Clinical Note

Evaluation of the Female Urethra With Intraurethral Magnetic Resonance Imaging

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The purpose of this study was to demonstrate feasibility of intraurethral magnetic resonance imaging (MRI) for in vivo assessment of the female urethra and to determine the anatomy of the urethra and periurethral attachments as depicted using an endourethral MR coil. Twenty-three continent volunteers were studied with a 14F endourethral MR coil. Intraurethral MRI allowed detailed visualization and measurements of the muscular layers of the urethral sphincter and permitted the evaluation of supporting ligaments. This technique may become useful in the evaluation of anatomical defects associated with female urethral sphincter deficiency.

Key Words: female urethra; urethral sphincter; urethra anatomy; magnetic resonance; endourethral MR coil


THE ANATOMIC PROPERTIES of the urethral sphincter that promote continence are coaptation (mucosal seal, inner wall softness), compression (extracellular matrix, collagen, elastin, urethral smooth muscle, urethral striated muscle), periurethral support, and neural control (1). Coaptation and the status of the mucosa are best assessed with cystourethroscopy. Neural control can be assessed with sphincter electromyography. Evaluation of the urethral muscle and periurethral ligaments requires direct visualization. Traditionally, study of the urethra and its surrounding tissue has been possible with procedures that indirectly evaluate urethral structure and function, such as videourodynamic evaluation with urethral pressure measurements, lateral chain urethrocystography, or cystourethrography. However, direct visualization of the urethral wall can be performed with ultrasound and with magnetic resonance imaging (MRI).

Urethral pathology has previously been evaluated with MRI using a pelvic phased-array coil (2). Intracavitary MR coils, endovaginal (3–5) and endorectal (6), have subsequently allowed urethral MRI with both increased spatial resolution and high signal-to-noise ratio (SNR). With the advent of the endourethral coil, dedicated high-resolution MRI of the female urethra became possible (7,8). MRI of formalin-fixed and freshly harvested female human cadavers as well as in vivo animal experiments have recently shown the potential for endourethral imaging of the sphincter (7).

The purpose of this study was to evaluate a continent patient population to determine the anatomy of the normal female urethra as depicted using an endourethral MR coil and high-resolution MRI. Our hypothesis is that detailed definition of the female urethra when evaluated in vivo with intraurethral MRI will be useful to characterize underlying anatomic abnormalities in patients with urinary incontinence related to urethral hypermobility and intrinsic sphincter deficiency. Detailed demonstration of the morphology of the female urethra and periurethral attachments may contribute to the understanding of urinary incontinence, one of the most common conditions in a female population, which has severe economic and psychosocial impact.

MATERIALS AND METHODS

Patients

We evaluated 23 continent volunteers (age range = 23–56, mean = 42) recruited via advertisement. Volunteers had no history or symptoms of urinary incontinence. Informed consent, approved by our Institutional Review Board for Human Subjects Research, was obtained after the nature of the procedure had been fully explained.

Imaging Technique

MRI was performed using a 1.5-T MR imager (Signa LX, GE Medical Systems, Waukesha, WI) using the body coil as the transmit coil. The receive coil consisted of a disposable sterile 14F endourethral MR microcoil.

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Surgi-Vision, Inc., Gaithersburg, MD) (Fig. 1) coupled with the posterior and anterior surface coils (diameter/H11005 20 cm) using a phased-array adapter. The use of a phased-array adapter helped to combine the images acquired from all three coils into one combined image, as well as separate images using the saveinter mode.

The endourethral coil is comparable in size and shape to a conventional Foley catheter and was very well tolerated by the patients. The coil was inserted using a sterile technique and anesthetic gel. The coil tip was inserted into the bladder approximately 0.5–1.0 cm, and there were no complications from insertion. Patients were imaged in the supine position.

Diagnostic pulse sequences consisted of T2-weighted (T2W) fast spin echo (FSE) images in the axial, sagittal, and coronal planes. A multilayered appearance of the urethra can be seen on proton density and T2W axial images. However, although the proton density-weighted images reveal a markedly higher SNR, the soft tissues of the urethra are better demonstrated on the T2W images, also documented by Quick et al (7). Therefore, the diagnostic imaging of the urethra in our study was based on T2W images. Axial image parameters were TR = 3000–6300 msec, TE = 60–75 msec, NEX = 6–10, echo train length = 16–32, slice thickness = 2.5–3.0 mm, spacing = 0.5–2.0 mm, field of view (FOV) = 5–6 cm, slices = 5–8, average duration = 6:40. Sagittal and coronal acquisitions were T2W FSE with FOV = 6 cm, slice thickness = 2.5 mm, spacing = 0.5 mm, slices = 5, imaging time average = 4:30. The image matrix was 256 × 256 pixels.

Dynamic evaluation of the urethral mobility was performed in the sagittal plane with patients at rest and during straining. Patients were asked to strain to maximum, as if they were ready to evacuate. No control pressure measurements were performed during strain. Dynamic MRI was performed using a single-shot FSE pulse sequence with acquisition parameters TR = ×, TE = 60–70, NEX = 0.5, slice thickness = 3.0–4.0 mm, spacing = 1.0 mm, FOV = 10–12 cm, slices = 3, and imaging time = 0:06. The degree of urethral descent and rotation was assessed by measurement of the pubourethral angle, the angle between the main axis of the pubis and the long axis of the urethra.

Morphological Assessment

The entire urethra was imaged, from the bladder base to the external meatus. Four urethral levels were assessed: 1) internal urethral meatus and intramural urethra in the bladder neck, 2) midurethra, 3) urethra at the urogenital diaphragm, and 4) distal urethra to the level of external meatus. At the bladder neck level, the status of the internal meatus was assessed at rest and during strain. At the midurethra level, between the internal meatus and the urogenital diaphragm, we assessed the urethral wall signal characteristics, thickness of the striated and smooth muscle layers at the anterior, lateral, and posterior walls, and the sphincter area. At the level of the urogenital diaphragm, we evaluated the compressor muscle integrity and symmetry. The length of the urethral sphincter was measured on the coronal or sagittal plane, from the internal to external meatus. The images were reviewed on the Advantage Windows workstation (GE SUN Advantage Windows AW4.0_02, GE Medical Systems) magnified and windowed to optimize the contrast between muscular layers. The measurements of the urethral wall thickness, cross-sectional sphincter area, and urethral length were performed using the distance and area-measuring tool available on the workstation. An intensity correction algorithm (7) was applied to remove the near-field artifact and to increase the contrast between muscular layers.

Intra- and Interobserver Variability in Urethral Measurements

To evaluate the reproducibility of sphincter measurements, we assessed the intra- and interobserver variability in urethral wall thickness and length measurements. One reader (K.J.M.) examined the selected group of five volunteers three times (total of 318 measurements of the midurethra), with a one- to two-month interval between measurements. Two readers (K.J.M., T.L.B.) independently examined the same group of five volunteers (total of 159 measurements of the three segments of the midurethra—upper, mid, and lower). To

![Figure 1. 14F endourethral microcoil (top arrow). For comparison, 16F straight urethral catheter (bottom arrow).](image-url)
quantify the reproducibility of measurements of the urethra, we used the coefficient of variance. The intra- and interobserver agreement in measurements was assessed as a percentage of agreement between two readings for all measurements. We considered an agreement between two measurements if the difference between the results was less than or equal to one SD (SD was calculated for the entire normal population studied, 23 volunteers) for the particular segment of the urethra measured. We also calculated the correlation coefficient between intra- and interobserver measurements.

RESULTS

Intraurethral MRI Appearance of the Normal Female Urethra

Intraurethral MRI allowed for visualization of the four anatomic landmarks along the urethra according to a histologic study of urethral anatomy by De Lancey (9) (Fig. 2).

INTRAMURAL URETHRA

At the level of the bladder neck, the urethra passes through the wall of the bladder where the muscle fibers (low intensity on T2W imaging) of the detrusor extend as far as 20% of the urethral length below the internal urethral meatus (Fig. 2). At the termination of the detrusor fibers, the striated muscle that surrounds the urethra and vagina starts. At the bladder neck, the layer of smooth muscle is not present.

MIDURETHRA

In the axial plane, T2W images of the midurethra show a multilayered target appearance (Fig. 3). A narrow circumferential low-intensity layer around the coil represents submucosa, best seen on the intensity-corrected images where the near-field artifact is reduced (Fig. 3). The inner smooth muscle layer (10) shows high signal intensity. The smooth muscle layer is thickest at the midurethral level and on the ventral side of the urethra. The outer layer of low-intensity tissue encircling the smooth muscle represents striated sphincter muscle (rhabdosphincter). The striated urethral sphincter extends from 20% to about 60% of the urethra length. The striated muscle is thicker on the ventral and lateral sides of the urethra, and thinner on the dorsal side.

On the transverse sections, the target-like appearance of the urethra differs slightly at the upper, middle, and lower urethra segments (Fig. 3). The thickness of the smooth and striated muscle layers also differs along the urethra length, with upper and midsegments thicker than the lower segment (Table 1). In continent volunteers, at the upper urethra, the anterior and lateral sphincter walls were thicker than the posterior wall; the mean anterior cross-sectional thickness of the wall was 4.3 ± 0.9 mm and the striated muscle thickness was 2.3 ± 0.6 mm. The striated muscle was thicker than the smooth muscle anteriorly (the ratio of the striated to smooth muscle thickness was 1.2 ± 0.5) and became thinner than the smooth muscle laterally (ratio = 0.92 ± 0.4). There was further thinning of the striated muscle in the posterior wall, with the ratio of the striated to smooth muscle being 0.75 ± 0.3. The ratio of the area of the striated muscle to the area of the smooth muscle at the upper urethra was 1.05 ± 0.5. At the middle and lower segments of the urethra, similar proportions of muscles were seen, with the anterior and lateral sphincter walls thicker than the posterior wall, and the striated muscle layer thicker at the anterior
Figure 3. A 41-year-old continent woman. Axial FSE T2W images (TR = 3400, TE = 68, slice = 2.5 mm, space = 2.5 mm, FOV = 5 × 5 cm) of the urethra with a target-like appearance. 

a: Axial FSE T2W image of the proximal urethra. The hypointense outer striated urethral sphincter (arrow) is circularly oriented and surrounds the hyperintense smooth muscle of the urethral wall. The periurethral ligament (curved arrow) and paraurethral ligaments (open curved arrow) provide an important supportive role for the urethra.

b: Intensity-corrected image of the proximal urethra.

c: Axial FSE T2W image of the midurethra. The striated muscle (arrow) layer of the urethra is thickest anteriorly. Periurethral ligament, curved arrow; pubourethral ligament, open arrow.

d: Intensity-corrected image of the midurethra.

e: Axial FSE T2W image of the distal urethra. The striated muscle (arrow) gradually fans out laterally to end in a condensation of striated muscle compressor urethrae. Note that the urethra assumes a more ovoid shape at its inferior aspect near the urogenital diaphragm. Intensity-corrected image of the distal urethra.
and lateral aspects with posterior thinning. The urethral sphincter was larger in the upper (total sphincter area = 151 ± 27 mm²) and midsegments (142 ± 31 mm²) than in the lower segment (116 ± 33 mm²).

**Urogenital Diaphragm**

At about 60% of the length of the urethra, from the internal meatus level, the smooth muscle thickness is reduced and the striated muscle fans out laterally to end in a condensation of striated muscle compressor urethrae (Fig. 3). The muscle fibers in this area no longer run circularly around the urethra but surround both the urethra and vagina, as the urethrovaginal sphincter, or pass laterally to insert into the urogenital diaphragm near the pubic ramus as the compressor urethrae.

**Distal Urethra**

Between 80% and 100% of the length of the urethra, the urethral wall is composed of only fibrous tissue, lacking both skeletal and smooth muscle (Fig. 2).

**Pubourethral Angle and Total Length of Urethra**

Dynamic evaluation of the urethral mobility was possible with the endourethral coil. We were able to evaluate both the pubourethral angle and the status of the internal meatus during strain. During strain, the pubourethral angle ranged from 39°–69° at rest and from 45°–78° during strain. Continent volunteers did not show funneling at the internal meatus. The urethral length in continent volunteers, when measured on either sagittal or coronal view of the entire urethra, was 38 ± 3 mm.

**Intra- and Interobserver Variability in the Urethral Measurements**

The intraobserver agreement in measurements of the urethral wall thickness in continent volunteers was 85% (mean) (range = 78% to 93%) for measurements repeated three times (271 agreements within one SD in a total of 318 measurements). The interobserver agreement in measurements of the urethral wall thickness in continent volunteers was 85% (mean) (range = 85% to 93%) for measurements repeated three times (271 agreements within one SD in a total of 318 measurements). The interobserver variability in measurements of the urethra resulted in 159 measurements. The coefficient of variance for measurements of the first reader was mean 26% for all 159 measurements, minimum 9.6% for urethral length, and maximum 44.3% for midurethra anterior smooth muscle measurement. The coefficient of variance for measurements of the second reader was mean 26% for all 159 measurements, minimum 10.8% for urethral length, and maximum 64.4% for lower urethra anterior striated muscle thickness. The correlation coefficient between two intraobserver measurements was r = 0.99 for K.J.M. and r = 0.98 for T.L.B., and between the two readers, the interobserver correlation coefficient was r = 0.98.

The interobserver agreement and variability in urethral measurements were comparable. The moderate variability in measurements of the urethra resulted from 1) anatomical variability among patients, 2) different slice selection for the upper, mid-, and lower urethra levels, 3) differences in windowing and magnification of the images during measurements, 4) differences in distinctiveness of the urethral muscle layers at different urethral levels, and 5) small size of the organ measured with length of 3.8 cm and thickness in the range of millimeters.

**DISCUSSION**

We have demonstrated feasibility of endourethral MRI for in vivo assessment of the female urethra, with excellent delineation of the striated and smooth muscle layers and the ability to evaluate the muscle integrity and thickness, as well as visualization of the periurethral attachments. Anatomic depiction of urethral features concurs with the histologic assessment of the anatomical landmarks of the female urethra (10). We demonstrated that at the midurethra level, the region of maximum urethral closure pressure, the urethra is composed of both the striated urethral sphincter and the smooth muscle of the urethra. The rhabdosphincter is most prominent at the anterior and lateral aspects of the urethra and thins out posteriorly. Also, the smooth muscle layer is thinner posteriorly. The total smaller
volume of the muscle within the posterior urethral wall might play a role in development of incontinence or urethral wall defects.

De Lancy (11) demonstrated on cadaver study that the urethra lies on a supportive hammock composed of endopelvic fascia and the anterior vaginal wall. When the posterior sphincter wall function diminishes, with muscle atrophy or disruption (from prior trauma, e.g., surgery or childbirth), the urethropelvic ligaments and urethrovaginal attachments become important in providing the posterior urethral support. MRI offers excellent soft tissue contrast and multiplanar acquisition that is needed for detailed assessment of the female urethra and periurethral tissues. Visualization of the urethropelvic ligaments and vaginalelevator attachments has not been consistent during conventional pelvic MRI (12,13). However, application of endoluminal MR coils, endovaginal (4,5) and endorectal (14), provided high-resolution imaging needed for visualization of subtle periurethral attachments.

Using the intravascular MRI, we were able to evaluate the pubourethral ligament, periurethral ligament, and paraurthral ligaments. This approach is useful in assessment of the status of the ligaments: present vs. absent, symmetric vs. asymmetric, attached vs. disrupted. As the ligaments provide crucial posterior urethral support, evaluation of their status may become important in diagnosis of urinary incontinence.

A limitation of the intravascular MRI is placement of the coil within the urethral lumen, which stretches the mucosa and stiffens the urethral wall. However, with endourethral coil in place, dynamic strain imaging of the urethra is possible. Intraluminal coil placement does require application of a signal intensity correction algorithm to remove the near-field artifacts and to evaluate submucosal and mucosal details (7). The signal intensity of images acquired with an endoluminal coil is highly nonuniform due to the $B_1$ inhomogeneity of the receiver. There is signal saturation around the coil, due to high sensitivity of the receiver coil in the immediate surrounding area. The signal drops off with about $1/r^2$ with increasing radius, $r$, away from the coil. Simple adjustments in the contrast and brightness of the images do not allow optimal visualization of all anatomic structures at once. A solution to this problem was suggested by Quick et al (7): calculate a uniform signal intensity image by dividing the image intensity by the corresponding sensitivity map of the coil. By doing this, noise on the images is not uniform and will increase toward the periphery of the image, but a single brightness and contrast level can be used for a convenient display of the central parts of the image. The urethra was found to lie within the near field of the coil, which provided high SNR. The signal decrease from the region of the smooth muscle, about 4 mm from the center of the coil to the periurethral region at 10 mm from the coil, was about twofold. However, signal penetration depth beyond the urethra was sufficient to depict the periurethral structures, such as periurethral and paraurthral ligaments. Postprocessing and display of the images with image intensity correction reliably removed signal inhomogeneities and hot spots due to the coil conductors, thus facilitating the visualization of structures adjacent to the coil, such as submucosal tissue, previously hidden behind signal saturation on the T2 images.

A small FOV is needed for urethral imaging, limited by rapid diminution of signal intensity with increasing distance from the coil. Therefore, imaging using an endourethral coil requires coupling with the surface coil. We used the external coils and the internal coil with a phased-array adapter, which combined the images acquired from all three coils and created a composite image, as well as separate images using the saveinter mode. The best contrast resolution allowing the distinction of the anatomic structures of the urethra was achieved on the images reconstructed from the endourethral coil only. These images were intensity corrected and used for urethral sphincter assessment. The images of the urethra can be obtained with the use of endourethral coil only, by using a surface coil adapter directly plugged into the scanner's port and a coaxial cable as an extension to provide an adequate length.

Another limitation of the endourethral coil placement may be the risk of urethral injury due to instrumentation and risk of urinary tract infection. The standard evaluation of the urethra with vesicourethrography also requires catheter placement with the same risks involved. We had no complications from intravascular coil placement, and all patients tolerated the procedure very well.

The application of the endorectal and endovaginal coil is less invasive and provides an alternative to imaging of the urethra and urethral ligaments. However, endovaginal coil placement does not guarantee stable positioning during imaging with strain, and also, endovaginal coil placement displaces the posterior periurethral tissues and urethrovaginal attachments by elevation of the urethra. The transrectal approach allows for easier and more comfortable coil insertion, with no disruption of the periurethral tissues, but places the coil away from the urethra. The use of an endourethral coil allows for acquisition of ultra-high-resolution MR images with a spatial in-plane resolution 78 $\times$ 78 $\mu$m (7). In our volunteer group, we achieved an in-plane resolution 98 $\times$ 98 $\mu$m (for FOV = 50 $\times$ 50 mm and matrix = 512 $\times$ 512), with a typical resolution of 195 $\times$ 195 $\mu$m. The spatial resolution for the endovaginal coil is about 300 $\times$ 600 $\mu$m (5), whereas for the endorectal coil it is typically 550 $\times$ 550 $\mu$m.

In conclusion, we have demonstrated a new MR method for evaluation of the female urethra and morphometric assessment of continent volunteers. Anatomic measurements derived using this technique are reproducible between experienced observers. In the future, this new approach may allow us to evaluate women with urinary incontinence and may enhance the understanding of anatomical changes of the urinary sphincter that lead to incontinence.

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