Automatic Measurement of Ultrasound-Estimated Bladder Weight (UEBW) from Three-Dimensional Ultrasound

Vikram Chalana, PhD, Stephen Dudycha, MSE, Jong-Tae Yuk, PhD,
Gerald McMorrow, MSEE

Diagnostic Ultrasound Corporation, Bothell, WA

Ultrasound-estimated bladder weight (UEBW) has the promise to become an important indicator for the diagnosis of bladder outlet obstruction. Our goal was to develop and evaluate an approach to accurately, consistently, conveniently, and noninvasively measure UEBW using three-dimensional (3D) ultrasound imaging. A 3D image of the bladder is acquired using a hand-held ultrasound machine. The infravesical region of the bladder is delineated on this 3D data set to enable the calculation of bladder volume and the bladder surface area. The outer anterior wall of the bladder is delineated to enable the calculation of the bladder wall thickness. The UEBW is measured as a product of the bladder surface area, bladder wall thickness, and bladder muscle specific gravity. The UEBW was measured on 20 healthy male subjects and each subject was imaged several times at different bladder volumes to evaluate the consistency of the UEBW measurement. Our approach measured the average UEBW among healthy subjects to be 42 g (SD = 6 g). The UEBW was found to be fairly consistent with an average standard deviation of 4 g across a single subject at different bladder volumes between 200 mL and 400 mL. Our surface area measurements show that the bladder shape is significantly nonspherical.
[Rev Urol. *2005;7(suppl 6):S22-S28*]

Key words: Ultrasound-estimated bladder weight • Bladder wall mass • Bladder wall thickness • Bladder outlet obstruction • 3D ultrasound

Benign prostatic hyperplasia and other disorders can cause mechanical bladder outlet obstruction. Such an outlet obstruction can in turn cause hypertrophy of the bladder detrusor muscle, which may lead to additional irritative urinary symptoms. Such a hypertrophy manifests as increased detrusor wall thickness and an increased bladder weight. In laboratory animals, a 3- to 6-fold increase in bladder weight has been shown within 2 weeks of partial ligation of the urethra.[1,2]

In humans, several studies have shown the bladder wall thickness (BWT) measured from ultrasound images and ultrasound-estimated bladder weight (UEBW) as important surrogate markers for bladder outlet obstruction and acute urinary retention caused by benign prostatic hyperplasia and other disorders.[3-7] Studies have also shown a reversal of bladder hypertrophy and a consequent reduction in the UEBW after surgical or medicinal treatments.[8,9]

Kojima and colleagues[3,4] and other groups have estimated bladder weight by filling the bladder to a certain fixed volume and then measuring the thickness on high-resolution B-mode ultrasound images. They then used the following steps to measure the UEBW:

1. Using the known filled intravesical volume, V_i, and assuming the bladder to be a sphere, first estimate the inner radius, r_i, of the bladder as:

$$r_i = \sqrt[3]{\frac{3V_i}{4\pi}}$$

2. Next, using the measured thickness, t, estimate the outer radius, r_o, of the bladder shell as:

$$r_o = r_i + t$$

3. Using the outer radius, estimate the total vesical volume, V_o, as:

$$V_o = \frac{4}{3}\pi r_o^3$$

4. Finally, estimate UEBW by calculating the bladder muscle volume as the difference between the total vesical volume and the intravesical volume and multiplying this bladder muscle volume with the specific gravity, ρ, of the bladder muscle tissue:

$$UEBW = (V_o - V_i)\rho$$

Our approach described in this paper extends the pioneering work above and results in a fully automatic and convenient method to estimate bladder weight. In our method, a subject is scanned using the BladderScan® BVM 6500 device (Diagnostic Ultrasound, Bothell, WA), which produces three-dimensional (3D) V-mode® images. Immediately after the scan, the device displays the volume of urine inside the bladder along with aiming information to enable the correct placement of the probe with respect to the bladder. The aiming information allows the user to repeat the scan to get a well-centered image of the bladder within 200 and 400 mL.

Once the scan is complete, the 3D data are transmitted securely to a server computer to be processed automatically on the remote computer network. Computer programs on the server's computer array calculate the BWT and bladder weight. First, the bladder region is delineated precisely using image-processing algorithms. From this delineated bladder region, the actual surface area, S, of the bladder is calculated. Also, starting from this delineated bladder region, the outer wall of the anterior portion of bladder wall is delineated. The BWT, t, is then automatically calculated as the distance between the outer and the inner surfaces of bladder wall. Finally, the bladder weight is estimated as the product of the surface area, thickness, and bladder muscle specific gravity, ρ:

$$\text{UEBW} = S \times t \times \rho$$

The main benefit of our approach is that it produces more accurate and consistent estimates of UEBW. The reasons for higher accuracy and consistency are:

- The use of 3D data instead of 2D data to calculate the surface area and thickness
- The use of the true surface area instead of using surface area under spherical assumptions
- The automatic and consistent measurements of wall thickness and surface area using advanced image processing algorithms.

Additional benefits of our approach are its noninvasiveness, its speed, and its ease of use—our approach measures UEBW over a range of bladder volumes, thereby eliminating the need to catheterize the patient to fill up to a fixed volume.

Methods

A battery-powered 3D hand-held ultrasound system, the BladderScan BVM 6500 instrument, is used for UEBW data acquisition. This system uses a focused 3.7 MHz single-element transducer steered mechanically to acquire a 120-degree cone of

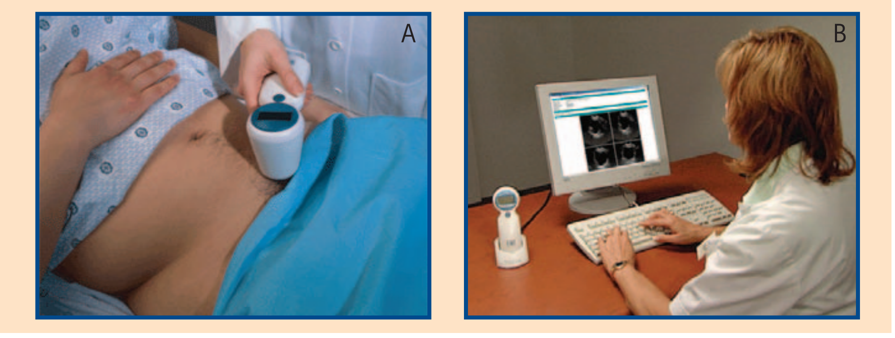


Figure 1. *Images showing (A) the patient being scanned by the BVM 6500 device and (B) the data being uploaded to the server.*

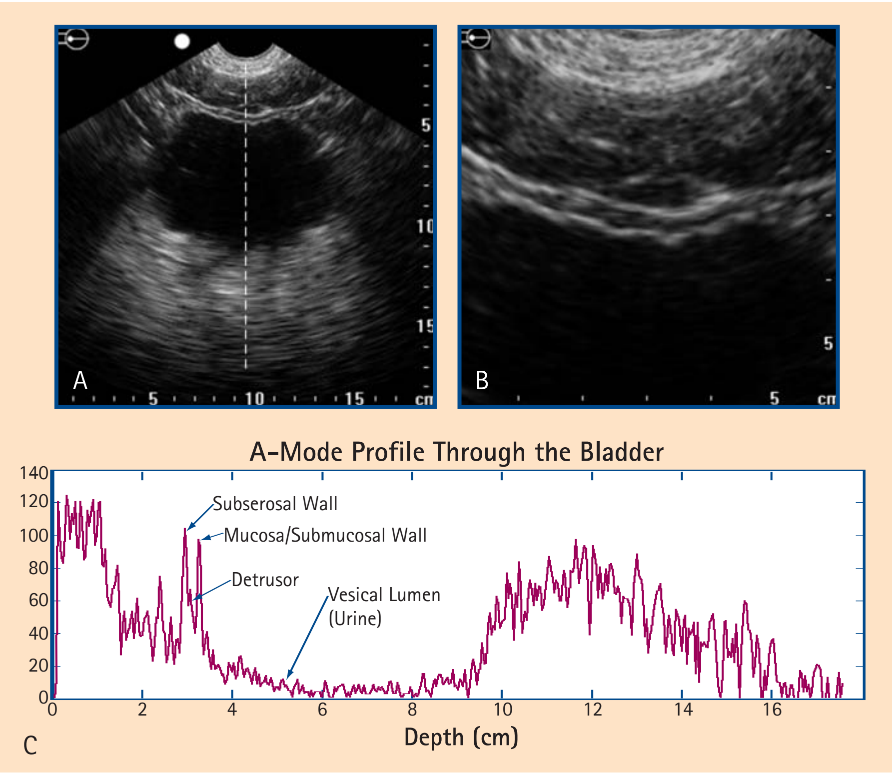


Figure 2. *(A) A B-mode ultrasound image of a bladder in a transverse section using our 3.7 MHz device. (B) A close-up of the image in (A) showing the anterior bladder wall. (C) A log-compressed A-mode line through the bladder corresponding to the dotted line on (A) illustrating the features of the bladder wall.*

V-mode (multiple, aligned B-mode images) ultrasound data.

The scan protocol for UEBW is identical to the well-known BladderScan protocol. The scanner is placed approximately 1 inch above the symphysis pubis with the scan head aimed slightly towards the coccyx (Figure 1A). The 3D ultrasound data are collected immediately upon pressing the scan button on the scanner. After the scan is complete, the LCD on the device displays aiming information in the form of arrows. A flashing arrow indicates to the user to alter the aim in the direction of the arrow and rescan. The scan is repeated until the device displays only a solid arrow or no arrow. The LCD on the device also displays the calculated bladder volume. For UEBW measurement, the required bladder volume is between 200 mL and 400 mL. If the bladder volume reading is less than 200 mL, the patient could be given some fluids and scanned after a short time interval. Once the scanning is complete and the patient has a bladder volume between 200 mL and 400 mL, the device is then placed on a communication cradle that is attached to a personal computer (Figure 1B) and the data are uploaded securely to a server where they are processed by our bladder weight estimation algorithm (version number 2.7.9/3.00).

The scan protocol for UEBW is identical to the well-known BladderScan® protocol.

Figure 2A shows the ultrasound appearance of a transverse section of a bladder using our imaging device. Notice that the bladder is the hypoechoic region in the middle of the image. The zoomed image (Figure 2B) and a log-compressed A-mode line (Figure 2C) show the appearance of the anterior wall of the bladder. The submucosal plus mucosal layer of the wall, the subserosal layer, and the detrusor muscle are quite easily visualized in this particular set of zoomed B-mode and the A-mode data. These two layers of the bladder wall are most clearly visible when the ultrasound beam is normally incident to the bladder wall. As the ultrasound incidence deviates from normal, the two layers start appearing as one and may not be reliably detected. Whereas in many data sets these two layers of the bladder wall are clearly visible at normal incidence, there are some cases when the perivesical tissue (such as the perivesical fascia) impinges on the bladder wall and merges with the subserosal layer.

Figure 3 shows the patented algorithm used to calculate UEBW from

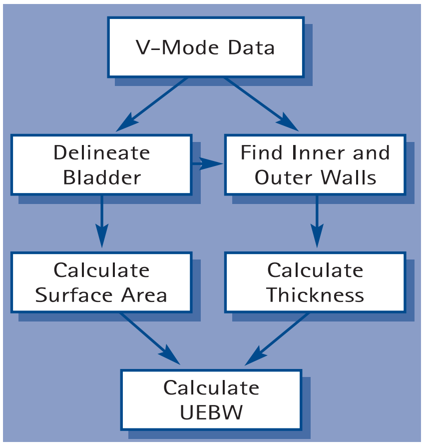


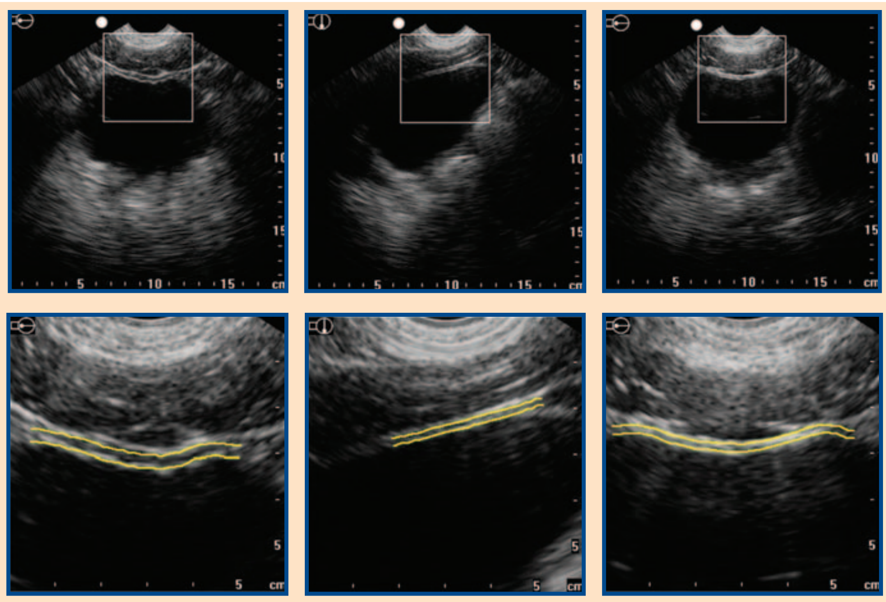
Figure 3. *Algorithm for the calculation of UEBW from V-mode ultrasound data.*

V-mode ultrasound data. The first step in the algorithm is to delineate the bladder region. This delineated bladder region is then used to calculate the bladder surface area. Using the delineated bladder region and the input V-mode data, the anterior wall of the bladder is determined. This anterior wall delineation is used to calculate the BWT. Finally, the surface area and the thickness measurements are combined to calculate the UEBW.

An image-processing algorithm is used to delineate the bladder. This algorithm incorporates the knowledge of the key characteristics of the bladder appearance—a hypoechoic region surrounded by bright echoes anterior and posterior to it—combined with additional assumptions about the smoothness of the bladder wall. Sample images showing the delineated bladder are presented in Figure 4.

Once the inner surface of the bladder has been delineated on a set of data planes, a computer graphics algorithm known as the “Marching Cubes algorithm”[10] is used to calculate the 3D surface area of the bladder. The marching cubes algorithm is intended to create a triangulated 3D surface that can be easily rendered by a computer graphics engine. Once the triangulated surface is available, calculating the surface area of that 3D surface is simply a matter of summing up the areas of all the triangles constituting the 3D surface.

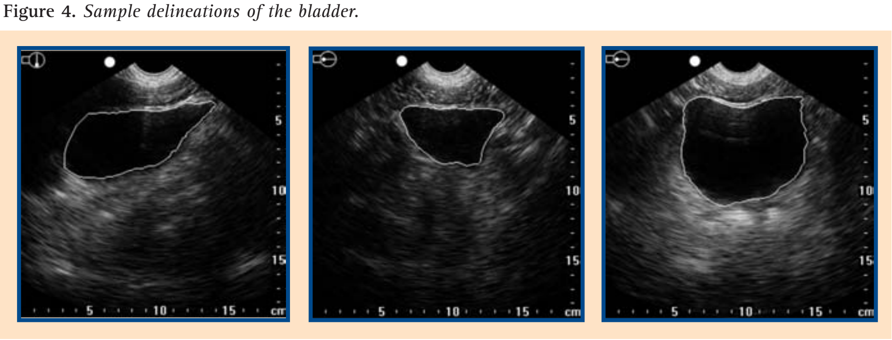
Figure 5. *Sample delineations of the anterior bladder wall muscle. The top row shows the full images and the bottom row shows the zoomed images with the walls overlaid.*



Using the delineated bladder surface as a starting point, the anterior wall of the bladder muscle is then determined to enable thickness calculation using the following model:

- When the ultrasound beam is normally incident to the bladder surface, the bladder wall appears as two bright regions representing the submucosal plus mucosal layer and the subserosal layer, separated by a dark region representing the detrusor muscle (Figure 2).
- Thus, first the angle of incidence of a scan line to the bladder surface is determined and then on all scan lines approximately normal to the bladder surface two bright peaks immediately anterior to the vesicle lumen are located automatically and are labeled as the inner and the outer walls of the bladder muscle.

Figure 4. *Sample delineations of the bladder.*



Once the inner and outer layers of the anterior bladder muscle have been delineated, the thickness calculation simply involves determining the distance between the two surfaces. The average distance between the inner and outer wall is determined on all scan lines approximately normal to the bladder surface; this distance is reported as output and also used for the bladder weight calculation. The rendered bladder wall on the output images shows this average thickness plotted along the two leading edges of the bladder muscle. Some sample bladder wall delineations are shown in Figure 5.

Once the bladder wall thickness, t, and the surface area, S, are available, UEBW is simply calculated as:

$$\text{UEBW} = S \times t \times \rho$$

The specific gravity, ρ, used for UEBW calculation is 0.957 as measured by Kojima and associates.[3]

VOL. 7 SUPPL. 6 2005 REVIEWS IN UROLOGY S25

Twenty healthy male subjects between the ages of 24 and 55 consented to be scanned to study the performance of this UEBW system. The study protocol used was approved by the Western Institutional Review Board, a third-party review organization.

Each subject was scanned during 1 to 8 visits within a period of 4 months. A registered ultrasonographer scanned each subject with 3 different BVM 6500 devices. The sonographer also scanned each subject with a Sonosite® 180 (Sonosite, Inc., Bothell, WA) ultrasound machine using the 10-5 MHz linear array probe. The BWT was manually measured on transverse and sagittal images on the Sonosite machine from the leading edge of the subserosal layer to the leading edge of the submucosal plus mucosal layer. The subject then voided into a uroflow device to measure the total voided volume. Finally, the postvoid residual volume was measured using the same 3 BVM 6500 devices. All scans that were outside the specified 200 mL to 400 mL volume range were rejected from the analysis, as were scans that did not produce well-centered or well-aimed images, based on aiming arrow information.

The accuracy of existing methods to estimate bladder weight is limited because of the assumption that the bladder is spherical in shape. Our results have shown that the bladder is significantly nonspherical in shape.

Results

Using data gathered from a total of 216 examinations, our approach measured the average UEBW among healthy male subjects to be 42 g, with a standard deviation of 6 g. Figure 6 shows a boxplot of the actual UEBW measurements for the 20 subjects. The ends of the boxes mark the first and the third quartiles, the lines extend to the minimum and maximum values, and the cross represents the median UEBW value for each subject. The UEBW was found to be fairly consistent across a single subject at different volumes between 200 mL and 400 mL and between different instruments. The average standard deviation of the UEBW measurement for a single subject was found to be 4 g and it ranged between a minimum of 2 g and a maximum of 6 g. This corresponds to an average coefficient of variation (standard deviation divided by the mean) of 9%. When calculating UEBW by multiplying the thickness measured by the sonographer using the Sonosite machine and the surface area measured by our UEBW device, we found an average coefficient of variation of 11%, indicating a somewhat lower consistency in manual measurements of thickness.

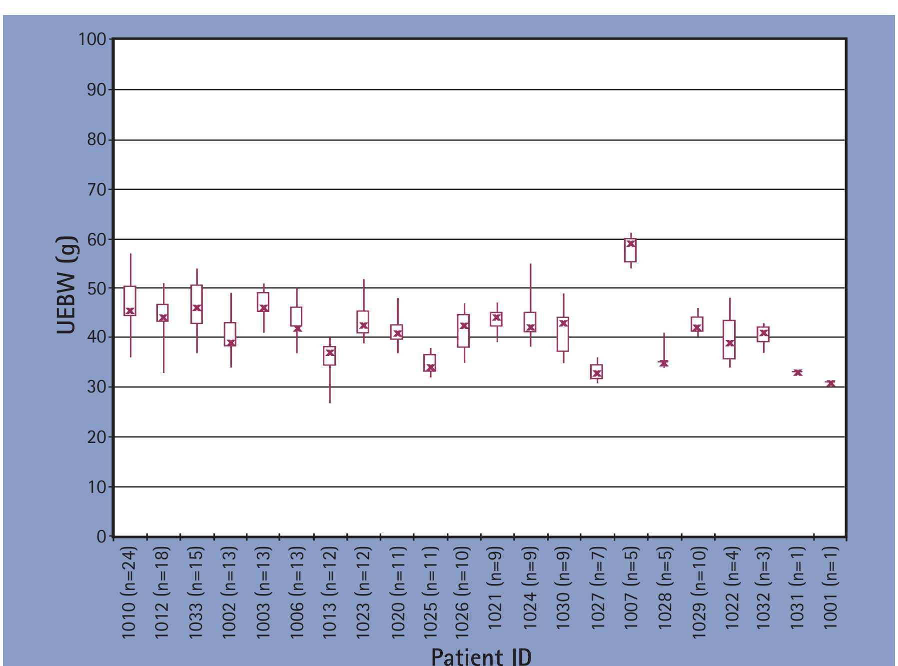


Figure 6. *UEBW distribution by patient. Box marks first and third quartiles, lines mark minimum and maximum, x marks the median. UEBW, ultrasound-estimated bladder weight.*

Figure 7 shows the bladder surface area calculated by our method plotted against the bladder volume. The blue line in the figure shows the bladder surface area if we assume the bladder to be a spherical structure. The bladder surface area calculated by our method is on average 18% higher ($P < .001$, minimum of 3% and maximum of 67%) than the surface area calculated under the spherical assumption, indicating that, as expected, the bladder surface cannot be well approximated by a sphere.

The prevoid bladder volume measured by our device was compared to the sum of the uroflow-measured voided volume and the postvoid residual. A mean difference of −4.6% (95% CI, −2.7 to −6.4) was found in the volume measurement, which

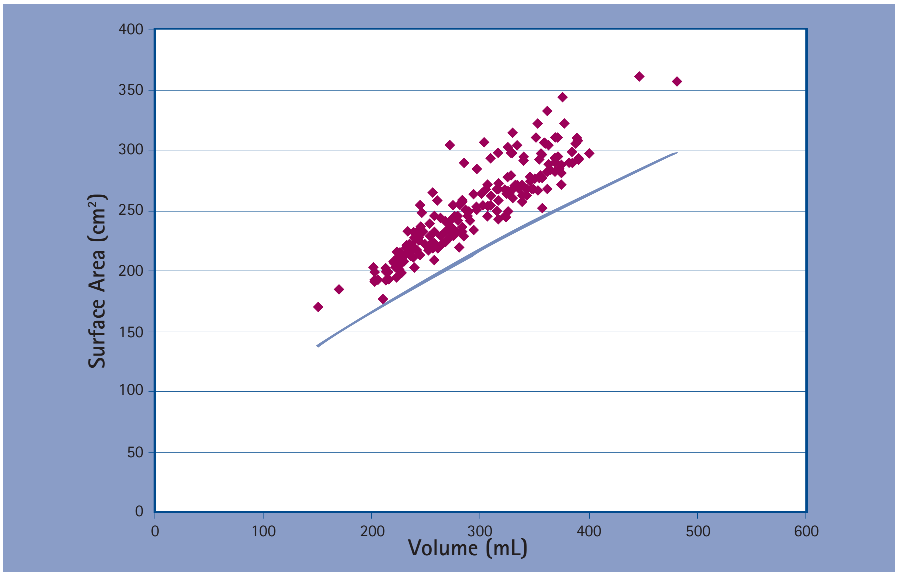


Figure 7. *Calculated bladder surface area versus bladder volume. The blue line corresponds to the surface area of a spherical surface of the given volume.*

corresponds to a difference of −17 mL (95% CI, −11 to −23).

Discussion and Conclusions

We have developed an automatic and convenient method to estimate UEBW. Our preliminary results show that we can consistently and reproducibly assess UEBW using 3D V-mode ultrasound when the 3D ultrasound scan is well centered and the bladder volume is between 200 mL and 400 mL. Aiming information and bladder volume measurement are provided immediately to the user to acquire the optimal scan.

Although several researchers have previously proposed the measurement of UEBW, their methods have had several limitations that our method overcomes. The accuracy of existing methods to estimate bladder weight is limited because of the assumption that the bladder is spherical in shape. Our results have shown that the bladder is significantly nonspherical in shape. Also, because in the existing methods the thickness is measured manually, the bladder wall measurements suffer from high inter- and intra-observer variability.[7,11] Moreover, such measurements in everyday practice are difficult due to both the requirement of filling the patient's bladder to a known fixed volume using a catheter and the required availability of an expensive high-resolution B-mode ultrasound machine and an ultrasound technician. Our approach is noninvasive, accurate, reliable, and easy to use.

The 4 g average variability found in UEBW using our method results from a combination of several sources of variability, which need to be studied further. Errors in surface area and thickness measurements are 2 of the possible sources of variability. Differences among the 3 devices used are another possible source of variability. We have noticed diurnal variations in the actual bladder weight and this is

Main Points

- Ultrasound-estimated bladder weight (UEBW) has the promise to become an important indicator for the diagnosis of bladder outlet obstruction. Previously researchers have estimated bladder weight by filling the bladder to a fixed volume and measuring the thickness on high-resolution B-mode ultrasound images.
- A subject is scanned with a device that produces 3D V-mode images. The device shows the volume of urine in the bladder along with aiming information to enable the correct placement of the probe, resulting in a well-centered image of the bladder.
- The accuracy of existing methods to estimate bladder weight is limited because of the assumption that the bladder is spherical in shape. Our results have shown that the bladder is significantly nonspherical in shape. Also, because in the existing methods the thickness is measured manually, the bladder wall measurements suffer from high inter- and intra-observer variability.
- The main benefit of this new approach is that it produces more accurate and consistent estimates of UEBW. The reasons for this include: 1) the use of 3D rather than 2D data to calculate bladder surface area and thickness, 2) the use of the true surface area instead of an assumed spherical surface area, and 3) the automatic and consistent measurements of wall thickness and surface area using advanced image processing algorithms.
- Additional benefits of this approach are its noninvasiveness and ease of use—UEBW is measured over a range of bladder volumes, thereby eliminating the need to catheterize the patient to fill up to a fixed volume.

another potential source of variability. Yet another possible source of variability is that the bladder weight itself, as measured by our method, may not be constant at all bladder volumes. In a recent study by Oelke and associates,[6] it was shown that although the detrusor wall bladder thickness decreased continuously during the first 50% of the bladder capacity, between 60% and 100% of bladder capacity the detrusor muscle thickness remained stable. This result implies that the UEBW increases depending on the bladder volume after the bladder is half full.

Our average UEBW measurements for normal subjects are somewhat higher than the 35 g average value reported by Kojima and colleagues.[3,4] This difference may be explained by their assumption of a spherically shaped bladder. The actual bladder shape is significantly different from a sphere and using the actual surface area will lead to a UEBW measurement that is at least 18% higher. A second reason for the difference between their UEBW measurements and ours may be the method of measuring thickness. Our wall thickness measurements are calculated by measuring the distance between the visible peaks in the submucosal plus mucosal layers and the subserosal layer whereas the measurements made by Kojima and colleagues[3,4] presumably use a leading edge to leading edge distance, contributing to some methodological differences.

In conclusion, we have presented an automatic, convenient, and consistent method to estimate UEBW. We believe that such a consistent and reproducible UEBW measure holds great promise as a diagnostic marker for bladder outlet obstruction problems. ■

[*Note: The methods and systems described in this publication are protected by the US patents 492681, 5235985, 6569097, 6110111, 6676605, and other pending US and international patents.*]

References

1. Levin RM, Haugaard N, O'Conner L, et al. Obstructive response of human bladder to BPH vs rabbit bladder response to partial outlet obstruction: a direct comparison. *Neurol Urodyn.* 2000;19:609-629.
2. Mattiason A, Uverlius B. Change in contractile properties in hypertrophic rat urinary bladder. *J Urol.* 1982;128:1340-1342.
3. Kojima M, Inui E, Ochiai A, et al. Ultrasonic estimation of bladder weight as a measure of bladder hypertrophy in men with infravesical obstruction: a preliminary report. *Urology.* 1996;47:942-947.
4. Miyashita H, Kojima M, Miki T. Ultrasonic measurement of bladder weight as a possible predictor of acute urinary retention in men with lower urinary tract symptoms suggestive of benign prostate hyperplasia. *Ultrasound Med Biol.* 2002;28:985-990.
5. Manieri C, Carter SS, Romano G, Tubaro A. The diagnosis of bladder outlet obstruction in men by ultrasound measurement of bladder wall thickness. *J Urol.* 1998;159:761-765.
6. Oelke M, Hofner K, Wiese B, et al. Increase in detrusor wall thickness indicates bladder outlet obstruction in men. *World J Urol.* 2002;19:443-452.
7. Muller L, Bergstrom T, Hellstrom M, et al. Standardized ultrasound method for assessing detrusor muscle thickness in children. *J Urol.* 2000;164:134-138.
8. Kojima M, Inui E, Ochiai A, et al. Reversible change of bladder hypertrophy due to benign prostate hyperplasia after surgical relief of obstruction. *J Urol.* 1997;158:89-93.
9. Tubaro A, Dario S, Marco P, et al. Effect of tamsulosin on bladder wall hypertrophy in patients with lower urinary tract symptoms suggestive of bladder outlet obstruction. ICS Abstract, 2004.
10. Lorensen WE, Cline HE. Marching cubes: a high resolution 3D surface construction algorithm. *Computer Graphics.* 1987;21:163-169.
11. Naya Y, Kojima M, Honjyo H, et al. Intraobserver and interobserver variance in the measurement of ultrasound-estimated bladder weight. *Ultrasound Med Biol.* 1999; 24:771-773.