Pelvic Floor Anatomy & Function: Agreements & Disagreements
Workshop 36
Tuesday 24 August 2010, 09:00 – 13:00

Time	Time	Topic	Speaker
9.00	9.10	Introduction	Ravinder Mittal MD
09.10	09.40	The anatomical basis of pelvic floor function in normal and abnormal states	John Delancey MD
9.40	10.10	Pelvic Floor Ultrasound: the method of choice in pelvic floor assessment	Hans Peter Dietz MD
10.10	10.30	Discussion	
10.30	11.00	BREAK	
11.00	11.30	Pelvic floor function and dysfunction in urinary continence	Chris Constantinou PhD
11.30	12.00	Pelvic floor function in anal continence	Ravinder Mittal MD
12.00	12.20	Discussion	
12.20	12.50	Measurement of pelvic floor muscle function and strength	Kari Bo PhD
12.50	13.00	Discussion	

Aims of course/workshop

Pelvic floor is relevant to a number of subspecialties of medicine, i.e., gynecology, urology, uro-gynecology, colorectal surgeons and gastroenterology. Even in the year 2010 a number of controversies continues to surround anatomy, neural innervations and functional assessment of the pelvic floor muscle. Lack of agreement has been a huge hurdle in the progress of understanding and treatment of pelvic floor disorders. Magnetic resonance imaging, 3D-Ultrasound imaging and various types of pressure/force measurement techniques have shed important light into the anatomy and function of pelvic floor muscles. The goal of this symposium is to highlight advances in the assessment of anatomy and function of pelvic floor muscle using novel approaches used in the first decade of new millennium. This workshop brings together leaders in the field, each of the speakers has contributed significantly to new advances and has authored a number of important articles published during the last decade.

Speakers and Summary of their Presentation

John Delancey MD: Modern cross sectional imaging (MRI and Ultrasound) has allowed injuries of the levator ani muscles to be investigated in both symptomatic and asymptomatic women allowing hypotheses to be tested about its association with PFD. Defects can be seen in 10% to 15% of asymptomatic parous women, but are not seen in nulliparous women. The injuries primarily involve the pubic origin ("Pubococcygeal or its synonym; pubovisceral muscle") but do not involve the puborectal muscle. The iliococcygeal muscle is less often injured. Among women with pelvic organ prolapsed, 55% have major injuries (>50% of muscle involved) while the injury rate in normal volunteers matched for age and race is 16%. There is no difference in the occurrence of levator ani injury in typical middle aged women with stress urinary incontinence although the injuries are seen more often in women with *de novo* stress incontinence seen during the first year after first vaginal birth. Less is known about the association between levator ani injury and fecal incontinence but emerging data suggest it is seen more commonly in older women with fecal incontinence than healthy age and parity matched controls.

Progress is now being made in assessing the connective tissue abnormalities also seen with MRI. Descent of the apex is responsible for approximately 60% of cystocele suggesting that this is the most significant contributing factor to cystocele formation. An additional 17% of cases are explained by increase in vaginal length. Recent developments have made it possible to measure distance that the pubocervical fascia is displaced from its normal location to quantify the size of paravaginal defects and also the width of the vagina to estimate midline defects. The etiology of prolapse and incontinence involve both muscle and connective tissue defects and the advent of modern biomechanical models now allows us to assess the interactions between these defects.

Chris Constantinou PhD: Pelvic Floor Muscles (PFM) contributes to a variety of functions rangin from the mechanical support of abdominal contents to conception, delivery, urinary and fecal continence. Consequently their response varies according to the purpose demanded and can be voluntary or triggered by reflex reactions. In this presentation identification will be made of the biomechanical factors involved in the kinematic response of major contained structures as the bladder, urethra and rectum using ultrasound imaging. Visualizations will be presented of the active reflex reaction of the anatomical displacements such as coughing as well as the passive response to voluntarily initiated actions such as straining and contractions. Results will focus primarily on the normal response of asymptomatic subjects and some the differences in subjects with urinary incontinence. The influence of posture in considering the results will be demonstrated in terms of new parameters developed specifically for these studies. Distinction will be made between the visualization of pelvic floor dynamics measured using imaging and the vaginal force measurements using a probe. Controversies surrounding the strengths and weaknesses of each type of measurement will be illustrated using video presentations.

Hans Peter Dietz MD: Surely there is more disagreement than agreement regarding the assessment of pelvic floor anatomy and function, between clinicians and researchers, between imaging specialists and clinicians, and between ultrasound and MR practitioners. Dr Dietz will cover the following areas: **1:** Ultrasound and magnetic resonance imaging in the pelvic floor assessment. **2:** Urethral support and its role in continence: what's stopping people from leaking? **3:** How to prevent, diagnose and treat levator macro- and micro-trauma? He will summarize how far we have come over the last ten years in translating clinical imaging research into practice, and will also attempt an outlook on what to expect over the next decade.

Ravinder K. Mittal MD: Along with internal anal sphincter, external anal sphincter, puborectalis muscle plays important role in the pathogenesis of anal continence. Whether external anal sphincter consists of 3 parts, subcutaneous, superficial and deep parts or only 2 parts i.e., subcutaneous and superficial has been debated for more than 50 years. Our findings prove that deep part of the external anal sphincter is indeed puborectalis muscle. Current understanding is that the rest and squeeze pressures of the anal canal are related to internal and external anal sphincter respectively. Puborectalis muscle, on the other hand, is responsible for the formation of anorectal angle formation. However recent studies from our laboratory prove that puborectalis muscle is responsible for the closure of upper half of the anal canal. How does puborectalis muscle cause closure of the anal canal? Since it is a “U” shaped muscle, upon contraction it causes closure of the pelvic floor hiatus and compresses anal canal against vagina and urethra. Therefore, it is likely that puborectalis muscle is involved in the continence functions of both anal canal and urethra. Pelvic floor function is assessed by techniques that measure vaginal pressure/force, either digitally or through various other techniques and instruments. We believe that vaginal closure is also related to the puborectalis muscle. The later is one component of the levator ani or pelvic floor muscles which has two major functions, i.e., constrictor and elevator. We propose that the constrictor function of pelvic floor is contributed by the puborectalis muscle and elevator function is related to ileococcygeus muscle. I will discuss how novel imaging techniques, 3D-US, MRI and high definition manometry help in assessing physiologic functions of pelvic floor, ie., the constrictor and the elevator functions.

Kari Bo PhD. Norwegian University of Sport & Physical Education, Oslo Norway -Responsive, reliable and valid measurement tools are important in assessing pelvic floor muscle function and strength. Visual observation and digital palpation are important methods in the clinic to assure that the patients are able to contract correctly and to give feedback of the contraction. However, these methods are not reliable enough for measurements of muscle strength or automatic responses. Pelvic floor muscle strength can be measured with manometers and dynamometers. Ultrasound and MRI can reliably measure muscle morphology during rest and contraction, and automatic responses to single task activities such as coughing and increases in intra-abdominal pressure.

Pelvic Floor Anatomy and Applied Physiology

Varuna Raizada, MD, Ravinder K. Mittal, MD*

KEYWORDS

- Levator ani • External anal canal • Internal anal canal
- Function

Pelvic floor muscles have two major functions: they provide support or act as a floor for the abdominal viscera including the rectum; and they provide constrictor or continence mechanism to the urethral, anal, and vaginal orifices (in females). This article discusses the relevance of pelvic floor to the anal opening and closure function, and discusses new findings with regards to the role of these muscles in the vaginal closure mechanisms.

The bony pelvis is composed of sacrum, ileum, ischium, and pubis. It is divided into the false (greater) and true (lesser) pelvis by the pelvic brim. The sacral promontory, the anterior ala of the sacrum, the arcuate line of the ilium, the pectineal line of the pubis, and the pubic crest that culminates in the symphysis pubis, mark the pelvic brim. The shape of the female bony pelvis can be classified into four broad categories: (1) gynecoid, (2) anthropoid, (3) android, and (4) platypelloid. The pelvic diaphragm is a wide but thin muscular layer of tissue that forms the inferior border of the abdominopelvic cavity. Composed of a broad, funnel-shaped sling of fascia and muscle, it extends from the symphysis pubis to the coccyx and from one lateral sidewall to the other. The urogenital diaphragm, also called the "triangular ligament," is a strong, muscular membrane that occupies the area between the symphysis pubis and ischial tuberosities and stretches across the triangular anterior portion of the pelvic outlet. The pelvic ligaments are not classic ligaments but are thickenings of retroperitoneal fascia and consist primarily of blood and lymphatic vessels, nerves, and fatty connective tissue. Anatomists call the retroperitoneal fascia "subserous fascia," whereas surgeons refer to this fascial layer as "endopelvic fascia." The connective tissue is denser immediately adjacent to the lateral walls of the cervix and the vagina. The broad ligaments are a thin, mesenteric-like double reflection of peritoneum stretching from the lateral pelvic sidewalls to the uterus. The cardinal, or Mackenrodt's, ligaments extend from the lateral aspects of the upper part of the cervix and the vagina to the pelvic wall.

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The uterosacral ligaments extend from the upper portion of the cervix posteriorly to the third sacral vertebra.

The pelvic floor is comprised of a number of muscles and they are organized into superficial and deep muscle layers. There is significant controversy with regards to the nomenclature, but generally speaking the superficial muscle layer and the muscles relevant to the anal canal function are the external anal sphincter (EAS), perineal body, and possibly the puboperineal (or transverse perinei) muscles (**Fig. 1**). The deep pelvic floor muscles consist of pubococcygeus, ileococcygeus, coccygeus, and puborectalis muscles. Puborectalis muscle is located in between the superficial and deep muscle layers, and it is better to view this as the middle muscle layer of the pelvic floor. In addition to the skeletal muscles of the pelvic floor, caudal extension of the circular and longitudinal smooth muscles from the rectum into the anal canal constitutes the internal anal sphincter (IAS) and EAS of the anal canal, respectively. Discussed are the salient and the controversial aspects of anatomy of the pelvic floor and anal sphincter muscles, followed by a discussion of the function of each component of the pelvic floor muscles and their role in anal sphincter closure and opening.

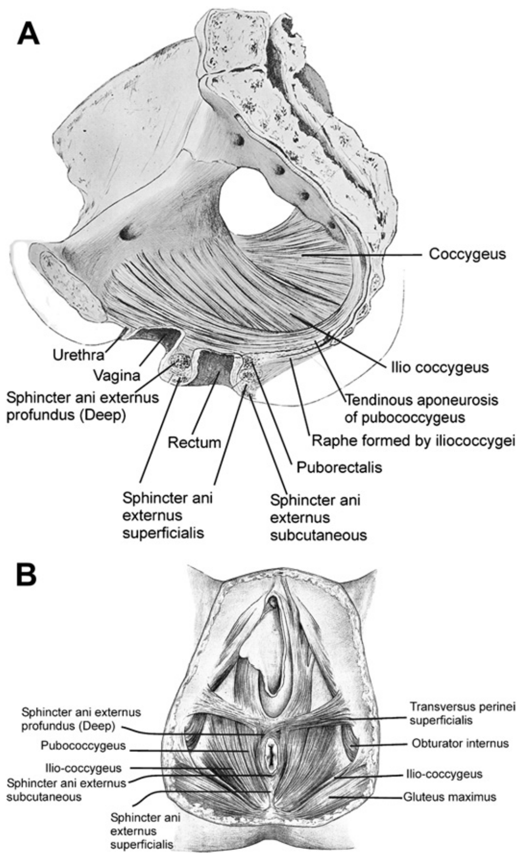

Fig. 1. (*A*) Pelvic floor muscles seen in the sagittal section of pelvis. (*B*) Pelvic floor muscles as seen from the perineal surface. (*Adapted from* Thompson P. The myology of the pelvic floor. Newton (MA): McCorquoddale; 1899; with permission.)

ANATOMIC CONSIDERATIONS

Internal Anal Sphincter

Circular muscle layer of the rectum expands caudally into the anal canal and becomes the IAS. The circular muscles in the sphincteric region are thicker than those of the rectal circular smooth muscle with discrete septa in between the muscle bundles. Similarly, the longitudinal muscles of the rectum extend into the anal canal and end up as thin septa that penetrate into the puborectalis and EAS muscles. Longitudinal muscle of the anal canal is also referred to as the "conjoined tendon" (muscle) because some authors believe that skeletal muscles of the pelvic floor (puboanalis) join the smooth muscles of the rectum to form a conjoint tendon. Immunostaining for the smooth and skeletal muscles in this region shows, however, that the smooth muscles make up the entire longitudinal muscle layer of the anal canal.[1,2]

The autonomic nerves, sympathetic (spinal nerves) and parasympathetic (pelvic nerves), supply the IAS.[3] Sympathetic fibers originate from the lower thoracic ganglia to form the superior hypogastric plexus. Parasympathetic fibers originate from the 2nd, 3rd, and 4th sacral nerves to form the inferior hypogastric plexus, which in turn gives rise to superior, middle, and inferior rectal nerves that ultimately supply the rectum and anal canal. These nerves synapse with the myenteric plexus of the rectum and anal canal. Most of the tone of the IAS is myogenic (ie, caused by unique properties of the smooth muscle itself). Angiotensin 2 and prostaglandin $F_{2\alpha}$ play modulatory roles. Sympathetic nerves mediate IAS contraction through the stimulation of α and relaxation through $\beta_{1,}$ β_2, and β_3 adrenergic receptors. Recent studies show a predominance of low affinity β_3 receptors in the IAS. Stimulation of parasympathetic or pelvic nerves causes IAS relaxation through nitric oxide–containing neurons located in the myenteric plexus.[4] Vasointestinal intestinal peptide and carbon monoxide are other potential inhibitory neurotransmitters of the inhibitory motor neurons but most likely play limited roles. There are also excitatory motor neurons in the myenteric plexus of IAS and the effects of these neurons are mediated through acetylcholine and substance P. Some investigators believe that the excitatory and inhibitory effects of myenteric neurons on the smooth muscles of IAS are mediated through the Interstitial cells of Cajal (ICC), but other investigators do not necessarily confirm these findings.[4] Degeneration of myenteric neurons resulting in impaired IAS relaxation is the hallmark of Hirschsprung's disease.[5]

External Anal Sphincter

In his original description of 1769, Santorini[6] stated that EAS has three separate muscle bundles: (1) subcutaneous, (2) superficial, and (3) deep. Large numbers of publications continue to show EAS to be made up of these three components. Several investigators have found, however, that the subcutaneous and superficial muscle bundles only constitute the EAS.[7–10] The subcutaneous portion of the EAS is located caudal to the IAS and the superficial portion surrounds the distal part of IAS. The deep portion of the EAS is either very small and merges imperceptibly with the puborectalis muscle, or in the authors' opinion has been confused with the puborectalis muscle. In several schematics published in the literature,[11] including the one by Netter (**Fig. 2**), the EAS is made of three components. A close inspection of these schematics reveals that the puborectalis muscle is entirely missing from these drawings. Based on three-dimensional ultrasound (US) and MRI, the authors believe that the puborectalis muscle is actually the deepest part of the EAS. Shafik[9] described that the EAS consists of three loops; the puborectalis muscle forms the top loop in his drawing (**Fig. 3**). Histologic studies by Fritsch and coworkers[1] and the MRI imaging study of Stoker and

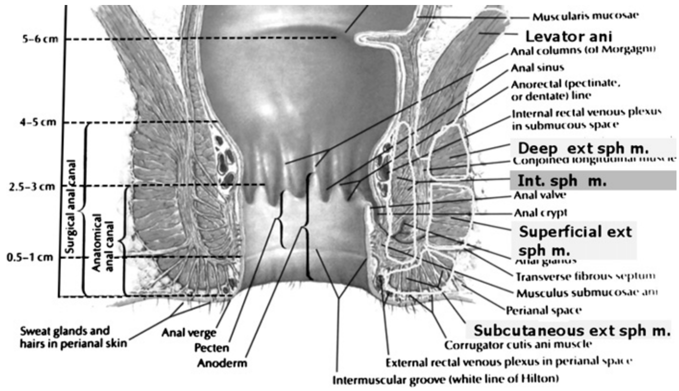

Fig. 2. This schematic shows that the external anal sphincter is made up of a subcutaneous, superficial, and deep part. It is believed that deep external anal sphincter is actually the puborectalis muscle. (*Reprinted from* Netter Anatomy Illustration Collection, © Elsevier Inc. All Rights Reserved. The image has been cropped from its original format to show relevant portion.)

colleagues[12] (**Fig. 4**) are quite convincing that the EAS muscle is composed of only the subcutaneous and superficial portions.[1] Anteriorly, the EAS is attached to the perineal body and transverse perinei muscle, and posteriorly to the anococcygeal raphae. EAS, however, is not a circular muscle in its entirety; rather, it is attached to the transverse perinei (also called "puboperineal") muscle on either side.[8] The posterior wall of the EAS is shorter in its craniocaudal extent than the anterior wall. This should not be misconstrued as a muscle defect in the axial US and MRIs of the lower anal canal. Another implication of this peculiar anatomy is when the anal canal pressure is measured using circumferential side holes; the posterior side holes exit first from the anal canal,[13] thereby causing apparent circumferential asymmetry of the anal canal pressures. The muscle fibers of EAS are composed of fast and slow twitch types, which allow it to maintain sustained tonic contraction at rest and also to contract rapidly with voluntary squeeze. Motor neurons in Onuf's nucleus (located in the sacral spinal cord) innervate EAS muscle through the inferior rectal branches of the right and left pudendal nerves.[11]

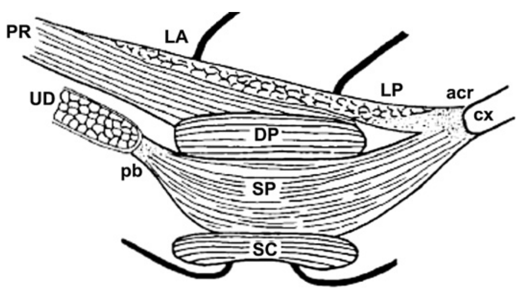

Fig. 3. A sketch of the external anal sphincter from a lateral view, as described by Shafik. External anal sphincter is described as made of three loops: basal loop (BL), intermediate loop (IL), and deep loop (DP). Note the relationship between the puborectalis muscle (PR) and DP. It is believed that DP is actually the posterior part of the puborectalis muscle. LA, levator ani; LP, levator plate; DP, deep portion; SP, superficial portion; SC, subcutaneous portion; cx, coccyx; UD, urogenital diaphragm. (*Adapted from* Bogduk N. Issues in anatomy: the external anal sphincter revisited. Aust N Z J Surg 1996;66:626–9; with permission.)

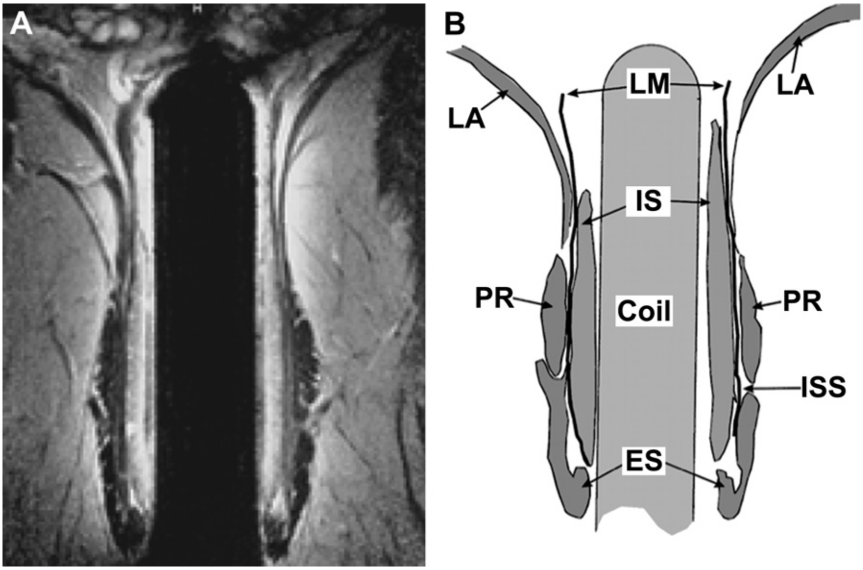

Fig. 4. Anatomy based on MRI. (*A*) Coronal mid anal T2-weighted fast-spin-echo (2500/100) MRI obtained with an endoanal coil. (*B*) Corresponding drawing demonstrates the internal sphincter (IS), intersphincteric space (ISS), longitudinal muscle (LM), external sphincter (ES), puborectalis muscle (PR), and levator ani muscle (LA). These MRIs show that a part of the external anal sphincter is located below and a small portion surrounds the internal anal sphincter. Puborectalis muscle surrounds the upper part of the internal anal sphincter. Based on MRI it is quite clear that external anal sphincter consists of only two parts: subcutaneous (below the internal anal sphincter) and superficial (around the internal anal sphincter). (*Adapted from* Stoker J, Halligan S, Bartram CI. Pelvic floor imaging. Radiology 2001; 218:621–41; with permission.)

PUBORECTALIS AND DEEP PELVIC FLOOR MUSCLES

In 1555, Vesalius[14] wrote an account of the pelvic floor muscles, which he named "musculus sedem attollens." This was later replaced by the more definitive name of "levator ani" by Von Behr and coworkers.[15] The pelvic diaphragm, first so named in 1861 by Meyer,[16] included primitive flexors and abductors of the caudal part of the vertebral column. These muscles included coccygeus (also referred to as "ischiococcygeus"), ileococcygeus, and pubococcygeus and these three muscles were believed to constitute the levator ani muscle. They originate from the pectinate line of the pubic bone and the fascia of the obturator internus muscle and are inserted into the coccyx. Holl,[17] a German anatomist, in 1897 described that some of the pubococcygeus muscle fibers, instead of inserting into the coccyx, looped around the rectum and to these fibers he assigned the name "puborectalis" or "sphincter recti." It seems that the puborectalis muscle originates from the middle of inferior pubic rami rather than from the pubic symphysis. The puborectalis muscle is now included in the levator ani muscle group and the term "levator ani" is used synonymously with pelvic diaphragm muscles. Thompson[18] in a classic text on this subject, quoted Sappey,[19] writing that "the levator ani is one of those muscle which has been studied the most, and at the same time one about which we know the least." Sappey also stated that the "The doctrine of continuity of fibers between two or more muscles of independent actions has been applied to the levator ani at various scientific epochs, and this ancient error, renewed without ceasing, has singularly contributed to complicate its study." It is interesting that to this date the nomenclature, anatomy, neural innervation, and functions of the levator ani and pelvic diaphragm are still veiled in deep mystery. Based on anatomic dissection studies, the pubococcygeus, puborectalis, and puboperineal muscles originate from the pubic bone and are difficult to differentiate from each other. These muscles have also been collectively called the "pubovisceralis muscle," a concept originally championed by Lawson[20] and currently supported by Delancey[21,22] in most of his writings. The term pubovisceral muscle is well accepted in the urogynecologic texts; however, it is rarely mentioned in the anatomic textbooks or gastroenterology literature. Lawson[20] believed that the portions of the pubovisceral muscle are inserted into the urethra, vagina, perineal body, and anal canal and to those portions he assigned the names pubouretheralis, pubovaginalis, puboperinealis, and puboanalis muscles, respectively. According to Lawson, the major function of these muscles is to provide physical support to the visceral organs.

Branches from the sacral nerve roots of S2, S3, and S4 innervate the pelvic floor muscles. There is considerable controversy, however, as to whether the pudendal nerves actually innervate the levator ani muscles. An electrophysiologic study by Percy and colleagues[23] found the electrical stimulation of the pudendal nerve did not activate the puborectalis muscle. It is possible, however, that in their study the electrodes may not have been precisely located in the puborectalis portion of the levator ani muscle. The authors' opinion is that the puborectalis muscle (middle layer of pelvic floor muscle) is actually innervated by the pudendal nerve[24] (from below) and the deep muscles (pubococcygeus, ileococcygeus, and coccygeus) are innervated by the direct branches of sacral nerve roots S3 and S4.[3] The significance is that pudendal nerve damage may cause dysfunction of puborectalis muscle and EAS muscles (both constrictor muscles) and this in turn may cause fecal incontinence.

PELVIC FLOOR IMAGING

Advances in MRI, CT scanning, and three-dimensional US imaging have provided novel insights into the anatomy and function of the pelvic floor muscles. Ultrafast CT scanning can image dynamic changes in the pelvic floor muscle during contraction and defecation.[25] These studies reveal that the levator hiatus becomes smaller during pelvic floor contraction and larger during the act of defecation (**Fig. 5**). The changes in the pelvic floor hiatus size are predominantly related to the puborectalis muscle and

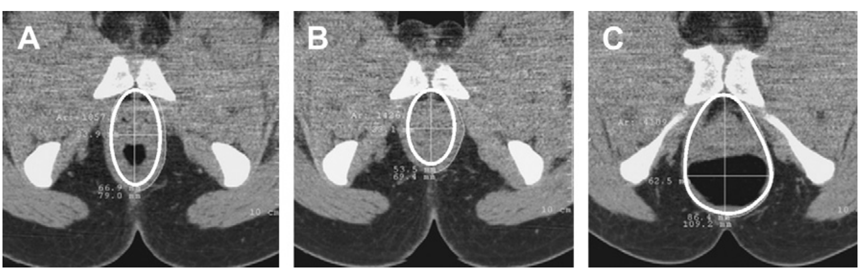

Fig. 5. Seated CT defecography. Axial images of puborectalis at rest (*A*), squeeze (*B*), and defecation (*C*). Note that the pelvic floor hiatus becomes smaller during squeeze and larger during defection. (*Adapted from* Li D, Guo M. Morphology of the levator ani muscle. Dis Colon Rectum 2007;50:1831–9; with permission.)

they reflect the constrictor function of pelvic floor. The ascent (elevation) and descent of the pelvic floor, however, including the levator plate, is mostly likely related to the contraction and relaxation of the pubococcygeus, ileococcygeus, and ischiococcygeus muscles.

MRI studies have outlined the anatomy of pelvic floor muscles much more clearly than was possible with anatomic dissection studies. Hoyle and colleagues[26] developed imaging programs to outline the details of pelvic floor muscle. Their studies reveal physiologic gaps in the ileococcygeus muscle, which one may perceive as defects in the pelvic floor muscles. Elegant studies by Bharucha and colleagues,[27–29] using dynamic MRI technique, have demonstrated changes in the anorectal angle during squeeze and during the act of defecation. Changes in the anorectal angle reflect the constrictor function of pelvic diaphragm muscle, and it is believed that these changes in the anorectal angle are caused by the contraction and relaxation of the puborectalis muscle (**Figs. 6** and **7**). It is likely, however, that craniocaudal movements of the anorectal angle are predominantly related to the pubococcygeus, ileococcygeus, and ischiococcygeus muscles. During pelvic floor contraction, the anorectal angle becomes acute and it moves cephalad. During relaxation and defecation, however, the anorectal angle becomes obtuse and moves caudad.

Two-dimensional and three-dimensional endoanal US are used widely to detect defects in the anal sphincter complex. More recently, three-dimensional US using cutaneous (transperineal) approach provided novel insights into the anatomy and function of the anal sphincter muscles and pelvic floor muscles. The major advantages of three-dimensional transperineal US are that (1) it is subject friendly (no insertion of the transducer into the anal canal is required); (2) it can be performed in the physician's office; and (3) it is relatively inexpensive. Dietz and coworkers[30–32] have used this technique quite effectively to study the physiology and pathophysiology of pelvic floor muscles under various conditions. This technique is relatively simple; it requires placement of

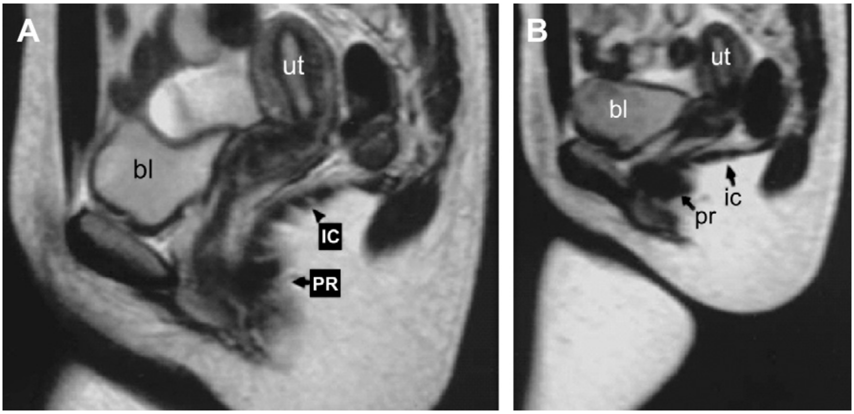

Fig. 6. MRIs at rest and squeeze in the mid sagittal plane. These images show movements of the anorectal angle and levator plate (formed by the ileococcygeus muscle). Sagittal at rest (*A*) and straining (*B*) showing the changes in the different components of the levator ani. On straining, the resting convex shape of the IC becomes flattened, and the genital hiatus reduces in size because of ventral movement of the puborectalis. bl, bladder; ut, uterus; IC, ileococcygeus; PR, puborectalis. (*Adapted from* Singh K, Jakab M, Reid WM, et al. Three-dimensional magnetic resonance imaging assessment of levator ani morphologic features in different grades of prolapse. Am J Obstet Gynecol 2003;188:910–5; with permission.)

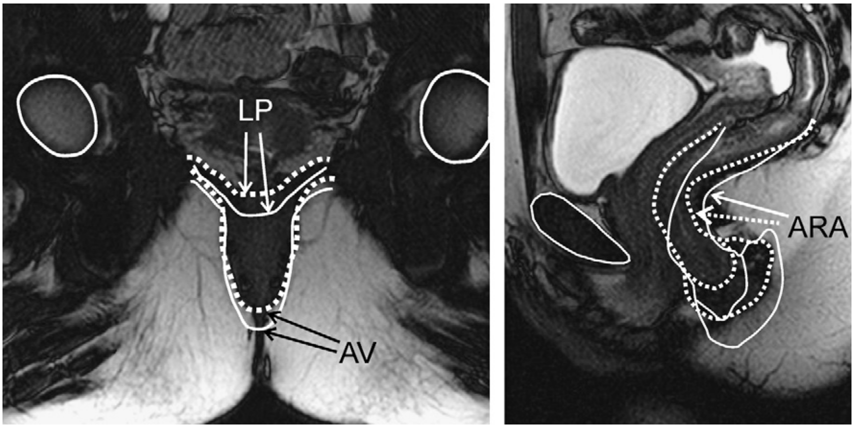

Fig. 7. Magnetic resonance images (MRI) in the mid sagittal and coronal planes; these images were obtained at rest (solid) and squeeze (dotted) and then the images were overlapped to show the movement of various anatomical structures during squeeze. Note the cranial and ventral movements of the anal canal and change in the anorectal angle with squeeze. In the coronal images, note the vertical movement of the anus, and flattening of the levator plate with squeeze. Obtained from author.

the US transducer on the skin of the perineum. A three-dimensional US volume is acquired over a period of 6 to 8 seconds and US images can be analyzed off-line in the coronal, sagittal, transverse, or any other plane. This technique also allows capturing of dynamic or cine images in two or three planes and makes it possible to study the motion of various pelvic floor structures in real time. In addition, the software program can slice these image volumes at every 1 mm or any desired distance to provide the two-dimensional tomographic images at close distances (**Fig. 8**). The authors have extended the use of three-dimensional US imaging to study the anal canal closure mechanism,[33] vaginal high-pressure zone,[34] and the role of puborectalis muscle in the genesis of anal canal and vaginal canal pressures. Defects in the anal sphincter and puborectalis muscles can be detected relatively easily using the three-dimensional US imaging technique.[35]

SENSORY FUNCTION OF THE RECTUM AND ANAL CANAL

Similar to other viscera, colonic distention results in nondescript discomfort and at higher degrees of distention one feels pain that is poorly localized. Rectal distention, however, is perceived as rectal fullness that is more localized and somewhat defined (ie, as a desire to defecate). In addition to mucosal nerve endings, there are also low threshold, slowly adapting mechanoreceptors in the muscularis propria of the rectum. These intraganglionic laminar endings detect mechanical deformation of the myenteric ganglia and are most likely involved in detecting tension in the circular and longitudinal muscles of the rectum. The anal canal responds to distention and mechanical shearing stimuli. It is lined by numerous free and organized nerve endings (ie, Meissner's corpuscles, Krause's end-bulbs, Golgi-Mazzoni bodies, and genital corpuscles). The nerve ending are exquisitely sensitive to light touch, pain, and temperature. Sensory traffic from the rectum and anal canal is conveyed to the spinal cord by unmyelinated small C fibers and larger A fibers.[11]

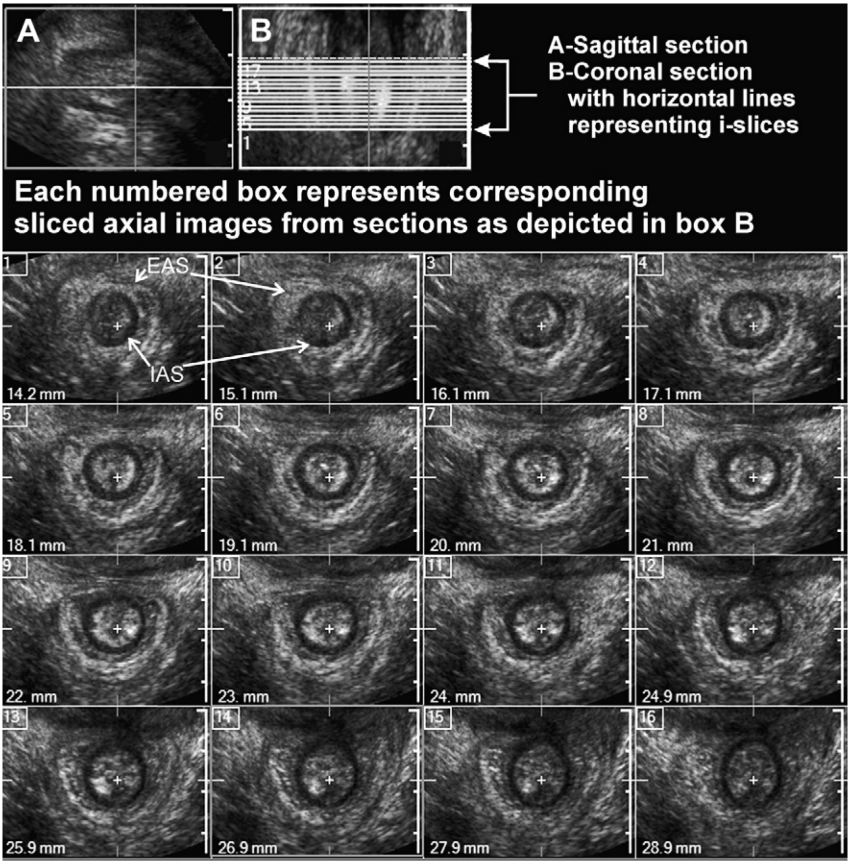

Fig. 8. Ultrasound images of the anal canal obtained from the 3D-US volume: cross-sectional (axial) images along the length of anal canal in a nulliparous subject. In this example the anal sphincter complex is shown at every 1 mm distance using I-Slice function of HD-11 (Philips). Marked in the figure are the IAS (black circle) and the EAS (white outer ring) are smooth, uniform and symmetrical. Obtained from author.

APPLIED PHYSIOLOGY

Ideally speaking, one should describe the function of each component of the pelvic floor muscle individually; however, no such information is available. Broadly, the pelvic floor muscles can be considered to have two important functions. They provide support or "floor" to the pelvic viscera; and they provide constrictor functions to the urethra, vagina, and anal canal. Described next is the role of the pelvic floor muscles on the rectum and anal canal, touching on their role in the closure function of the vagina. Furthermore, it is quite likely that the puborectalis muscle plays an important role in the urethral closure mechanism; however, more studies are needed in this area. In cadavers, the pelvic floor is shaped like a basin but in living individuals it is shaped like a dome.[36,37] Why is that the case? Muscles in general have relatively simple function; they shorten as they contract. Generally, the insertion point of the muscle moves toward the point of the origin (sphincter muscles being an exception). In the case of pubococcygeus, ileococcygeus, and ischiococcygeus, such an action results in the movement of coccyx anteriorly (ventrally) toward the pubic bone.[38] During pelvic floor contraction the coccyx moves ventrally and cranially. The change in the shape of the pelvic floor during contraction, from a basin to dome, is caused by the shortening of the pubococcygeus, ileococcygeus, and ischiococcygeus muscles. At the same time, conversion from basin to the dome lifts the pelvic viscera (including the rectum) in the cranial direction and provides mechanical support or floor to the rectum and other pelvic floor viscera. It is likely that the weakness of these muscles results in perineal descent. Decent of the pelvic visceral organs (including rectum) can be measured in radiologic studies (MRI or barium defecography) by determining the location of the anorectal angle in relationship with the pubococcygeus line.[39,40] The latter is an imaginary line connecting the lower edge of pubic symphysis and the tip of coccyx. In normal individuals, the anorectal angle is located either cranial or very close to the pubococcygeal line and it moves below the pubococcygeal line with the descending perineal syndrome or weakness of the pelvic floor muscle. There is general consensus that the IAS and EAS are the major constrictors of anal canal. The puborectalis muscle is generally believed to be important in maintenance of the anorectal angle.[27,41] Contraction of puborectalis muscle results in an acute anorectal angle and relaxation (during defecation) causes this angle to become obtuse. The anorectal angle can be measured with barium defecography[42] or MRI.[27] As described in the following paragraphs, however, recent studies show that the puborectalis muscle is actually involved in the anal canal closure mechanism (ie, in the genesis of anal canal pressure).[33,43]

ANAL CANAL PRESSURE

Anal canal pressure is a major determinant of the strength of anal continence mechanism and its brief discussion is extremely relevant. Anal canal pressure can be measured with perfusion manometry (using either side hole or sleeve sensor); solid-state transducers; or more recently with a large number of closely spaced array of pressure sensors (high-resolution manometry).[29] Furthermore, the pressures can be displayed in the form of colored topographic (contour) plots, which are convenient to visualize. Classical studies by Duthie and Watts[44] have shown that most of the resting pressure (70%–80%) in the anal canal is related to the IAS and the remainder to the EAS. With voluntary anal squeeze, the increase in the anal canal pressure is mostly caused by the EAS. Anatomic and functional studies, using simultaneous three-dimensional US imaging and side hole perfusion manometry, have provided novel insights into the genesis of anal canal pressure.[43] Based on the three-dimensional US images one can determine the precise length and the anatomic relationship of the IAS, EAS, and puborectalis muscle and then locate the anal canal pressures in relationship with these anatomic structures. These studies reveal that in the proximal part of the anal canal the closure pressures are related to the contraction of IAS and puborectalis muscle, in the middle to the contraction of the EAS, and in the distal part to the contraction of only the EAS (**Figs. 9** and **10**).

VAGINAL HIGH-PRESSURE ZONE

How does puborectalis, a U-shaped muscle, increase the anal canal pressure? The two anterior limbs of puborectalis muscle are attached to the two pubic rami and posteriorly they join each other behind the anal canal. Contraction of the puborectalis muscle lifts up the anal canal in the ventral or anterior direction and in so doing causes compression of the anal canal, vagina, and urethra against the back of pubic symphysis (**Fig. 11**). It then follows that there would be a high-pressure zone in the vagina,

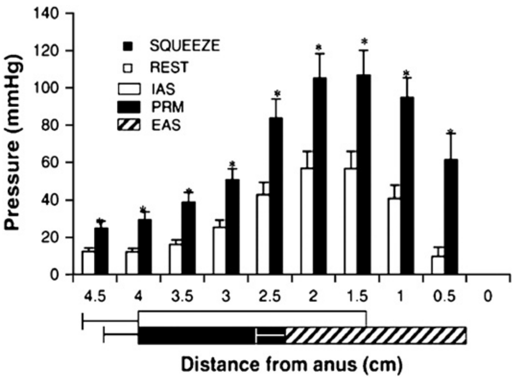

Fig. 9. Anal canal pressures along the length of the canal and its relationship with anatomical structures: Anal canal pressure was measured using the station pull through technique. Each bar represents mean+SE from the 17 subjects. Note the baseline pressure and the squeeze pressures at each station. The pressures during squeeze at all stations are significantly higher than at rest ($p < 0.005$). Also note, the location of Internal anal sphincter (IAS), puborectalis (PRM) and external anal sphincter (EAS) along the length of the anal canal. Obtained from author.

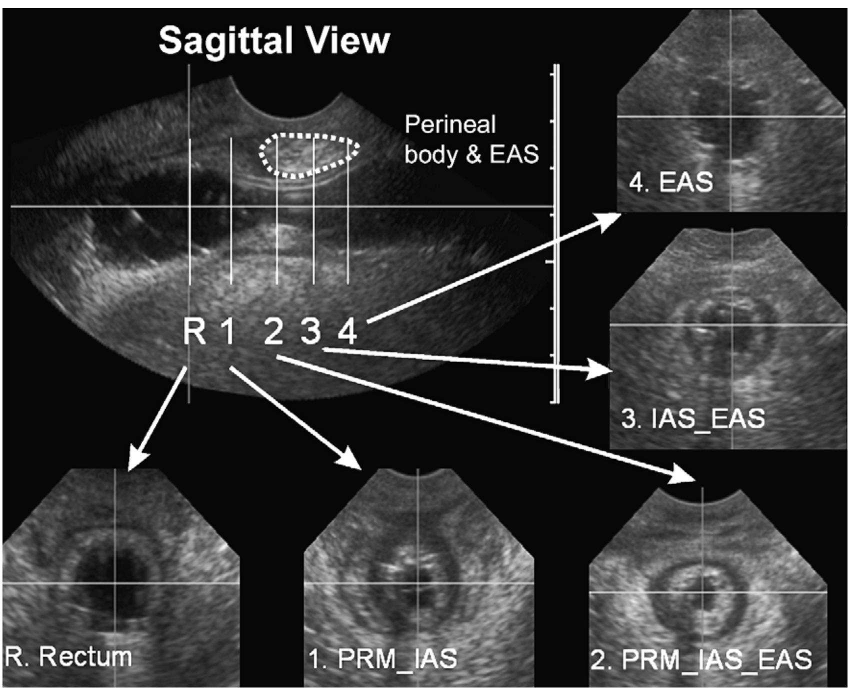

Fig. 10. Ultrasound images of the anal canal in the sagittal and axial planes with a water filled bag placed in the anal canal: the sagittal image shows the anal canal along its entire length. Axial images at various locations along the length of anal canal allow visualization of various components of the anal closure mechanism. Axial images at R=rectum, 1=Puborectalis (PRM) & Internal sphincter (IAS), 2 = PRM, IAS, and external anal sphincter (EAS), 3 = IAS & EAS, 4 = EAS only. Obtained from author.

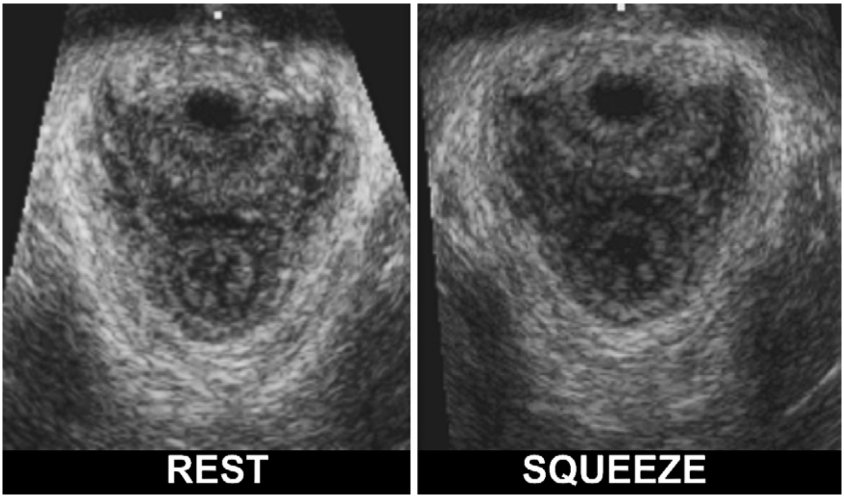

Fig. 11. Pelvic Floor Hiatus Captured from the 3D ultrasound images at rest and during a pelvic floor contraction: Note that with contraction the hiatus becomes smaller and the puborectalis muscle moves towards the pubic symphsis. The anterior motion of the puborectalis muscle compresses, anal canal, vagina and urethra against the back of pubic symphsis, which constitutes the constrictor function of pelvic diaphragm. Obtained from author.

which is indeed true.[45] Pressure characteristics of the vaginal high-pressure zone reveal that the anterior and posterior pressure in the vagina are higher than the lateral pressure, which suggests that vagina is compressed in the anteroposterior direction by the puborectalis muscle. Three-dimensional US images show that the pelvic floor hiatus becomes smaller and larger with the contraction and relaxation of the puborectalis muscle, respectively.[24,46] Pudendal nerve block increases dimensions of the pelvic floor hiatus and decreases vaginal pressure.[24] Distention of the vagina increases the anteroposterior length of the puborectalis muscle and allows it to contract stronger (based on the length tension principle). Anal canal pressure in the proximal part of the anal canal (part surrounded by the puborectalis muscle) and not the distal part (surrounded by the EAS) increases with vaginal distention.[47]

Because the vagina does not possess any intrinsic sphincter mechanism, the vaginal high-pressure zone is entirely related to the puborectalis muscle. The significance of the latter finding is that one can easily assess the puborectalis muscle function using vaginal manometry. It is likely that future studies will use this important understanding further to define the role of puborectalis muscle in fecal continence, incontinence, and other pelvic floor disorders.

Pelvic Floor Muscles and Fecal Incontinence

The etiology of fecal incontinence is multifactorial and can be broadly divided into problems related to (1) diarrhea or excessive amount of liquid stools, (2) reservoir or rectal dysfunction, and (3) anal canal closure dysfunction. It is quite clear that the three separate and distinct anatomic structures (IAS, EAS, and puborectalis muscle) guard the anal canal opening (triple security). Does this represent redundancy or is it rather that a fine orchestration of these three structures is crucial in keeping continence under different circumstances and for different rectal contents (air, liquid, and solids)? Further studies are needed to prove or disprove these points. Read and colleagues[48] in the 1980s, based on anal canal pressure studies, found that the dysfunction of EAS is the most common cause of fecal incontinence. A small subset of patients was also found to have a defective IAS.[49] Endoanal US imaging studies of Sultan and colleagues[50] found anatomic defects in the EAS muscle of 35% of women following vaginal delivery. The latter also suggests that anatomic defects of the EAS are one of the most common causes of fecal incontinence. More recent studies suggest, however, a "multihit hypothesis" in the genesis of fecal incontinence. Fernandez-Fraga and coworkers[51] used a novel instrument (perineal dynamometer) to study the pelvic floor function in patients with fecal incontinence. They found that patients have functional defect in more than one muscle of anal continence and the severity of fecal incontinence was related to the composite effect of damage to the three continence muscles. Biofeedback therapy resulted in improvement of fecal incontinence symptoms and the improvement correlated best with the improvement in levator ani function, rather than with the improvement in the IAS, EAS pressure. A study by Bharucha and colleagues[28] confirmed findings of Fernandez-Fraga and coworkers[51] and their study lends further credence to the "multihit hypothesis" of fecal incontinence.

Studies by Delancey and coworkers[52] and Dietz and Lanzarone[53] show that anatomic disruptions of the puborectalis muscle are quite common following childbirth (20%–35%). It is clear, however, that all these subjects do not have symptoms of fecal incontinence. The authors' studies in asymptomatic multiparous women confirm findings of Jung and colleagues.[33] Further studies are required to determine the relationship between anatomic disruptions as seen on the imaging studies and functional impairment of puborectalis muscle function. It is clear, however, that patients with fecal incontinence have defects in more than one muscle of continence and the symptoms are more severe in patients with defects in the multiple muscles.

Pelvic Floor Muscles and Constipation

Constipation affects 20% to 30% of the adult population in the United States[54] and its etiology, similar to that of fecal incontinence, is multifactorial. Broadly, there are two major types of constipation: slow transit type, in which the movement of fecal material through the colon is slow; and outlet obstruction type, in which the patient has trouble evacuating rectal contents. Hirschsprung's disease, characterized by failure of caudal migration of myenteric plexus, may be considered as a cause of outlet obstruction type of constipation. Hirschsprung's disease is uncommon, however, in adults. Outlet obstruction, secondary to pelvic floor dysfunction, accounts for 50% or more cases of constipation in adults.[55] Originally described by Preston and Lennard-Jones[56] in 1985 as anismus, the entity has received several names (ie, pelvic floor dyssynergia, paradoxical puborectalis muscle contraction, paradoxical sphincter contraction, and dyssynergic defecation).[55] Normally, during the act of defecation or Valsalva maneuver the respiratory diaphragm and abdominal wall contract together, which results in an increase in intra-abdominal and rectal pressure. Simultaneously, there is relaxation of the pelvic floor muscles and anal sphincter muscles during defecation. Based on the rectal and anal sphincter pressure recordings, Olsen and Rao[55] categorized dyssynergic defecation disorders into three different types: type 1, increase in the rectal pressure and anal sphincter contraction; type 2, no increase in the rectal pressure and sphincter contraction; and type 3, increase in the rectal pressure but either absent or incomplete sphincter relaxation. Dyssynergic defecation is usually acquired but in some cases the symptoms are present from childhood, which suggests that the individual never "learned the defecation process" correctly.

Paradoxical pelvic floor contraction can be recognized on the anal sphincter recording; electromyographic recordings (using anal plug electrodes or cutaneous electrodes); and imaging studies. The latter can be performed using radiograph fluoroscopy (barium defecography); CT fluoroscopy; and MRI. During the act of defecation two events occur in the pelvic floor muscles: pelvic floor descends and pelvic floor hiatus becomes larger. The descent of pelvic floor muscles is seen as a drop in the anorectal angle to below the pubococcygeal line (an imaginary line connecting the lower end of pubic symphysis and coccyx) and widening of the pelvic floor hiatus (also seen as increase in the anorectal angle). With pelvic floor contraction, the anorectal angle moves cranially and ventrally. The reverse occurs during defecation. In patients with constipation, MRI defecography studies show heterogeneity of abnormalities of the abdominal wall contraction, pelvic floor descent, and puborectalis muscle relaxation.[40] The most important finding in these studies is that the puborectalis muscle either does not relax or it does so incompletely. The latter results in either no change or in a slight decrease in the anorectal angle. The advantage of MRI defecography is that it allows clear visualization of the pelvic viscera and various other anatomic abnormalities associated with pelvic floor disorders (eg, rectocele, cystocele, rectal intussusception, and prolapse). Recent studies show that biofeedback treatment for constipation is quite effective in treating constipation related to the pelvic floor muscle dysfunction and results in amelioration of the physiologic muscle abnormalities.[54,57]

SUMMARY

Pelvic floor muscles have two important functions: they provide physical support to the pelvic viscera; and they provide constrictor mechanism to the anal canal, vagina, and urethra. Newer imaging and physiologic studies strongly suggest that these two functions of the pelvic floor are quite distinct and are likely related to different components of the pelvic floor muscles. The pubococcygeus, ileococcygeus, and ischiococcygeus most likely provide the physical support or act as a floor for the pelvic viscera. The puborectalis muscle provides the constrictor function to the anal canal, vagina, and urethra.

The urethra and anal canal each have two constrictors or sphincters of their own. In the case of anal canal these are the IAS and EAS, and in the case of urethra they are the smooth muscle sphincter (located at the bladder neck) and rhabdosphincter (external urethral sphincter). Based on physiologic studies, it seems that the puborectalis muscle is the third constrictor or the sphincter of anal canal. Future studies are likely to reveal that puborectalis muscle also serves as a constrictor for the urethra. Vagina, however, has only one constrictor mechanism, which is solely provided by the puborectalis portion or the pelvic floor muscle. The authors believe that puborectalis muscle is the common link between gastroenterologist, colorectal surgeon, urologist, and urogynecologist, the specialties of medicine caring for patients with pelvic floor disorders.

Pelvic floor disorders are many and are generally lumped together. It may be possible, however, broadly to subclassify them into disorders of pelvic floor support (prolapse, descending perineal syndrome) and constrictor function (urinary and fecal incontinence). Furthermore, these disorders may be further divided into dysfunctions of pelvic floor contraction (fecal and urinary incontinence) and relaxation (constipation and urinary retention). As a clear picture of functional anatomy of pelvic floor muscles emerges, it is imminent that different components of the pelvic floor muscles will be implicated in different pelvic floor disorders. With such a functional classification "splitter approach" it may be possible to target specific therapeutic strategies to treat specific pelvic floor muscle disorders more effectively.

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GENERAL GYNECOLOGY

Pelvic floor ultrasound: a review

Hans Peter Dietz, MD, PhD

Imaging currently plays a limited role in the investigation of pelvic floor disorders. It is obvious that magnetic resonance imaging has limitations in urogynecology and female urology at present due to cost and access limitations and due to the fact that it is generally a static, not a dynamic, method. However, none of those limitations apply to sonography, a diagnostic method that is very much part of general practice in obstetrics and gynecology. Translabial or transperineal ultrasound is helpful in determining residual urine; detrusor wall thickness; bladder neck mobility; urethral integrity; anterior, central, and posterior compartment prolapse; and levator anatomy and function. It is at least equivalent to other imaging methods in visualizing such diverse conditions as urethral diverticula, rectal intussusception, mesh dislodgment, and avulsion of the puborectalis muscle. Ultrasound is the only imaging method able to visualize modern mesh slings and implants and may predict who actually needs such implants. Delivery-related levator trauma is the most important known etiologic factor for pelvic organ prolapse and not difficult to diagnose on 3-/4-dimensional and even on 2-dimensional pelvic floor ultrasound. It is likely that this will be an important driver behind the universal use of this technology. This review gives an overview of the method and its main current uses in clinical assessment and research.

Key words: female pelvic organ prolapse, levator ani, pelvic floor, 3-dimensional ultrasound, translabial ultrasound

It has taken more than 2 decades for imaging to develop as a mainstream diagnostic tool in the investigation of female pelvic organ prolapse, urinary and fecal incontinence, and defecation disorders. Physicians have been slow in realizing that clinical assessment alone is a poor tool to assess pelvic floor function and anatomy. Our examination skills are quite simply inadequate, focusing on surface anatomy rather than true structural abnormalities. Because the best procedure in the hands of a highly competent surgeon will be a failure if performed on the wrong patient, it is not at all surprising that recurrence after pelvic reconstructive surgery is common.[1] The problem is not poor treatment–it is poor diagnostics. Sonography is an accepted component of any clinical assessment in both obstetrics and in gynecology–so why should it be any different in urogynecology and female urology?

Imaging techniques can provide immediate objective confirmation of findings obtained on examination. In some instances this can lead to markedly enhanced clinical assessment skills. To give just one example: the missing link between vaginal childbirth and prolapse (major levator trauma in the form of avulsion of the anteromedial aspects of the puborectalis muscle off the pelvic sidewall[2,3]) is palpable, but palpation of levator trauma requires considerable skill and teaching,[4-6] preferably with imaging confirmation. Certainly, diagnosis by imaging is more reproducible than diagnosis by palpation,[6] and it is easier to teach. After all, vision is our primary sensory organ. And suspected levator trauma or abnormal distensibility (ballooning) of the hiatus is by no means the only reason to perform pelvic floor imaging (Table).

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Equipment and examination technique

This review will be limited to translabial/transperineal ultrasound, and this is reflected in the following comments on equipment and examination technique. However, many clinical questions can be answered just as well by what some investigators call "introital ultrasound," a technique that is generally understood to involve the use of front-firing vaginal endoprobes placed in the introitus. Although such probes can provide higher resolutions, there are obvious downsides to their use, especially when it comes to assessing the effect of maneuvers and imaging of the levator ani, and this technique will not be discussed further in this review.

Standard requirements for basic 2-dimensional (2D) translabial pelvic floor ultrasound include a B-mode capable 2D ultrasound system with cineloop func-

TABLE
Indications for pelvic floor ultrasound

- Recurrent urinary tract infections
- Urgency, frequency, nocturia, and/or urge urinary incontinence
- Stress urinary incontinence
- Insensible urine loss
- Bladder-related pain
- Persistent dysuria
- Symptoms of voiding dysfunction
- Symptoms of prolapse, ie, sensation of lump or dragging sensation
- Symptoms of obstructed defecation, eg, straining at stool, chronic constipation, vaginal or perineal digitation, and sensation of incomplete bowel emptying
- Fecal incontinence
- Pelvic or vaginal pain after antiincontinence or prolapse surgery
- Vaginal discharge or bleeding after antiincontinence or prolapse surgery

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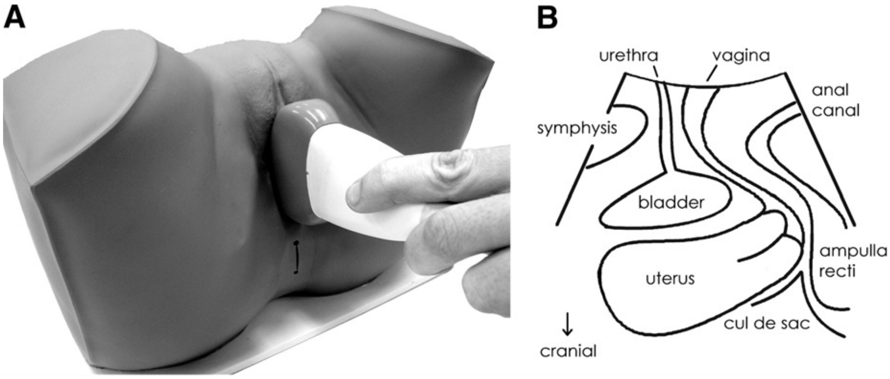
FIGURE 1

Transducer placement for translabial/perineal ultrasound



A, Transducer placement on perineum and **B,** schematic representation of imaging in midsagittal plane.

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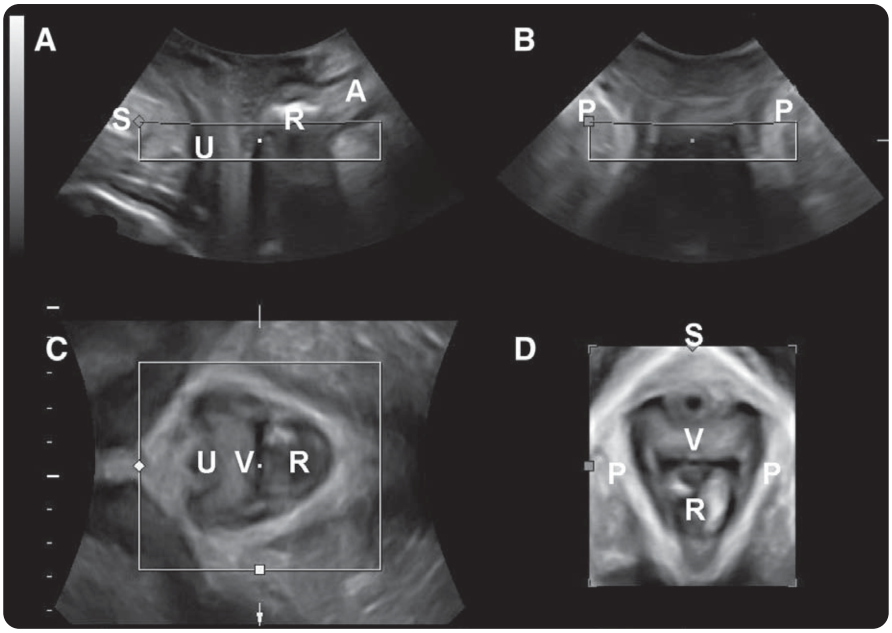
tion, a 3.5- to 6-MHz curved array transducer and a monochrome videoprinter. In essence, any setup used for imaging of the fetus (or a child's or adult's kidney) will be appropriate. We obtain a midsagittal view by placing a transducer (usually a curved array with frequencies between 3.5-6 MHz) on the perineum (Figure 1, A) after covering the transducer with a nonpowdered glove, condom, or thin plastic wrap. Powdered gloves should be avoided as they can substantially impair imaging quality due to reverberations. Alcohol wipes are usually considered sufficient for transducer cleaning after removal of gel and debris.

FIGURE 2

Standard acquisition screen of 3-dimensional pelvic floor ultrasound



A, Midsagittal, **B,** coronal, and **C,** axial planes and **D,** rendered axial plane (ie, semitransparent representation of all pixels in *box* [region of interest] seen in **A**-**C**).

A, anal canal; *P*, puborectalis muscle; *R*, rectal ampulla, *S*, symphysis pubis; *U*, urethra; *V*, vagina.

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Imaging is performed in dorsal lithotomy position, with the hips flexed and slightly abducted, or in the standing position. Requiring the patient to place her heels close to the buttocks will often result in an improved pelvic tilt. Bladder filling should be specified; usually prior voiding is preferable. The presence of a full rectum may impair diagnostic accuracy and sometimes necessitates a repeat assessment after bowel emptying–especially if there is a degree of fecal impaction. Parting of the labia can improve image quality. The latter will also depend on the hydration state of tissues, which generally is best in pregnancy and poorest in elderly women with marked atrophy. Vaginal scar tissue can also reduce visibility, especially in the posterior compartment, but obesity virtually never seems to be a problem.

The transducer can be placed firmly against the symphysis pubis without causing significant discomfort, unless there is marked atrophy. A cough will part the labia, expel air bubbles and detritus, and ensure good contact between the transducer and tissues. It is essential to not exert undue pressure on the perineum so as to allow full development of pelvic organ descent. The standard midsagittal view includes the symphysis anteriorly, the urethra and bladder neck, the vagina, cervix, rectum, and anal canal (Figure 1, B). Posterior to the anorectal junction a hyperechogenic area indicates the central portion of the levator plate. The cul-de-sac may also be seen, filled with a small amount of fluid, echogenic fat, or bowel. Parasagittal or transverse views often yield additional information, eg, confirming urethral integrity, enabling assessment of the puborectalis muscle, and for imaging of mesh implants.

There is no agreement on image orientation, and the published literature contains at least 3 different options. The first published translabial images were either obtained with the perineum at the top and the symphysis pubis on the left[7,8] or the same rotated by 180 degrees.[9] Other authors have used mirrored versions of the same.[10] The author of this review prefers the original orientation as on conventional transvaginal ultrasound (cranioventral aspects to the left, dorsocaudal to the right). This orientation is very convenient when using 3-dimensional (3D)/4-dimensional (4D) systems as shown in Figure 2, a representation of a 3D volume of the pelvic floor. The top left represents the midsagittal plane, with the bottom left an axial-plane slice, and the bottom right representing a rendered volume showing the levator hiatus.

In the following paragraphs, I'll describe the main clinical applications of translabial ultrasound in urogynecologic imaging.

Anterior compartment

As clinicians, we say "cystocele" when we really mean "anterior vaginal wall descent." Of course, anterior vaginal wall descent usually implies descent of the bladder, ie, a "cystocele," but behind this term there may hide a number of different conditions. Ultrasound can be very helpful in determining whether it is really the bladder that is descending and in ascertaining the configuration of urethra and bladder neck. The original indication for pelvic floor ultrasound, however, is the assessment of bladder neck mobility and funneling of the internal urethral meatus, both of which are important in women with urinary incontinence. Figure 3 shows the standard orientation used to describe bladder neck mobility.[11] The position of the bladder neck is determined relative to the inferoposterior margin of the symphysis pubis or relative to a system of coordinates based on the central axis of the symphysis pubis.[12] Measurements are taken at rest and on maximal Valsalva, and the difference yields a numerical value for bladder neck descent. Comparative studies have shown good correlations with radiological methods.[12-16] The reproducibility of measurements of bladder neck mobility are high.[17,18]

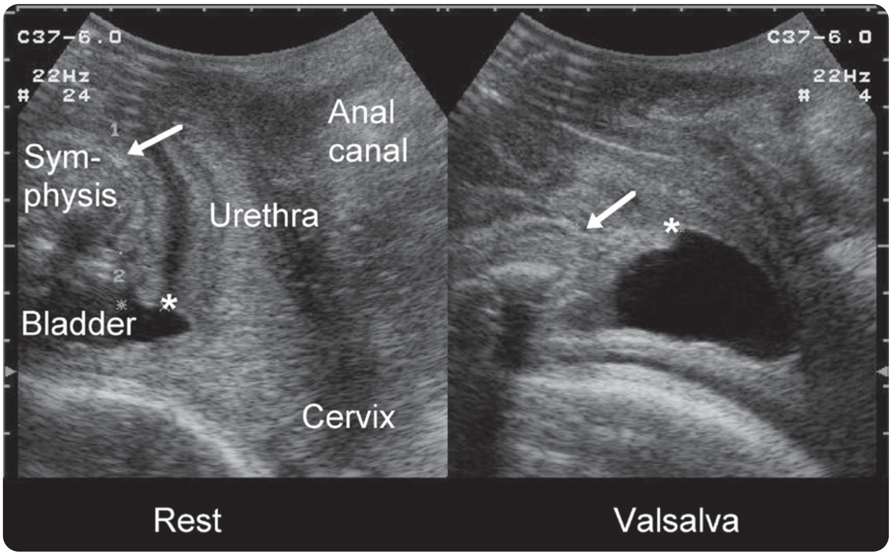
On Valsalva, the proximal urethra will be seen to rotate in a posteroinferior direction to a greater or lesser degree, due to the fact that the urethra and anterior vaginal wall are tethered to the symphysis pubis and the pelvic sidewall. Incidentally, this rotation markedly changes the echogenicity of the longitudinal smooth muscle of the urethra, which becomes isoechoic and less easy to identify, as evident in Figure 3. Proximal urethral rotation can be measured by comparing the angle of inclination between the proximal urethra and any other fixed axis. Some investigators measure the retrovesical angle (or posterior urethrovesical angle) between proximal urethra and trigone, others determine the angle γ between the central axis of the symphysis pubis and a line from the inferior symphyseal margin to the bladder neck.[19]

There is no definition of normal for bladder neck descent although cutoffs of 20, 25, and 30 mm have been proposed to define hypermobility. Bladder filling, patient position, and catheterization all have been shown to influence measurements[20] and it can occasionally be quite difficult to obtain an effective Valsalva maneuver, especially in nulliparous women who frequently coactivate the levator muscle.[21] Perhaps not surprisingly, publications to date have presented widely differing reference measurements in nulliparous women.[18,22-24] I have obtained measurements of 1.2-40.2 mm (mean, 17.3 mm) in a group of 106 stress-continent nulligravid young women of 18-23 years of age.[17] It is likely that methodologic differences account for the above discrepancies, with all known confounders tending to reduce descent.

The etiology of increased bladder neck descent is likely to be multifactorial. The wide range of values obtained in young nulliparous women suggests a congenital component. Vaginal childbirth is probably the most significant environmental factor,[25,26] with a long second stage of labor and vaginal operative delivery associated with increased postpartum descent. This association between increased bladder descent and vaginal parity is also evident in older women with symptoms of pelvic floor dysfunction.[27]

In patients with stress incontinence, but also in asymptomatic women,[28] funneling of the internal urethral meatus may be observed on Valsalva and sometimes even at rest. Funneling is often (but not necessarily) associated with leakage. Marked funneling has been shown to be associated

FIGURE 3
Determination of bladder neck mobility



Pelvic floor ultrasound, midsagittal plane at rest (*left*) and maximal Valsalva (*right*). *Arrow* identifies inferior margin of symphysis pubis, ie, point of reference for measurement of bladder neck position (*).

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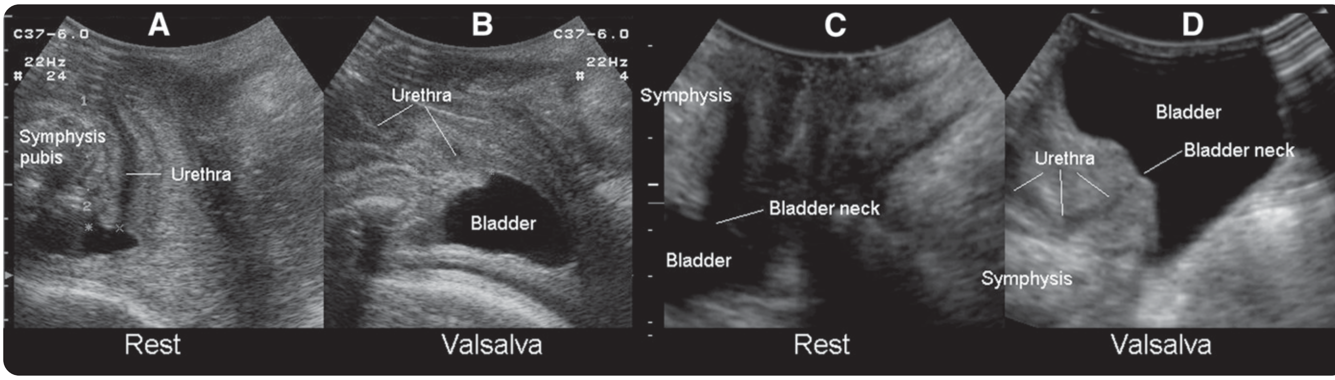
FIGURE 4
Cysto-urethrocele and custocele with intact retrovesical angle



Two main types of cystocele as imaged on maximal Valsalva in midsagittal plane: cystourethrocele (green type II; **B**), associated with urinary stress incontinence and good voiding function, and isolated cystocele (green type III; **D**), associated with prolapse and voiding dysfunction rather than stress incontinence. **A** and **B**, Retrovesical angle on Valsalva is at about 180 degrees, and bladder neck is lowest point of bladder. **C** and **D**, Retrovesical angle on Valsalva, **D**, is intact at 90-120 degrees, and bladder base is lower than bladder neck.

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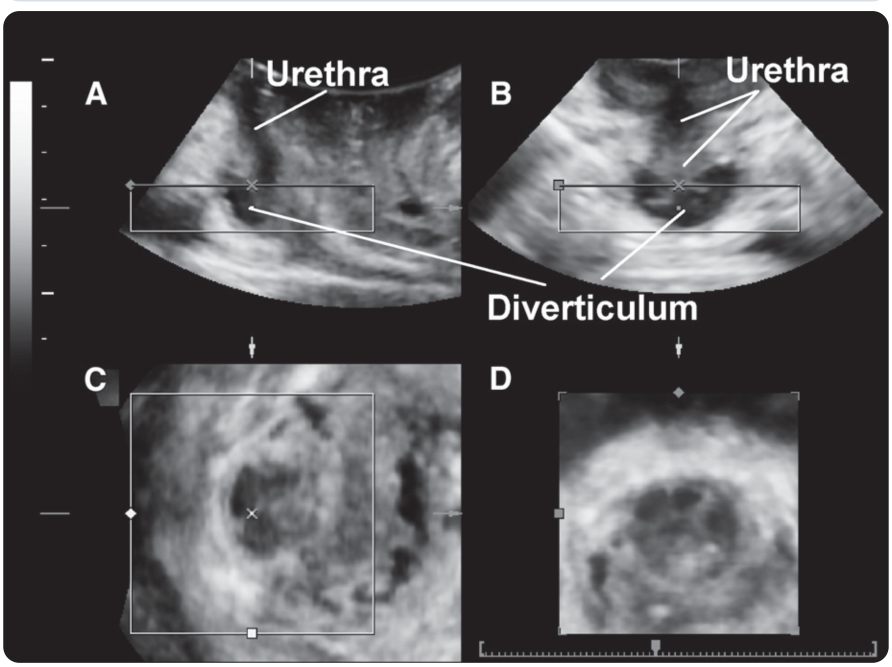
with poor urethral closure pressures.[29,30] Other indirect signs of urine leakage on B-mode real-time imaging are weak gray-scale echoes (streaming) and the appearance of 2 linear (specular) echoes defining the lumen of a fluid-filled urethra. Color Doppler ultrasound can directly demonstrate urine leakage on Valsalva maneuver or coughing,[31] if this is desired. Agreement between color Doppler and fluoroscopy was high in a controlled group with in-dwelling catheters and identical bladder volumes.[32] Color Doppler imaging may also facilitate the documentation of leak point pressures.[33]

FIGURE 5
Anterior urethral diverticulum on 3-dimensional pelvic floor ultrasound



A-C, Orthogonal planes clearly illustrate location and extent of diverticulum.

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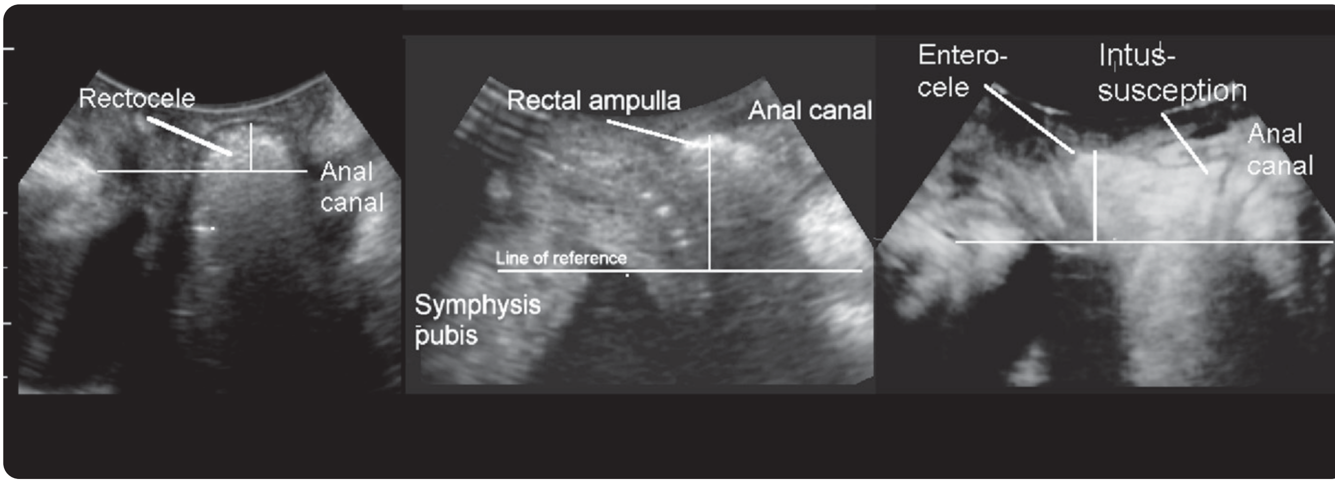
Clinical examination is limited to grading anterior compartment prolapse, which we call "cystocele." In fact, imaging will identify a number of anatomic situations that are difficult, if not impossible, to distinguish clinically. There are at least 2 types of cystoceles with very different functional implications (Figure 4), which were first described in this Journal in the 1970s.[34] A cystourethrocele is associated with above-average flow rates and urodynamic stress incontinence whereas a cystocele with intact retrovesical angle is generally associated with voiding dysfunction and a low likelihood of stress incontinence.[35]

Occasionally, a cystocele will turn out to be due to a urethral diverticulum (Figure 5, for a 3D representation of an unusual anterior urethral diverticulum), a Gartner duct cyst, or an anterior enterocele.[36,37] Urethral diverticula are often overlooked for years in women with recurrent bladder infections and symptoms of frequency, urgency, and pain or burning on voiding, until imaging is undertaken.[38-40] Urethral structure and spatial relationships are much better ap-

FIGURE 6

Rectocele, perineal hypermobility, and rectal intussusception



Distinction among true rectocele, ie, defect of rectovaginal septum (*left*); perineal hypermobility, ie, descent of rectal ampulla without fascial defect (*middle*); and rectal intussusception (*right*). All 3 conditions can manifest as clinical rectocele and are impossible to distinguish on examination.

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preciated in the axial plane (Figure 5), which is particularly useful in the differential diagnosis of Gartner cyst and urethral diverticulum.

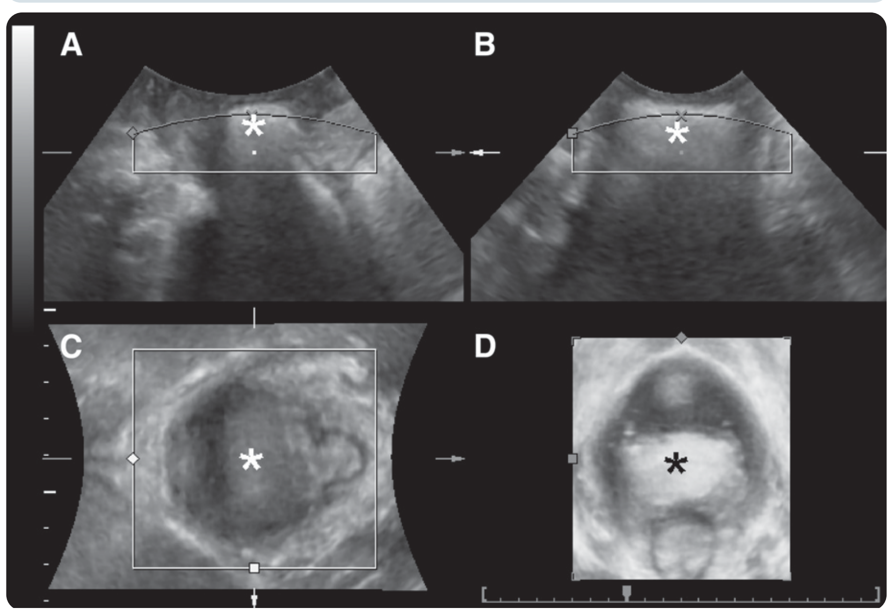
Finally, translabial ultrasound may detect foreign bodies or bladder tumors[20,37] and can be used to determine residual urine,[41] using a formula originally developed for transvaginal ultrasound.[42] Although detrusor wall thickness has probably been overrated as a diagnostic tool in the context of detrusor overactivity,[43,44] increased detrusor wall thickness seems associated with symptoms of the overactive bladder,[45-48] and may be a predictor of postoperative de novo urge incontinence and/or detrusor overactivity after anti-incontinence procedures. As opposed to the situation in men, detrusor wall thickness in women is not predictive of voiding dysfunction.[49]

Central compartment

Generally, uterine prolapse is obvious clinically, as is vault descent. Having said that, ultrasound can graphically show the effect of an anteriorized cervix in women with an enlarged, retroverted uterus, explaining symptoms of voiding dysfunction and supporting surgical intervention to improve voiding in someone with a retroverted fibroid uterus.[50] On the other hand, mild descent of an acutely anteverted uterus can result in compression of the anorectum, explaining symptoms of obstructed defecation–a situation that is described as a "colpocele" on defecation proctography. The uterus can be difficult to identify due to its isoechoic nature, sim-

FIGURE 7

Rectocele on 3D translabial ultrasound



True rectocele (*) as imaged in **A,** midsagittal, **B**, coronal, and **C,** axial planes and in **D,** axial plane rendered volume. Images **A** and **B** show rectocele to be typically located at anorectal junction and symmetrical, **C** and, even more clearly, **D,** illustrate that it occupies a very substantial part of levator hiatus.

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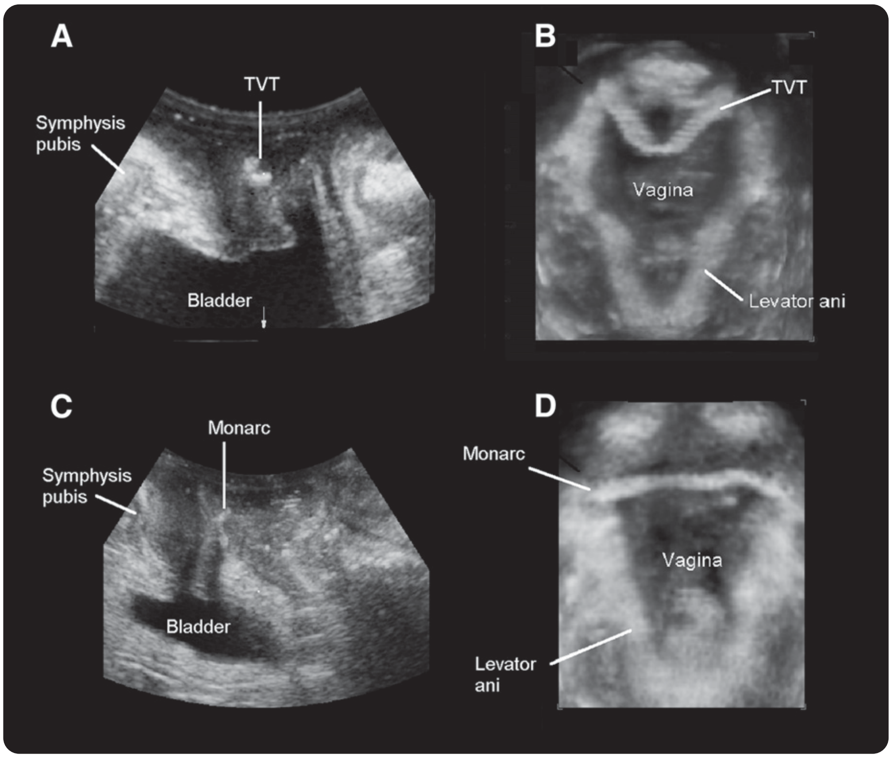
FIGURE 8
Suburethral slings as seen on translabial ultrasound



A and **C,** In midsagittal plane 2 slings, 1 a transretzius (**A**), the other transobturator sling (**C**), are essentially indistinguishable. Both are hyperechogenic and located dorsal to midurethra. **B** and **D,** In axial plane, distinction is quite obvious: **B,** a tension-free vaginal tape (TVT) is curving ventrally toward symphysis pubis, whereas **D,** a Monarc tracks laterally toward insertion of puborectalis muscle and obturator foramen.

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ilar in echotexture to the vaginal wall, especially in postmenopausal women with small, atrophic uteri. In premenopausal women the uterus is often quite obvious, especially if anteverted. Sometimes Nabothian follicles help identify the cervix.

Posterior compartment

Pelvic floor ultrasound is particularly useful in the posterior compartment, although we have in no way realized its potential benefits for clinical practice. We see descent of the posterior vaginal wall and diagnose a rectocele, usually quite unaware that at least 5 different anatomically distinct conditions can cause this appearance. A stage II rectocele could be due to a true rectocele, ie, a defect of the rectovaginal septum (most common, and associated with symptoms of prolapse, incomplete bowel emptying, and straining at stool);[51] an abnormally distensible, intact rectovaginal septum (common and associated only with prolapse symptoms); perineal hypermobility, ie abnormal candad displacement of the levator plate; a combined recto-enterocele (common); and an isolated enterocele (uncommon); or just a deficient perineum giving the impression of a bulge.[52] Occasionally a rectocele turns out to be a rectal intussusception, an early stage of rectal prolapse, where the wall of the rectal ampulla is inverted and enters the anal canal on Valsalva; see Figure 6 for a comparison of 3 of those conditions. Figure 7 shows a simple true rectocele in the 3 orthogonal planes and in a rendered volume. Images in the coronal and axial plane demonstrate that this rectocele, as most others, is symmetrical, suggesting a high transverse defect of the rectovaginal septum.

It is not surprising that colorectal surgeons have started using this technique in the initial investigation of women with defecatory disorders, although they tend to use ultrasound gel as a contrast medium.[53-55] Several studies have recently shown that ultrasound is much better tolerated than defecation proctography,[56,57] and of course it is much cheaper. If there is a rectocele or a rectal intussusception/prolapse on ultrasound, this condition is very likely to be found on x-ray imaging.[57,58] Consequently, it is likely that ultrasound will replace radiologic techniques in the initial investigation of women with defecatory symptoms.

Although it is not always clear what kind of therapeutic consequences one should draw from imaging findings, one would not expect a rectocele repair to alleviate symptoms caused by rectal intussusception. If there is a defect of the rectovaginal septum then the patient is an obvious candidate for a defect-specific rectocele repair as first popularized by Cullen Richardson.[59] If a clinical rectocele is due to a hyperdistensible fascia or levator hiatus (perineal hypermobility) then one should not be too surprised if on surgical dissection one does not find any defect to close–which is what has prevented the universal acceptance of defect-specific rectocele repair. Such patients probably respond best to fascial plication or even a levatorplasty. Needless to say, it makes no sense whatsoever to remove rectal wall in someone who has a herniation of that rectal wall through a defect in the rectovaginal septum as with transanal methods such as the stapled transanal rectal resection procedure.[60]

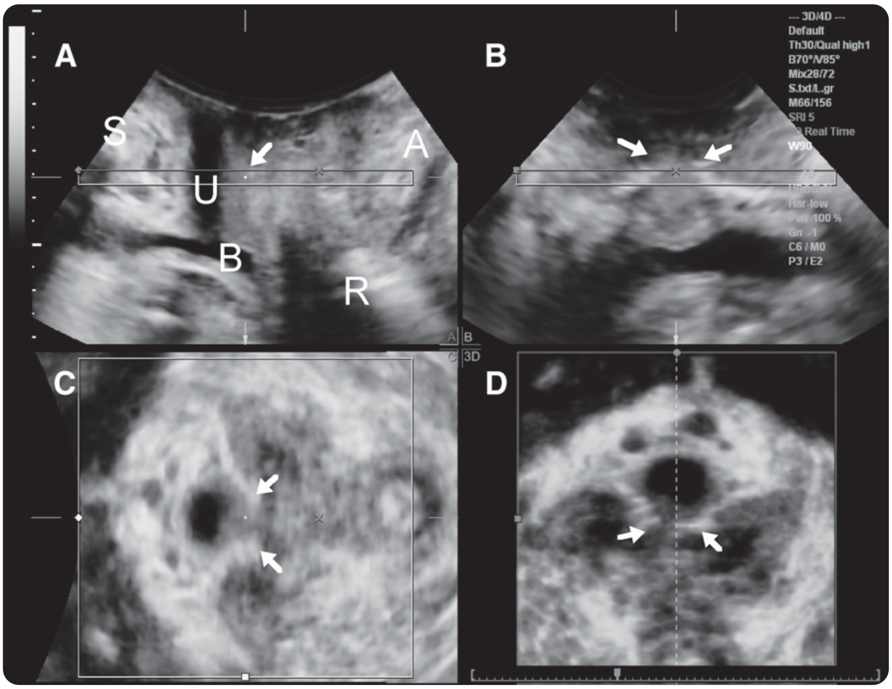
Assessment of the anal sphincter will not be discussed in any detail here. The anal sphincter is generally imaged by endoanal ultrasound. This method is firmly established as one of the cornerstones of a colorectal diagnostic workup for anal incontinence and is beyond the scope of this review. Due to the limited availability of such probes in gynecology, obstetricians and gynecologists have used high-frequency curved array or endovaginal probes placed exoanally, ie, transperineally, in the coronal rather than the midsagittal plane.[61-63] There are advantages to this approach–not just from the point of view of the patient. Exoanal imaging reduces distortion of the anal canal and allows dynamic evaluation of the anal sphincter and mucosa at rest and on sphincter contraction, which seems to enhance the definition of muscular defects. However, resolutions are quite likely to be inferior[64] to those obtained by endoanal ultrasound, and good comparative studies are lacking at present.

Implants

Since the late 1990s, synthetic suburethral slings have become very popular. Ultrasound can confirm the presence of such a sling, distinguish between transobturator and trans-Retzius implants, especially when examining the axial plane (Figure 8), and even allow an educated guess regarding the type of implant.[65] As these meshes are highly echogenic, ultrasound is superior to magnetic resonance (MR) in identifying implants[66] and has helped elucidate their mode of action.[67] It is also very helpful when assessing women with complications of suburethral slings such as voiding dysfunction and de novo symptoms of urgency, helping the surgeon to decide whether to cut a sling. Sling division usually results in a 5- to 10-mm gap between mesh arms (Figure 9).

There is a worldwide trend toward the use of permanent vaginal wall meshes, especially for recurrent prolapse, and complications such as support failure, mesh erosion, and chronic pain are not that uncommon. Polypropylene meshes such as the Perigee (American Medical Systems, Minnetonka, MI), Prolift (Ethicon Gynecare, Somerville, NJ), and Apogee (American Medical Systems, Minnetonka, MI) are highly echogenic (Figure 10), and their visibility is limited only by persistent prolapse and distance from the transducer. Three-dimensional translabial ultrasound has demonstrated that the implanted mesh often is nowhere near as wide as it is supposed to be, and this finding has been interpreted as evidence of mesh

FIGURE 9
Patient after TVT division due to de novo urgency, urge incontinence, and chronic mild obstruction



A, Midsagittal plane. *Arrow* indicates most likely tape location, but tape is invisible in midsagittal plane. **B** and **C**, Coronal and axial views, with 2 free tape ends (*arrows*). Gap between 2 tape ends is also evident in **D,** axial plane rendered volume.

A, anal canal; *B*, bladder; *R*, rectal ampulla; *S*, symphysis pubis; *U*, urethra.

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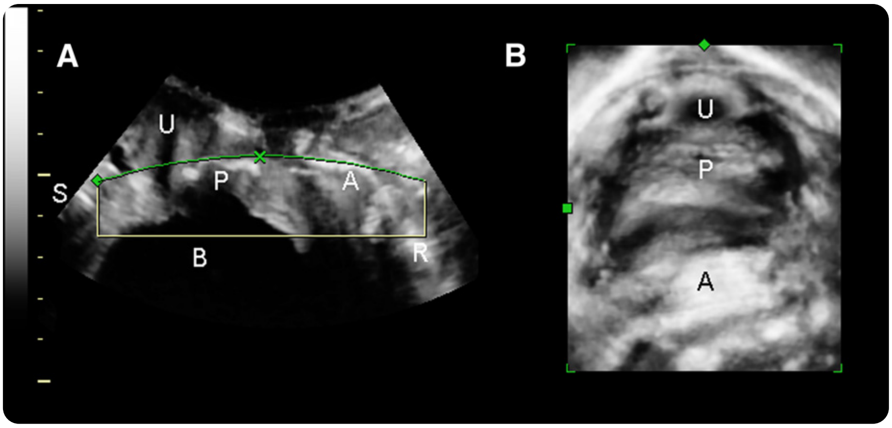
FIGURE 10
Anterior and posterior compartment mesh implants



A, Midsagittal view and **B,** axial plane rendered volume in patient after successful Perigee (P) and Apogee (A) implantation. **A,** Midsagittal plane demonstrates absence of prolapse on Valsalva, despite severe levator ballooning evident in **B,** axial plane in this patient with bilateral avulsion injury.

B, bladder; *R*, rectal ampulla; *S*, symphysis pubis; *U*, urethra.

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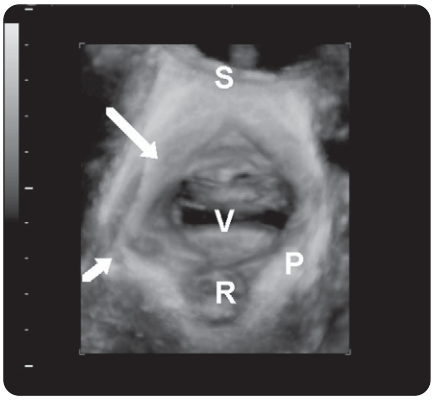
FIGURE 11
Rendered volume (axial plane) of typical unilateral avulsion



Prior insertion of muscle (*long arrow*), now completely devoid of any hyperechogenic tissue, and retracted puborectalis muscle (*short arrow*).

P, puborectalis muscle; *R*, rectum; *S*, symphysis pubis; *V*, vagina.

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shrinkage, contraction, or retraction.[68] In the view of the author, the phenomenon of mesh retraction remains unproven to date. A more likely explanation is that the mesh did not remain flat but folded up on itself, either during the implantation or immediately after closure. Surgical technique seems to play a role here as fixation of mesh to underlying tissues results in a flatter, more even appearance. The position, extent, and mobility of vaginal wall mesh can be determined, helping with the assessment of individual technique, and ultrasound may uncover complications such as dislodgment of anchoring arms.[69]

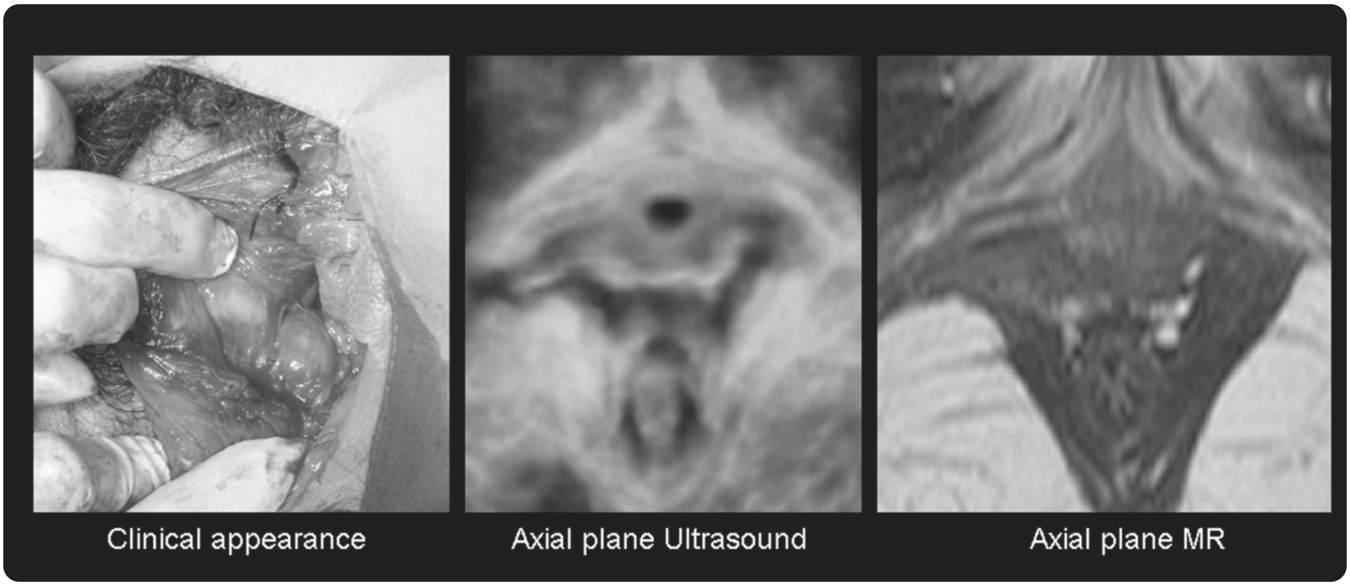
Clearly, translabial 4D ultrasound will be useful in determining functional outcome and location of implants, and will help in optimizing both implant design and surgical technique. Finally, although this is not much more than an afterthought in this age of minimally invasive slings, most of the injectables used in antiincontinence surgery are also highly echogenic and can be visualized as a hyperechoic donut shape surrounding the urethra.[20] Sometimes the material turns out in unexpected locations, such as underneath the bladder neck, protruding into the bladder itself, in the space of Retzius, or even tracking toward the obturator foramen.

The axial plane

Access to the axial plane, previously the domain of cross-sectional imaging, has markedly increased the usefullness of ultrasound in the assessment of pelvic floor disorders. Although side-firing vaginal transducers can image the axial plane on 2D, such instruments were never very common and have major disadvantages. In the mid-1990s, such systems were used in clinical research,[70,71] but the most significant abnormality visible in the axial plane, levator avulsion, was overlooked. In consequence, results of such studies were published only 10 years later,[72] well after the "rediscovery" of levator trauma by translabial 3D imaging.

Clearly, the translabial use of abdominal 4D probes has major advantages over endosonography, even if resolutions are potentially lower. A single volume obtained at rest with an acquisition angle of 70° or higher will include the entire levator hiatus with symphysis pubis, urethra, paravaginal tissues, the vagina, anorectum, and puborectalis muscle, from the pelvic sidewall in the area of the arcus tendineus of the levator ani to

FIGURE 12
Right-sided avulsion of the puborectalis muscle



Delivery-related levator trauma as seen on exploration of large vaginal tear after vaginal delivery (*left*), as imaged on translabial 4-dimensional ultrasound (*middle*), and on magnetic resonance (MR) (*right*).

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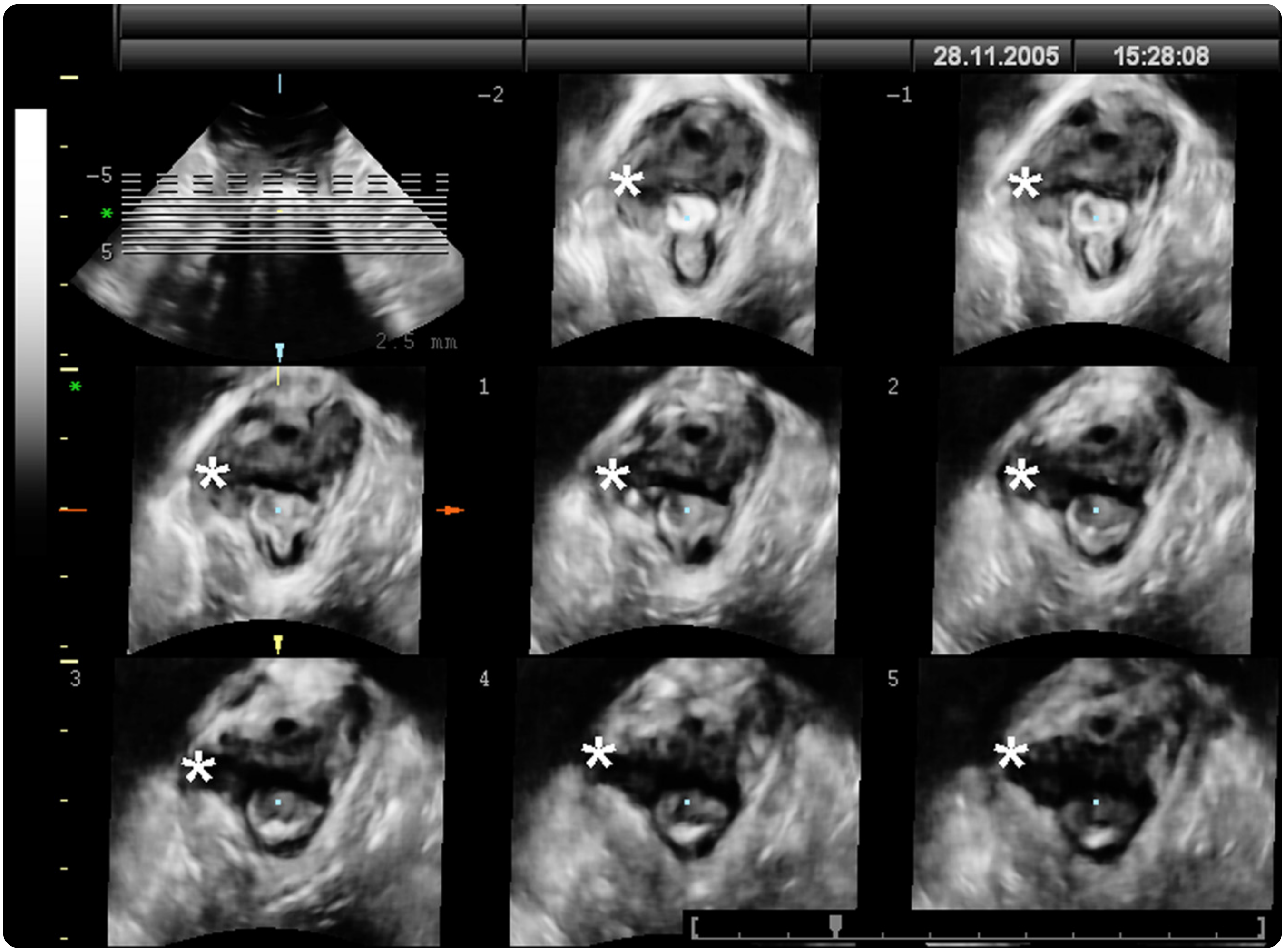
FIGURE 13
Quantification of trauma on multislice/tomographic ultrasound imaging



Typical right-sided levator defect (*) measuring about 2 cm in (dorsoventral) width and at least 1.75 cm in (craniocaudal) depth as it is apparent in all 8 slices.

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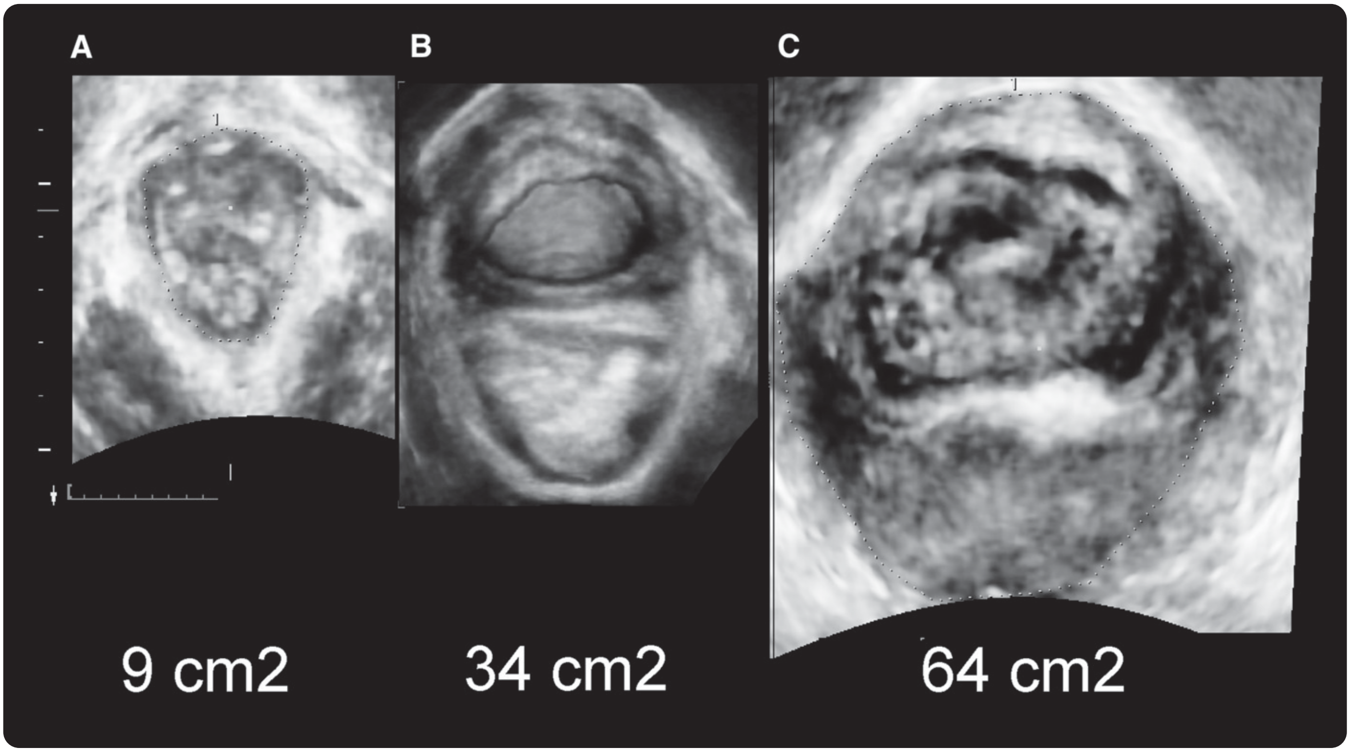
the posterior aspect of the anorectal junction. A Valsalva maneuver, however, may result in lateral or posterior parts of the puborectalis being displaced outside the field of vision, especially in women with significant prolapse. For this reason higher acquisition angles of 80° or 85° are preferable in pelvic floor imaging. Further technical details on volume data acquisition are available in a recent review article.[73]

Display modes

Figure 2 demonstrates the 2 basic display modes on 3D pelvic floor ultrasound. The orthogonal display mode shows cross-sectional planes through the volume in question, each plane at right angles to the 2 others. For pelvic floor imaging, this means the midsagittal, the coronal, and the axial plane. Contrary to the situation on MR, imaging planes on 3D ultrasound can be varied in arbitrary fashion to enhance the visibility of a given anatomical structure, either in real time during the examination or offline at a later time. The levator ani, for example, usually requires an axial plane that is slightly tilted in a dorsocaudal to ventrocaudal direction, and the required tilt may change substantially with maneuvers. This is what makes it so difficult to obtain predictable axial planes on dynamic MR imaging (MRI), with a consequent reduction in accuracy.[74]

The 3 orthogonal images are complemented by a rendered image, ie, a semitransparent representation of all voxels in an arbitrarily definable region of interest. Figure 2 shows a standard rendered image of the levator hiatus, with the rendering direction set from caudally to cranially. The result is an image that corresponds to observing the patient's pelvic floor from below, that is, from the

FIGURE 14
The levator hiatus in the plane of minimal dimensions



Hiatal area measurements (**A**, normal narrow hiatus; **B**, moderate ballooning in parous patient; **C**, severe ballooning in patient with bilateral avulsion and 3 compartment prolapse) illustrating range of findings that may be obtained in women with symptoms of lower urinary tract dysfunction and pelvic organ prolapse.

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perspective of the examining clinician. In some instances, rendering greatly enhances the visibility of a given structure and helps patients and caregivers understand anatomic relationships much better (see Figure 7 for an orthogonal and rendered representation of a rectocele).

4D imaging

Four-dimensional, as opposed to 3D, imaging implies the real-time acquisition of volume ultrasound data, that is, a succession of volumes over time, not just a single volume. Typically, modern systems acquire anywhere between 0.5-20 volumes per second, depending on acquisition angle and quality settings. For pelvic floor imaging, that is, with acquisition angles of 70-85°, 4 volumes per second can usually be achieved without compromising quality. The resulting cineloops of volume data are particularly useful for the evaluation of functional anatomy, that is, for observing morphologic changes during maneuvers such as a pelvic floor contraction or a Valsalva. Even on 2D single-plane imaging, a static assessment at rest gives little information compared with the evaluation of maneuvers to assess levator function and delineate levator or fascial trauma.

The ability to perform a real-time 3D (or 4D) assessment of pelvic floor structures makes pelvic floor ultrasound superior to MRI for this application. Prolapse assessment by MR requires ultrafast acquisition,[75] which is of limited availability and does not allow optimal resolutions. Alternatively, some systems allow imaging of the sitting or erect patient, but again accessibility will be limited for the foreseeable future. The sheer physical characteristics of MR equipment make it much harder for the operator to ensure efficient maneuvers as >50% of all women will not perform a proper pelvic floor contraction when asked,[76] and a Valsalva is often confounded by concomitant levator activation.[21] Without real-time imaging, it is impossible to control for these confounders. Therefore, ultrasound has major potential advantages when it comes to describing prolapse, especially when associated with fascial or muscular defects, and in terms of defining functional anatomy. In addition, the offline analysis packages marketed by manufacturers of such equipment allow distance, area, and volume measurements in any user-defined plane (oblique or orthogonal), which is much superior to what is currently possible with DICOM (Digital Imaging and Communications in Medicine) viewer software on a standard set of single-plane MRI.

Clinical applications

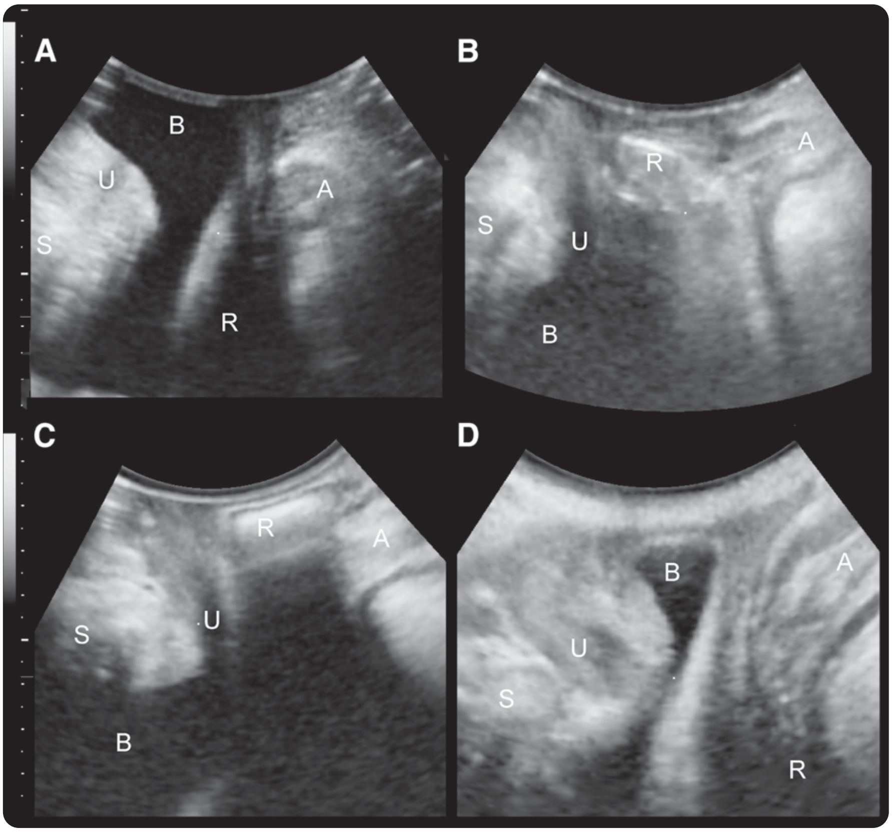
Axial-plane imaging is particularly suited to the assessment of the levator ani muscle, extending to paraurethral tissues in patients with diverticula or strictures. Translabial ultrasound has vindicated 60-year-old clinical data[77] and confirmed MRI studies[78] showing that major morphologic abnormalities of levator structure and function are common in vaginally parous women.[79] Although MR images showing morphologic abnormalities of the levator ani were usually considered to be the result of pudendal nerve trauma, this interpretation became untenable on considering findings on rendered volumes. Clearly, appearances (as in Figure 11) suggest trauma rather than atrophy, with the muscle completely removed from the pelvic sidewall.

It can now be regarded as proven that such morphologic abnormalities are usually due to traumatic avulsion of the muscle at the time of vaginal delivery (see Figure 12 for a comparison of MR, ultrasound, and clinical findings in patients with unilateral levator avulsion).[2,80] Such trauma can be documented on 2D ultrasound– either with a side-firing endocavitary probe[72] or with a parasagittal probe orientation.[81] However, the most convenient and reproducible approach is by using an abdominal 3D/4D probe–the technology that is used to image the face of a fetus in utero. Just as in that situation, a rendered volume, with the rendering direction set from distally to proximally, results in very graphic, impressive images, but for the reproducible diagnosis of levator trauma multislice or tomographic imaging (Figure 13) is preferred.[82,83]

Major delivery-related levator trauma, affecting the inferomedial aspects of the puborectalis muscle, seems to be part of the missing link between vaginal childbirth and prolapse. Although there are bound to be other factors, including microtrauma or altered biomechanics of otherwise intact muscle, and fascial trauma, levator avulsion enlarges the hiatus[84,85] and results in anterior and central compartment prolapse.[79,86] The larger the defect, the higher is the likelihood of prolapse,[83] as quantified on multislice or tomographic ultrasound (Figure 13). Levator defects seem to be associated with cystocele recurrence after anterior repair,[87] hysterectomy and antiincontinence and prolapse surgery[88] substantially increase the likelihood of anterior and central compartment prolapse,[86] and are associated with reduced contractile strength.[89,90] These defects are palpable, but palpation requires significant teaching[4,5] and is clearly less repeatable (kappa = 0.41)[91] than identification by ultrasound (kappa = 0.83 on analysis of whole volumes and kappa = 0.61 for single slices in own data).[82,92] There seems to be a high prevalence of levator defects in women with anal sphincter defects, which is not really surprising given the overlap in risk factors.[93,94] Bilateral defects are more difficult to detect because there is no normal side to compare with, but they have a particularly severe impact on pelvic floor function[85] and organ support.

Another factor only apparent on axial-plane imaging is the degree of hiatal distension on Valsalva. Figure 14 gives an impression of the range of hiatal area measurements in patients attending a pelvic floor clinic. Measures of hiatal dimensions seem highly repeatable[95-99] and correlate well with findings on MRI.[73] Hiatal enlargement to >25 cm^2 on Valsalva is defined as "ballooning" on the basis of receiver operator characteristic statistics and normative data in young nulliparous women.[95,100] It can

FIGURE 15
Surgical audit with translabial ultrasound



A and **B**, Patient with **A,** large cystocele who developed **B,** rectocele 6 months after successful Perigee anterior compartment mesh (which is invisible due to shadowing from air-filled rectocele). **C** and **D**, Patient with large rectocele (**C**, imaged here before full development of rectocele to improve visualization) who developed **D,** cystocele 6 months after successful defect-specific rectocele repair.

A, anal canal; *B*, bladder/cystocele; *R*, rectal ampulla/rectocele; *S*, symphysis pubis; *U*, urethra.

Dietz. Pelvic floor ultrasound: a review. Am J Obstet Gynecol 2010.

be measured in axial-plane slices at the plane of minimal hiatal dimensions or in rendered volumes, and because the hiatal plane is non-Euclidean (warped rather than flat), measurements obtained in rendered volumes may be more valid and more reproducible as well as easier to obtain.[101] The degree of distension is strongly associated with prolapse and symptoms of prolapse,[100] and both avulsion and ballooning seem to be independent risk factors.[102] It seems that ballooning is associated with prolapse recurrence after rectocele repair,[103] and the same probably holds for other forms of prolapse surgery.

If delivery-related trauma and excessive distensibility of the levator are indeed risk factors for female pelvic organ prolapse and recurrence after reconstructive surgery, then these conditions need to be diagnosed preoperatively, and in future we will have to adjust our surgical approach accordingly. Some forms of prolapse are probably impossible to cure surgically unless one uses mesh implants. We should aim to develop surgical methods that reduce the size and distensibility of the hiatus or reconnect the detached muscle in an attempt to prevent recurrence–and in 2009 this is no longer a hypothetical goal.[80,104] As always, proper diagnosis has to come before treatment, and ultrasound imaging is now an indispensable part of a complete preoperative workup.

Finally, but most important in clinical practice, another major advantage of the new technology is the ease with which preoperative and postoperative data can be compared using stored volume data sets and postprocessing software (see Figure 15 for a comparison of preoperative and postoperative findings in 2 patients with recurrent prolapse). This capability is already enhancing postoperative audit and our understanding of how certain procedures work (or do not work). In future it very likely will influence surgical development and teaching.

Conclusion

Even before the widespread introduction of 3D/4D imaging, pelvic floor ultrasound was a highly useful diagnostic tool for physicians dealing with pelvic floor disorders. As of 2009, this includes not just gynecologists, urologists, urogynecologists, and radiologists, but also colorectal surgeons and gastroenterologists. Current trends, ie, the near universal introduction of 4D ultrasound, new software options, and increasing availability of training, will likely lead to more general acceptance of ultrasound as a standard diagnostic option in pelvic floor medicine. The issue of levator trauma, one of the most significant developments in clinical obstetrics since the introduction of fetal monitoring, will take pelvic floor ultrasound from a niche application into the mainstream and speed the convergence of clinical specialties dealing with pelvic floor disorders. The crucial issue, as always, is teaching and the provision of up-to-date resources, and it may still be another decade or 2 before this method truly becomes a fully accepted part of the diagnostic workup in women with pelvic floor disorders.

For further information see my World Wide Web site at http://www.medfac.usyd.edu.au/people/academics/profiles/pdietz.php and the *Atlas of Pelvic Floor Ultrasound*.[105] ■

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Summary:

Responsive, reliable and valid measurement tools are important in assessing pelvic floor muscle function and strength. Visual observation and digital palpation are important methods in the clinic to assure that the patients are able to contract correctly and to give feedback of the contraction. However, these methods are not reliable enough for measurements of muscle strength or automatic responses. Pelvic floor muscle strength can be measured with manometers and dynamometers. Ultrasound and MRI can reliably measure muscle morphology during rest and contraction, and automatic responses to single task activities such as coughing and increases in intra-abdominal pressure.

Workshop 36: K.Bø: Measurement of pelvic floor muscle function and strength

The pelvic floor muscles (PFM) comprise the urogenital and pelvic diaphragm. It is a three-layer muscle group with several different muscles, all with different fiber directions. Hence, contracting single muscles of the pelvic floor would give different actions. However, any voluntary contraction is most probably a mass contraction with a combination of constriction around the pelvic openings and an inward lift. Dynamic MRI has demonstrated that there is a movement of the coccyx in a forward/ upward direction during contraction, meaning that this is a concentric contraction. During straining the coccyx is moved dorsally.

Several studies have shown that more than 30% of women are not able to contract the PFM correctly at their first consultation, even after thorough instruction. In addition, 49% are performing a contraction that has no effect on the urethra. An effective PFM contraction lifts the levator plate inside the pelvis, decreases the levator hiatus and constricts the pelvic openings, increases the urethral pressure, and it may stop decent of the urethra during increase in intra-abdominal pressure. In order to perform a strong and quick contraction, the PFM must be well positioned and have sufficient thickness (muscle volume/cross sectional area). A voluntary contraction before and during physical exertions such as coughing and sneezing can be learned, and can prevent urinary leakage and decent of internal organs. However, in healthy continent women, the PFM contraction is an antecipatory and automatic response. Voluntary contractions can be used during single bouts of physical exertion e.g to prevent leakage during coughing or lifting. The aim of PFM training is to build up the muscle morphology and function to the point where an automatic response/co-contraction with increase in intra-abdominal pressure is possible.

Assessment of PFM anatomy, function and strength is import to:
*be sure that the patient is contracting correctly and to be able to give feedback of performance to the patient
*control that the training is effective, as untrained muscles will improve in muscle strength if the dosage is high enough, the patient adhere to the protocol and the measurement tool is responsive, reliable and valid

PFM strength is a proxy for possible morphological and neurological adaptations following muscle training such as: increased cross sectional area (thickness), lift of the levator plate, narrowing of the hiatus, stiffness of the connective tissue in and around the muscles, increased recruitment of total number of activated motor units, increased frequency of exitation, increased synchronization of motor units, decreased activation of antagonists and coordination of all motor units involved in the function, possibly leading to an automatic response.

Different measurement methods can be used to assess PFM voluntary function and strength. In clinical practice visual observation of perineal movement and vaginal (rectal in men) palpation is often used to evaluate PFM function or ability to contract. (squeeze and lift). Dynamic MRI and ultrasound can also be used for this purpose, and because of cost and ability to measure in a standing position ultrasound may be considered the gold standard method as it visualizes the actual contraction as it occurs inside the pelvis. Several palpation protocols are available. However, palpation and visual observation may be considered too subjective, and too have too low responsiveness for scientific purpose of measuring muscle strength. Visible observation and palpation of automatic function, eg during cough is questionable from a scientific point of view.

PFM strength can be measured with urethral, vaginal or rectal pressures. However, any increase in intra-abdominal pressure may increase pressure. Therefore to ensure correct contraction (inward lift and not straining downward) simultaneous observation of inward movement of the perineum or catheter is necessary. Urethral pressure measurement may be the most valid method. Because of risk of infections, vaginal squeeze pressure is the most commonly used method in clinical practice. Several studies have shown that measurement of vaginal squeeze pressure has good intra- and interrater reliability. Dynamometers measure force directly, and has also shown to be reliable. However, they too are flawed with other muscle (abdominal, gluteal and hip adductors) activities influencing the measurements. EMG measures muscle activation and not strength. Surface EMG has shown to give reproducible results, but it may not be valid due to the likelihood for cross-talks from other muscle groups, especially during other activities such as walking and coughing.

MRI and ultrasound are newer methods with great potentials for increasing our understanding of PFM anatomy and function. These methods can reliably measure muscle thickness, length of the muscle, location of the PFM inside the pelvis and levator hiatus dimensions. A recent single blinded RCT investigating morphological changes after PFM training has found a statistically significant difference between the PFM training group and control in:

*muscle thickness: ↑ 15.6%, 1.9 mm (95% CI: 1.1-2.7)

*LH area: ↓ 6.3%, 1.8 cm^2 (95% CI: 0.4-3.1)

*muscle length: ↓ 4.2%, 6.1 mm (95% CI: 1.5-10.7)

*position of bladder neck: ↑ 4.3 mm (95% CI: 2.1-6.5)

*position of rectal ampulla: ↑ 6.7 mm (95% CI: 2.2-11.8)

Hence PFMT can positively change some of the possible patophysiological factors causing FM disorders. There is a positive and strong correlation between muscle strength and muscle thickness.

The challenge of measurement of PFM function is the assessment of automatic function during different activities. So far, we do not have reliable and valid measurement tools for this purpose. To date, standing ultrasound and ambulatory urodynamcis are options that may be further explored.

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Dynamics of female pelvic floor function using urodynamics, ultrasound and Magnetic Resonance Imaging (MRI)

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ABSTRACT

In this review the diagnostic potential of evaluating female pelvic floor muscle (PFM) function using magnetic and ultrasound imaging in the context of urodynamic observations is considered in terms of determining the mechanisms of urinary continence. A new approach is used to consider the dynamics of PFM activity by introducing new parameters derived from imaging. Novel image-processing techniques are applied to illustrate the static anatomy and dynamics of PFM function of stress incontinent women pre- and post-operatively as compared to asymptomatic subjects. Function was evaluated from the dynamics of organ displacement produced during voluntary and reflex activation. Technical innovations include the use of ultrasound analysis for movement of structures during maneuvers that are associated with external stimuli. Enabling this approach is the development of criteria and fresh and unique parameters that define the kinematics of PFM function. Principal among these parameters, are displacement, velocity, acceleration and the trajectory of pelvic floor landmarks. To accomplish this objective, movement detection, including motion tracking algorithms and segmentation algorithms were developed to derive new parameters of trajectory, displacement, velocity and acceleration, and strain of pelvic structures during different maneuvers. Results highlight the importance of timing the movement and deformation to fast and stressful maneuvers, which are important for understanding the neuromuscular control and function of PFM. Furthermore, observations suggest that timing of responses is a significant factor separating the continent from the incontinent subjects.

1. Introduction

Anatomically, the pelvic floor (PF) contains many visceral organs having diverse functions ranging from: urination, defecation, ejaculation, orgasm, conception, labor and parturition. These multiple organ systems interact and coordinate with each other in performing their normal physiological function. Under certain conditions, these functions are subject to disruption, manifesting as incontinence: sexual dysfunction, pain or any of a spectrum of complex symptoms whose origin may or may not be readily identifiable. In this context, pelvic floor dysfunction (PFD) constitutes a global burden affecting the quality of life of the individual, their family and society in general. Clearly within the general categorization of PFD, there is broad spectrum of symptoms having diverse origins. In women, because of the magnitude of the problem, a great deal of attention has been placed on the implication of PF function as it relates to urinary incontinence (UI) and stress urinary incontinence (SUI) involving the involuntary leakage of urine on coughing, sneezing, exertion or effort to the extent that it has been termed by DeLancey to be a hidden epidemic [1]. As a consequence, diagnostic methodologies under the umbrella of urodynamic testing evolved to address the epidemic. However, as with urodynamic testing there is an analogous endeavor to formalize and systematize the evaluation of the function of PFM. Evidently the technical requirements of PF dynamics technology are complex and challenging requiring a contextual approach and the least possible invasive means. In current practice, imaging and manual muscle testing per vagina or rectum is the technique used by most clinicians to evaluate the PF muscles. Unfortunately due to the location of the PF muscles defining its normal function in a non-invasive way is clinically and technically challenging.

2. Basic considerations

The PF is a complex 3D arrangement of muscle and connective tissue, attached to the bony pelvis. The PF is a collective name for the levator ani and ischiococcygeus. The levator ani muscle consists of the pubococcygeus, the puborectalis, and the iliococcygeus muscles. The pubococcygeus and the puborectalis muscles form a U-shape as they originate from the pubic bone on either side

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of the midline and pass behind the rectum to form a sling. The iliococcygeus muscle arises laterally from the arcus tendineus levator ani and forms a horizontal sheet that spans the opening in the posterior region of the pelvis, thereby providing a ‘‘shelf’’ upon which the pelvic organs rest [2]. The muscles and fascias of the pelvic diaphragm are inserted on the ischial spines either directly or indirectly through the sacrospinous ligament and the tendinous arch of the pelvic fascia. The result of a PFM contraction is a medial pull on the ischial spines to produce a more rigid and narrower pelvic floor [3].

Various diagnostic approaches have been applied to evaluate PFM function directly or indirectly and assess their dynamic properties, contractility and tissue quality and strength using palpation, visual observation, electromyography, dynamometers, ultrasound and MRI. Compared collectively, each tool has its own qualities and limitations [4]. Most recently, using a reliable instrumented speculum, incontinent women demonstrated lower values in passive force, endurance and speed of contraction than continent women, however, differences between the two groups for maximal force reached the statistically significant level only in the endurance parameter [5]. PFM strengthening exercises do diminish the symptoms of SUI [6,7]. Little research has focused upon the mechanisms of therapeutic change to help identify the specific critical muscle components of manipulation [8] so it is unknown whether PFM manipulation mimics the normal physiological behavior of the PFM or is an compensation strategy, nor whether program awareness is indeed the most efficient method of conservative rehabilitation. It seems appropriate to determine whether other properties of muscle function generated from imaging are also important in defining PFM function and dysfunction, as well as gaining a greater understanding of why PFM manipulation is effective in some cases and not in others. A useful approach to understand the mechanisms involved can be made by considering the relative effect of PFM activation on the urethra under involuntary reflex conditions as well as during volitional or anticipatory contractions. Fig. 1 illustrates the anatomical as well as functional changes taking place during PFM contraction.

As indicated by Fig. 1, voluntary PFM contraction elevates the bladder and acts upon the urethra U thereby generating an increase in closure pressures above the resting pressure. The increase in pressure is not uniform and depends on the position along the length of the urethra producing a pressure gradient and closure. Clinically while the increase in the closure pressures produced can be felt during pelvic examination through the vagina Fig. 1b shows that the urethra is also squeezed synchronously with the PFM contraction. Clearly active PFM contraction pressures are superimposed above the resting vaginal and urethral closure given that neither structure can be considered as passive. Distinction between the relative influence of vagina and urethral can only be made if vaginal closure is measured at rest as well as during PFM contraction. Enabled by a probe system [12], the closure forces at various locations in the vagina were measured. Using this probe, a resting vaginal pressure profile VPP was characterized and Fig. 2 illustrates the distribution of closure along the length of the vagina.

In measuring the vaginal pressures with a probe, it is appropriate to consider that there is mechanical deformation of the tissues involved and consequently values obtained in the anterior as compared to the posterior require adjustment [13]. Nonetheless the VPP has provided clinically useful information in delineating the distribution of forces along the length of the vagina in continent as well as in SUI subjects [14]. Indeed the VPP, as illustrated by Fig. 2, may be considered analogous to the urethral pressure profile UPP given that the urethra is cradled by the vaginal for a considerable region of its length.

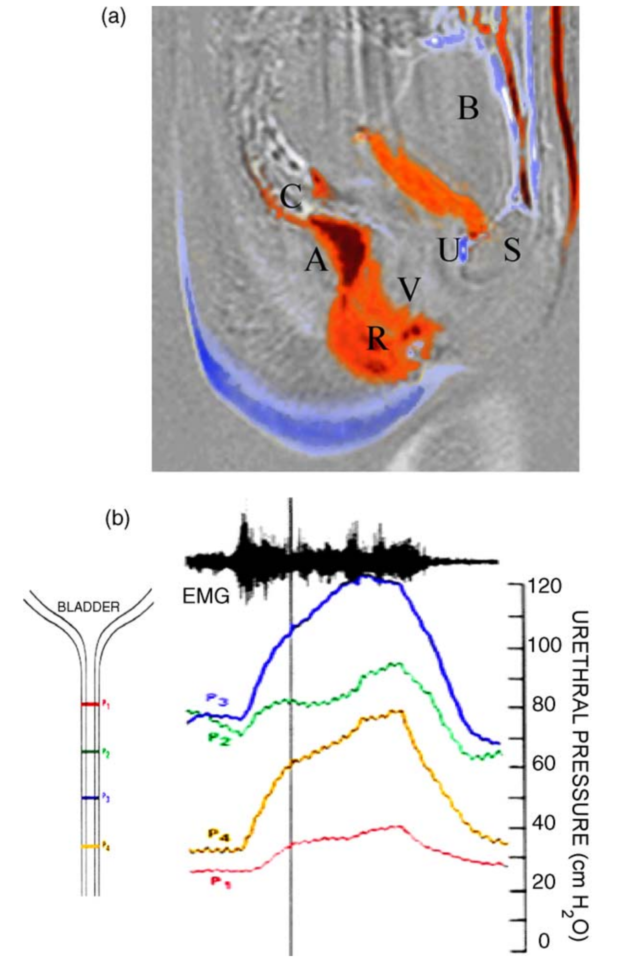

Fig. 1. Subtraction MRI image showing (a) the differences between resting and contracting pelvic floor muscles [9,10] where: A: anorectal junction, B: bladder, S: symphysis pubis, R: rectum, U: urethra and V: vagina. Red denotes region where contraction compresses while blue where it is vacated. Fig. (b) illustrates the changes in urethra pressures all measured simultaneously at different regions using the approach described in [11]. Urethral pressure rise U is shown by Fig. 1b to be generated over and above the resting pressures P1–P4. As shown by the schematic diagram associated with Fig. 1b P1 defines the pressure at the base of the bladder, having the lowest baseline pressure while P2 P3 and P4 are located 7 mm apart towards the urethral sphincter and meatus. Fig. 1b clearly shows that the maximum increase in urethral pressure from baseline can be localized at a region distal sphincter. The electromyogram shown at the top obtained with co-axial needle electrodes of the anal sphincter, is characteristic of a sustained voluntary contraction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

3. Imaging/urodynamics studies

As demonstrated by Fig. 1, voluntary PFM contractions can be readily viewed using MRI primarily because the contraction can be sustained for a sufficiently long time, 10–15 s to acquire the image. Thus as indicated by imaging studies using ultrasound or MRI a voluntary contraction of the PFM changes the anorectal angle (ARA) [15] and can displace the urethra in a direction towards the pubic symphysis [11,16–19]. Yet PFM contraction in some women increase the intra-urethral pressure, but not in others [20]. It is known that in women there is recruitment of PFM motor units [21,22] and an increase in intra-urethral pressure [23] prior to an increase in intra-abdominal pressure during a stress. Two hypothetical questions then arise: Is the contractile force of the PFM as applied to the urethra diminished or the timing of urethra closure in SUI slow in responding? To clarify these questions, it is appropriate to consider the available evidence, in terms of clinical

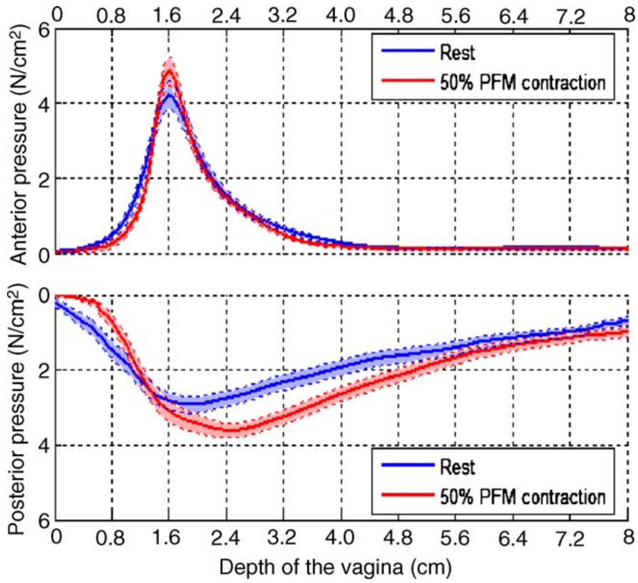

Fig. 2. Vaginal pressure profile measured with a vaginal probe at rest (blue) and also during sustained voluntary PFM contraction. As indicated anterior pressures are higher than the posterior values while spread of the pressurized zone in the posterior is higher. [13,14]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

conditions, where urethral response to the cough reflex was evaluated.

As indicated by Fig. 3a the pressure rise in the urethra compared to that of the ratio between the elevation in urethral pressure $\Delta U/\Delta B$ of continent subjects varies by region. The position of maximum transmission is located distal to the external sphincter and is higher than 100% suggesting that an external force elevates the bladder and acts upon the urethral lumen. In SUI subjects, transmission is less than 100% suggesting that the external forces acting on the urethra are attenuated. Such attenuation may be considered to be due to weaker PFM muscles or the anatomical position of urethral lumen is such that the PFM are not effective. However, the evidence provided from postoperative urodynamic studies of SUI subjects immediately after endoscopic bladder neck demonstrates that pressure transmission is restored immediately (3–4 days) after surgery. Assuming that there is no significant PFM strengthening during this brief time period, it is evident that increased transmission can be accounted by the anatomical reorganization produced by the surgical procedure.

In view of these observations, the question arises as to the importance of timing of the PFM contraction relative to the cough reflex. Altered PFM activation patterns during a cough, enabled by anal electromyography measurements in SUI compared to healthy volunteers have also been reported, [22] as having with shorter activation periods suggesting that the duration of activity may be critical. These observations may be viewed in the context that PFM are involved in generating intra-abdominal pressure given that respiration and incontinence have a strong correlation [24,25]. Furthermore, in studies of continent women, co-activation was observed, suggesting the need to evaluate multiple PFM responses occurring at a relatively fast rate (<0.1 s) [26]. In addition to address the need to examine the response of multiple PFM and their influence during activation, it is essential to use the least invasive imaging methods, providing good temporal resolution. Fortunately, developments in two dimensional (2D) ultrasound imaging and three dimensional (3D) real time reconstructions technology, associated with frame-by-frame software analysis are a valuable tool to explore the dynamics of the PFMs to facilitate a better understanding of the mechanisms of continence.

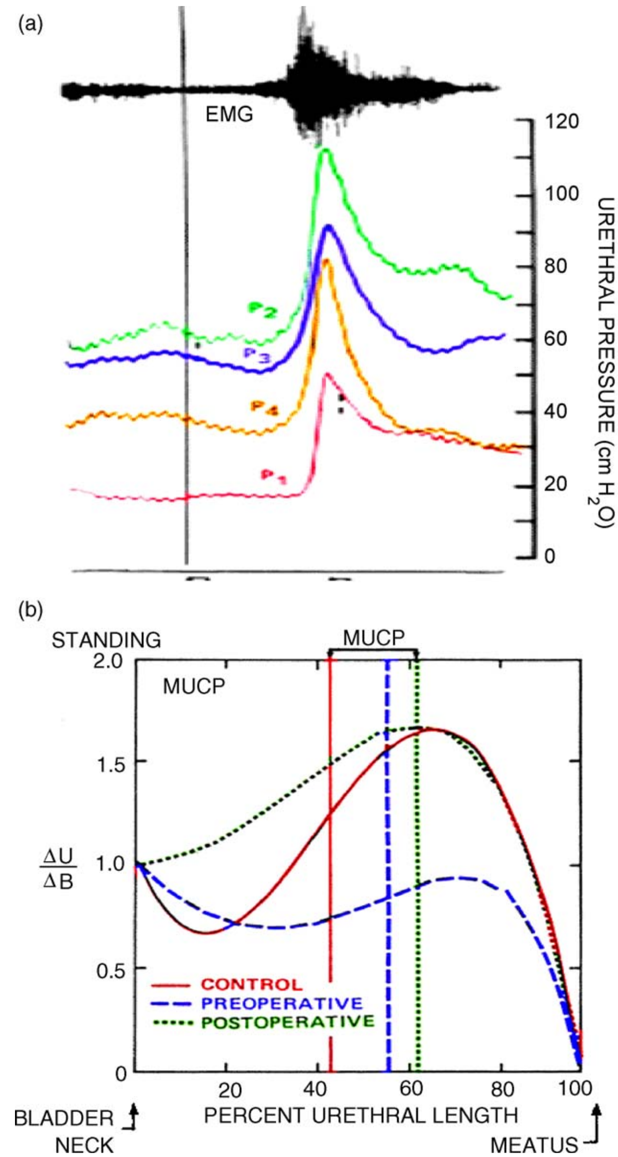

Fig. 3. (a) Clinical data illustrating typical recordings, of urethral pressure distribution along four regions of the urethra associated with a cough using the methodology illustrated by Fig. 1b. The electromyogram shown at the top, is characteristic to that of a short duration cough reflex response. (b) Illustrates measurements designed specifically to provide clinical evidence by evaluating the differences between continent subjects and those who present with SUI and are scheduled for surgery. Vertical axis is given as the ratio of the incremental rise of urethral pressures to that of the bladder. This ratio was used in order to normalize the variability between different intensity of coughs and resting pressures. By taking the ratio of bladder pressure rise to urethral pressure rise a more accurate quotient of the relative response can thus be generated. Similarly, the units of the horizontal axis are given as a % of urethral length in order to normalize the individual variations of the urethra. Data to generate these curves were obtained from asymptomatic volunteers and patients presenting with stress urinary incontinence pre-operatively, tested post bladder neck suspension using the Stamey procedure. Details of the methodology and clinical criteria can be found in [23].

4. Dynamics of 2D and 3D ultrasound imaging

In analogy to cardiac imaging, 2D transperineal ultrasound imaging can acquire dynamic information on the morphology of the urogenital organs. In particular, perineal, introital and trans-vaginal ultrasound has become an imaging platform for the evaluation of the PF and for the treatment planning of many uro-gynecological conditions [4,18,27]. By its nature, 2D ultrasound imaging provides a very large amount of dynamic data that cannot be visually assimilated by the observer in its totality, particularly during fast occurring reflex events. Such dynamic events contain information relating to the integrity of the supporting structures of the bladder neck, the role of the PFM, and the compliance of pelvic floor structures [28] to deform. Furthermore, because the urogenital structures are anatomically interconnected, ultrasound-based dynamic imaging can substantiate the findings of urodynamic observations of the effective spatial and temporal distribution and timing of pressure transmission to the urethra [11,23,28]. State-of-the-art 3D ultrasound imaging techniques provide 3D visualization of the pelvic floor structures with higher resolution. However, current 3D ultrasound technology is not swift enough for the purpose of visualization of the movement of tissues in fast and stressful maneuvers like coughing, which may provoke urinary incontinence.

Until recently, real time ultrasound imaging, containing the diagnostically important information of the dynamic response of the PF such as coughing occur at such high speed, that all anatomical movements cannot be assimilated and quantified by the observer during the scanning process. The direction and the timings of the movement of the PF tissues, which may be more important than the amplitudes in the mechanism of female urinary continence, are usually missed and sometimes ignored. Clinical measurements of 2D ultrasound images can only tell us about the resting position of the urethra and the displacement at the end of events such as Valsalva, voluntary PFM contraction and coughing. [18,28,29]. The difficulties with accurately determining the finishing point of any swift maneuver, are numerous and are a potential source of error [30]. The operator has had to either make multiple on-screen measurements, or determine the exact peak moment, or end position of the maneuver, visually freeze it on the screen, and then measure the change in position manually on screen or with in-built electronic calipers. Without correcting for probe movement relative to the pubis symphysis the percentage errors range from 18 to 87% [31,32]. Clearly in order to define normal PFM function it is essential to capture and visualize the sequence of dynamic changes the PFM produced on the urethra, vagina and rectum using digital image-processing methods. To determine the deviation from normal function it is useful to target the evaluation of asymptomatic volunteers and to develop a number of functional parameters to facilitate comparison with those with SUI.

5. Trans-perineal ultrasound imaging

Visual examination of the ultrasound images suggested that the displacement of the PF tissues during maneuvers contains components that can best be defined as a ventral (anterior) component towards or dorsal (posterior) component away from the symphysis pubis and a cephalad (superior) component upwards or caudad (inferior) component downwards. This is supported by other studies that suggest that in a functional PFM contraction, the bladder neck has been shown by Miller et al. to move in a ventro-cephlad direction [17] increasing the closure pressure within the urethra as it is displaced towards the symphysis pubis [20] and during Valsalva, as the intra-abdominal pressure increases, the bladder neck moves in an dorsal-caudad direction [29].

Practical details of the ultrasound scanning system and approach are given by Peng and Jones. [27] Briefly, the approach taken is to outline the symphysis, urethra and rectum interfaces on a frame-by-frame basis for sequences of stress inducing events such a cough, Valsalva and voluntarily induced PFM contractions. During each event, the trajectory of the boundary of each structure was identified to characterize the sequential history of the ensuing movement. The resulting image analysis focused to reveal the anatomical displacement of the urogenital structures and to enable the evaluation of their biomechanical parameters in terms of displacement.

Fig. 4a shows that the two axes of the coordinate system are parallel and vertical to the urethra at rest, respectively, which is fixed during the maneuver, so when the subject deforms the bladder (From State1 to State2), the coordinate system will maintain its original position and the ensuing measurements can be made relative to this fixed axis. Visual examination of the ultrasound images suggested that the displacement of the PF tissues during maneuvers contains components that can best be defined as a ventral (anterior) component towards or dorsal (posterior) component away from the symphysis pubis and a cephalad (superior) component upwards or caudad (inferior) component downwards. Such movements are supported by other studies that suggest that in a functional PFM contraction. Evidently the transition from State1 to State2, as illustrated by Fig. 4a, represents highly simplified characterization of PF dynamics. In our preliminary studies we were able to map the trajectory of the bladder, urethra and ARA and define the physical characteristics associated with the neuromuscular activation of the PF. Thus, the transition from State1 to State2 shown by Fig. 1a occurs relatively fast and translates into a sequence of overlapping frames separated in time. A convenient visualization of these frames, is illustrated by Fig. 4b and c. In these figures the temporal/spatial transition was color coded to facilitate identification of the path taken by the bladder and anorectal when the PF is activated. Thus the timing of the movement of tissues in pelvic floor during a typical PFM contraction in the same volunteer can be visualized so that when the volunteer contracts her PFM, (Fig. 4b) the urogenic structures move in a ventral-cephlad direction (forward and up). As she releases the contraction, or relaxes the PFM (Fig. 4c) the tissues return to the original resting position.

Intuitively the direction of movement in a Valsalva is in the opposite direction compared to the PFM contraction illustrated by Fig. 4. Thus, Fig. 5a shows the timing of the movement of tissues in pelvic floor during a typical Valsalva. As the volunteer performs this forced expiration technique, the urogenic structures move from their resting position in a dorsal-caudal direction (down and back) before returning to their resting position as the volunteer completes the maneuver.

6. Motion tracking

Fig. 4 demonstrates that the influence of PFM contraction can be identified and the outlines of structures are now amenable to analysis that can form the foundation of PFM dynamics. As such, we are enabled to be further parameterize and generate values that potentially can characterize the dynamics of PFM. A readily visible, clearly resolved anatomical structure in perineal ultrasound imaging is the angle the rectal ampulla forms with the anal canal, the (ARA). The movement of ARA can be used to analyze the PFM function because the sling of the PFM or levator ani muscles wrap around the anorectal junction, and its displacement is closely associated with a PFM contraction [7,15]. The utility of motion tracking of the ARA from perineal ultrasonography was demonstrated by Peng et al. in 2008 using data obtained from 22 asymptomatic females and 9 SUI subjects with a broad age distribution and parity. Fig. 6 illustrates the differences between continent and incontinent women in the magnitude and ventral-dorsal and cranio-caudal displacement during a cough. As clearly indicated by Fig. 6, both the direction and temporal sequence of the ARA movement are distinctly different between the continent and incontinent women. During a cough, in continent women the ARA moves ventrally towards the SP. In incontinent women the ARA moves dorsally away from the symphysis. Furthermore, the amplitude of the maximum caudal movement of the incontinent

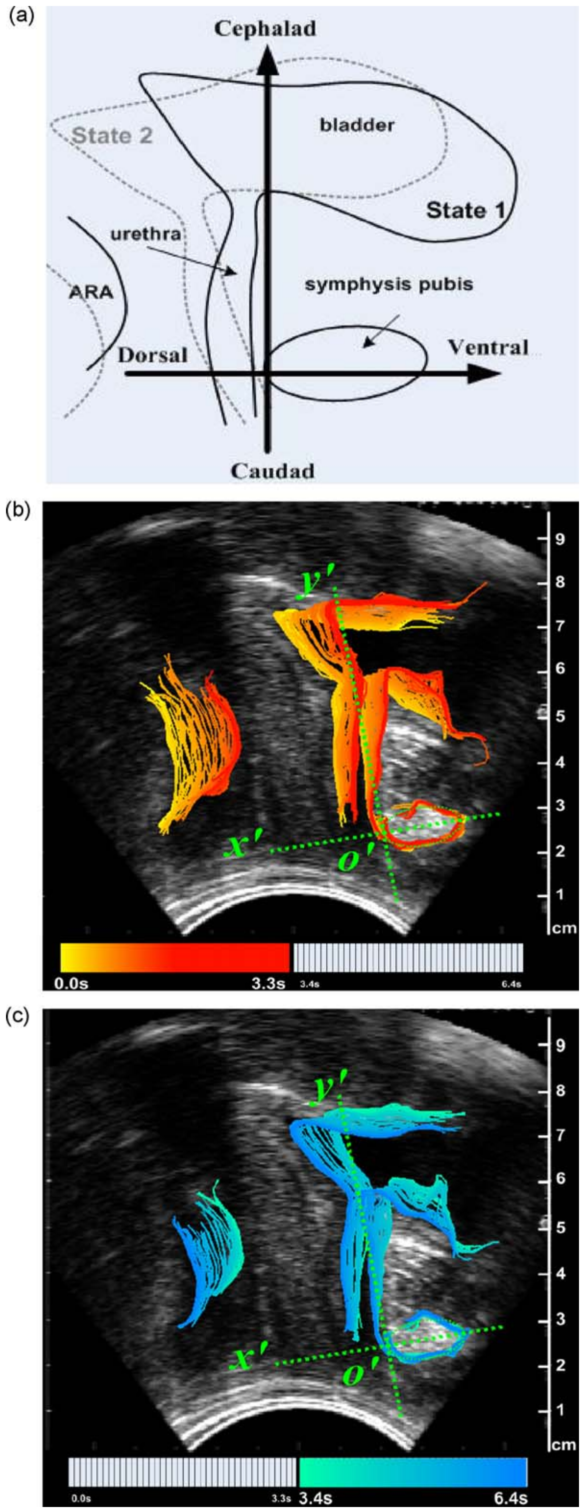

Fig. 4. (a) Schematic of the localization system fixed on the symphysis pubis illustrating the two axis (ventral-dorsal and cephalad-caudad) of displacements reflects PFM functions of squeezing the urethra and supporting the bladder, respectively. (b) Corresponding timing of the movement of tissues in pelvic floor during the onset of a typical PFM contraction of an asymptomatic volunteer. (c) Timing of the relaxation of PFM to original position. Sequence takes approximately 6.4 s. Adapted from [33].

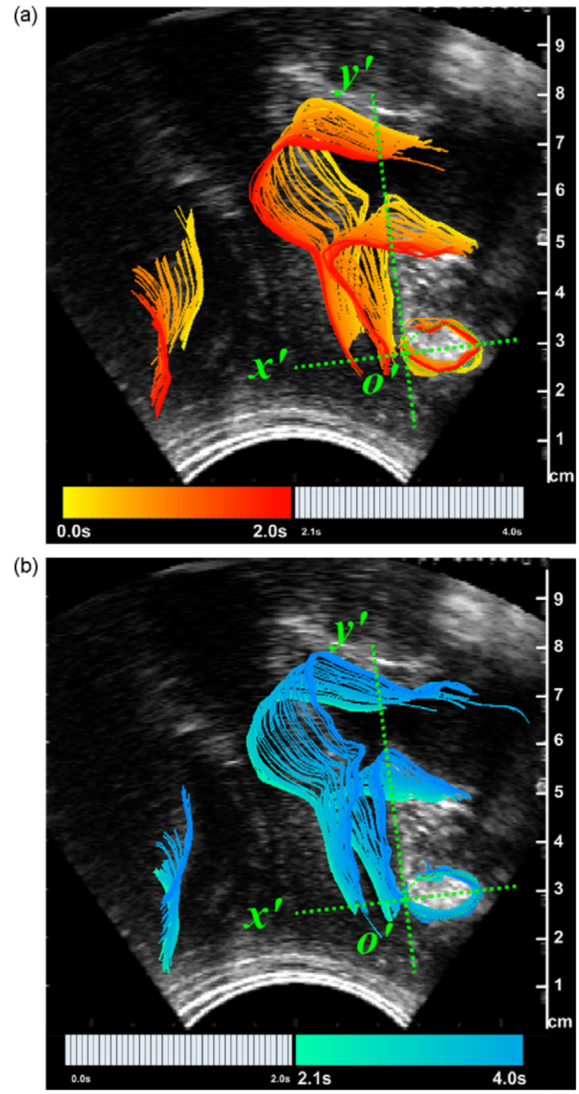

Fig. 5. Displacement of ARA consequent to a 4 s Valsalva sequence. (a) Onset of Valsalva showing the downward movement for the 2 s. (b) Termination of Valsalva showing the restoration of outlined structures to their original state. Adapted from [33].

women' ARA and urethrovesical junction are significantly larger than those of the continent women.

Fig. 6 summarizes the parameters generated from imaging of asymptomatic and SUI subjects. On the strength of these studies outlined above, we suggest that by using non-invasive ultrasound imaging, we can translate our methodology from the evaluation of the PF of asymptomatic and incontinent subjects to include a generalized assessment of pelvic floor dysfunction. In deriving physiological values from the imaging procedures it is now possible to make comparisons between different dysfunctional conditions using new parameters in a statistically robust way. As Fig. 6 shows, the biomechanical and timing parameters generated as a result of reflex contractions can be calculated where the internal displacement produced and associated biomechanical strain in structures contained by PFM can generate the basis of a model, a mechanical model. One important parameter of relevance is muscle strain ε and strain rate was evaluated by Rahmanian et al using data from the displacement measurements shown by Fig. 6 [33]. The biomechanical results comparing of maximun strain of the PFM in healthy and SUI women show that strain as a parameter is significantly different between the two groups—0.088 $\pm$ 0.007 via 0.041 $\pm$ 0.002. Furthermore, consideration of strain rate during reflex contraction shows that the maximum strain rate in incontinent women is significantly higher than that of continent subjects, incontinent women having a strain rate that is 716.4 $\pm$ 73.3% higher than in controls. Clearly, dynamic

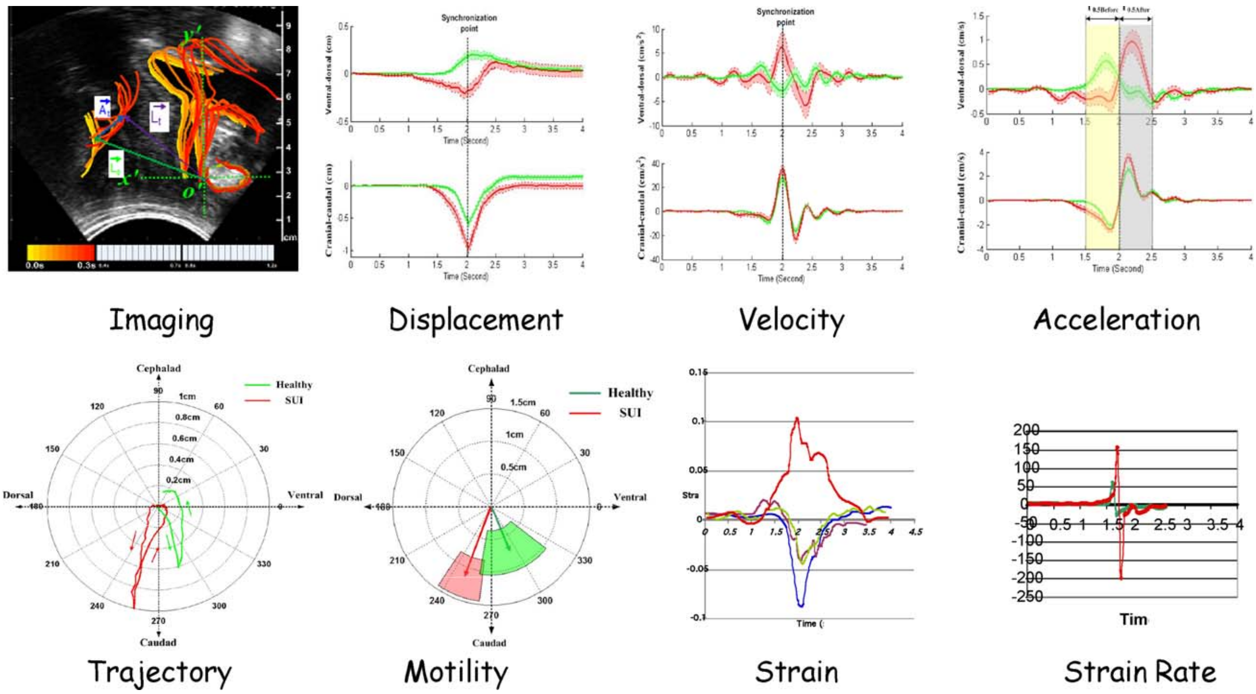

Fig. 6. Characteristic patterns of quantitative data generated by processing and analyzing the response of the pelvic floor. Data generated from the evaluation of assymptomatic and SUI subjects investigated and have been reported by [27,33].

visualization of the PFM studies provides an abundance of functional information that occurs so swiftly that it cannot be captured by the observer let alone be quantified. In particular reflex phenomena, the guarding reflex in this case, incorporates multiple physiological processes whose timing and convergence cannot be simultaneously assimilated by the visual observation of images alone. It is therefore essential to process dynamic sequences of image in order to derive obtainable physical parameters. Inevitably in using the term "strain" a number of limitations and assumptions are made that are inherent to the derivation of geometrical parameters from imaging. Principal among these is that the pelvic floor muscle is lined up parallel to the plane of the image, deformation takes place along the defined attachment points, and the reference lengths need to be determined in a geometrically correct alignment. Practically it is important to be aware of these assumptions are appropriate to keep in mind that these could and could vary. Thus, in considering the analysis and interpretation of our results it would be more accurate to describe the data as relative displacements between two anatomical landmarks rather than specific strain measurements of pelvic floor muscle. It is also important to be vigilant in documenting differences in the "resting position" and consider the magnitude and consistency of these limitations. In our current analysis we are attempting to overcome these limitations by examining the differences in displacements made between maximum contractions which is a forward/upward movement in association with the Valsalva which is a downward/backward movement. Using the fixed reference of the suprapubic line (SP) we are interpolating the "apparent resting position" as the basis in motion tracking.

In summary we quantitatively demonstrated some of the characteristic responses of cough induced contractions on urethral closure using urodynamics and imaging in relation to magnetic resonance and ultrasound imaging. In particular, evidence of these observations is provided from a more recent analysis using imaging the ARA response to the cough reflex as well as voluntary contractions of asymptomatic women. Evidence was provided to show that the status of continent and asymptomatic women could be clearly identified from those with incontinence on the basis of a number of parameters such as the displacement, velocity and acceleration of the ARA movement. Furthermore because these studies were obtained using the non-invasive nature of trans-perineal ultrasound, the value of the results is enhanced in the study of the population targeted by this application. As a consequence of the degree of the analytical treatment applied to the temporal sequence of the data, important aspects of the role of the PFM in general function gained may prove critical in identifying the physiological impact of the a variety of PF dysfunctions. As described, the data obtained by each maneuver will inevitably yield a large number of parameters that represent the neuromuscular characteristics of each individual subject, of a given disposition. It is encouraging that so much useful information can be generated from a test having the minimum of invasion and takes so little time to perform.

While quantitative measures, and analysis of the movement during PFM maneuver yielded new parameters of PF function, confidence is still required to validate the ultrasound approach with subjects having a broader age group and pathology. While visualization and analysis of PF activities using 2D ultrasound imaging is likely to develop further, new measures of the PFM functions that are more sensitive and specific than current methods should be pursued particularly with the availability of 3D ultrasound imaging. In this way more objective ways can be found to categorize different sub groups of patients within a particular pathology and determining the most appropriate treatment, intervention and its effects. Ultimately it would be fruitful to translate this approach to not only become a more widespread, non-invasive, time-saving and clinically validated methodology in the study of pelvic floor function defined above but also expand our knowledge in terms of parameters such as blood flow. To this end significant progress has already been reported by Noguti et al who have shown using doppler visualization that the vascularization of the levator ani decreases in an age dependent way [34]. Taking these observations into account it may be possible to explain some of the variations in the dynamic parameters observed in these in the context of blood flow.

It is expected that by understanding the processes and, the mechanisms involved in the functioning of the PF we can better identify more sensitive clinical diagnoses and have treatment outcomes in the management of incontinence. In the future, it is anticipated that as the imaging and urodynamic technology develops these techniques will be applicable to study other groups with PFD, such as prolapse, pelvic pain, vulvodynia and sexual dysfunction.

Condensation

This review considers the mechanisms involved in urinary continence as evaluated from urodynamic, ultrasound and imaging studies introducing new quantitative parameters.

Conflict of interest

No conflict of interest.

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