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Use of Ultrasound Urodynamics to Identify Differences in Bladder Shape Between Individuals With and Without Overactive Bladder

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Abstract

Objectives: The objective of this study was to identify differences in bladder shape changes between individuals with overactive bladder (OAB) and unaffected individuals during ultrasound urodynamics.

Methods: A prospective urodynamic study was performed with concurrent transabdominal ultrasound (ultrasound urodynamics) on individuals with and without OAB based on validated International Consultation on Incontinence Questionnaire - OAB survey scores. Three-dimensional ultrasound images were acquired at 1-minute increments during filling and used to measure bladder diameters in the height, width, and depth orientations. The engineering strain for each diameter was compared between participants with OAB and controls during urodynamic filling. The height-to-width ratio at capacity was used to determine if individuals were shape outliers.

Results: A total of 22 subjects were enrolled, including 11 with OAB and 11 without OAB. During urodynamic filling in both groups, the greatest degree of geometric strain was found in the height orientation, indicating that bladders generally fill in a craniocaudal shape. The mean $\pm$ SD

height-to-width ratio of the control group was 1.06 ± 0.12 yielding a 95% confidence interval of 0.82 to 1.30. Five (45.5%) of 11 OAB subjects had height-to-width ratios outside this interval as compared with none of the control subjects, identifying a potential shape-mediated subgroup of OAB.

Conclusions: Three-dimensional ultrasound urodynamics can be used to identify differences in bladder shape comparing individuals with and without OAB. This method may be used to identify a subset of OAB patients with abnormal bladder shapes which may play a role in the pathophysiology of their OAB symptoms.

Overactive bladder (OAB) is a common problem for women. Estimates vary greatly, but large studies show prevalence between 10.7% and 16.6% of the population.^{1,2} Patients who suffer from OAB experience problems with quality of life, sexual satisfaction, and sleep. Furthermore, OAB-related problems are expected to become more costly given the aging population and the increasing OAB prevalence with age.

Detrusor wall tension is thought to be a key contributor to the pathophysiology of OAB.³ Detrusor wall tension is affected by numerous factors including muscle compliance as well as filling volume and pressure. Tension-sensitive afferent nerve fibers in the bladder wall likely contribute to the feelings of urgency associated with OAB, as these are in series with detrusor smooth muscle cells.⁴ In addition, acute or chronic changes in bladder shape/geometry may play a role in the development of bladder wall tension. In this regard, an ideal bladder would fill as a perfect sphere, as tension would be equally distributed at all points on the wall. In practice, bladders are not perfect spheres, but any deviation from a bladder's constrained filling shape would create areas of increased wall tension and could lead to heightened sensations of urgency and, ultimately, OAB.^{5,6}

Although the criterion standard for the evaluation of bladder function and all forms of voiding dysfunction is the pressure-flow urodynamic study (UDS), this technique does not currently allow for the measurement of detrusor wall tension or bladder shape. Several investigators have begun using ultrasound during both UDS and hydration protocols and have developed techniques to evaluate bladder vibrometry,⁷ bladder shear wave elastography,⁸ and ultrasound-based assessments of bladder biomechanics.⁵ However, a study to characterize and compare shape changes during the filling phase of bladders in individuals with and without OAB has not been performed. We hypothesized that a novel 3-dimensional (3D) ultrasound urodynamics method can identify individuals with OAB whose bladders fill in abnormal shapes. In addition, this technique could potentially be used to characterize a novel shape-mediated subtype of OAB with different geometric strain patterns.

MATERIALS AND METHODS

This prospective study was approved by the Institutional Review Board of Virginia Commonwealth University. This study recruited a total of 22 individuals with and without OAB. Overactive bladder patients were recruited from urology and urogynecology clinics, and control subjects were recruited from the general population. All participants completed the International Consultation on Incontinence Questionnaire OAB survey⁹ after

recruitment, with division of the subjects using question 5a (“Do you have to rush to the toilet to urinate?”). All control participants scored 0 on question 5a (answer = never), with less than 1 on all remaining questions. All OAB patients scored greater than or equal to 3 on question 5a (answers = most of the time/all of the time). Additional information recorded for all subjects included age, body mass index, race, medications, and medical comorbidities.

Urodynamics Protocol

All participants underwent an initial UDS fill at an infusion rate of 10% maximum voided volume per minute obtained from a 3-day void diary. The initial fill was used to determine the cystometric capacity defined as the voided volume plus postvoid residual volume (obtained by syringe aspiration and confirmed with ultrasound). The next fill used 10% cystometric capacity per minute as a standardized fill rate to enable comparisons between participants.

Ultrasound Protocol

On all participants, the second UDS fill was performed with concurrent 3D ultrasound images acquired once every minute during bladder filling. Transabdominal ultrasound was performed by a certified ultrasound technologist using a GE Voluson E8 system with a 4 to 8 MHz transabdominal transducer (GE Healthcare, Zipf, Austria). During post hoc analysis, a trained individual manually traced the complete perimeter of all bladder images for each subject in both the transverse and sagittal planes using 4D View software (GE Healthcare, Zipf, Austria). Diameters were then measured in the craniocaudal (height, H), lateral (width, W), and anterior-posterior (depth, D) orientations as seen in Figure 1. MATLAB (MathWorks Inc, Mass) was used to interpolate diameters from 20% (initial diameter) to 100% capacity (final diameter) for all subsequent analyses. Capacity of 20% was used as the initial diameter because of the inherent difficulty in tracing bladder walls at lower capacities.¹⁰ The engineering strain for each diameter (change in diameter/initial diameter) was evaluated at every 10% increase in capacity during the bladder fill. The height-to-width ratio at the end of filling (100% capacity) was used to determine if individuals were outliers by defining a 95% confidence interval.

Statistics

Unless specified, data are reported as mean $\pm$ SD. Comparison of continuous variables was performed with Student *t* tests, and comparison of categorical variables was performed using Fisher exact tests.

RESULTS

The study consisted of 11 females with OAB and 11 female controls (Table 1). As expected, the average age was higher in the OAB group ($P < 0.001$). Body mass index (BMI) and bladder capacity were not significantly different between the 2 groups.

Mean bladder diameter increased in the depth, width, and height directions in both the control group (Fig. 2A) and the OAB group (Fig. 2B) over the course of the bladder fill. The geometric strain in all 3 directions likewise increased across the fill (Figs. 3A–C), most

significantly in the height orientation, which grew by about 2-fold in both the control and the OAB groups (Fig. 3C). This suggests that typical bladders of all types do not fill spherically but tend to fill in an elongated shape in the craniocaudal direction. The geometric strain was significantly greater in the depth direction at 30, 40, 50, 60, 70, 80, 90, and 100% capacities for the control group as compared with the OAB group (Fig. 3A).

The mean height-to-width ratio of the control group was 1.010 ± 0.084 with a 95% confidence interval of 0.845 to 1.175. None of the control participants had a height-to-width ratio outside the confidence interval, but 5 (45.5%) of 11 OAB subjects had height-to-width ratios outside the confidence interval (3 above and 2 below, $P = 0.035$) (Fig. 4), identifying these individuals as possibly having a shape-mediated OAB subtype.

DISCUSSION

The key finding of this study is that, during UDS filling, the bladders of OAB patients expand in different geometric patterns as compared with control subjects. Indeed, this investigation demonstrates a potential shape-mediated subtype of OAB. In both groups, bladders displayed the most significant shape change in the craniocaudal dimension during urodynamic filling, which is consistent with prior studies.¹¹ In general, this finding suggests that the shape of bladder expansion transitions from a laterally oriented grape to a hamburger bun on its side as opposed to a more spherical “orange” shape.⁶ Importantly, this finding occurred in women with similar BMI, suggesting that compression from increased abdominal wall fat did not contribute to the observed shape differences. Furthermore, control bladders undergo greater geometric strain than OABs in the depth direction, highlighting a lack of accommodation to increasing volume in OABs.

Two different types of abnormal shape were identified in this investigation. Three OAB participants had abnormally large height-to-width ratios (tall, elongated eggplant bladders), whereas 2 OABs had abnormally small height-to-width ratios (pancakeshaped bladders). Because bladder smooth muscle cells are in series with tension-sensitive afferent nerves,¹² it is expected that greater deviations from normal-shaped filling will directly lead to an increased sensation of urinary urgency. In this regard, knowledge of bladder shape during filling using our 3D ultrasoundurodynamic methods may be important in the identification of a shape-mediated subtype of OAB. The outlier analysis presented in our study, where 45% of OAB subjects were found to fill in abnormal shapes (eggplant or pancake), supports this concept of a shape-mediated OAB subtype (Figs. 1, 4).

Previous studies have highlighted the importance of shape in bladder function. Studies over the last 60 years have used imaging techniques including cystograms, computed tomography, and magnetic resonance imaging to examine bladder shape and noted banana-like shapes in individuals with pelvic lipomatosis who tended to suffer from urinary urgency.^{13–15} Although the bladder has historically been modeled as a sphere or spheroid,^{6,16,17} imaging has shown that bladder shape is variable and irregular.^{6,11,18–21} Analytical biomechanical analysis,^{5,6} statistical shape modeling,¹¹ and finite element modeling^{20,21} all demonstrate that nonspherical bladder shape changes during filling significantly affect its mechanical behavior inside the body.

The use of ultrasound either during UDS or as a method to evaluate voiding function or other bladder dysfunction has been previously performed for a number of applications. These include measurement of bladder volume,^{10,18,19,22} measurement of bladder wall thickness,^{23,24} and estimation of intravesical bladder pressure.⁸ However, this study is unique in its use of 3D ultrasound throughout the course of filling in both individuals with OAB and in controls. An advantage of the imaging technique in this study is that it can be used noninvasively in hydration studies^{20,25,26} without the need for bladder catheterization.

Limitations of the current investigation include the use of young healthy control population as compared with the OAB group, which was older. Certainly, the effects of age need to be evaluated as an independent variable that could affect bladder shape in future studies. However, this speaks to the inherent difficulty of recruiting age matched controls who have minimal symptoms of urinary urgency. The use of this control population helps to establish an ideal baseline of bladder filling shape/geometry, which could be used in larger and more specific comparative studies in the future. In addition, the sample size in this investigation was relatively small but was necessary in this initial study aimed more at establishing a novel ultrasound methodology for defining shape changes during UDS filling.

This study shows that noninvasive 3D ultrasound can potentially be used to identify differences in bladder shape and dimensions between individuals with and without OAB. This method was used to identify a subset of OAB patients with abnormal bladder shapes (eggplant or pancake shape). This ultrasound-UDS methodology may allow for improved phenotyping of OAB as well as more rationally designed trials and treatments (ie, weight loss, bowel care, postural changes, surgical therapies to alleviate bladder compression) potentially targeted towards individuals with shape-mediated OAB.

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FIGURE 1.

Ultrasound method for determining bladder shape during urodynamics and examples of different bladder shapes. Orange lines indicate measured diameters: width (W), depth (D), and height (H). A, Overactive bladder with pancake-shaped bladder (height-to-width ratio below the confidence interval). B, Overactive bladder with a typical-shaped bladder (height-to-width ratio near the center of the confidence interval). C, Overactive bladder with an elongated eggplant-shaped bladder (height-to-width ratio above the confidence interval).

FIGURE 2.

Filling patterns for the control (A) and OAB (B) groups. Plots show individual diameters in the depth (top left), width (top right), and height (bottom left) directions as well as composite averages for all 3 directions (bottom right).

FIGURE 3.

Strain patterns for the control and OAB groups. Average bladder diameter strain for the control group (blue stars) and OAB group (orange triangles) in the depth (top left), width (top right), and height (bottom left) directions as a function of % capacity (normalized volume). Stars indicate a significant difference between controls and OABs with $P < 0.05$.

FIGURE 4.

Bladder height-to-width ratios in control and OAB groups. Ratio of height-to-width diameters from controls (red) and OABs (blue). Thick black line indicates the average for the control group, whereas thin black lines are reflective of the 95% confidence interval used to identify outliers for height-to-width ratios. Individuals are in BMI order within their control or OAB category. Any symbols above or below the thin lines are considered shape outliers. Bladders circled in orange can be visualized in Figure 1.

TABLE 1.

Demographic Information

Subject Information	Control (n = 11)	OAB (n = 11)	P
Age, y	29.9 ± 13.2	52.3 ± 12.3	<0.001
BMI, kg/m ²	29.6 ± 7.66	29.1 ± 7.68	0.89
Bladder capacity, mL	626.7 ± 163.1	533.0 ± 331.2	0.40

Included are the mean and standard deviations for each subject group.