and the levator ani. The unique properties of these cells include anatomic features such as their uniformly smaller
size and dense dendritic bundling with extensive interconnections, as well as high numbers of noradrenergic and serotonin terminals not seen in adjacent cells. Their distinctive character is further substantiated by their relative resistance to polio and amyotrophic lateral sclerosis, both of which affect other anterior horn cells, and their selective involvement in multiple system atrophy.\textsuperscript{15,88}

**Pudendal Nerve.** After forming on the posterior aspect of the pelvis as part of the sacral plexus, the pudendal nerve exits the pelvic cavity below the piriformis via the greater sciatic foramen. It reenters the pelvic cavity by curving around the sacrospinous ligament just medial to the ischial spine and passing through the lesser sciatic foramen. Finally, it runs forward along the lateral wall of the ischiorectal fossa in the pudendal (or Alcock’s) canal.\textsuperscript{2,118} There are three major branches of the pudendal nerve: the dorsal nerve of the penis/clitoris that arises proximally and travels with the major trunk of the pudendal nerve in the pudendal canal, continuing forward along the ischiopubic ramus to provide cutaneous supply to the clitoris/penis; the inferior rectal nerve which leaves the main trunk of the pudendal nerve within the canal and crosses the ischiorectal fossa to supply the lining of the lower anal canal, the external anal sphincter, and the skin around the anus; and the perineal nerve which divides into cutaneous branches to the posterior labia and lower vagina/scrotum and ventral penis\textsuperscript{144} and distal urethra,\textsuperscript{2,15} and muscular branches to the superficial and deep perineal muscles, including the external urethral sphincter\textsuperscript{2} and parts of the levator ani.\textsuperscript{2,67,118}

**Bladder.** The bladder is a muscular organ which resides in the pelvis when empty but expands into the abdominal cavity as it fills.\textsuperscript{1,2,118} It is composed of an outer adventitial layer of connective tissue, an inner mucosal layer consisting of transitional epithelium (or urothelium) and submucosal lamina propria, and a middle muscular layer, the detrusor muscle.\textsuperscript{1,2,42} The muscle layer consists of circular smooth muscle situated between inner and outer layers of longitudinal muscle, but large interlacing bundles of smooth muscle cells may travel between layers forming a meshwork.\textsuperscript{1,2,38} The trigone is a specialized area of the bladder base extending from the two ureteric orifices to the internal urethral meatus. It is characterized by the presence of a superficial muscle layer, which is morphologically distinct from the deeper trigonal detrusor, consisting of small diameter muscle bundles which are continuous with those of the intramural ureters above and the smooth muscle of the proximal urethra below.\textsuperscript{1,2,38,52}

The detrusor muscle of the bladder is richly innervated by parasympathetic cholinergic nerve fibers with ganglion cells in the anterior portion of the pelvic plexus (vesical plexus) as well as the bladder wall itself. There are also sympathetic noradrenergic fibers to the detrusor but they are few in number and generally, though not exclusively, innervate the vascular supply.\textsuperscript{1,2,38,52} In contrast, the superficial trigone muscle has relatively few parasympathetic cholinergic nerves while sympathetic noradrenergic fibers are prevalent. Sensory fibers have been identified as a suburothelial plexus beneath the epithelial lining of the bladder.\textsuperscript{2} It is somewhat sparse throughout the dome of the bladder, but becomes progressively denser approaching the trigone and bladder neck and extends into the urethra.\textsuperscript{38}

The bladder neck, i.e., the internal urethral orifice, is 3–4 cm behind the lower symphysis pubis. In males the bladder neck rests on the prostate.\textsuperscript{2} At this level, smooth muscle forms a complete collar of circular fibers surrounding the prostatic urethra to serve as an internal sphincter, with a well-defined adrenergic innervation which prevents retrograde ejaculation,\textsuperscript{1,2} but has an uncertain role in continence.\textsuperscript{2,38,52} In females the bladder neck is associated with the endopelvic fascia and supporting pubovesical ligaments with smooth muscle extending from the trigone and continuing obliquely or longitudinally into the urethral wall. The circular smooth muscle sphincter seen in the male is poorly developed or absent\textsuperscript{1} and few adrenergic fibers are identified.\textsuperscript{38} In contrast to the male, the bladder neck of the female receives an abundant supply of cholinergic fibers.\textsuperscript{1,38,50}

**Pelvic Floor.** The pelvic floor can be thought of in layers\textsuperscript{34} with the pelvic viscera and supporting endopelvic fascia forming the first layer. The next layer is the muscular diaphragm (Fig. 2) consisting of the levator ani and two muscles of the lower limb (piriformis and obturator internus). The piriformis arises from the sacrum and the ilium and forms the posterolateral wall of the pelvis. The obturator internus arises from the inner surface of the obturator foramen, forming the anterolateral wall. Both attach to the greater trochanter.\textsuperscript{116,118} The levator ani is a complex sheet of muscle arising from the posterior aspect of the pubic bone, the inner surface of the obturator fascia extending along the arcuate line to the ischial spine, and from the ischial spine itself.\textsuperscript{115,118} Collectively, the fibers run down and back with varying degrees of obliquity to form a funnel which inserts into the anococcygeal ligament and the coccyx posteriorly, while narrowing to encircle
and fuse with the urethra, the vagina (in females), and the anal canal inferiorly.\textsuperscript{118} Although not well-defined, several named regions are described, sometimes with variations in terminology between authors. The pubococcygeus runs almost horizontally from the pubis to insert into the anococcygeal ligament and the coccyx posteriorly. The most medial fibers bordering the urogenital hiatus are often referred to as the pubovaginalis in the female and the pubourethralis/levator prostate in the male. Posteriorly, the muscle fibers encircle the anal canal, sometimes blending with the longitudinal fibers of the rectal muscle. Inferiorly, muscle fibers from each side unite with the contralateral fibers behind the rectum to form a “sling” at the level of the anorectal angle. This region of muscle, referred to as the puborectalis portion of the pubococcygeus muscle, maintains the anorectal angle which is critical for anal continence.\textsuperscript{2,101} The iliococcygeus arises from the arcuate line and the ischial spine and runs posteriorly to join with fibers from the opposite side and form a raphe just superior to (and sometimes continuous with) the anococcygeal ligament and the coccyx inferior to the attachment of the pubococcygeus.\textsuperscript{2,118} The ischiococcygeus (sometimes referred to as a separate muscle, the coccygeus)\textsuperscript{118} is the most posterior and superior portion of the levator ani, arising from the ischial spine and running posteriorly to insert on the lateral margins of the lower sacrum and coccyx. In some cases it may be tendinous rather than muscular.\textsuperscript{2}

Just below the muscular diaphragm, the perineal membrane, sometimes referred to as the urogenital diaphragm, spans the anterior portion of the pelvic outlet. It consists of striated muscles including the deep transverse perineal muscles as well as the compressor urethrae and the urethrovaginal sphincter in the female.\textsuperscript{1,34,85} The urethral sphincter muscle in the male is vertically oriented and does not contribute to the urogenital diaphragm.\textsuperscript{92}

The most superficial layer of the pelvic floor is the external genital muscles consisting of the bulbocavernosus (BC) also referred to as the bulbospongiosus, the ischiocavernosus (IC) and superficial transverse perineal muscles anteriorly, with the external anal sphincter located posteriorly.\textsuperscript{34,118} In the male the BC lies at midline anterior to the perineal body and runs forward with the contralateral sides united by a median raphe. Its fibers encircle the bulb of the penis and adjacent corpus spongiosum extending anteriorly to spread over the corpora cavernosa. In the female the BC attaches to the perineal body and runs anteriorly on each side of the vagina, covering the vestibular bulbs.\textsuperscript{2,118}

The levator ani is innervated on its pelvic surface by small twigs arising directly from the S3, S4,\textsuperscript{101,118} and sometimes S5 nerve roots.\textsuperscript{8} The anterior portion of the levator ani, particularly the puborectalis, may
also receive some innervation from the pudendal nerve, but the primary source of innervation for the puborectalis is direct branches of S3 and S4. The posterior portion of the levator, especially the ischiococcygeus, is thought to receive innervation from S5. The most superficial layer of pelvic floor muscles (BC, IC, and transverse perineal) is innervated on its inferior aspect by distal (perineal) branches of the pudendal nerve.

**Urethral Sphincter System.** As indicated above, there are differences between the male and female urethral sphincter systems. In the male there is an internal sphincter composed of smooth muscle at the level of the bladder neck which is innervated by the sympathetic nervous system and functions primarily to prevent retrograde ejaculation. The external urethral sphincter (EUS), also known as the intramural sphincter or rhabdosphincter, consists of circularly oriented striated muscle surrounding the smooth muscle of the urethral wall starting at the base of the bladder and extending distally to the perineal membrane. It completely encircles this segment of the urethra except where it is interrupted posteriorly by the prostate and corresponds to the zone of peak urethral closure pressure (Fig. 3). As the urethra and EUS pass through the pelvic floor, the adjacent fibers of the levator ani surround them as the periurethral sphincter.

In the female no circular smooth muscle sphincter can be identified. The EUS is composed of three parts. Proximally, the urethral sphincter completely encircles the smooth muscle of the urethral wall, starting at the base of the detrusor and becoming fully developed in the middle one-third to two-fifths of the urethra, corresponding to the zone of maximal urethral closure pressure. More distally, at the level of the urogenital diaphragm, some of the muscle fibers surround both the urethra and the vagina as the urethrovaginal sphincter, while other fibers pass laterally to insert on the pubic rami forming the compressor urethrae (Fig. 4). Again, the periurethral sphincter is composed of the surrounding muscle fibers of the levator ani.

The EUS is a striated muscle, composed almost exclusively of small, type 1 fibers. While it may have a role in the maintenance of continence, it has also been proposed as a sensory mechanism, providing feedback to the bladder and periurethral muscle. This is particularly interesting, as the EUS is reported to be devoid of muscle spindles. The periurethral sphincter is a striated muscle, consisting of both type 1 and type 2 fibers, but with a predominance of type 1 fibers, making it well-suited for its role in the maintenance of continence at rest, as well as during sudden increases in intraabdominal pressure.

The innervation of the urethra is surprisingly complicated and controversial. The nerve supply to the EUS is classically described as somatic fibers from S2 to S4 that reach the EUS through the perineal branch of the pudendal nerve. However,
some investigators report that at least a portion,1,26 if not all,67 of these fibers take a separate intrapelvic course, whereas others report that they travel through the pelvic plexus67 to the EUS. It is also claimed that parasympathetic fibers in the pelvic plexus innervate the EUS.38 The innervation of the smooth muscle of the urethra is autonomic, via the pelvic plexus to the vesical plexus and cavernous nerves.1,52,143,165 The periurethral sphincter has generally been reported to be innervated by the perineal branch of the pudendal nerve,16,38,118,130 but this must be further evaluated in light of mounting evidence of nonpudendal innervation of the remainder of the levator ani.8

**Anal Sphincter.** The human external anal sphincter (EAS) is an oval tube of striated muscle which surrounds the lowest portion of the anal canal.5,113 It is attached anteriorly to the perineal body and posteriorly to the coccyx.2,118 It extends upward from the skin at the anal margin inferiorly to blend with the fibers of the puborectalis superiorly2,94,118,161 (Fig. 5). The EAS is comprised of three anatomically distinct layers: subcutaneous, superficial, and deep,2,94,118 but the subcutaneous and superficial fibers are closely associated, as are the deep EAS and the puborectalis. All four components are conjoined anteriorly in females.94 The muscle is composed predominantly of small (15 μm) type 1 fibers, as would be expected for a tonically active muscle.123

The innervation of the EAS is classically described as being provided by the inferior rectal branch of the pudendal nerve2,67,118 with significant crossover of the nerve supply occurring from one side to the other.162 However, exceptions are common, and perhaps even the rule. A ventral to dorsal distribution of different branches of the pudendal nerve, as well as spinal segments S2, S3, and S4, has been described.46 Although the middle and dorsal portions of the EAS are supplied by the inferior rectal nerve in the majority of cases, the pudendal nerve itself, or its perineal branch, supplies the ventral portion up to 91% of the time.46 An appreciation of the variability in the innervation of the EAS is important for the electromyographic (EMG) evaluation of this muscle.

**CLINICAL EXAMINATION**

Although discussion of a complete neurologic examination is beyond the scope of this monograph, the basic principles are familiar to all neurophysiologists. As always, adequate history is critical. In this situation, in addition to routine questions used to identify nervous system involvement, the intent is to elicit symptoms of voiding dysfunction (hesitancy, straining, incomplete emptying—perhaps with associated daytime frequency and nocturia incontinence, and/or frequent urinary tract infections) or incontinence (with stress symptoms such as leakage with cough, laugh, sneeze, or with urgency, often with associated daytime frequency and nocturia). Detailed questions regarding bowel and sexual function are also pertinent because of the common in-
nervation. Inquiry regarding autonomic dysfunction, especially orthostatic hypotension, may also be indicated. When possible, it is helpful to have the patient complete a voiding diary indicating voided volumes, as well as episodes of incontinence, for several days prior to examination.

The basic physical examination of the nervous system should be supplemented to include sensory testing of the lower abdomen, perineum, and proximal lower extremities with correlation to findings in the lower extremities if abnormalities are identified. Pertinent reflex testing includes the anal wink and bulbocavernous/clitoroanal reflex. Again, testing in the lower extremities, such as the Achilles reflex, and flexor testing of the foot may be helpful to further define the extent and type of lesion if identified. Assessment of muscle function in the pelvic floor should include testing of perianal and perivaginal muscles (in females) with observation of initial resting tone, presence of contraction and lift of the pelvic floor, as well as subsequent relaxation. Of course, the inability to contract may not indicate a neurologic lesion. The patient may be uncomfortable or unfamiliar with testing. In addition, the impact of high resting tone, disuse and atrophy, or even muscle disruption should be considered as alternative sources of weakness. Again, correlation with the examination of other proximal and lower extremity findings is essential. Inspection of the patient’s lower spine may also be revealing. For example, the presence of a dimple, hairy tuft, or abnormal gluteal cleft may indicate the presence of occult spinal dysraphism and should be further evaluated. Finally, if possible, a postvoid residual should be measured. Although bladder scanning is acceptable, the sterile specimen obtained with catheterization may be submitted for urinalysis and/or culture.

**NEUROPHYSIOLOGIC TESTING**

Urodynamic and EDX studies provide functional assessment of the lower urinary tract and its neural control. As with any diagnostic test, these studies must be ordered, performed, and interpreted in the context of the patient’s entire clinical picture. Evaluation of the central nervous system should be completed when appropriate. Anatomic studies of the pelvis such as ultrasound, computerized tomography urography, and magnetic resonance imaging provide complementary information and should be used when indicated. In addition, functional testing of the lower gastrointestinal tract, such as colonic transit testing with sequential lower gastrointestinal films after ingestion of radiopaque markers, manometry, and defecography may also provide relevant information. Finally, while the subsequent discussion focuses on testing of the bladder and muscles and nerves of the pelvis, other tests of autonomic function as well as nerve conduction studies (NCSs) and EMG examination of the trunk and limbs may

---

**FIGURE 5.** Puborectalis and external anal sphincter from the right. Adapted from McMinn in Roberts with permission from Lippincott Williams & Wilkins and Elsevier.
be necessary to define the extent of abnormalities should they be identified.

Prior to testing, these procedures should be fully explained to the patient. If voiding is to be monitored the patient should be asked to avoid urinating prior to arrival in the clinic. Otherwise, the patient should be given the opportunity to use a private toilet immediately prior to testing. After removing the undergarments, the patient should be draped appropriately in a warm, secure room. A urodynamics chair may accommodate both urodynamic and EDX testing. Alternatively, the patient may be positioned on his or her side or supine with the legs gently spread apart or placed in stirrups for EDX testing. If needle or wire EMG is planned, anesthetic cream containing 2.5% lidocaine and 2.5% prilocaine (EMLA cream by Astra, Westborough, Minnesota) may be applied periurethrally and/or perianally 20 min prior to needle insertion. The ground electrode may be placed on the proximal thigh. If a reference electrode is required, it may be placed on the mons pubis or on the ipsilateral proximal thigh.

**URODYNAMIC TESTING**

Urodynamic testing generally refers to any/all of a series of functional tests used to assess lower urinary tract storage and/or emptying. Methods range from simple noninvasive procedures such as uroflowmetry to highly sophisticated and invasive techniques such as videocystometrography. Testing is tailored to the individual patient depending on the nature of the clinical picture, much as various EDX tests are performed to investigate a patient’s nervous system. While urodynamic testing is indirect, it documents various aspects of bladder and sphincter function, allowing inferences to be made regarding peripheral somatic and autonomic, as well as central nervous system function in the context of the patient’s clinical picture. It is the best tool available for the investigation of sacral parasympathetic activity.

The goal of urodynamic testing is to reproduce the patient’s symptoms while monitoring the lower urinary tract to provide an objective description of its function and/or dysfunction. Abnormalities are not specific for a particular diagnosis, but facilitate identification of pathophysiology and contribute to diagnosis, prognosis, and, ultimately, implementation of optimum management. Unfortunately, the nature of the study makes it prone to artifact and this must always be considered in the interpretation of results.

Most patients with neurologic impairment and lower urinary tract signs or symptoms should undergo urodynamic testing to characterize the function of the bladder, the urethra, the pelvic floor, and their coordination. Indications include central nervous system lesions such as stroke, spinal cord injury, and multiple sclerosis, and peripheral nervous system disorders such as cauda equina syndrome and diabetic neuropathy with cystopathy, as well as combined disorders such as myelodysplasia (e.g., in which testing is indicated within the first months of life to direct appropriate management and prevent upper urinary tract injury). Exceptions are the few diseases in which empirical, conservative therapy can be safely implemented (e.g., incontinence following cortical stroke without associated urinary retention) with subsequent urodynamic testing if management is unsuccessful. Of course, testing may also be helpful in identifying neurologic involvement.

**Uroflowmetry.** Uroflowmetry is a simple, noninvasive study of bladder emptying performed by measuring urine flow during voiding. Ideally, this study is done after a patient arrives with a comfortably full bladder (with a minimum of 150–200 ml) because flow is influenced by the voided volume. However, it is often impossible for patients to comply with this request due to urgency, frequency, and/or incontinence, and artificial filling may be required. After uroflowmetry, the postvoid residual is determined with ultrasound or catheterization to determine adequacy of emptying and to allow calculation of the total volume in the bladder. The data are usually displayed as a graph of urine flow in milliliters versus time in seconds. The normal shape of the curve is a smooth, continuous, slightly asymmetric bell curve which reaches its peak in the first third of flow (Fig. 6). Key measures include maximum and mean flow rates, voided volume, and flow time. Results are nonspecific because flow is determined by a combination of abdominal pressure, detrusor pressure, and outflow resistance, but they provide a reasonable screen of voiding function when normal. In addition, this approach is most likely to document the patient’s typical flow pattern because the study can be performed before examination or instrumentation of any kind. It can then be compared with data collected subsequently with catheters and other monitors in place.

Patients with neurologic impairment may have reduced flow, due to impaired detrusor contractility or because of outlet obstruction such as detrusor sphincter dyssynergia (DSD). Flow may be irregular
due to abdominal strain voiding in the absence of detrusor function, fluctuating detrusor contractility, or variable outlet resistance as may also occur with DSD or other sphincter and pelvic floor dysfunction. Of course, abnormal waveforms with the same characteristics may be observed in patients without neurologic involvement and normal waveforms may be produced via abnormal mechanisms in patients with neurologic disease.1,122,137

Cystometry. Cystometry is the measurement of the intravesical pressure during filling and/or emptying of the bladder.1,62,137 Because vesical pressure is the sum of the detrusor pressure and the abdominal pressure, detrusor pressure is calculated by measuring the abdominal pressure (in the rectum or vagina) and subtracting from the vesical pressure. Simultaneous recording of EMG activity from pelvic floor muscles allows assessment of the pattern of firing during filling and emptying. Activity is typically recorded from the anal or urethral sphincter with surface or wire electrodes.

During filling, every attempt is made to reproduce symptoms such as incontinence or pathological conditions, such as elevated detrusor pressure, while the patient provides input. Information is collected regarding sensation, detrusor activity, compliance, capacity, and incontinence if it occurs. Depending on the clinical picture and goals of the test, provocative measures such as coughing, straining, standing, bouncing on the heels, and listening to running water may be utilized to reproduce symptoms. Rapid filling at nonphysiological rates with cool filling media may enhance detection of uninhibited detrusor contractions, but these maneuvers may also induce artificial detrusor activity in patients with suprasacral injury and are used selectively.

Graphic representation of the data as time in seconds versus fill volume in milliliters, vesical, abdominal, and detrusor pressure in cmH₂O and EMG activity allows analysis of related events, as well as identification of artifact (Fig. 7). Key measures include the bladder volume at first sensation of fill and normal and strong desire to void, the volume when uninhibited detrusor contractions appear (if present) and if they are detected by the patient, the compliance and capacity of the bladder, and the occurrence of incontinence. If there is incontinence with abdominal pressure elevation in the absence of a detrusor contraction, a diagnosis of urodynamic stress incontinence is made4 and the Valsalva leak point pressure (VLPP) is determined. The VLPP is the minimum vesical pressure elevation sufficient to induce leakage4 and is a measure of continence. In contrast, if there is uninhibited detrusor activity present, the detrusor leak point pressure (DLPP) is determined. The DLPP is the minimum detrusor pressure sufficient to induce leakage and is a measure of storage pressure in the urinary tract. The DLPP is also determined when leakage occurs in the absence of increased abdominal pressure or a detrusor contraction, as may occur with an underactive or acontractile detrusor, when passive vesical pressure exceeds outlet resistance.

Pressure Flow Studies. Pressure flow studies are the simultaneous recording of detrusor pressure and urine flow during voiding. This combination allows assessment of the voiding mechanism which is not possible with uroflowmetry or cystometry alone.5,94,137 The addition of kinesiologic assessment of the pelvic floor with monitoring of EMG activity enhances interpretation, particularly in the presence of obstructive flow patterns. It is helpful in any patient with retention or suspected dysfunctional voiding but is especially important in the presence of neurologic disease.1,62,113 Videourodynamic studies performed with fluoroscopy and the addition of a radiopaque contrast material to the filling medium may also be helpful in this setting. Normal voiding is initiated with relaxation of the external urethral sphincter and contraction of the detrusor muscle with subsequent onset of urine flow producing a smooth continuous waveform, as described above, followed by detrusor relaxation and resumption of
sphincter activity. Abdominal pressure rises minimally or not at all\(^1,21,113,146\) (Fig. 8). Key measures include the voided volume, maximum flow rate, and detrusor pressure at maximum flow. Following completion of the study the postvoid residual is determined to calculate the cystometric capacity.

Patients with lower motor neuron dysfunction may have impaired sensation and an elevated capacity with high compliance, the detrusor may be underactive or acontractile, and there may be associated stress and/or “overflow” incontinence with an elevated residual. These findings are exemplified by patients with diabetic cystopathy.\(^{27,44,64}\) Patients with upper motor neuron dysfunction may also have impaired sensation but the capacity is often low, compliance may be reduced, and (neurogenic) detrusor overactivity with incontinence is common. The residual may be elevated in spite of high voiding pressures due to DSD.\(^{1,68,157}\) Essentially any combination of these features may also occur. In each case, specific measures of function are clinically relevant, not only to direct symptomatic treatment, but also to avoid upper urinary tract deterioration which is associated with low compliance, DSD, and a DLPP of more than 40 cmH\(_2\)O.\(^{20,76,84,126,157}\)

**ELECTRODIAGNOSTIC TESTING**

EDX testing generally refers to the combination of NCSs and EMG used in the physiological assessment of the peripheral nervous system. It may also provide information regarding function of the central nervous system, albeit indirectly in most applications. The following descriptions are limited to studies pertinent to the evaluation of lower urinary tract function.

In this context, EDX testing is indicated for the evaluation of urinary incontinence and/or voiding dysfunction that may be attributed to a peripheral nervous system lesion. Involvement may be suspected on the basis of congenital abnormalities such as spinal dysraphism, trauma (including surgery) to the pelvis or sacrum, or more widespread disease such as multiple system atrophy.\(^{88,162}\) Alternatively, a combination of clinical findings such as fecal incontinence, sexual dysfunction, and/or lower extremity symptoms in addition to urinary incontinence or retention without an apparent cause may suggest an underlying neurological etiology.\(^{131}\) Patients with unexplained urodynamic findings, particularly the combination of an acontractile bladder and stress incontinence, or urinary retention in a young wom-
an\textsuperscript{70} should also be evaluated. EDX testing is not indicated for the routine evaluation of patients with incontinence or voiding dysfunction.\textsuperscript{149,151} Neither is it useful as a screening tool for neuropathic lesions.\textsuperscript{104}

**Nerve Conduction Studies. Sacral Reflex Testing.**

Sacroccygeal reflexes are the contraction of the perineal muscles in response to stimulation of the perineum, urethra/bladder, or anus.\textsuperscript{145,151,152} Testing of the sacral reflexes assesses the integrity of the sacral spinal cord at S2 to S4 as well as the associated afferent and efferent pathways.\textsuperscript{5,124,151} The afferent pathway of the reflex may be somatic, sympathetic, or parasympathetic, depending on the site of stimulation, but the efferent pathway is somatic and usually monitored in muscles innervated by the pudendal nerve. Two of these reflexes are commonly used clinically:\textsuperscript{145,151} the bulbocavernosus reflex, elicited with compression of the glans penis or clitoris, and the anal reflex, elicited with pinprick of the mucocutaneous junction of the anus. In each case a response may be observed or palpated in the bulbocavernosus muscle or the anal sphincter.

With electrical stimulation, sacral reflexes may be elicited from virtually any site in the lower sacral dermatomes or the lower urinary or gastrointestinal tract.\textsuperscript{105} Recordings may be made from any of the perineal muscles or sphincters using surface or needle electrodes. Thus, it is possible to isolate both the stimulus and the response, defining the pathways more precisely, and increasing the specificity of the data obtained, in addition to measuring the latency and increasing the sensitivity of detection.\textsuperscript{22,158} While current convention refers to all somatic reflexes as the bulbocavernosus reflex, this is nonspecific and sometimes misleading with multiple potential stimulation and recording sites. No consensus has been reached, but nomenclature has been proposed which identifies the stimulating and recording sites in the name.\textsuperscript{105}

The sacral reflexes that have the most general application in the EDX laboratory are the peniloanal reflex (PAR) and penilobulbocavernosus reflex in the male and the homologous clitoroanal reflex (CAR) in the female. The urethroanal reflex and the bladder (or vesico) anal reflex, sometimes referred to as visceral reflexes, have potential utility in patients with focal anatomic injury to the urethra, involvement of the bladder, and/or pelvic injury,\textsuperscript{13,18,151} but have remained primarily limited to research thus far.\textsuperscript{151} The anal (or anoanal) reflex, which is a nociceptive reflex with wide variability in latencies, is not commonly used.\textsuperscript{151} Interestingly, a perineal response may also be observed during testing of the flexor response of the foot, or with posterior tibial nerve stimulation.\textsuperscript{58,99} This reflex provides an afferent pathway in an anatomically distinct region which could be diagnostically useful, but it has not been widely investigated or applied.
Penile/Clitoral Reflex. The PAR/CAR utilizes pudendal nerve afferent and efferent pathways, as well as the sacral roots and sacral spinal cord with suprasacral modulation during voiding. In the male the reflex is elicited by stimulating the dorsal nerve of the penis with either ring electrodes on the glans and shaft of the penis or with a standard bipolar stimulator at the base of the penis with the cathode proximal. The response is recorded from the EAS with a surface or needle electrode. It is also convenient to record with a surface electrode on an anal plug inserted into the anus to record from the anal sphincter. However, this electrode does not allow for unilateral recording. The reflex may also be recorded from the BC muscle or the EUS. In the female the reflex is elicited with transcutaneous stimulation of the dorsal nerve of the clitoris on either side of the base of the clitoris. The response is recorded from the EAS with either needle or surface electrodes as indicated above.

Adequate stimulation intensity is important to elicit the response and most laboratories report the use of 3–4 times the sensory threshold but responses are sometimes elicited at higher intensities. Paired stimuli (2–5 ms apart) may also be necessary to facilitate the response even in normal individuals and the response should not be considered absent with single stimuli. An initial, oligosynaptic response is recorded which is stable and does not habituate. A second component with a longer latency has also been described, but it is less consistently identified as a discreet response and may require higher stimulation intensity to elicit. Finally, volitional responses may also be recorded following the reflex response (Fig. 9). Averaging is typically not used due to variation in waveforms. The onset latency is recorded from each side with typical mean latencies of 31–38.5 ms. However, the range of reported latencies is wide in individual normal subjects, with one report documenting latencies up to 102 ms. Also, it has been shown that latencies vary up to 2 ms with different recording sites within the same muscle and 2–7 ms from side to side. Therefore, disparities must be interpreted cautiously. Krane and Siroky reported lesion localization to the right or left and efferent or afferent pathways by virtue of the unilateral afferent and bilateral efferent pathway of the reflex. Others have corroborated this finding. It has been debated by some authors, but Recht-hand nicely demonstrates the elicitation of a bilateral response in spite of unilateral dorsal nerve block. The PAR/CAR is inhibited during voiding and some authors have found loss of inhibition to be a sensitive and specific indicator of suprasacral lesions.

As with other NCSs, a supramaximal stimulus is required to record the most robust response with the shortest latency. However, as the stimulation intensity increases reflex contractions may be elicited in any of the perineal muscles. In addition, with high-intensity stimulation there may be short latency responses, at 5–13 ms, due to direct, rather than reflex stimulation of the nerve, and these responses may initially be confusing. Because sacral reflexes are based on conduction (and not amplitude), they are not sensitive to incomplete lesions, whether

demyelinating or axonal. Thus, a normal response does not exclude a lesion. Finally, most authors report difficulty eliciting the sacral reflexes in some normal patients.

Sacral reflex testing may be helpful in evaluating lower motor neuron/peripheral nervous system lesions of the conus, sacral roots, plexus, or branches of the pudendal nerve. With a complete lesion, the reflex is absent. An incomplete lesion may be associated with a prolonged latency and a diminished or absent response. However, to reiterate, a normal response does not exclude a lesion. It is also important to note that even markedly prolonged latencies may be associated with normal bladder and sphincter function, as has been documented in patients with hereditary motor and sensory demyelinating neuropathy. Finally, an unusually short latency has been documented in cases of tethered cord syndrome and should not be disregarded. Thus far, sensitivity and specificity of sacral reflexes have not been determined and clinical relevance has not been clearly demonstrated.

Somatosensory Evoked Potentials. Somatosensory evoked potentials (SEPs) are waveforms recorded from the peripheral and central nervous system after activation of afferent nerve fibers. Large-diameter myelinated afferent fibers from the urogenital region and lower extremities generate impulses which enter the spinal cord and travel rostrally in the ipsilateral dorsal columns, synapse in the nucleus gracilis, and cross to the contralateral brainstem to continue rostrally as the medial lemniscus and terminate in the ventral posterolateral thalamic nucleus (VPL). Neurons in the VPL project to the somatosensory cortex. An additional pathway in the spinothalamic tract may also participate in transmission of these impulses. The somatosensory region representing the urogenital region and lower extremity is located along the medial aspect of the cerebral hemisphere.

SEPs may be used clinically to investigate conduction in neural pathways extending from the peripheral site of stimulation to the parietal sensory cortex. The tibial SEP is a routine study with well-established techniques and normal values for evaluation of L4 to S2 (S3) pathways from the lower extremity and will not be discussed here. The pudendal SEP with S2 to S4 pathways from the pelvis is sometimes used in an attempt to evaluate urologic function more specifically. It is elicited with stimulation of the dorsal nerve of the penis or the dorsal nerve of the clitoris using ring or bar electrodes, as indicated above for the sacral reflexes. Stimulation intensity is set at 2–4 times the sensory threshold and cortical potentials are recorded from Cz with reference to Fz or Fpz. One hundred to five hundred responses are averaged and then repeated to document reproducibility. The potential is readily elicited and consists of a positive peak, with amplitudes of 0.5–12 µV designated as P1 or P40 (with a normal range of 30–49 ms) followed by a series of additional waveforms which are more variable and of uncertain significance. Amplitudes have not been found to discriminate between normal and pathologic responses. It should also be noted that even experienced authors report some difficulty recording bilateral responses in all women. A spinal potential may be recorded in men from T12 to L1 with reference to the iliac crest or spine, but it is difficult to record in women, likely due to activation of small numbers of afferent fibers. It is also difficult to record in obese male subjects and it is not routinely performed. The somewhat slower conduction in the pudendal response, compared to that in the tibial response, has been attributed to slower conducting spinal pathways.

Although this technique is technically feasible, and theoretically appealing, its utility in the evaluation of urologic function is limited. For example, peripheral neuropathies which may affect the bladder, particularly if there is small fiber involvement that could be expected to involve the pudendal sensory fibers. In general, EDX studies are more appropriately performed in the limbs to make the diagnosis of a neuropathy and urodynamic testing provides more useful information regarding bladder function. Further, in patients with diabetic neuropathy, abnormal tibial SEPs were correlated with both the presence of lower urinary tract symptoms and urodynamic abnormalities, while abnormal pudendal SEPs were not. Central nervous system lesions in these pathways are also more likely to be identified with tibial SEPs. Even in patients with multiple sclerosis and bladder symptoms, the tibial SEP is more likely to be abnormal than the pudendal SEP. In patients with urologic complaints but no other neurologic symptoms and a normal neurologic examination, pudendal SEPs are unlikely to be abnormal.

In patients with acute, traumatic tetraplegic SCI, recovery of both bladder and urethral sphincter function correlate better with the American Spinal Injury Association (ASIA) score and tibial SEPs than with pudendal SEPs. However, if a pudendal SEP can be elicited, at least some recovery of bladder function can be predicted. In patients with acute paraplegic SCI, ASIA scores, tibial and pudendal SEPs are...
all predictive of recovery of urethral sphincter function but not of bladder function. The pudendal SSEP appears more sensitive than the tibial SSEP in this regard.\textsuperscript{29} SEPs have also been elicited from the urethra and bladder in an attempt to assess transmission along small unmyelinated autonomic afferent fibers.\textsuperscript{59} The proximal urethra or bladder is stimulated with a bipolar surface electrode mounted on a Foley catheter. (Use of monopolar stimulation with the anode on the skin has been demonstrated to stimulate somatic afferent nerves and the bipolar technique is used to minimize their activation.)\textsuperscript{59} Cortical responses are recorded from Cz referenced to Fz. The most prominent and reproducible potential is a negative peak with a latency of \(\approx 100\) ms, though earlier components may be identified. Amplitudes are low, typically less than 1 \(\mu\)V, and configuration is variable, making it difficult to identify even in some normal subjects.\textsuperscript{15,59,147,151} These factors, as well as the requirement for placement of the urethral ring electrode, which is somewhat uncomfortable, particularly in men, have limited its use. However, if the response is present it may help exclude a subpontine lesion in patients with bladder dysfunction.\textsuperscript{15}

**Pudendal Nerve Conduction Studies.** In 1984 Kiff and Swash\textsuperscript{72,133} described a method for the transrectal stimulation of the pudendal nerve. The initial reports were enthusiastically received. The technique was refined, commercially available electrodes were produced, and studies were performed to develop normative data based on age, gender, and parity.\textsuperscript{72,77,96} Prolonged pudendal nerve latencies were reported in obstetrical lesions, constipation, perineal descent, and fecal and urinary incontinence.\textsuperscript{57,71,72,127,129,151,152} Unfortunately, a number of issues related to this approach are now apparent and the utility of the test has been questioned and found lacking.\textsuperscript{11,45,55,61,78,98,149,151} To perform the study, the St. Mark’s electrode (Dantec, Skovlunde, Denmark) is affixed to the examiner’s gloved hand with a bipolar stimulating electrode at the tip of the index finger and recording electrodes at the base of the finger. The finger is inserted vaginally or rectally and the pudendal nerve is stimulated as it reenters the pelvis near the ischial spine. The response of the inferior rectal nerve is recorded from the anal sphincter with the electrodes at the base of the index finger (or with surface electrodes over the anal sphincter) as the pudendal nerve terminal motor latency (PNTML).\textsuperscript{72} Because the pudendal nerve branches distal to the stimulation site, the response from the perineal nerve (perineal nerve terminal motor latency [PeNTML]) may also be recorded from the urethral sphincter with a bipolar surface electrode mounted on a Foley catheter.\textsuperscript{133} Typical latencies of 1.9 ms and 2.4 ms were initially reported to the anal sphincter and urethral sphincter, respectively,\textsuperscript{133} but the range reported in normal subjects is quite variable, from 1.4 to 5.6 ms\textsuperscript{72,96} to the anal sphincter and 1.7 to 3.8 ms to the urethral sphincter.\textsuperscript{96} As with all NCSs, the terminal motor latency is determined by the fastest response with axonal integrity. In this case, the stimulation site is fixed (at the ischial spine) without measurement of the nerve pathway in spite of differences due to patient size or position of the perineum. Further, the distance between the stimulation site and pickup changes as the examiner positions the electrode to obtain an optimal waveform. Latencies are not only variable, but curiously short when compared to antidromic sensory responses recorded with this technique\textsuperscript{5} or to other motor conduction techniques using transperineal stimulation.\textsuperscript{100,152} In addition, the response may be absent or uninterpretable in up to 30% of studies even in experienced laboratories.\textsuperscript{55,159} Due to local anatomy, it is not possible to stimulate a second site; thus, a nerve conduction velocity cannot be obtained. Neither is it possible to localize focal changes in myelination if they are present.

Anatomical factors which may be confounding the technique include the proximity of the sacral nerve branches to the levator muscle near the ischial spine where stimulation occurs.\textsuperscript{8} In addition, the recording site is over multiple components of the sphincter mechanism, including the puborectalis and all the layers of the EAS. Studies using sacral magnetic stimulation with needle recording electrodes in each muscle of the sphincter mechanism have documented the shortest latency to the puborectalis, with increasing latencies to the deep, superficial, and subcutaneous EAS with differences of 5.0 ms or more from deepest to most superficial.\textsuperscript{121} Simultaneous recordings of latencies with surface electrodes and needle electrodes may be similar, have different responses, or even be present in one and absent in the other.\textsuperscript{45}

The amplitude of the response, which would provide information regarding axonal integrity, has not been reliable. This may be due to anatomic factors as above, but it is also likely influenced by positioning of both the active and the reference electrodes over the sphincter muscle. While the contribution of the reference electrode has not been systematically studied, this configuration likely reduces the amplitude and may have other unrecognized consequences as
well. Finally, correlation with function has not been demonstrated.

Theoretically, in spite of these limitations, pudendal nerve stimulation could be useful in distinguishing an upper motor neuron lesion from a lower motor neuron lesion if a response is obtained. It also has potential utility in differentiating axonotmesis from neurotmesis but clinical queries of this type are uncommon. It has been used to optimize stimulator placement during neuromodulation and it may have a role in monitoring acute change, particularly for research purposes. However, routine use of this technique cannot be recommended. Electromyography. As with muscles in other areas of the body, EMG of the pelvic floor may be performed with various surface electrodes, fine wire electrodes, or needle electrodes. Selection is determined primarily by the type of information required and the ease and comfort of application, but other factors such as cost and examiner familiarity may also be considered. Surface electrodes are noninvasive and easy to apply but not all muscles are accessible and specificity is limited by volume conduction. They are useful for monitoring the presence or absence of activity, and may provide kinesiologic data during urodynamic testing. Fine wire electrodes have the additional advantages of precise and stable placement, even during provocative testing for incontinence and voiding, with less susceptibility to volume conduction, but they are more invasive. In addition, after placement, wires may not be relocated. Investigation of specific muscle fiber and motor unit activity, such as insertional and spontaneous activity, motor unit action potential (MUAP) morphology, and recruitment requires needle EMG. This approach also allows accurate localization, with the option of repositioning as needed. The application of quantitative analysis to needle EMG provides automatic measurement of amplitude, duration, area, number of phases and turns, rise time and duration of negative peak, and mean frequency of firing with calculation of thickness and size index. Single-fiber EMG has also been used extensively to determine fiber density as an index of reinnervation, but is primarily limited to research applications.

All findings on needle EMG are nonspecific and must be interpreted based on the electrophysiology of muscle, in the context of the patient’s clinical picture, to establish the most likely underlying process. Previous urethral or anal procedures, sphincter defects, or obstetric trauma and repairs should be noted. Interpretation of needle EMG findings in the sphincters is further complicated by several unique features of which the EDX physician must be aware. Normal MUAPs may have low amplitudes (with mean values of 300–600 μV) and short duration (with mean values of 5–7 ms but individual units of 3 ms) with complexity in as many as 15%–30% of units examined with concentric needle EMG. Thus, it may be difficult to identify and/or differentiate changes reflective of myogenic (and/or neurogenic) involvement. Also, normal sphincter muscles are tonically active and most patients are unable to completely relax them, except during normal reflex inhibition of the pelvic floor during voiding. The combination of these factors may make it difficult to distinguish fibrillation potentials from MUAPs.

The selection of muscles for examination follows the principles common to all needle EMG studies and is determined with thoughtful consideration of both the ease of examination and the amount of discomfort to the patient, as well as the diagnostic information to be gained. As all relevant pelvic floor muscles are innervated by several sacral nerve roots, any normal muscle may suffice to exclude a diagnosis of cauda equina syndrome if deemed a sufficient sample based on the clinical setting. However, once an abnormality is identified, additional studies are required with evaluation of both pudendal- and non-pudendal-innervated muscles to determine the extent of involvement. If only pudendal-innervated muscle is involved, consideration should be given to evaluation of muscles innervated by the perineal and the inferior rectal branches to further localize the site of the environment. Disparate findings have been well documented between the EUS and EAS as well as other muscles of the pelvic floor. Alternative strategies may be appropriate for the selection of muscles in other clinical settings. For example, the EAS is often selected for the assessment of sphincter involvement in atypical parkinsonism. In contrast, the EUS must be included in the evaluation of urinary retention in a woman with possible Fowler’s syndrome. A protocol for the examination of the pelvic floor has been proposed by Podnar and Vodusek and may serve as a guide.

Even with thorough investigation, it is not always possible to clearly define the site of injury, particularly in proximal lesions, such as the cauda equina, because paraspinal abnormalities are not present due to the lack of sacral innervation. The picture may be further complicated if multiple lesions exist and/or confounding issues such as previous surgery or obstetric trauma coexist. In spite of these limitations, needle EMG is the most informative tool in the
evaluation of focal lesions in this group of patients, documenting the integrity or involvement of the peripheral nervous system, defining the severity, and contributing to the diagnosis and prognosis.\textsuperscript{109,147,149,151}

**External Urethral Sphincter.** The EUS has a fundamental role in maintenance of urinary continence and in voiding. Assessment is critical in the diagnosis of Fowler's syndrome.\textsuperscript{20} Examination provides information about the integrity of the sacral roots and plexus, the pudendal nerve, and the perineal nerve branch.

In the female the EUS may be approached transvaginally or perirectally. The transvaginal approach is theoretically less painful, as the vaginal wall has a relative absence of pain fibers and specialized sensory nerve endings.\textsuperscript{80} However, while comparison of the two approaches documented higher pain scores with perirectal examination, patients reported mild to moderate pain with both methods and the difference was not significant.\textsuperscript{95} Furthermore, twice as many MUAPs were identified using the perirectal technique. In this approach, 20 min after the application of anesthetic cream, a 25-mm needle electrode is inserted \( \approx 5 \) mm anterior or lateral to the urethral meatus and advanced 10–20 mm while listening for EMG activity\textsuperscript{21,37,80,95,115,116} (Fig. 4).

In the male the EUS is usually examined with a transperineal approach. A 75-mm needle is inserted in the midline, \( \approx 4 \) cm anterior to the anus at the base of the penis and advanced toward the apex of the prostate. Localization may be facilitated by palpation of the apex of the prostate in the rectum, but the finger should be withdrawn as the needle electrode is inserted\textsuperscript{21,37,115} (Fig. 3).

**Bulbocavernosus.** The BC muscle is easily accessible in the male and provides information about the integrity of the sacral roots and plexus, the pudendal nerve, and the perineal nerve branch. Thus, it may serve as an alternative to the EUS in the appropriate setting. It may facilitate identification of muscle membrane irritability, as it is not tonically active at rest.\textsuperscript{109} The muscle lies superficially behind the scrotum on either side of midline in the perineal region, where it surrounds the bulb of the penis (Fig. 3). The needle electrode is inserted through the perineal skin about 1 cm lateral to the bulb of the penis and advanced toward midline until EMG activity is identified within the first 2–5 cm\textsuperscript{107} (Fig. 5). The needle is then directed medially, toward the anal canal, and advanced until the superficial and deep muscles are entered at a depth of 1–5 cm\textsuperscript{19,107,115} (Fig. 5).

**Levator Ani.** The levator ani provides information about the integrity of the sacral roots and has the distinction of nonpudendal innervation which may be helpful diagnostically. As this muscle is a continuum of ill-defined regions which generally function as a unit, isolating separate portions may be difficult, and in many instances unnecessary. The levator is examined by inserting a 75-mm needle electrode 1–2 cm outside the anal mucocutaneous junction at the 3 to 4 o’clock or 9 to 10 o’clock position (in dorsal lithotomy position) for the left and right sides, respectively. The needle is advanced until EMG activity is identified 2–5 cm from the skin surface\textsuperscript{102,125} (Fig. 2). In females the pubococcygeus is accessible just inside the vaginal introitus. The needle is inserted obliquely through the vaginal mucosa, while palpating the muscle with a digit of the contralateral hand. Localization is facilitated if the patient activates the muscle by squeezing as if to delay urination.\textsuperscript{73,81} Alternatively, the ischial spine may serve as a landmark with needle placement medial to the ischial spine through the vaginal epithelium into the pubococcygeus iliococcygeus.\textsuperscript{65,155,156} The puborectalis portion of the pubococcygeus is particularly useful in the evaluation of patients who have fecal incontinence because of the key role it plays in the maintenance of the anorectal angle. A 50–75-mm needle electrode is inserted 1 cm inside the mucocutaneous junction between the 3 and 6 o’clock position on the left and
the 6 and 9 o’clock position on the right (in lithotomy position). The electrode is directed medially and cephalad, paralleling the long axis of the rectum. The needle is advanced through the EAS to enter the puborectalis at a depth of 4–5 cm. In some cases, there is a subtle decrease in the EMG activity between the two muscles which is helpful in confirming location. Localization may also be facilitated by palpating the puborectalis sling posteriorly in the rectum to estimate the depth required (Fig. 5).

CONCLUSION

In conclusion, urodynamic and EDX studies are complementary tests of the neural pathways involved in continence and voiding. While urodynamic testing is an indirect measure of neurologic function, it allows inferences to be made regarding peripheral somatic and autonomic, as well as central nervous system integrity. Findings contribute to the diagnosis of bladder and pelvic floor dysfunction and are used to direct clinical management. Urodynamic testing is indicated in most patients with known or suspected neurologic disorders and lower urinary tract signs or symptoms. EDX testing is a more direct measure of neural integrity which assesses primarily somatic function and is recommended in a subset of patients with incontinence or voiding dysfunction in whom there is suspicion of a focal lesion in the peripheral nervous system or the conus. In this setting, sacral reflexes and needle EMG are most likely to be helpful, with needle EMG the most informative investigation. EDX testing is not recommended for the routine evaluation of patients with incontinence or voiding dysfunction.

REFERENCES


126. Sidi AA, Dykstra DD, Gonzalez R. The value of urodynam- 
127. Smith AR, Hosker GL, Warrell DW. The role of pudendal 
nerve damage in the aetiology of genuine stress inconti- 
129. Snoeks SJ, Badenoch DF, Tiptaft RC, Swash M. Perineal 
nerve damage in genuine stress urinary incontinence. An 
130. Snoeks SJ, Barnes PR, Swash M. Damage to the innerva- 
tion of the voluntary anal and periurethral sphincter muscu-
lar in incontinence: an electrophysiological study. J Neurol 
131. Snoeks SJ, Barnes PR, Swash M, Henry MM. Damage to 
the innervation of the pelvic floor musculature in chronic con-
132. Snoeks SJ, Henry MM, Swash M. Anorectal incontinence 
and rectal prolapse: differential assessment of the innervation to 
subrectal and external anal sphincter muscles. Gut 1985; 
26:470–476.
133. Snoeks SJ, Swash M. Perineal nerve and transcutaneous 
spinal stimulation: new methods for investigation of the 
urethral striated sphincter musculature. Br J Urol 1984;56: 
406–409.
134. Snoeks SJ, Swash M, Mathers SE, Henry MM. Effect of 
vaginal delivery on the pelvic floor: a 5-year follow-up. Br J 
135. Stenechever MA, Droegemueller W, Herbst AL, Mishell DR. 
136. Swash M, Snoeks SJ, Henry MM. Unifying concept of pelvic 
911.
bladder, bowel and sexual dysfunction, vol. 23. Boston: But-
138. Tackmann W, Vogel P, Forst H. Somatosensory evoked po-
tentials after stimulation of the dorsal penile nerve: norma-
tive data and results from 145 patients with erectile dysfunc-
139. Takahashi S, Homma Y, Fujishiro T, Hosaka Y, Kitamura T, 
Kawabe K. Electromyographic study of the striated urethral 
sphincter in type 3 stress incontinence: evidence of myogen-
140. The Endocrine Society. Diabetes/insulin. The Endocrine 
Society. 2006;7:3-19.
141. Thom DH, Haan MN, Van Den Eeden SK. Medically recog-
nized urinary incontinence and risks of hospitalization, nurs-
ing home admission and mortality. Age Ageing 1997;26:367– 
374.
142. Thomas C, Lefaucheur JP, Galula G, de Parades V, Bour-
guignon J, Atenia P. Respective value of pudendal nerve 
terminal motor latency and anal sphincter electromyogra-
phy in idiopathic fecal incontinence with endocochlear magnetic 
143. Wu J, Baguley IJ. Urinary retention in a general rehabilita-
tion unit: prevalence, clinical outcome, and the role of 
144. Wunderlich M, Swash M. The overlapping innervation of the 
two sides of the external anal sphincter by the pudendal 
145. Yamamoto T, Sakakibara R, Uchiyama T, Liu Z, Ito T, Awa Y, 
Yamamoto K, Kinou M, Yamanishi T, Hattori T. When is 
Onuf’s nucleus involved in multiple system atrophy? A 
sphincter electromyography study. J Neurol Neurosurg Psy-
146. Vereecken RL, Verdun H. The electrical activity of the paraurethral and perineal muscles in normal and pathologi-
147. Vereecken D, Fowler CJ. Clinical neurophysiology. In: Fowler 
CJ, editor. Neurology of bladder, bowel and sexual dysfunc-
143.
148. Vereecken DB. Pudendal SEP and bulbocavernous reflex in 
136.
149. Vereecken DB. The role of electrophysiology in the evalu-
ation of incontinence and prolapse. Curr Opin Obstet Gynecol 
150. Vereecken DB. Bulbocavernous reflex revisited. Neurourol 
151. Vereecken DB, Amarengo G, Batra A, Benson T, Bharucha AE, 
Cardozo L, Khoury S, Wein A, editors. Incontinence, 3rd 
International Consultation on Incontinence, June 26-29, 
2004, Monaco, Plymouth, UK: Health Publications; 2005, 
152. Vereecken DB, Janko M, Lokar J. Direct and reflex responses 
in perineal muscles on electrical stimulation. J Neurol 
153. Vereecken DB, Zidar J. Pudendal nerve involvement in pa-
ients with hereditary motor and sensory neuropathy. Acta 
154. Wagner TH, Hu TW. Economic costs of urinary inconti-
155. Weidner AC, Jamison MG, Branham V, South MM, Borawski 
KM, Romero AA. Neuropathic injury to the levator ani oc-
curs in 1 in 4 primiparous women. Am J Obstet Gynecol 
2006;195:1851–1856.
156. Weidner AC, Sanders DB, Nuededkar SD, Bump RC, Quan-
titative electromyographic analysis of levator ani and exter-
nal anal sphincter muscles of nulliparous women. Am J 
157. Weld KJ, Graney MJ, Dmochowski RR. Clinical significance 
of detrusor sphincter dyssynergia type in patients with post-
158. Wester C, FitzGerald MP, Brubaker L, Welgoss J, Benson JT. 
Validation of the clinical bulbocavernous reflex. Neurourol 
159. Williams AB, Malouf AJ, Bartram CI, Halligan S, Kamm MA, 
Kniot WA. Assessment of external anal sphincter morphol-
ogy in idiopathic fecal incontinence with endocochlear magnetic 
160. Wu J, Baguley IJ. Urinary retention in a general rehabilita-
tion unit: prevalence, clinical outcome, and the role of 
161. Wunderlich M, Swash M. The overlapping innervation of the 
two sides of the external anal sphincter by the pudendal 
162. Yamamoto T, Sakakibara R, Uchiyama T, Liu Z, Ito T, Awa Y, 
Yamamoto K, Kinou M, Yamanishi T, Hattori T. When is 
Onuf’s nucleus involved in multiple system atrophy? A 
sphincter electromyography study. J Neurol Neurosurg Psy-
163. Yang CC, Bradley WE. Reflex innervation of the bulbocav-
164. Yang CC, Kromm BG. New techniques in female pudendal 
somatosensory evoked potential testing. Somatosens Mot 
165. Yucel S, de Souza A Jr, Baskin LS. Neuroanatomy of the 
195.