Urol Res (1993) 21:339–343

Urological Research

The dynamic pressure response to rapid dilatation of the resting urethra in healthy women: an in vivo evaluation of visco-elastic properties

P. Bagi, P. Thind, H. Colstrup, J.K. Kristensen

Department of Urology, D-2111, Rigshospitalet, University of Copenhagen, Blegdansvej 9, DK-2100 Copenhagen, Denmark

Received: 12 March 1993 / Accepted: 4 June 1993

Summary. The urethral pressure response to a sudden forced dilatation was studied at the bladder neck, in the high-pressure zone and in the distal urethra in ten healthy female volunteers. The pressure response was fitted with a double exponential function of the form $P_t = P_{\text{equ}} + P_\alpha e^{-t/\tau\alpha} + P_\beta e^{-t/\tau\beta}$, where P_{equ}, P_α and P_β are constants, and τ_α and τ_β are time constants; this equation has previously been demonstrated to describe the pressure decay following dilatation. On the basis of a theoretical model the elastic and viscous constants for the urethral tissues were computed. The results showed significant differences along the urethra, with the high-pressure zone showing the highest maximum and equilibrium pressures, fastest pressure decay and highest elastic coefficient. The pressure response represents an integrated stress response from the surrounding structures, which reflects the visco-elastic properties of the tissues involved. The findings seem therefore to correlate well with the anatomical findings, which have shown a high fibre density of the horseshoe-shaped rhabdosphincter in the mid-portion of the urethra. The method permits a detailed assessment of static and dynamic urethral responses to dilatation which can be applied as an experimental simulation of urine ingression, and is therefore presumed to be of value in the evaluation of normal and pathological urethral sphincter function.

Key words: Female urethra – Field-gradient method – Incontinence – Stress relaxation – Visco-elasticity

The urethral response to a sudden forced dilatation is a steep pressure increase, followed by an exponential pressure decay over the ensuing seconds (Fig. 1). This pressure response is part of the visco-elastic property of the urethra, which emerges as an integrated tissue reaction to stretch of the periluminal structures. The phenomenon has been studied by Lose and Colstrup [21] and Thind et al. [29], who applied arbitrary time constants to the description of the decay phase, and could thus demonstrate significant differences between normal and genuinely stress incontinent women. We recently published a more detailed mathematical analysis of the relaxation phenomenon [4, 5]. It was shown that the pressure decay after a sudden forced dilatation of the urethra followed a double exponential function of the following form:

$$P_t = P_{\text{equ}} + P_\alpha e^{-t/\tau\alpha} + P_\beta e^{-t/\tau\beta}$$

where P_{equ}, P_α and P_β are constants, and τ_α and τ_β are time constants [4]. It was demonstrated that the time constants were insensitive to the circumstances of dilatation, whereas the pressure parameters (P_{equ}, P_α and P_β) were influenced by the size and/or the velocity of dilatation, and it was concluded that the time constants were characteristic of a given location in a given urethra. On the basis of a mechanical model the analyses were extended, and the elastic and viscous constants for the involved urethral tissue elements were computed [5].

The aim of the present study was to evaluate the dynamic mechanical properties of the female urethra by means of a mathematical analysis of the pressure response following rapid dilatations at well-defined urethral locations.

Materials and methods

Ten healthy nulliparous female volunteers aged 21–45 years (median 25 years), without past or present urological or gynaecological complaints, participated in the study. Informed consent and approval by the local ethics committee were obtained.

Urethral dilatations were studied using a specially designed double-microtip transducer catheter [20]. The proximal sensor was covered with a water-filled, fully distensible rubber balloon, in which the cross-sectional area was measured over a segment (2 mm long) according to the field-gradient principle [14]. The inflation of the balloon was performed using a gravity-operated pump, which allowed variation of volumes and rates of the inflation [27].

The women were examined in the supine position with an empty bladder. The probe was placed with the tip sensor in the bladder and

Correspondence to: Per Bagi, FAX: +(45)35452158

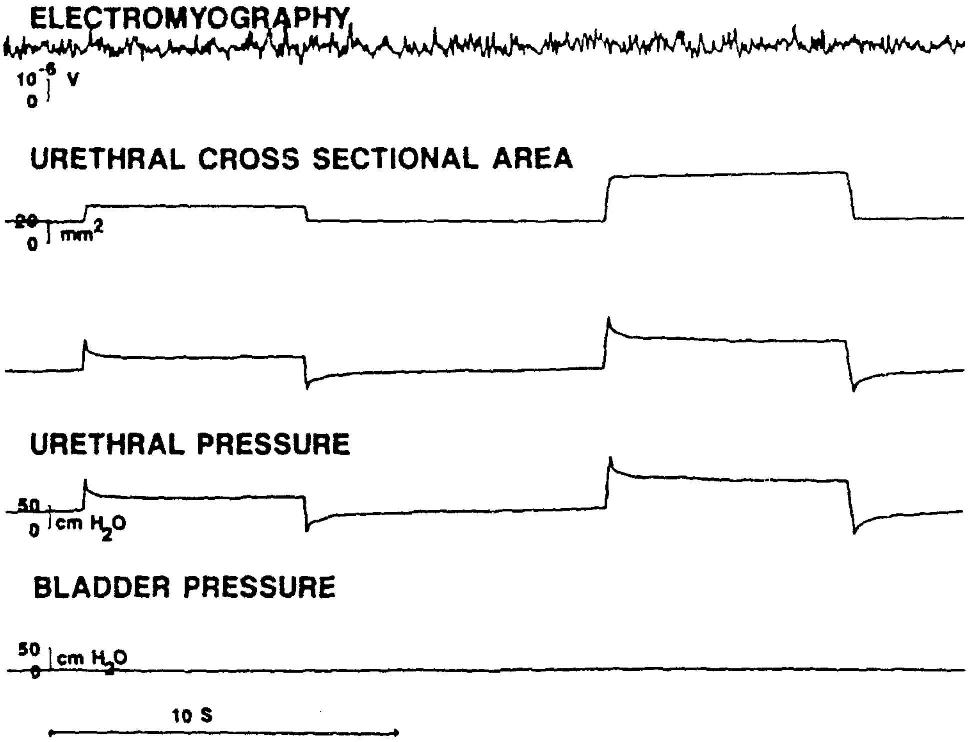

Fig. 1. Urethral pressure response to sudden increase in cross-sectional area. The urethral pressure and cross-sectional area are shown together with the pelvic floor EMG and bladder pressure

the balloon (i.e. the cross-sectional area measuring segment) either 0.75 cm from the bladder neck, in the high-pressure zone or 0.75 cm from the external meatus (distal urethra). At each location four identical dilatations were performed, all initiated at a cross-sectional area of 20 mm^2. Changes in cross-sectional areas of 20 and 40 mm^2, and dilatation rates of 50 and 150 mm^2/s were used. The electromyographic (EMG) signal from the pelvic floor was measured by surface electrodes placed at the mid-portion of the anterior vaginal wall to exclude striated muscle contraction during measurement.

All parameters were measured and displayed on a six-channel recording system (DISA URO-system 21F16 2100). The frequency response of the amplifying system was 100 Hz. A paper speed of 15 mm/s was used.

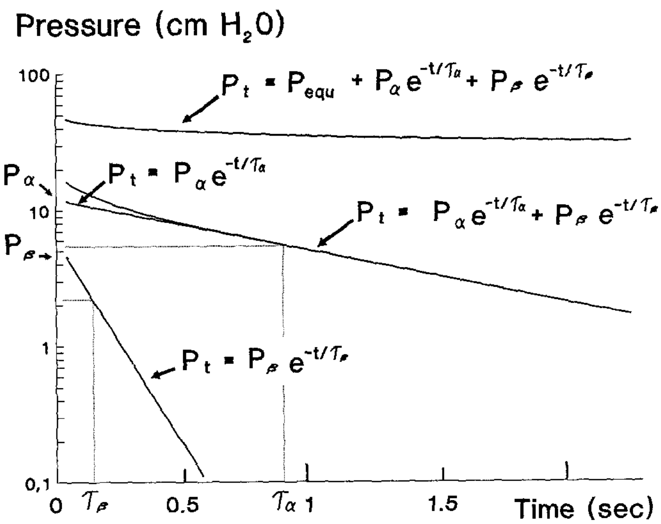

Fig. 2. Urethral pressure response to sudden increase in cross-sectional area. The original pressure is shown together with its components. Pressure is plotted on a logarithmic scale

Statistical analyses were performed using Friedmann's test for unordered alternatives. Significance was taken as $P < 0.05$ [25].

Data analysis

At all dilatations the pressures were read at steady state before inflation, after each 0.1 s during the first second, after each 0.5 s during the next 2 s, and then every second until equilibrium was reached. The pressures from the decay phases were subsequently fitted with an exponential function of the following form:

$$P_t = P_{equ} + P_\alpha e^{-t/\tau\alpha} + P_\beta e^{-t/\tau\beta}$$

where P_t is the pressure at time t, P_{equ} is the equilibrium pressure, P_α and P_β are constants which represent the pressure decay, and τ_α and τ_β are time constants (Fig. 2).

On the basis of a mechanical model (Figs. 3, 4), which has been described in detail previously [5], the elastic (E) and viscous (η) constants of each participating component (α, β, γ) were then computed according to the following formulas:

Elastic constants:

$$E_\gamma = (P_{equ} \times \sqrt{CA_{equ}} - P_{orig} \times \sqrt{CA_{orig}})/[\sqrt{\pi} \times (\sqrt{CA_{equ}/CA_{orig}} - 1)]$$

$$E_\alpha = \{(P_{max} - P_{equ}) \times \sqrt{CA_{equ}}/[\sqrt{\pi} \times (\sqrt{CA_{equ}/CA_{orig}} - 1)]\} \times P_\alpha/(P_\alpha + P_\beta)$$

$$E_\beta = \{(P_{max} - P_{equ}) \times \sqrt{CA_{equ}}/[\sqrt{\pi} \times (\sqrt{CA_{equ}/CA_{orig}} - 1)]\} \times P_\beta/(P_\alpha + P_\beta)$$

where P_{orig} is the pressure before dilatation, P_{max} is the maximum pressure at the end of dilatation, P_{equ} is the equilibrium pressure after dilatation, and CA_{orig} and CA_{equ} are cross-sectional areas before and after dilatation.

Viscous constants:

$$\eta = \tau \times E$$

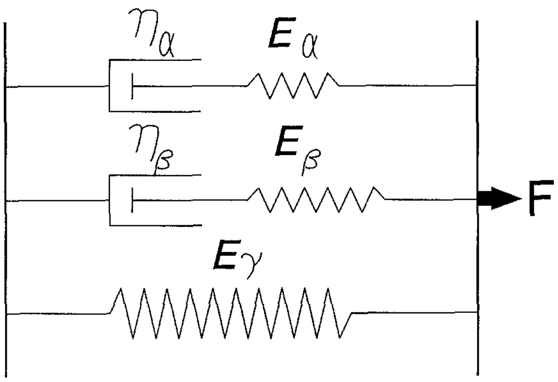

Fig. 3. Mechanical model consisting of two Maxwell elements (α- and β-components) and one hooke element (γ-component) coupled in parallel. The decay in force (F) following a stretch mimics that observed for the urethra

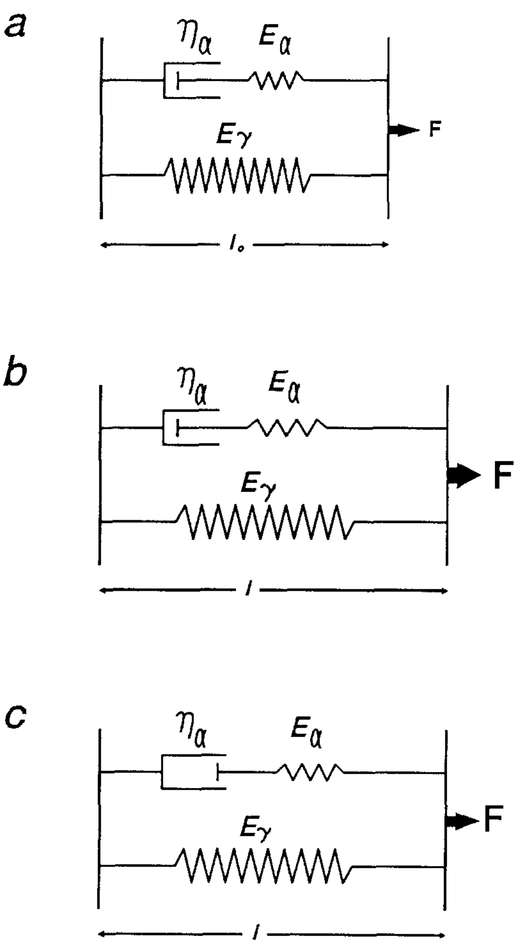

Fig. 4a–c. Demonstration of the time-dependent function for the model shown in Fig. 1. For simplicity only one Maxwell element is shown. **a** Condition in resting state before stretch. **b** Immediately after elongation both spring elements have increased in length, but the viscous element has not. **c** At equilibrium the viscous element has increased in length and its corresponding elastic element has decreased. It is a prerequisite for this model that the stretch is a mathematical step-function with zero duration, as otherwise the viscous element will have started elongation at the end of stretch and the measured force will have declined

Results

Two women demonstrated one exponential function only in all four test situations at one of the urethral locations, and a further three recordings from different locations/patients were omitted for similar reasons. This left 109 recordings (91%) for analysis.

The pressure parameters (P_{max}, P_{equ}, P_α and P_β and the time constants (τ_α and τ_β) are related to urethral site of measurement in Table 1. It appears that P_{equ} and P_{max} varied significantly along the urethra, with the high-pressure zone showing the highest pressures. Similarly, the time constant τ_α differed significantly between sites, with the values from the high-pressure zone being fastest. When looking at the elastic and viscous coefficients, only E_γ showed a significant variation along the urethra, again with the values from the high-pressure zone being highest (Table 2).

Discussion

Evaluation of urethral closure function is essential for the understanding of the continence mechanism, but even though a large number of techniques have been proposed, they have not contributed substantially to a clarification of normal and pathological sphincter function. However, the majority of previous studies have been based on intraurethral pressure measurements during rest or stress episodes performed at fixed urethral dilatations, which were given by the dimensions of the measuring probes [2,

Table 1. Pressure parameters P_{max}, P_{equ}, P_α and P_β (cmH_2O) and time constants τ_α and τ_β (s) related to urethral site of measurement

	Bladder neck	High-pressure zone	Distal urethra
P_{equ}	82 (57–106)	109 (100–143)	95 (78–111)[b]
P_{max}	116 (83–150)	158 (133–191)	132 (105–154)[b]
P_α	15 (8–22)	16 (11–22)	14 (10–20) NS
P_β	16 (10–20)	20 (11–31)	13 (6–23) NS
τ_α	1.08 (0.92–1.24)	0.97 (0.87–1.05)	1.06 (1.0–1.2)[a]
τ_β	0.23 (0.17–0.28)	0.21 (0.16–0.26)	0.24 (0.2–0.3) NS

Values are median and quartiles
[a] $P<0.01$
[b] $P<0.001$
NS, Not significant

Table 2. Elastic coefficients E_γ, E_α and E_β (N/m) and viscous coefficients η_α and η_β (Ns/m) related to urethral measurement site

	Bladder neck	High-pressure zone	Distal urethra
E_γ	34 (27–39)	41 (38–49)	37 (32–41)[a]
E_α	12 (7–19)	11 (8–16)	12 (8–16) NS
E_β	13 (9–17)	14 (7–24)	10 (6–15) NS
η_α	12 (7–17)	10 (7–13)	13 (8–17) NS
η_β	2.8 (1.7–3.8)	3.1 (1.5–5.7)	2.5 (1.4–3.5) NS

Values are median and quartiles
[a] $P<0.001$
NS, Not significant

6, 9, 16, 31]. In contrast, the present method offers a direct evaluation of the efficiency of the closure apparatus by a dynamic assessment of the sphincter's resistance to dilatation.

Urethral dilatation induces stretching of the periluminal structures, and is therefore equivalent to the classical biorheological stress – strain studies [1, 12]. The stretch imparts energy to the tissues; however, part of this energy is dissipated, so the stress declines until a new equilibrium is reached within a few seconds. This phenomenon represents an integrated stress response from the participating structures, the character of which is determined by the composition of the tissues involved. Obviously, these tissues may be intramural as well as extramural, but basically they consist of collagen, elastin and muscle, all of which have fundamentally different visco-elastic properties. A description of the urethral stress – strain relation following forced dilatation will therefore represent a characterization of the participating tissue structures. For a number of reasons, however, urethral wall stress is not measurable in vivo, but stress and intraluminal pressure are intimately interrelated; therefore changes in stress subsequent to urethral dilatation are accurately reflected by changes in pressure [4].

The visco-elastic properties at a given urethral location have previously been shown to be unaffected by the circumstances of dilatation, which indicates that the contributing structures are more or less identical within certain limits of dilatation [4, 5]. However, it remains to be resolved which tissue components are responsible for these phenomena [15, 28]. The wall of the female urethra is rich in collagen and smooth muscle fibres, which are both arranged predominantly longitudinally in parallel with each other [3, 15]. The contribution to the pressure response from these structures therefore seems to be small. The horseshoe-shaped intramural rhabdosphincter, on the other hand, with its abundant circularly arranged slow-twitch striated muscle fibres in the mid-portion of the urethra, seems to be the major contributor to the integrated pressure response [13, 23]. Its uneven distribution along the urethra correlates well with the findings in the present study of higher pressures ($P_{\max}$ and P_{equ}) and static elasticity (E_y) in the high-pressure zone, and are in line with previous results concerning urethral pressure and compliance in healthy women [7, 19]. The impact of voluntarily acting muscles has, on the other hand, been shown to be greatest in the proximal half of the urethra [8, 22]. In agreement with the incontestably higher fibre density of the rhabdosphincter at the mid-urethra and distal urethra as compared with the proximal part, this signifies the impact of peri-urethral muscles on the proximal part of the urethra, which further correlates well with anatomical findings showing that the levator ani muscle exerts its effect on the proximal urethra through tendinous connections [10, 11, 24].

The pressure decay/energy dissipation following dilatation, as represented by P_α and P_β, showed no variance along the urethra. This implies that the size of the integrated pressure response from muscle and connective tissues is almost identical throughout the urethra. The velocity of the pressure decay, however, varied significantly along the urethra, with the mid-urethral values being highest. These findings are inconsistent with the findings of previous studies, which have shown some arbitrary time constants to vary insignificantly along the urethra [21, 26, 28]. However, the more detailed analysis applied here may explain this discrepancy by revealing a difference in the dynamic mechanical properties along the urethra. Again, the rhabdosphincter seems to be the most likely explanation, because, as a dominant component of the circularly arranged structures in the high-pressure zone, it influences the stress-relaxation significantly towards a fast response characteristic of striated muscle, in contrast to the much slower response seen in smooth muscle [17].

Increasing evidence indicates that changes in the dynamic mechanical properties of the urethra are of significance in the development of genuine stress incontinence. The present method enables a detailed assessment of static and dynamic urethral responses to dilatation which can be applied as an experimental simulation of urine ingression [30]. The method may therefore be of value in a segmental characterization of the normal urethral sphincter function, and may provide further insight into pathological sphincter function with regard to mechanical properties as well as anatomical location.

References

1. Apter JT, Marquez E (1968) A relation between hysteresis and other visco-elastic properties of some biomaterials. Biorheology 50:285
2. Asmussen M, Ulmsten U (1976) Simultaneous urethro-cystometry with a new technique. Scand J Urol Nephrol 10:7
3. Astbury WT (1947) On the structure of biological fibres and the problem of muscle. Proc R Soc Lond [Biol]134:303
4. Bagi P, Thind P, Colstrup H (in press) In vivo evaluation of visco-elasticity in a biological tube. I. Stress relaxation in the female urethra studied by cross-sectional area and pressure measurements. Med Biol Eng Comput
5. Bagi P, Thind P, Colstrup H (in press) In vivo evaluation of visco-elasticity in a biological tube. II. Application of a mechanical model. Med Biol Eng Comput
6. Brown M, Wickham JEA (1969) The urethral pressure profile. Br J Urol 41:211
7. Colstrup H (1984) Rigidity of the resting female urethra. I. Static measurements. J Urol 132:78
8. Colstrup H (1985) Voluntary contractions in the female urethra. J Urol 134:902
9. Constantinou CE, Govan DE (1982) Spatial distribution and timing of transmitted and reflexly generated urethral pressures in healthy women. J Urol 127:964
10. DeLancey JOL (1988) Structural aspects of the extrinsic continence mechanism. Obstet Gynecol 72:296
11. DeLancey JOL (1989) Pubovesical ligament: a separate structure from the urethral supports. Neurourol Urodyn 8:53
12. Fung YC (1981) Biomechanics: mechanical properties of living tissues. Springer, Berlin Heidelberg New York
13. Gosling JA (1985) The structure of the female lower urinary tract and pelvic floor. Urol Clin North Am 12:207
14. Harris JH, Therkelsen EE, Zinner NR (1971) Electrical measurement of ureteral flow. In: Boyarski S, Tanagho EA, Gottschalk CW, Zimskind PD (eds) Urodynamics. Academic Press, New York
15. Hickey DS, Phillips JI, Hukins DWL (1982) Arrangements of collagen fibrils and muscle fibres in the female urethra and their implications for the control of micturition. Br J Urol 54:556
16. Hilton P, Stanton SL (1983) Urethral pressure measurement by

microtransducer: the results in symptom-free women and in those with genuine stress incontinence. Br J Obstet Gynecol 90:919
17. Hoyle G (1983) Muscles and their neural control. Wiley, New York
18. Huisman AB (1983) Aspects on the anatomy of the female urethra with special relation to urinary continence. Contrib Gynec Obstet 10:1
19. Lose G (1989) Mechanical properties of the urethra in healthy female volunteers: static measurements in the resting urethra. Neurourol Urodyn 8:451
20. Lose G, Colstrup H, Saksager K, Kristensen JK (1986) New probe for measurement of related values of cross-sectional area and pressure in a biological tube. Med Biol Eng Comput 24:488
21. Lose G, Colstrup H (1990) Mechanical properties of the urethra in healthy and stress incontinent females: dynamic measurement in the resting urethra. J Urol 144:1258
22. Lose G, Colstrup H (1991) Urethral pressure and power generation during coughing and voluntary contraction of the pelvic floor in healthy females. Br J Urol 67:573
23. Oelrich TM (1983) The striated urogenital sphincter muscle in the female. Anat Rec 205:223
24. Olesen KP, Grau V (1976) The suspensory apparatus of the female bladder neck. Urol Int 31:33
25. Siegel S, Castellan NJ (1988) Nonparametric statistics for the behavioral sciences. McGraw-Hill, New York
26. Thind P (1992) Stress relaxation phenomenon in the healthy female urethra. Br J Urol 69:71
27. Thind P, Colstrup H, Lose G, Kristensen JK (1991) Method for evaluation of the urethral closure mechanism in women during standardised changes of cross-sectional area. Clin Physiol Meas 12:163
28. Thind P, Lose G (1992) Urethral stress relaxation phenomenon in healthy and stress incontinent women. Br J Urol 69:75
29. Thind P, Lose G, Colstrup H (1992) Pressure response to rapid dilation of the resting urethra in healthy women. Urology 40:44
30. Thind P, Lose G, Colstrup H (1992) Resistance to forced opening of the resting urethra in healthy females assessed by experimental simulation of urine ingression. Neurourol Urodyn 11:201
31. Versi E, Cardozo L, Studd J, Cooper D (1986) Evaluation of urethral pressure profilometry for the diagnosis of genuine stress incontinence. World J Urol 4:6