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ORIGINAL ARTICLE

Variables affecting maximum urethral closure pressure (MUCP) and abdominal leak point pressure (ALPP) measurements

Bryan J. Hill[1,2] · **Sarah Fletcher**[3] · **Jeffrey Blume**[3] · **Rony Adam**[1] · **Renée Ward**[1]

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Abstract
Introduction and hypothesis The relationship between pelvic floor muscles and measurements of urethral function is not well studied. It is not known whether adjusting for clinical, demographic and urodynamic parameters would improve the association between MUCP and ALPP. Our hypothesis was that pelvic floor muscle strength (PFMS) influences the relationship between MUCP and ALPP.
Methods This was a retrospective study of women who underwent a complex urodynamic study with evaluation of MUCP and ALPP using ICD-9 codes with documentation of PFMS.
Results Urodynamic stress incontinence was confirmed in 478 patients, of whom 323 had MUCP recorded and 263 had both MUCP and ALPP recorded. Women with higher PFMS had a higher MUCP. In regression analysis ALPP at 150 mL and MUCP were weakly associated (coefficient 0.43, 95% CI 0.08–0.78; $p = 0.02$), whereas ALPP at capacity and MUCP were moderately associated (coefficient 0.60, 95% CI 0.25–0.95; $p < 0.001$).
Conclusions This study showed that MUCP and ALPP at 150 mL were weakly associated and that this improved to a moderate association for ALPP at capacity. MUCP increased with increasing PFMS among women with stress urinary incontinence and decreased with increasing age. There was no evidence that ALPP was associated with PFMS or age. The relationship between MUCP and ALPP was unchanged when accounting for covariates of PFMS (age, parity, BMI, prior procedure, urethral mobility, bladder capacity, stage of cystocele, or stage of uterine or apical prolapse).

Keywords Urodynamics · Kegel · Muscle · Incontinence

Introduction

Urinary incontinence (UI) is a common condition with a prevalence of at least 30% in the aging female population [1]. Compared to other medical conditions, women with UI are more likely to have more depressed feelings, perceive themselves to be in poor health, and experience decreased quality of life [2]. The diagnosis and management of female UI often depends on evaluation of urethral function. In multichannel urodynamics, female urethral function can be evaluated at rest by maximum urethral closure pressure (MUCP), a static technique, or during Valsalva maneuver with an abdominal leak point pressure (ALPP), a dynamic technique [3, 4]. Clinically, both measurements are used to identify intrinsic sphincter deficiency and a low pressure urethra; yet, only a weak to moderate association has been shown between MUCP and ALPP [5–9]. This suggests that either these are measuring different aspects of urethral function, or that other clinical and demographic variables modulate their impact on urethral function. Several studies have shown that MUCP declines with age and both MUCP and ALPP are inversely associated with body mass index (BMI) [10–13]. Additionally, contraction of the pelvic floor muscles in women with UI results in mean incremental increases in MUCP between 6 and 23.5 cm H_2O [14]

✉ Bryan J. Hill
bryan.j.hill@vanderbilt.edu

1 Department of OB/GYN, Division of Female Pelvic Medicine and Reconstructive Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

2 Vanderbilt University Medical Center, 1200 Medical Center North (MCN), 1161 21st Ave. South, Nashville, TN 37233, USA

3 Department of Biostatistics, Vanderbilt University, Nashville, TN, USA

and pelvic floor physical therapy can increase resting MUCP [15]. The relationship between pelvic floor muscles and ALPP is less well studied. What is not known is whether adjusting for other clinical, demographic and urodynamic parameters would improve the association between MUCP and ALPP.

To better understand this relationship, we conducted a retrospective cohort study of women who had undergone complex urodynamics at Vanderbilt University Medical Center. Our hypothesis was that pelvic floor muscle strength (PFMS) may influence the relationship between MUCP and ALPP. Our primary aim was to estimate how PFMS impacts the relationship between MUCP and ALPP and whether this and other clinical, urodynamic, and demographic variables could help elucidate why there is only a weak to moderate association between these objective measurements of urethral function.

Materials and methods

This was a retrospective, cross-sectional study of all women in the Vanderbilt University Medical Center Synthetic Derivative database who underwent complex urodynamics, had urodynamic stress UI (SUI) with urethral pressure measurements obtained. The Synthetic Derivative database is a de-identified repository of clinical information from the Vanderbilt University Medical Center electronic medical record. The study was approved by the institutional review board. Included in the study were patients who underwent complex urodynamics with evaluation of both MUCP and ALPP (CPT codes 51,797 and 51,772) and had demonstration of urodynamic SUI. The majority of urodynamics were performed to evaluate UI or to assess for the presence of occult SUI. Patients with a prior anti-incontinence procedure were included. Patients were excluded if they had one or more of the following: multiple sclerosis (ICD-9 group 340), anterior horn cell disease (ICD-9 group 335), occlusion of cerebral arteries (ICD-9 group 434), or cerebrovascular disease (ICD-9 groups 436–438). We obtained demographic information, patient characteristics, Pelvic Organ Prolapse Quantification (POP-Q) examination [16], BMI, and PFMS (Oxford grade 0–5) [17]) prior to urodynamic evaluation.

Urodynamic measurements included bladder capacity on filling cystometrogram, MUCP, ALPP at 150 mL and at capacity, presence of urodynamic SUI, volume at which leakage first occurred, and degree of urethral hypermobility. Urodynamic SUI was defined as leaking observed in the absence of associated detrusor activity. MUCP was measured with an empty bladder and again at capacity. The recorded value was the MUCP at capacity, except for rare circumstances when the MUCP with an empty bladder was the only available measurement due to severe detrusor overactivity. In our experience, the discrepancy between empty and full MUCP is typically <5–10 cm H_2O. To visualize associations, graphical representations of MUCP versus ALPP were stratified by categorized clinical, urodynamic, and demographic variables.

Complex multichannel urodynamic testing was performed using a Laborie Medical Technologies multiple task urodynamics system (Mississauga, Ontario, Canada), dual-sensor 7F air-charged urethral catheters and 7F air-charged abdominal sensors (T-DOC Co., LLC, Wilmington, DE). All procedures were done in a sitting erect position in a Sonesta birthing chair (Sonesta, LLC, Middleton, MA), with sterile water at room temperature. All terminology is in accordance with the 2010 IUGA/ICS joint report [4]. The filling rate was 50 cm^3/min unless this provoked urinary urgency and then a slower fill rate was used. ALPPs were measured during Valsalva maneuver at 150 mL and again at bladder capacity in the seated position, with the urethral catheter in place. No additional maneuvers were performed to obtain an ALPP if leakage was not demonstrated. No graded cough maneuvers were performed during ALPP evaluation. The abdominal pressure transducer was placed vaginally, unless the severity of prolapse necessitated rectal placement. Stage II or greater prolapse was reduced at the beginning of the study using a monovalve speculum, scopettes, and/or a pessary. All women underwent evaluation in an upright, seated position, regardless of prolapse stage. Provocative maneuvers, including water stimulation and cough, were used in an effort to provoke detrusor overactivity. Urethral pressure profilometry was performed using a mechanical puller at a rate of 1 mm/s. Both static and dynamic profiles were performed at cystometric capacity. Fluoroscopy was not performed as part of the standard urodynamic evaluation in this study. Data were recorded using REDCap [18] (version 6.11.1, grant UL1 TR000445 from NCATS/NIH), a secure online database. Data were analyzed with consultation from Vanderbilt University Department of Biostatistics using biostatistical software R (version 3.2.3). The statistical tests used were analysis of variance and multivariable regression. A p value <0.05 was considered statistically significant.

Results

A total of 837 women underwent a complex urodynamic study with evaluation of MUCP and ALPP using ICD-9 codes. Of these women, 550 had urodynamic records in the Synthetic Derivative database. Urodynamic SUI was confirmed in 478 women, of whom 323 had MUCP recorded, and of these, 263 had ALPP recorded. Of these 263 women with ALPP measurements, 199 leaked at 150 mL and 247 leaked at capacity (183 women leaked on ALPP at both 150 mL and capacity; Table 1). The mean age of the women was 59.1 ± 13.2 years, and 304 (94%) were Caucasian, 15 (5%) were African American, 2 (1%) were Asian/Pacific and

Table 1 Demographics, patient characteristics, and urodynamic measurements

Variable	Value
Age (years), mean ± SD	59.1 ± 13.2 (*n* = 323)
Parity, median (interquartile range)	2 (1) (*n* = 314)
Race	
African American	15/323 (5%)
Asian/Pacific	2/323 (1%)
Caucasian	304/323 (94%)
Other	2/323 (1%)
BMI (kg/m^2), mean ± SD	29.6 ± 6.6 (*n* = 293)
Volume at fist leak (mL), mean ± SD	154.3 ± 118.7 (*n* = 318)
Urethral mobility (°), mean ± SD	61.6 ± 20.2 (*n* = 289)
MUCP at capacity (cm H_2O), mean ± SD	45.5 ± 21.2 (*n* = 323)
ALPP at 150 mL (cm H_2O), mean ± SD	71.4 ± 33.5 (*n* = 199)
ALPP at capacity (cm H_2O), mean ± SD	68.3 ± 36.7 (*n* = 247)
UDS capacity (mL), mean ± SD	306.6 ± 97.2 (*n* = 321)
Prior anti-incontinence procedure	
No	261/308 (85%)
Yes	47/308 (15%)
POP-Q stage	
0	41/240 (17%)
I	55/240 (23%)
II	94/240 (39%)
III	36/240 (15%)
IV	14/240 (6%)
POP-Q stage of anterior compartment, median (interquartile range)	1 (2) (*n* = 240)
POP-Q stage of uterine or vaginal apex, median (interquartile range)	0 (1) (*n* = 240)
Pelvic floor muscle strength grade	
0	33/304 (11%)
1	94/304 (31%)
2	19/304 (6%)
3	72/304 (24%)
4	22/304 (7%)
5	64/300 (21%)

2 (1%) were of an other race. Their median parity was 2, and mean BMI was 29.6 ± 6.6 kg/m^2. The POP-Q stage of prolapse was distributed as follows: stage I (23%), stage II (39%), stage III (15%) and stage IV (6%). Low PFMS (Oxford grade 0 or 1) was observed in 40% of patients, medium PFMS in 29% (Oxford grade 2 or 3), and high PFMS in 27% (Oxford grade 4 or 5). Urethral hypermobility was observed in 244 patients (76%). The mean urethral mobility was 61.6 ± 20°. Only 45 women (15%) had undergone a prior anti-incontinence procedure.

Women with higher PFMS had a higher MUCP (Table 2). Women with a high PFMS had an average MUCP 10.3 cm H_2O higher than those with a low PFMS (95% CI 4.6–16.1; $p < 0.001$). This relationship persisted after adjusting for age and BMI ($p = 0.0375$). Linear regression was performed to evaluate associations between ALPP at 150 mL and MUCP, adjusting for PFMS, age, parity, BMI, prior anti-incontinence procedure, urethral mobility, bladder capacity, stage of cystocele, and stage of uterine or apical prolapse (Table 3). This was repeated using ALPP at capacity instead of at 150 mL. MUCP and age were inversely associated, while ALPP and age did not have a strong association. ALPP at 150 mL and MUCP were weakly associated (coefficient 0.43, 95% CI 0.08–0.78; $p = 0.02$), and ALPP at capacity and MUCP were moderately associated (coefficient 0.60, 95% CI 0.25–0.95; $p < 0.001$). ALPP at 150 mL and at capacity was not significantly associated with PFMS, age, parity, BMI, prior procedure, urethral mobility, stage of cystocele, or stage of uterine or apical prolapse. BMI was not significantly associated with MUCP or ALPP. This persisted when stratified by PFMS (Fig. 1).

Discussion

This study showed that in women with urodynamic SUI, MUCP and ALPP at 150 mL were weakly associated, and that this improved to a moderate association for ALPP at capacity. MUCP increased with increasing PFMS but decreased with increasing age. ALPP did not appear to be associated with PFMS or age. The relationship between MUCP and ALPP was unchanged when accounting for the covariates PFMS, age, parity, BMI, prior procedure, urethral mobility, bladder capacity, stage of cystocele, and stage of uterine or apical prolapse.

There were positive associations between MUCP at capacity and ALPP at capacity ($r = 0.60$) and between MUCP at capacity and ALPP at 150 mL ($r = 0.43$). This is consistent with the findings of other studies ($r = 0.56–0.62$) [5–7]. Nager et al. [7] evaluated the relationships between incontinence severity measures (including urethral excursion angle, pad weight after provocative activities, quality of life score, and SUI grade) and MUCP and leak point pressure (LPP) from data originally obtained in a clinical trial of a new urethral bulking agent. MUCP and LPP were modestly correlated ($r = 0.5–0.62$, $p < 0.001$), consistent with our findings. Women with more severe SUI had significantly lower MUCP and LPP values; however, only weak correlations were seen. Nager et al. did not include PFMS nor a regression analysis in their study [7].

Chai et al. [11] included PFMS in an assessment of urodynamic measures of urethral function among women with SUI enrolled in a randomized trial evaluating midurethral slings. PFMS was positively associated with urethral length ($p = 0.03$), but no relationship was found with MUCP or Valsalva leak point pressure (VLPP), and was not part of the final regression analysis. Chai et al. also looked at the

Table 2 Urodynamic parameters in 304 women categorized by strength of pelvic floor muscle strength (PFMS) and difference in means

Variable	Low PFMS (n = 127)		Medium PFMS (n = 91)		High PFMS (n = 86)		Difference in means for low to high PFMS (95% CI)
	Median quartile	Mean ± SD	Median quartile	Mean ± SD	Median quartile	Mean ± SD	
MUCP at capacity (cm H_2O)	37.0	40.6 ± 20.4	43.6	45.1 ± 19.4	49.0	51.0 ± 21.2	10.3 (4.6 to 16.1), $p < 0.001$
ALPP at 150 mL (cm H_2O)	68.5	71.2 ± 32.3	61.5	65.3 ± 31.2	68.5	73.6 ± 34.4	2.4 (−9.7 to 15), $p = 0.699$
ALPP at capacity (cm H_2O)	62.5	66.4 ± 39.1	60.0	66.8 ± 31.9	62.0	68.6 ± 37.3	2.1 (−9.9 to 14), $p = 0.729$

relationships between clinical and urodynamic variables (POP-Q stage, POP-Q point Aa, urethral excursion angle, pad weight, age, BMI, prior anti-incontinence surgery, duration of SUI and study arm assignment) and measures of urethral function (pressure of detrusor at maximum flow during urodynamics to MUCP, urethral length and VLPP). Similar to the findings of our study, they found an inverse relationship between MUCP and age (MUCP decreased with increasing age). They also found positive associations between BMI and MUCP and VLPP (MUCP and ALPP increased with increasing BMI), which we did not see in our study (Fig. 1). Chai et al. also found a positive association between MUCP and prior anti-incontinence surgery and between MUCP and detrusor pressure at maximum flow (*P*det at *Q*max), but a negative association between MUCP and pad weight. VLPP was positively associated with urethral excursion angle, BMI, and *P*det at *Q*max and negatively associated with duration of SUI [11]. Chai et al. included regression analysis, but did not assess how these variables affected the correlation between MUCP and VLPP [11].

Table 3 Regression model of the relationship between ALPP at 150 mL and covariates

Covariate	Coefficient	95% CI	p value
Intercept	45.91	−2.55 to 94.38	0.06
MUCP (full)	0.43	0.08 to 0.78	0.02
PFMS	−2.43	−8.20 to 3.34	0.41
Age	−0.36	−1.04 to 0.32	0.29
Age*[a]	−0.18	−1.01 to 0.66	0.67
Parity	0.33	−3.13 to 3.79	0.85
BMI	0.36	−0.37 to 1.10	0.33
Prior procedure	0.99	−11.26 to 13.24	0.87
Urethra mobility	0.07	−0.16 to 0.30	0.55
Stage cystocele	2.92	−2.61 to 8.44	0.3
Stage uterine or apex	−1.73	−6.91 to 3.46	0.51
Urodynamic capacity	0.05	0.00 to 0.10	0.04
MUCP+PFMS[b]	0.03	−0.09 to 0.14	0.66

[a] Cubic spline interpolation

[b] mutual interaction

The study populations in both of the studies discussed above differed from ours in that they were secondary analyses of women enrolled in trials, whereas our population was a cohort of women presenting for urogynecological care at a tertiary referral center. We observed no change in the relationship between MUCP and ALPP when covariates of PFMS, age, parity, BMI, prior procedure, urethral mobility, stage of cystocele or stage of uterine or apical prolapse were included in the regression model. This implies there is either a more complex link between MUCP and ALPP that was not measured in our study, or that these are inherently different measures and there are differences between static and dynamic urethral function.

In patients with high PFMS the mean MUCP was 10.3 cm H_2O higher than in patients with an absent/weak PFMS. Those with higher PFMS would on average have a higher MUCP. In a systematic literature review, Zubieta et al. evaluated the influence of pelvic floor physical therapy on changing urodynamic measurements, and found increases in MUCP in the range 4 to 25 cm H_2O compared with baseline after pelvic floor physical therapy [14]. This suggests a potential mechanism by which pelvic floor muscle exercises can improve SUI. In our study, women with higher PFMS had higher MUCP values. Physiologically, MUCP is a complex relationship between the pressure exerted by the urethral sphincter and the pelvic floor muscles, the strength of which is influenced by the degree of intactness and level of innervation of the muscle tissue [19, 20]. A mechanistic explanation likely involves the recruitment of more and larger motor units in the pelvic floor muscles in women with higher PFMS [11, 21]. Kenton and Brubaker found that the urethral sphincter is not activated by voluntary pelvic floor muscle squeeze [9]. This is consistent with the findings of anatomic dissections showing that the urethral sphincter derives its innervation from the perineal branch of the pudendal nerve, and the levator-ani are innervated by sacral roots 3 to 5 [19, 20].

We found a negative association between MUCP and age, and this is supported by prior studies showing that MUCP decreases

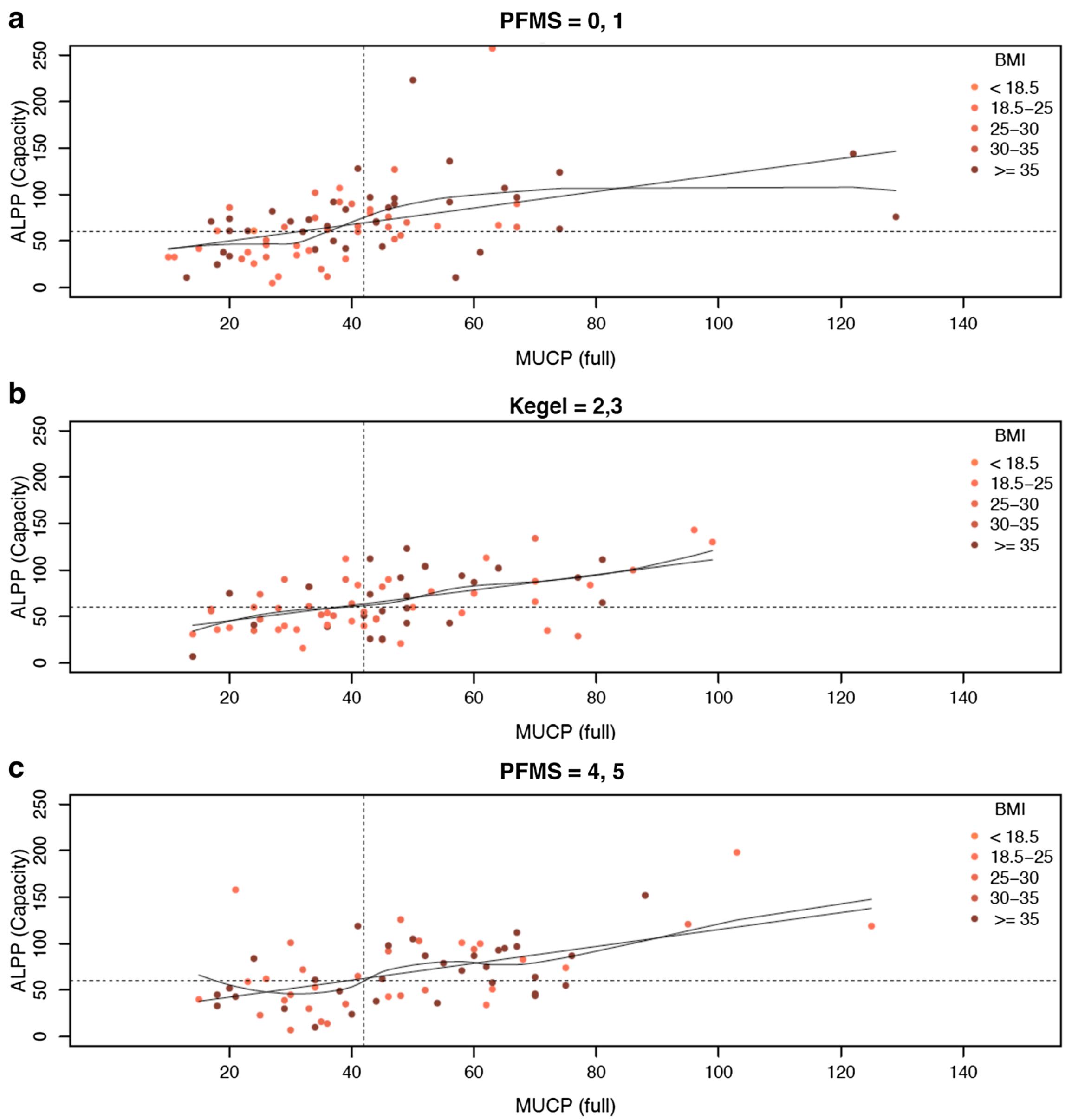

Fig. 1 ALPP at capacity versus MUCP at capacity stratified by pelvic floor muscle strength (**a** PFMS grade 0 or 1, **b** PFMS grade 2 or 3, **c** PFMS grade 4 or 5) and BMI. (*ALPP* abdominal leak point pressure,*MUCP* maximum urethral closure pressure, *BMI* body mass index)

with increasing age [22–24]. A likely mechanism is age-related neuromuscular degeneration of the urogenital sphincter, as a histological study of 13 cadaveric female urethras of various ages found that the number of intramuscular nerves in the urogenital sphincter decreases with increasing age [25].

The strengths of this study are that it included a large number of women presenting for urogynecological care at a tertiary referral center and a thorough statistical analysis using a multivariable regression model to account for potential confounders. There were a number of limitations to this study. This was a retrospective study and we were limited in our ability to assess whether MUCP or ALPP were related to severity or degree of bother of SUI given that validated patient questionnaires were not accessible in the Synthetic Derivative database. In order to de-identify patient information, the Synthetic Derivative database removes all identifying information in typed records within the electronic medical record, but does not have the ability to de-identify scanned documents and questionnaires. It is standard at our institution to measure MUCP at capacity and ALPP at 150 mL and at capacity, and we do not know if our results would have been affected if these parameters had been assessed at other volumes. Our results represent a comparison of measurements within a population prior to treatment for SUI, and we were unable to assess changes in urodynamic parameters after pelvic floor physical therapy.

This study was not designed to evaluate the physiology of the urethra, but a mechanistic explanation for our findings comes from prior studies that have shown that MUCP may be augmented in real-time by voluntary contraction of the levator ani muscles during the passage of the pressure transducer through the mid-urethra [26, 27]. Moreover, sustained increases in MUCP occur after pelvic floor muscle strengthening [14], as well as improvements in SUI [28]. Modalities to better identify which who will benefit from pelvic floor physical therapy could improve the utilization of conservative therapies.

Compliance with ethical standards

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Conflicts of interest None.

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