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A technique for measurement of related values of pressure and cross-sectional area in the male urethra

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Summary. A probe for measurement of related values of cross-sectional area and pressure in the male urethra was constructed. The probe allows induction of variable pressures or fluid volumes in a distensible balloon located in the urethra and simultaneous recording of related values of cross-sectional area and pressure. Cross-sectional area is measured in the range of 11–102 mm^2 using the field-gradient principle. Pressure is measured in the range of 0–250 cmH_2O using tip transducers. The time constant for cross-sectional area measurement is 0.02 s and that for pressure measurement, 0.007 s. The pressures required to reach the maximal and minimal cross-sectional areas of the balloon are 2.8 and −2.4 cmH_2O, respectively. The shape of the probe after its placement in the urethra was studied by transrectal ultrasound in five volunteers. The results showed that the measurement error caused by the slope of the balloon walls or the forced bending of the catheter did not exceed 5%. The method enables a description of the biomechanical properties of the male urethra at rest in terms of estimated pressure at zero cross-sectional area, elastance, and stress-relaxation and at voluntary contraction in terms of work and power as evaluated at well-defined anatomical locations.

Key words: Male urethra – Pressure/cross-sectional area relation – Field-gradient principle – Pressure – Elastance – Compliance – Work – Power

The dynamics of micturition are established by the balance between detrusor and outlet function, and a detailed knowledge of both components is important for a proper understanding of the complex mechanism of normal and disordered voiding. A major clue in the interpretation of the outlet function lies in the elasticity of the system per se or, more accurately, the elasticity of the flow-rate-controlling zone. The basic properties may thus be expressed by effective urethral cross-sectional area at a given pressure as reflected by urethral opening pressure and compliance [8, 9]. We therefore constructed a special probe for measurement of related values of cross-sectional area and pressure in the male urethra based on the principles originally described by Colstrup et al. [2]. The probe permits induction of variable pressures in a distensible balloon and recording of related cross-sectional area and vice versa, whereby it offers information permitting evaluation of static and dynamic urethral properties at rest and at voluntary contraction. The aims of the present study were (1) to describe the probe, (2) to describe a method for investigation of the pressure/cross-sectional area relations in the male urethra using this probe, and (3) to describe the ultrasonographic appearance of the probe during examination.

Description of the probe

The probe consists of (a) an outer 14-F polyvinylchloride (PVC) catheter equipped with a short (15 mm) 9-F Polyolefine tube with four electrodes mounted at the tip for cross-sectional area measurement and (b) an inner 7-F double-tip transducer (Dantec, Denmark) for pressure measurement in the bladder and balloon (Fig. 1). The

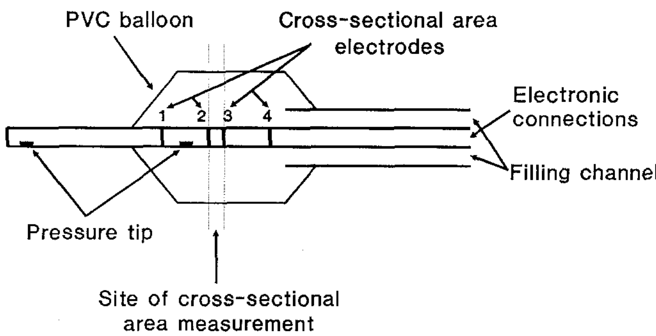

Fig. 1. Schematic longitudinal section of the measuring probe

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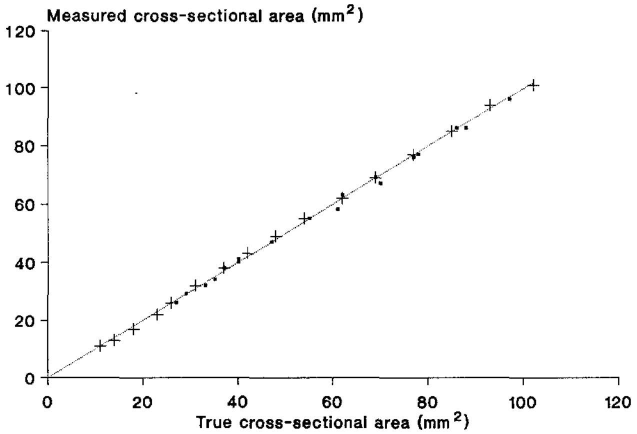


Fig. 2. Calibration in regular (+) and irregular (■) lumens (median, 10 measurements in each lumen)

Polyolefine tube is mounted with four coiled ring electrodes of 0.1 mm platinum glued to the surface, with a distance of 2 mm separating the two sensing electrodes. The balloon tip transducer is placed immediately distal to the Polyolefine tube, leaving 6 cm between the bladder tip transducer and the platinum sensing electrodes. The Polyolefine tube and the balloon tip transducer are covered by a balloon made of 0.01 mm PVC. The midportion of the balloon has the shape of a cylinder with a length of 15 mm and a circumference of 40 mm. The balloon is inflated and deflated through a space of 3.7 mm^2 between the PVC catheter (inner cross-sectional area; 7.6 mm^2) and the pressure transducer (outer cross-sectional area, 3.9 mm^2).

The cross-sectional area is measured using the field-gradient principle [5]. According to this, the impedance in an electrolyte-containing (0.9% NaCl) straight tube (the balloon) to a high-frequency (HF) alternating current (ac; 5 kHz, 45 μA) between two generating electrodes (1 and 4 in Fig. 1) is measured between two sensing electrodes (2 and 3 in Fig. 1). The voltage difference (V) between the two sensing electrodes with the distance λ will be $V = I \times \lambda / (\delta \times CA)$, where I is the current, δ is the conductivity of the fluid, and CA is the cross-sectional area of the tube (the balloon). As I, λ and δ are constants, it appears that V is inversely proportional to CA, and the electronic unit has therefore been equipped with a reciprocal generator giving a voltage output directly proportional to the cross-sectional area.

In the present study, the cross-sectional area and pressure measurements were recorded on a six-channel recorder (DISA UROsystem 21F16 2100, Dantec, Denmark).

In vitro testing of the probe

Cross-sectional area measurement

Linear range and measuring accuracy. A standard of known cross-sectional areas was made by drilling circular lumens into a block of hard PVC. Cross-sectional area measurements were made in these regular lumens as well as in irregular lumens made by inserting catheters of known cross-sectional area into the drilled lumens. Figure 2 shows a calibration curve obtained from ten measurements of each cross-sectional area. The lower limit is the cross-sectional area of the electrode-carrying catheter covered by the deflated balloon (10 mm^2), and the upper limit is the cross-sectional area of the balloon (127 mm^2). Acceptable linearity was found in the range from 11 to 102 mm^2. The median difference between the true and the measured cross-sectional area was 0 (range, from 3 to -2 mm^2). Measurements taken in lumens drilled into highly conductive material (stainless steel) were equal to those obtained in PVC. Thus, the PCV balloon provides adequate insulation to avoid shunting of the current to the surroundings.

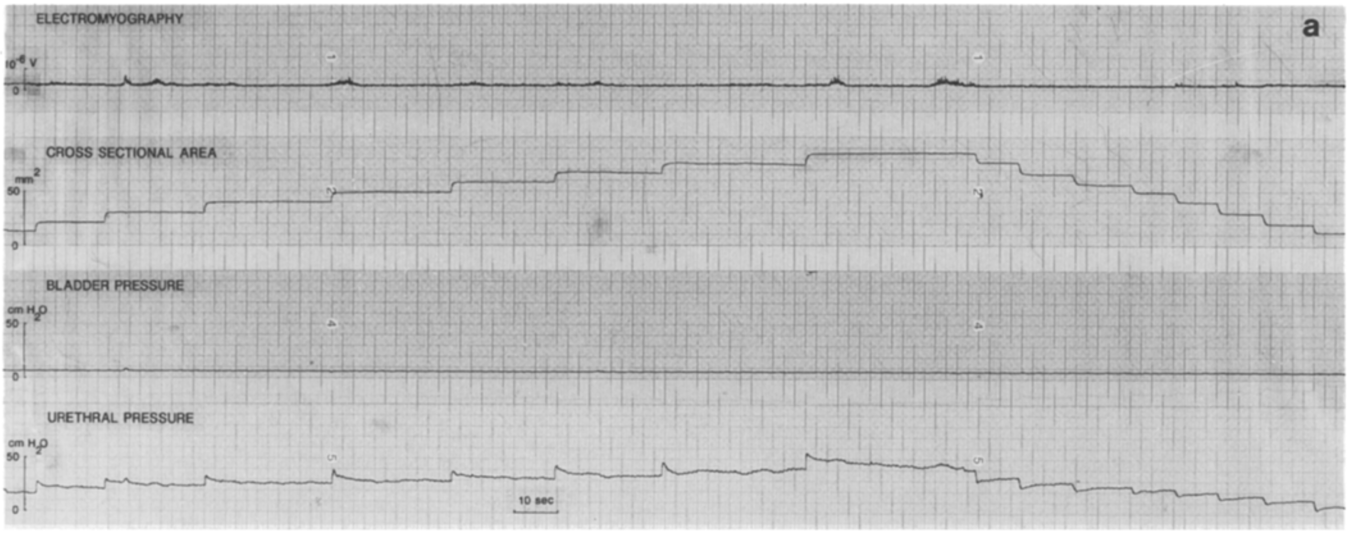
Probe-position effect. Displacing the electrode-carrying catheter from the center to the wall of circular lumens of 65 and 25 mm^2 resulted in errors in cross-sectional area measurement of 4 mm^2 (7%) and less than 1 mm^2 (<5%), respectively. In straight tubes, though, the design of the probe, with a balloon surrounding the electrode-carrying catheter, will secure a central position of the probe. However, in curved tubes the sensing electrodes may be displaced toward the wall. The significance of this phenomenon was studied in tubes with cross-sectional areas of 65 and 25 mm^2, curved according to circles with a radius of 5 and 3 cm, respectively. The resulting maximal measurement error was 4% (cross-sectional area, 65 mm^2; radius, 3 cm).

Time response for cross-sectional area measurement. The time response for cross-sectional area measurement was investigated by rapid retraction of the probe from a cylindrical lumen just capable of containing the probe into an infinite lumen. The cross-sectional response was found to be aperiodic, with the time constant, i.e., the time needed for the cross-sectional area to reach 63% of the final value, being 0.02 s [10].

Pressure measurement

Pressure of inflation and deflation. The PVC balloon was inflated and deflated in steps using a 1-ml syringe. A pressure of 2.8cm H_2O was required to fill the balloon to its maximal cross-sectional area, and the mininal cross-sectional area was reached at a pressure of -2.4 cmH_2O. The distance between the inflation and deflation curves was less than 0.5 cmH_2O. Measurements made in a pressure chamber with and without the pressure sensor being covered by the balloon gave identical results. Fast inflation at velocities of up to 300 mm^2/s resulted in a maximal pressure increase in the balloon of 3 cmH_2O when measured both in free air and in water.

Time response for pressure measuring in the balloon. The time response for pressure measurement was studied with the probe in a pressure chamber. Using the step-test method, the pressure response was found to be aperiodic, with the time constant being 0.007 s [3, 10].



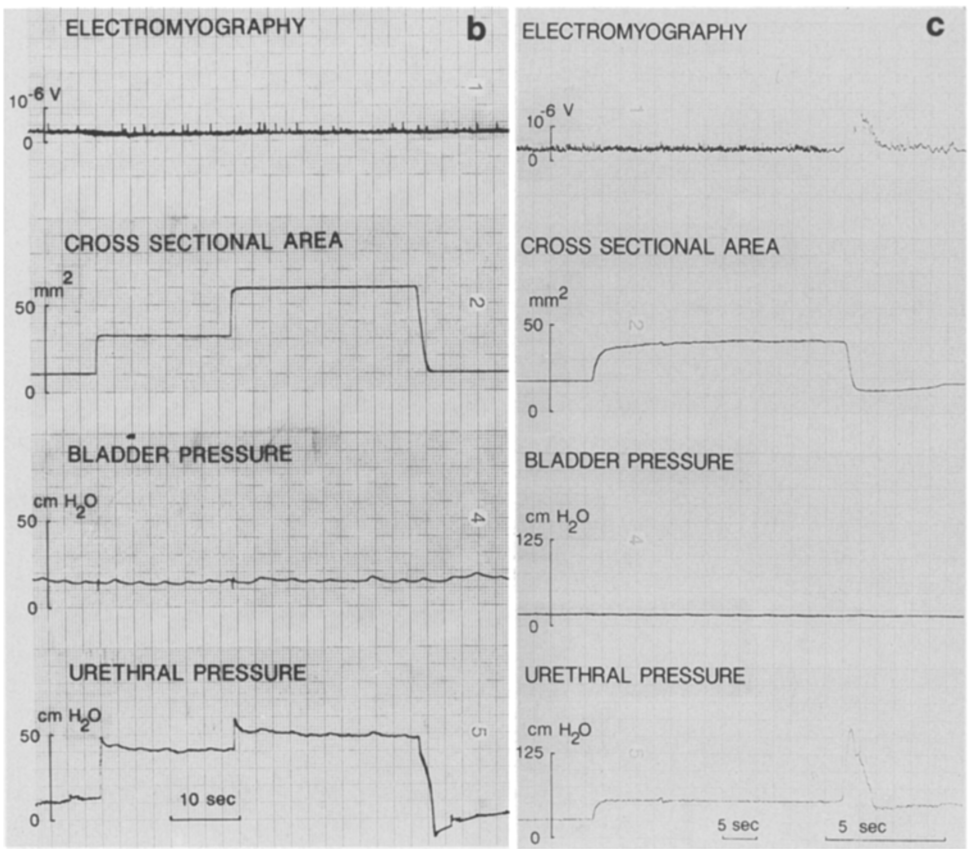


Fig. 3a–c. Simultaneous measurement of pressure and cross-sectional area in the balloon, bladder pressure, and anal surface EMG during **a** inflation and deflation of small (~10 mm^2) fluid volumes in the balloon, **b** inflation of large (~20 mm^2) fluid volumes in the balloon, and **c** squeezing

Clinical application

Method

Investigations are performed with the subject in the supine position with an empty bladder. The catheter is introduced into the urethra and placed with the balloon in the bladder. The catheter is then mounted in a specially designed retraction device, which permits well-defined retractions from a minimum of 1 mm. The balloon is connected to a pressure reservoir with a pressure of 10–15 cmH_2O above bladder pressure and is slowly retracted until the sensing electrodes enter the urethra as indicated by a fall in cross-sectional area. Measurements are initiated after the catheter is retracted a further 5 mm from the bladder neck and are repeated at 5-mm intervals until the membranous urethra is passed. At each measurement location the balloon is adjusted to a cross-sectional area of 12–13 mm^2 before the following procedures are performed:

1. The balloon is inflated in steps of approximately 10 mm^2 by means of a gravitationally driven pump [11]. After each inflation, pressure equilibrium as indicated by

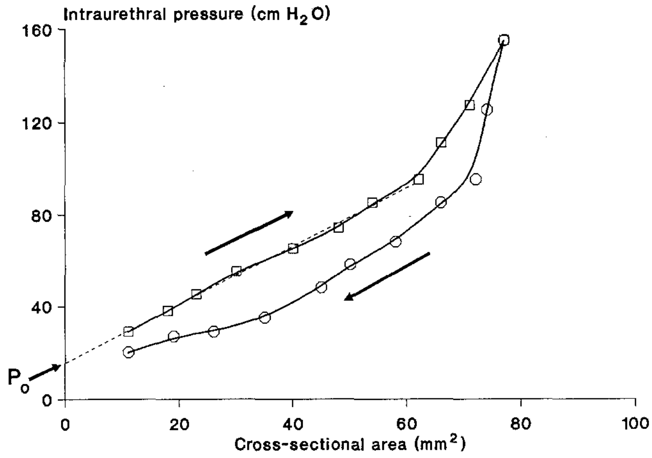


Fig. 4. Related values of pressure and cross-sectional area in the balloon measured at pressure equilibrium after inflation and deflation of the balloon. The estimated urethral pressure at zero cross-sectional area (P_0) is indicated

a constant balloon pressure (P_b) is awaited, and the inflation is continued until a cross-sectional area of 80 mm^2 or a balloon pressure of 150 cmH_2 is reached. The balloon is then deflated likewise until the minimal cross-sectional area is reached.

2. The inflation procedure is repeated using steps of approximately 20 mm^2.
3. The balloon is connected to a pressure reservoir with a pressure equal to that in the balloon at a cross-sectional area of approximately 40 mm^2 and is allowed to fill. After a stable cross-sectional area is reached, the subject is asked to squeeze while the balloon empties into the pressure reservoir.

An anal electromyogram (EMG) is registered during all examination procedures using surface electrodes and is recorded simultaneously with the cross-sectional area, balloon pressure, and bladder pressure on a six-channel recorder (DISA UROsystem 21F16 2100, Dantec, Denmark).

Handling of data

Recordings from the different types of examination procedures performed are shown in Fig. 3.

Parameters measured at rest. Compliance is defined as the ratio of volume (dV) to pressure (dP) change, and elastance is the inverse of compliance. For a urethral segment between the sensing electrodes with the distance λm, the change in volume is $\lambda \times$ dCa m^3, provided that the urethral walls have a slope of zero. The pressure is P_b (cmH_2O) $\times 10^2$ Pa, and the compliance is thus $\lambda \times dCA/dP_b \times 10^{-2}$ m^3 Pa^{-1}. It follows that dCA/dP_b is a constant function of the compliance, and, for unity of length, dCA/dP_b is identical with the compliance. Figure 4 shows related values of cross-sectional area and balloon pressure read at pressure equilibrium after each inflation/deflation. The regression line $P_b = P_o + (dP/dCA \times CA)$ through the almost linear part of the curve describes the pressure/cross-sectional area relation of the urethra at the level of measurement within a cross-sectional area range of 13–60 mm^2. The slope of the line (dP/dCA) denotes the elastance and $(dP/dCA)^{-1}$, the compliance. The intercept of the regression line with the pressure axis denotes the estimated theoretical pressure (P_o) in the uninstrumented urethra.

The measuring system permits sudden forced induction of a well-defined urethral dilatation and recording of the subsequent urethral pressure response (Fig. 3b), whereby it enables urethral stress-relaxation as reflected by the pressure response to be analyzed.

Parameters measured at voluntary contraction. During squeezing, the subject voluntarily empties the balloon partly or totally into the pressure reservoir (Fig. 3c). The work (W) produced by the segment of urethra between the sensing electrodes during this procedure is calculated as the reduction in volume multiplied by the balloon pressure (Pb), i.e., $W = -\lambda \times 10^2 \int P_b \times dCA$ m^3 Pa (Nm = J). Power (E) is the work per unit of time; thus, the power performed at contraction can be calculated as $E = -\lambda \times 10^2 \times P_b \times dCA/dt$ Nm/s (watt).

Ultrasound examination

Five male volunteers aged 28–85 years (median, 44 years) were examined by transrectal ultrasound. None had urological complaints, and urinalysis was normal in all cases. Informed consent and approval by the local ethics comittee were obtained. The examination was performed with the subject in the left lateral position. The catheter was introduced and placed as previously described, and the longitudinal and cross-sectional shape of the balloon during manual inflation was studied by means of transrectal ultrasonography (7-MHz rectal scanner, type 8551, Brüel & Kjaer, Denmark).

Results

The ultrasonographic appearance of the probe showed a characteristic and uniform pattern at the different examination levels in the five volunteers, even though significant differences in prostatic size were noted. The results are demonstrated in Fig. 5, which shows longitudinal and transverse sections obtained at various examination levels in a 32-year-old volunteer.

In longitudinal sections the walls of the balloon proved to be almost parallel in all five volunteers, with a slope of less than 10° being noted in the region of cross-sectional area measurement, irrespective of the anatomical location. The catheter followed the bending of the urethra, and the sharpest curve, which equalled a circle with a radius of 5 cm, was seen at the membranous part of the urethra. In cross-section the balloon appeared almost perfectly circular/elliptical at the bladder neck and in the external sphincter region, whereas impressions from the

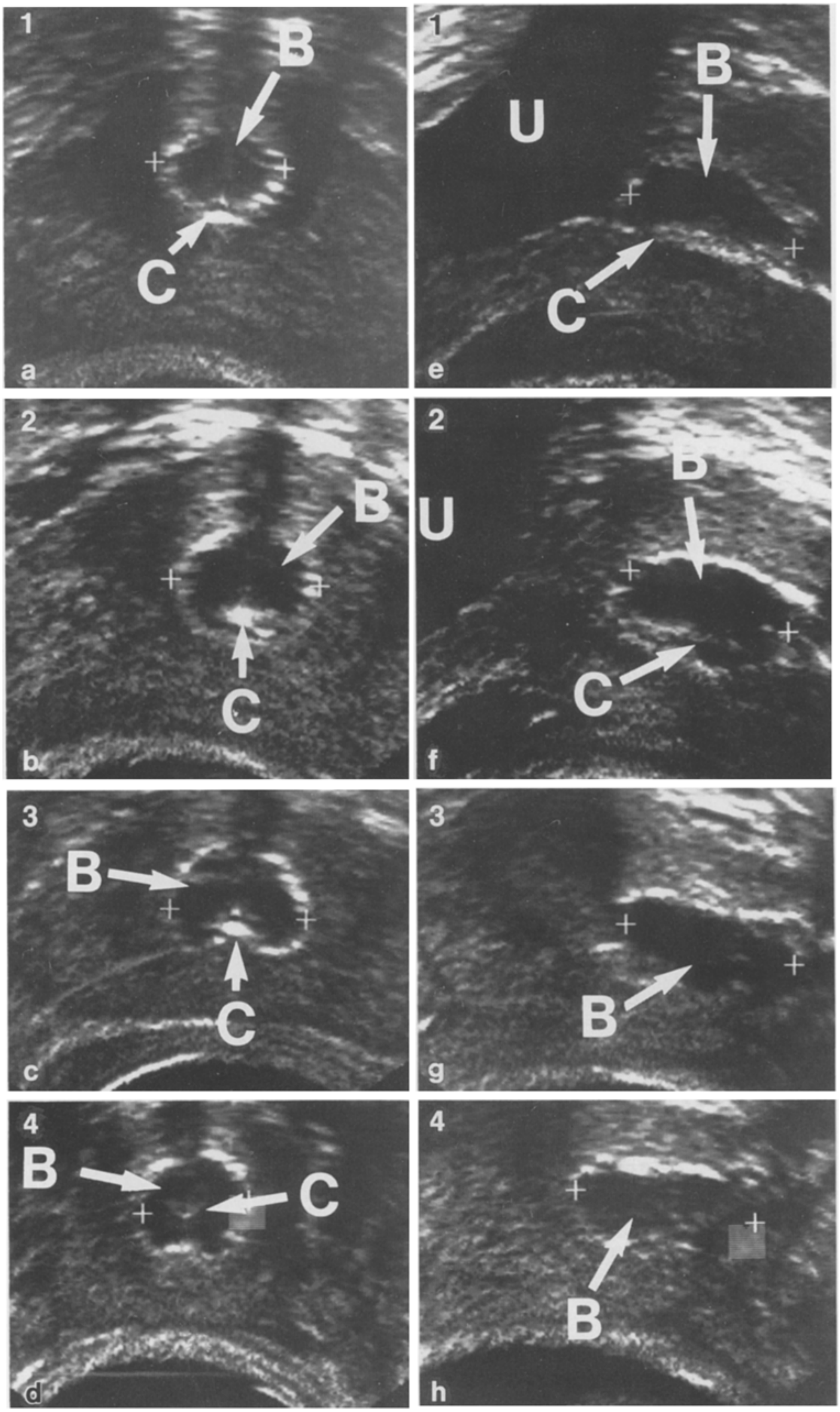


Fig. 5 a–h. Rectal ultrasonography in a 32-year-old volunteer. The *left pictures* (**a–d**) are transverse sections and the right pictures (**e–h**), longitudinal sections. The distance from the bladder neck is indicatd in cm in the *left upper corner* of the pictures. *C*, Catheter; *B*, balloon; *U*, bladder verumontanum caused the irregular appearance seen in the distal part of the prostatic urethra. The circumference of the lumen at cross-sectional areas of up to 80 mm^2 never exceeded 35 mm.

Discussion

Pressure measurements made in collapsible tubes like the urethra by means of inserted catheters carry a significant inherent drawback, namely, the unavoidable distension of the urethra at insertion. In a highly compliant tube, the pressure rise due to catheter insertion is small, whereas in more rigid tubes a significant pressure rise will result [1, 4]. This pressure rise, however, is part of the urethral response to dilatation and it will therefore have no influence on the measurements made with the present technique at cross-sectional areas within the measurement range of the catheter. At cross-sectional areas smaller than the measuring probe, including the totally closed urethra, measurements are impossible. However, the relation between pressure and cross-sectional area can be expressed mathematically, as this relation follows an almost straight line of the form $P_b = P_o + (dP/dCA \times CA)$ within a cross-sectional area range up to approximately 40–80 mm^2 depending on localization. Using this relation, it is thus possible to extrapolate the pressure of cross-sectional areas smaller than the measuring probe. The intersection of the line with the pressure axis at zero cross-sectional area indicates the theoretical pressure in the uninstrumented urethra (P_o). It should be realized, though, that the actual course of the line is unknown, wherefore this pressure remains an estimated parameter, which is based on the presumption that the urethral compliance remains constant at small cross-sectional areas. The probe precludes measurements at cross-sectional areas smaller than 11 mm^2.

The radial size of the balloon determines the maximal possible range for cross-sectional area measurement, but the possible complex geometrical configuration of the urethra may reduce the range from the maximum seen in a perfect circle to that of a figure given by the circumference of the balloon and the shape of the lumen. In the individual subject, however, it is impossible to know at which cross-sectional area the circumference of the lumen reaches the limits of the balloon unless the cross-sectional shape is simultaneously analyzed. This relation was therefore studied, and it appeared that the circumference of the balloon was not critical at cross-sectional areas up to 80 mm^2 in any of the five subjects studied. It should be noted, though, that extensive dilatation in very large prostates may influence the cross-sectional shape unless a larger balloon is used. The electronic measurements of cross-sectional area showed a high concordance between the measured and the real cross-sectional area in vitro when measured in both regular and irregular lumens; therefore, the cross-sectional shape seems to have little effect on the accuracy of measurements [7].

The length of the balloon is of minor significance for the measurements, as the cross-sectional area is determined between the two sensing electrodes (2 and 3 in Fig. 1). Thus, the probe actually measures the cross-sectional area of a 2-mm-long slice of the urethra in relation to the pressure in the balloon. The slope of the wall, on the other hand, is a possible source of error. The measurement of cross-sectional area is correct only provided that the slope of the tube wall between the sensing electrodes is negligible, and this criterion may not be fulfilled in a biological tube. According to Harris et al. [5], the error of measurement caused by a slope of the wall can be calculated as:

$$(V^0 - V)/V = 3/2 \times a^2 \times (\lambda/R)^2,$$

V^0 being the output that would have been recorded at a slope of zero: V, the actual recording; a, the slope of the wall; λ, the distance between the sensing electrodes; and R, the average radius of the balloon between the sensing electrodes. Experimentally, the validity of this equation was tested by Colstrup et al. [2] and Lose et al. [6], who found acceptable accordance between measured and calculated errors. From the results obtained at ultrasonography, it appeared that the maximal slope seen was less than 10°, and the maximal error caused by the slope of the wall was thus less than 5%. The bending of the catheter, which is caused by the course of the urethra, can be expected to result in similar measurement errors. As temperature influences the resistivity of saline, measurements and calibration should be performed at identical temperatures or corrected for any changes [7].

Reliable measurements during non-steady-state circumstances are dependent on the dynamic characteristics of the measuring system in relation to the dynamics of the physiological parameter studied. For the present setup, this implies that the lower limits for recordings with an error below 5% is a time constant of 0.06 s for cross-sectional area and 0.02 s for pressure [10]. During voluntary contraction it is not possible to restrict the non-steady-state parameter to only one, as the movement of fluid from the balloon requires a pressure gradient between the balloon and the pressure reservoir. However, the work performed during squeezing can be calculated using the formula $W = -\lambda \times 10^2 \int P_b \times dCA$ Nm, and power may be calculated at any moment during contraction using the formula $E = -\lambda \times 10^2 \times P_b \times dCA/dt$ Nm/s.

The present method enables a detailed description of passive as well as active biomechanical properties in the male urethra. The method may thereby prove to be of value in the evaluation of the physiological and pathophysiological characteristics of the urethra in the phase between micturitions. In the present design, the probe cannot be used for studies of the urethra in the voiding phase.

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