Practical Urodynamics for the Clinician

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Preface

Urodynamics have sometimes been considered to be confusing, ambiguous, and complex. However, with increasing improvements in technology, software, and equipment, this heretofore often perplexing series of tests has become significantly simplified for use by the clinician in today's busy urologic practice.

Many textbooks on this subject have relied heavily on long descriptions of the basic science of urodynamics and complex physiology. However, urodynamics in today's clinical world may produce very practical and clinically relevant data with significant impact on patient care. The objective of this book is to offer the reader a guide to the preparation, conduct, and interpretation of these studies in the everyday clinical scenario.

One must remember that the term urodynamics actually refers to a series of simple tests that are designed to be combined to produce useful information for a particular clinical situation. Very much like a high-performance race car engine is a complex and confusing machine, urodynamics can be thought of as a combination of multiple simple machines put together for a specific purpose. For instance, a radiator, a carburetor, fuel injector, and piston are all subcomponents of the complex car engine that when working in unison form a smooth well-running powerful device. In much the same manner, the urine flow, postvoid residual, cystometrogram, and EMG when combined together will give the clinician powerful data to apply to the specific clinical question at hand. It's also important to remember that one does not need to include all of the subcomponents in order to address a specific concern about a patient's complaint. For instance, one may only need noninvasive urodynamics (uroflow/postvoid residual) in one clinical scenario, while another may require a complex study with the combination of the cystometrogram, EMG, fluoroscopy, and pressure flow studies.

We have arranged this book into these components as outlined above. The book starts with a basic physiology section focusing on the relevant principles and equations needed for practical clinical urodynamics. The reader is then taken on a tour of all of the individual tools of urodynamics starting with noninvasive urodynamics, the cystometrogram, the pressure flow study, the EMG, and the use of fluoroscopy. In addition, we have included chapters with practical relevance to the clinician such as a description of the type of equipment needed to start a urodynamics lab, the use of the currently available nomograms, and a chapter on the special population of children. With the goal of this being primarily a handbook for use by the clinician, there is not a lot of discussion within this textbook about specific diagnoses and treatment.

We hope that clinicians and current learners of urology such as residents and fellows will be able to obtain the required practical knowledge about equipment, the type of testing, and the performance of this testing to become proficient in this important study.

I sincerely appreciate all the hard work the authors have provided for this great textbook—they are all busy clinicians and pioneers in the field of both urodynamics and voiding dysfunction/incontinence. To Dr. George Webster, I owe an enduring debt of gratitude for his medical training, mentorship, and support throughout my time both running our urodynamics laboratory at Duke and in production of this textbook.

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The Basic Science Behind Practical/Clinical Urodynamic Analysis

Matthew O. Fraser

The Lower Urinary Tract

Function

The function of the lower urinary tract is to collect and store urine, and then to periodically expel urine when the bladder is full and the situation is environmentally appropriate. **One of the hallmarks of mammalian evolution is the development of a urinary bladder-urethral complex, rather than the bladder emptying directly into a cloaca.** Although the bladder is the primary organ of urine storage and generates the pressure to evacuate urine, the urethra, a relatively recent evolutionary development, actively participates both in storage and release functions as well. The actions of these structures are coordinated through reflexes involving the spinal cord and brainstem, with inhibitory control exerted from higher cortical centers [1].

Anatomy

The lower urinary tract comprises the distal ureters, the trigone, the urinary bladder and the urethra. The ureters enter the bladder base and merge with the trigone. The trigone is a specialized region of intercalated ureteral and bladder smooth muscle [2] that extends dorsally down the proximal urethra.

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The bladder itself is a saccular muscular structure with greatest compliance laterally and ventrally [3]. The bladder muscle is referred to as the detrusor and is organized as a single layer of randomly oriented fibers at the dome which organizes into a three layer system at the base [4]. The longitudinal muscle layers (internal and external) surround the central circular smooth muscle layer. The bladder pattern extends into the mid-length of the intrapelvic urethra, with the inner longitudinal layer extending to 2/3 of the length from the bladder base [5]. Because these smooth muscle layers are continuous between the bladder and urethra, the term vesicourethral muscularis has been used to describe the bladder-urethral unit [6].

Perhaps the most defining characteristics of the urethra is the circumferential smooth muscle layer, which is very thin in the bladder but much more prominent in the urethra [5]**, the external layer of circumferential striated muscle (the rhabdosphincter), and that it passes through the pelvic floor.** In females it opens directly to the external environment in the vulvar vestibule. In males it traverses the ventral penis.

Figure 1 presents a highly stylized diagram of the vesicourethral muscularis and rhabdosphincter to illustrate the muscle layers (components not drawn to scale, outer longitudinal layer not included).

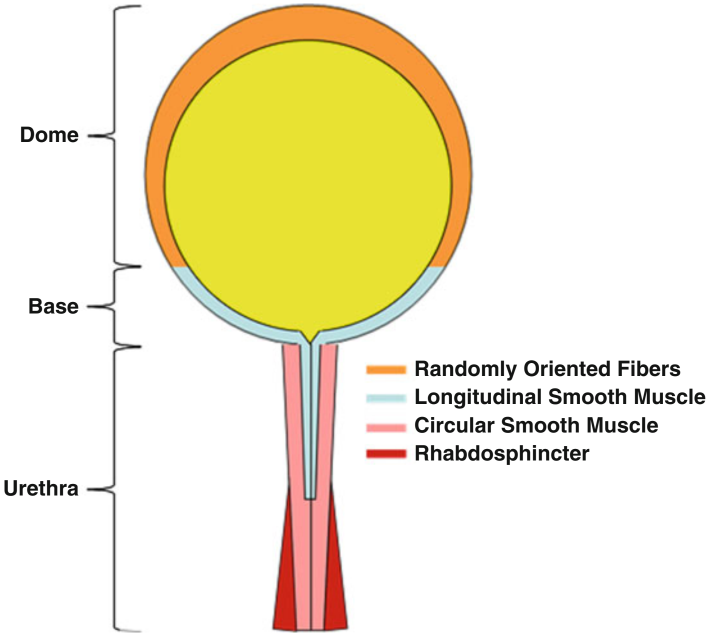

Fig. 1 Highly stylized diagram of the vesicourethral muscularis and rhabdosphincter to illustrate the muscle layers (components not drawn to scale, outer longitudinal layer not included)

The Neural Control of the Lower Urinary Tract

Control of the lower urinary tract is achieved through both branches of the autonomic nervous system (sympathetic and parasympathetic), and the somatomotor branch for the rhabdosphincter. Excellent in depth reviews of this topic may be found in Fowler et al. [1] and de Groat et al. [7]. For the purposes of this chapter, the following brief description should suffice.

During the storagephaseof the micturition cycle, active contraction of urethral circumferential smooth muscle and active relaxation of bladder smooth muscle are achieved via sympathetic stimulation of alpha-adrenergic and beta-adrenergic receptors, respectively, via the hypogastric nerves. In this case, the same neurotransmitter, norepinephrine, results in different effects because of regional differences in receptor subtype expression. Also during the storage phase, active tonic contraction of the rhabdosphincter is achieved by special motoneurons residing in Onuf's nucleus in the sacral spinal cord whose axons course through the pudendal nerve. These neurons are activated by a bladder-to-rhabdosphincter reflex and this reflex is important in maintain continence.

For the most part, bladder filling is not sensed at the conscious level, and these storage reflexes are governed by afferent input from the bladder at the level of the spinal cord. As filling approaches bladder capacity, and therefore approaches triggering of reflex micturition, afferent input from the bladder becomes sensed at the conscious level and inhibition of the pontine micturition reflex center is applied together with conscious activation of the rhabdosphincter while the individual seeks an appropriate environment to void. **Once an appropriate environment is found or established, conscious inhibition of the micturition reflex is relaxed and parallel pathways of inhibition of the bladder-to-rhabdosphincter spinal reflex and excitation of the neurons innervating the lower urinary tract within the parasympathetic nucleus allows for voiding to ensue.**

Postganglionic parasympathetic neurons that innervate the bladder contain either the paired smooth muscle excitatory transmitters acetylcholine (ACh) and adenosine triphosphate (ATP), neuronal nitric oxide synthase (NO; nitric oxide relaxes smooth muscle), or all of these. The distribution of these transmitters is not compartmentalized between bladder and urethra, as one might have predicted, and regional selectivity (i.e. bladder contraction and urethral smooth muscle relaxation) is achieved by the distribution of soluble guanylate cyclase, the target in smooth muscle for NO. In this case, the urinary bladder smooth muscle does not contain soluble guanylate cyclase, while the urethral circumferential smooth muscle does. It is not the case that ACh and ATP will not contract urethral circumferential smooth muscle, but rather that NO relaxation overcomes these and many, if not all, neurotransmitter- and prostaglandin-induced contractions of this layer of smooth muscle [8, 9].

That NO release in the urethra results in relaxation of urethral circumferential smooth muscle, even in the face of maximal alpha-adrenergic-mediated contraction pairs nicely with the fact that ACh stimulation of the degree experienced during micturition is not blocked by beta-adrenergic-mediated relaxation [10]. Therefore, in the absence of mechanical obstruction (e.g. stricture, pelvic floor prolapse or detrusor sphincter dyssynergia), once triggered, a micturition reflex is ensured. Thus, it is not necessary to shut off reflex sympathetic input to the system as a parallel step, although this may, in fact, occur as an evolutionary redundancy.

The sequence of events for a true micturition event is as follows: Parallel signals descend from the pontine micturition center. One signal is inhibitory to Onuf's nucleus and stops the bladder-to-rhabdosphincter spinal continence reflex. The other signal is an excitatory signal to the parasympathetic nucleus of the sacral spinal cord, stimulates parasympathetic preganglionic neurons that project to the pelvic ganglia to stimulate, in turn, the parasympathetic postganglionic neurons. The latter neurons project to the bladder and urethra. At the bladder, they cause contraction at the dome that, due to the random fiber orientation, is directed centrally and downward. The longitudinal muscle layers at the bladder base through the proximal 1/2–2/3 of the pelvic urethra also contract, which forces the bladder neck open into a funnel and provides sufficient tension to maintain the funnel shape rather than allowing the base-proximal urethra to balloon out. At the same time, the circumferential smooth muscle of the urethra relaxes, allowing the funneling to occur easily. The net result of longitudinal smooth muscle contraction is both a shortening of the distance between the bladder base and the length of the urethra that does not include longitudinal smooth muscle (i.e. the bladder descends into the pelvic floor) and an expansion of the urethral lumen, both of which reduce resistance to flow.

While this reflex seems capable of doing the job as described once initiated, there are likely modulatory afferent inputs arising from the urethra that refine the duration of descending signal. For example, upon the initiation of the void, urine that enters the proximal urethra may provide positive feedback via chemosensitive, distension sensitive and flow sensitive urethral afferents to promote continued bladder contraction, helping to ensure full emptying. Barrington [11, 12] described three such reflexes that support urethral-to-bladder positive feedback:

- Barrington's Reflex 2: A urethra-spinobulbospinal-bladder reflex—this is a long loop reflex, originating from pudendal afferents in response to intraluminal fluid flow, seen as a positive feedback mechanism that promotes efficient voiding.
- Barrington's Reflex 4: A urethra-spinal-urethra reflex—this is a short loop reflex, originating from pudendal afferents in response to intraluminal fluid flow and causes relaxation of the rhabdosphincter.
- Barrington's Reflex 7: A urethra-spinal-bladder reflex—this is a short loop reflex, originating in parasympathetic afferents, may also contribute normally as a positive feedback mechanism to promote efficient voiding.

The presence of these urethral-to-bladder reflexes remains controversial in humans, and one must recognize that differences in findings from clinical human and preclinical animal studies may reflect testing conditions and/or true species differences. However, if one were to design a system for efficient voiding, one would likely design such a system with such feedback mechanisms in place. It is tempting, therefore, to predict that such reflex pathways would be prevalent across mammalian species, including humans.

Physical Principles in Urodynamics

Fluid Dynamics

There are three states of matter, solid, liquid and gas. Liquids and gasses are considered fluids, but have differences that are of great importance as far as understanding and performing urodynamics is concerned. Primarily, they differ in terms of compressibility. **Gasses are highly compressible, while liquids are not. Pascal's Law (a.k.a the Principle of Transmission of Fluid-Pressure) describes the difference in pressure between two elevations of fluid in a column as determined by the weight of the fluid between the elevations.**

Pascal's Law: $\Delta P = \rho g(\Delta h)$

- ΔP = the hydrostatic pressure, or the difference in pressure at two points within a fluid column, due to the weight of the fluid
- ρ = the fluid density
- g = acceleration due to gravity
- Δh = the height of fluid above the point of measurement, or the difference in elevation between the two points within the fluid column

This is important to understand whenever one calibrates a liquid pressure recording system in terms of height of a liquid (e.g. cm H_2O or mm Hg) using the height of the meniscus of a column of liquid. Here a column can mean any closed outlet tubing with an open reservoir at the elevated end.

Pascal's Law not only applies to arbitrarily designated or physically defined elevations in a column of liquid, but also for any volume of liquids confined in a rigid space. This, therefore, means that any changes in pressure applied at any given point of the liquid are transmitted equally, instantaneously and with high fidelity throughout the continuum of the confined liquid volume.

This is not the case for gasses, which are compressible and therefore damp the pressure change and take time to attain a new steady state following applied pressure changes. **Gasses in line with a liquid pressure recording system, either by design or accident (liquid in lines not degassed) have the effect of decreasing fidelity of pressure changes and force application relationships** [13]**, and therefore are best avoided.**

Pressure-Flow relationships are utilized to diagnose outlet obstruction and bladder contractility issues [14]. Flow is defined as the quantity of fluid that has moved past a point in a given unit of time:

$$F = Q / t = \Delta Q$$

- F = flow
- Q = quantity
- t = time
- ΔQ = rate of change of mass or volume

As liquid flows through tubes, there is resistance between the fluid and vessel wall that opposes the flow.

$$R = \Delta P / \Delta Q$$

- R = resistance
- ΔP = change in pressure
- ΔQ = flow

These principles can be utilized, with important modifications to account for the biomechanical properties of the bladder and urethra, to determine outlet resistance and bladder contractile strength. In non-living systems (flexible catheters, solid tubes), R may be considered as constant. But in living systems, such as the urethra, R is dynamic and depends on the neuromuscular systems comprising the urethral outlet complex. In order to best represent the living system during urodynamic pressure flow studies, detrusor pressure at maximum voiding flow rate (P_{det} Q_{max}) and maximum voiding flow rate (Q_{max}) are plotted against each other to produce nomograms. Regions within the nomogram that represent degrees of outlet obstruction and strengths of bladder contractility are defined from mixed groups of patients [15].

Biomechanics of the Lower Urinary Tract

Biomechanics is the application of mechanical principles to living organisms and/or their tissues. Classical mechanics involves determinations of pressure, force, flow and resistance, which we have already discussed for fluid dynamics as they pertain to urodynamic investigations. Additionally, as we are dealing with tissues, considerations of solid mechanics are also important. Solid mechanical measures include stress (intensity of internal forces), strain (deformation; change in the metric properties), stiffness (resistance of an elastic body to deformation), compliance (reciprocal of stiffness), isotropy (uniformity in all directions) and anisotropy (directionally dependent). Solid behaviors in response to applied stresses include rigidity (resistance of shape change), plasticity (permanence of deformation following removal of applied stress), elasticity and viscoelasticity (both return to undeformed state, but viscoelastic solids have damping resulting in hysteresis in the stress-strain curve).

We have already discussed that the dome of the bladder has randomly oriented fibers and the base and urethra have longitudinal and circumferential fiber layers, and thus we may further define these regions as isotropic and anisotropic, respectively.

Compliance (the inverse of stiffness) is clearly an important component of urodynamic analysis.

$$C = \Delta V / \Delta P$$