Urol Res (1983) 11:139–143

Urological Research

A Probe for Measurements of Related Values of Cross-sectional Area and Pressure in the Resting Female Urethra

H. Colstrup, S. O. Mortensen, and J. K. Kristensen

Department of Surgery D, Section of Urology, Rigshospitalet, University of Copenhagen, Denmark

Accepted: January 18, 1983

Summary. A probe for measurement of related values of cross sectional area (c.a.) and pressure in the resting female urethra has been developed. C.a. can be measured in the range 0.07 to 0.79 cm^2 by means of the field gradient principle. Pressure is measured in the range 0 to 150 cm H_2O. Pressure needed for inflation and deflation of the balloon ranges from +4 to −5 cm H_2O with a hysteresis of 3 to 4 cm H_2O. The probe is able to follow changes of the c.a. up to 0.7 cm^2/sec. The method makes possible estimation of urethral stiffness/rigidity during distension of the balloon, estimation of the capability of contraction of the closure apparatus in terms of isometric and isotonic contraction, muscular work and power. Furthermore, hysteresis during inflation and deflation of the balloon can be described.

Key words. Urethral pressure, Urethral cross-sectional area, Field-gradient principle.

When urine passes through the urethra the closure pressure is negative. This can either be caused by an increase in bladder pressure or a decrease in urethral pressure or both as in normal micturition [12]. How much the urethra opens depends on how distensible it is, that is, the relation between the cross-sectional area (c.a.) of the urethra and the intraurethral pressure. During stress episodes this relation will be an important, limiting factor of urine loss. It is thus desirable to be able to measure related values of c.a. and intraurethral pressure in the urethra between micturitions – the resting urethra.

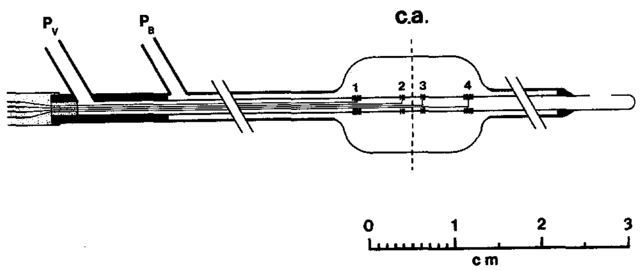
For the purpose of being able to measure these parameters a special probe has been developed. It carries a PVC balloon which makes possible induction of increasing intraurethral pressures. When the balloon pressure exceeds the closure pressure the urethra is distended. This distension can, by means of the field-gradient principle, be measured as cross-sectional area (c.a.) of the balloon. In this publication we report the measuring properties of the probe. Furthermore, special problems in using the field-gradient method in this probe will be discussed. Regarding general problems and principles attached to this method reference is made to Harris et al. [7].

Description of the Probe

The probe (Figs. 1 and 2) consists of a transparent outer 9F PVC catheter with a balloon 6 cm from the tip. The inner c.a. of this catheter is 0.038 cm^2. The balloon has a length of 1.5 cm and its midportion has the shape of a cylinder. In the inflated state the maximum diameter of the balloon is 1 cm corresponding to a c.a. of 0.79 cm^2. The balloon pressure can be measured separately. Inside the 9F catheter is placed a 5F catheter with cm markings. This catheter allows for the measurement of bladder pressure via a hole in the tip of the catheter and for c.a. measurements of the inflatable balloon by means of the field gradient principle. When the balloon is totally deflated around the inner catheter the minimum c.a. is 0.07 cm^2, thus giving a range of c.a. measurement of the probe of 0.07 to 0.79 cm^2. During recordings in the urethra the person investigated is in the supine position and the probe is attached to a withdrawal apparatus to ensure the position.

Measuring of C.A. in the Balloon

C.a. recording in a biological tube according to the field-gradient principle was first described by Harris et al. in 1971 [7]. A probe for measuring in the ureter by this principle was developed in 1976 by Rask Andersen & Djurhuus [11]. This probe was modified by Mortensen et al. [9], and this modification has been used in the present probe. Briefly the principle is: in a tube filled with an electrolyte containing fluid (0.9% NaCl), the impedance to a HF a.c. (10 kHz, 45 mA) between two generating electrodes (1 and 4 in Fig. 1) is measured between two sensing electrodes (2



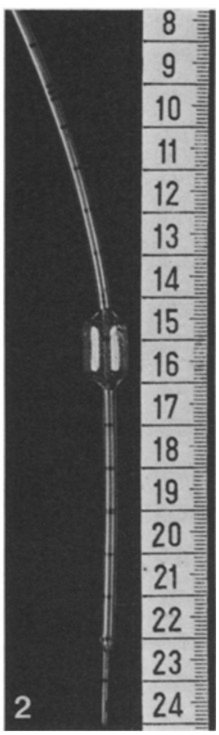


Fig. 1. Schematic longitudinal section of the probe. Cross-sectional area is measured at the *dotted line*. Platin windings are marked *1–4*, *1* and *4* being generating electrodes, *2* and *3* being detecting electrodes for measurements according to the field gradient principle. P_B, balloon pressure; P_V, vesical pressure; *c.a.*, cross-sectional area

Fig. 2. The actual probe, scale in cm. The balloon is maximally inflated. At the tip is seen the opening for pressure recording in the bladder

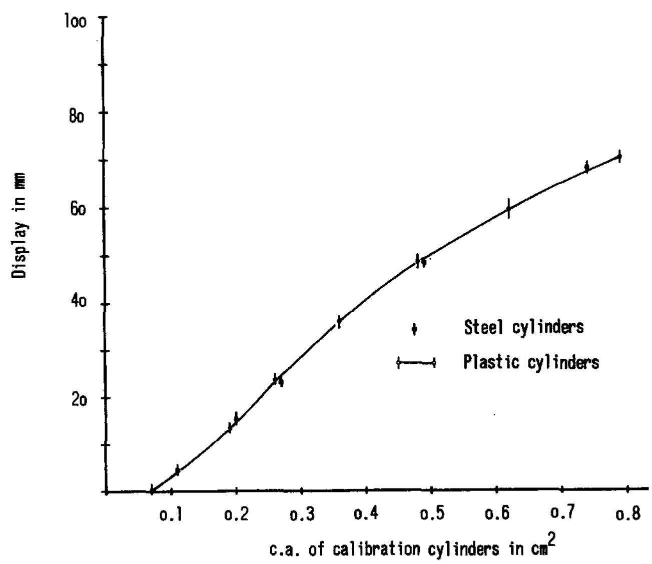


Fig. 3. Calibration in plastic and steel cylinders showing mean output on mingograph in mm +/– 2 SD. *n* = 10 in each cylinder

and 3 in Fig. 1). The drop in voltage V between the sensing electrodes with the distance d, will be

$$V = I \times d/\rho \times A \qquad (1)$$

I being intensity of the current, ρ the specific conductivity of the fluid and A the c.a. of the tube. It appears from Eq. (1) that when I, d and ρ are constant, the drop in voltage will be an expression of the c.a. of the tube. Since there is an inverse proportionality between V and A, the electronical unit has been equipped with a reciprocating unit, giving an output directly proportional to the c.a.

Calibration of C.A. Measurements

The c.a. measurements which were recorded on an Elema-Schönander mingograph 800 jet-ink recorder are calibrated in plastic cylinders with known c.a. at 37 °C. Figure 3 shows a calibration curve, made from 10 recordings in each tube. When measurements are performed in biological tubes, calibration curves are used for converting output on the mingograph to c.a. A number of factors should however be taken into consideration:

1. Shunting of Current

A condition for the use of the calibration curve is that shunting of current to the surroundings is avoided. It can be assumed that the PVC-material of the balloon is able to provide an adequate isolation. This has been confirmed in a calibration curve obtained by measurements in cylinders of a highly conductive material (stainless steel). In Fig. 3 such a calibration curve is seen to be identical with a curve made from recordings in plastic cylinders, confirming the assumption of the isolating properties of the balloon.

2. The Slope of the Wall

The tube in which the sensing electrodes 2 and 3 are situated should be without any slope of the wall. This condition is fulfilled when calibrating in cylinders, but it can not always be fulfilled in a biological tube. According to Harris et al. [7] the error of measurement, caused by eccentric position of the c.a. probe in relation to the center-axis and slope of the wall different from zero, can be calculated. When it is assumed that the deviation of the position of the probe from the center-axis is zero, the equation of the error caused by slope of the wall is:

$$(V_L^\circ - V_L)/V_L = a^2 \times (d/R)^2 \times 3/2 \qquad (2)$$

V_L° being the output that would have been recorded at a slope of zero, V_L the actual recording, d the distance between the sensing electrodes, a the slope of the wall between the

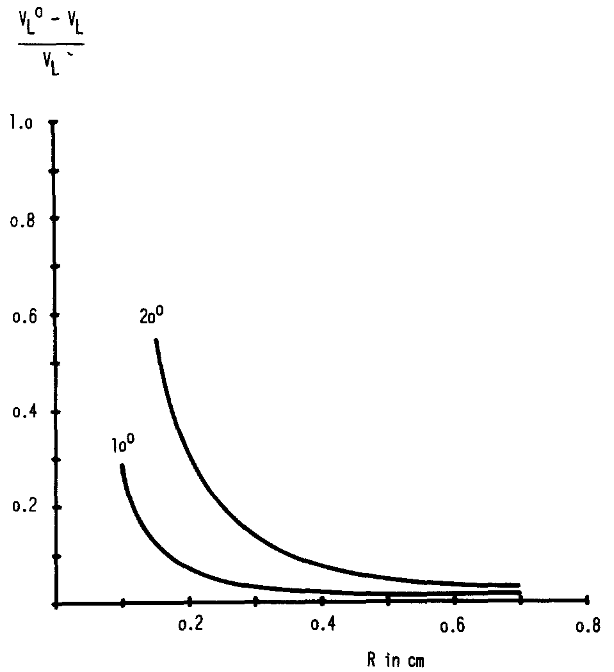


Fig. 4. The error in measurement of c.a. by means of the field gradient principle caused by the slope of the wall. The graphs show the correlation between the mean radius (R) of the balloon between electrode 2 and 3, and the error $(V_L^\circ - V_L)/V_L$ at different slopes

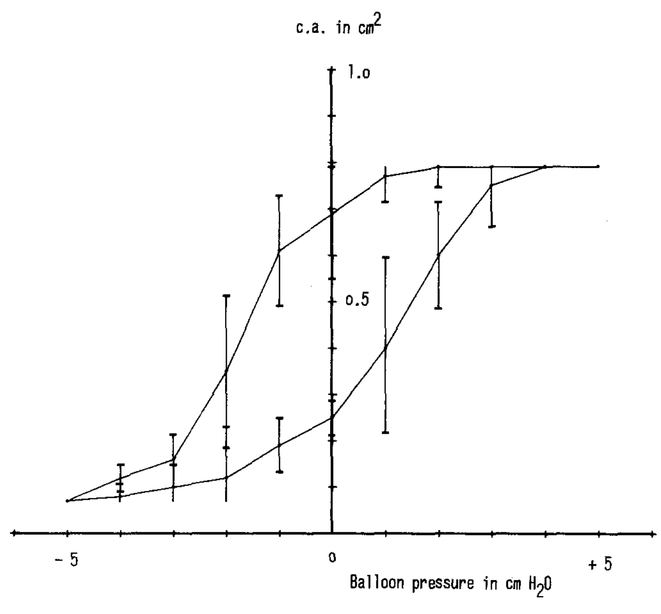


Fig. 5. Pressure c.a.-relation of the PVC balloon during five inflations and deflations in vitro at 37 °C, showing mean c.a. +/– 2 SD

sensing electrodes and R the average radius of the balloon between the sensing electrodes. d has a constant value of 0.25 cm. Hence the relation between $(V_L^\circ - V_L)/V_L$ and R can be calculated from Eq. (2) at various values of a. Figure 4 shows a graphical description of these calculations.

In an experimental set-up the validity of Eq. (2) has been investigated. The probe was placed in transparent plastic blocks in which conic lumens had been drilled. The slopes were 10° and 20°. This set-up made possible calculation of the exact c.a. (A°) and recording of c.a. (A), at the measuring site. Thus the error could be calculated from (A° – A)/A. This could be compared with $(V_L^\circ - V_L)/V_L$ since all the factors to the right in Eq. (2) were known. In 2 x 10 recordings at a 10° slope the measured error was found to be 3.0% (range 0.5 to 5.8) and 3.5% (–1.1 to 7.1) respectively while the calculated error was 1.5 and 2.0%; in 10 recordings at a 20° slope the measured error was 7.8% (4.4 to 11.6) and the calculated 8.5%. It appears that there is acceptable accordance between measured and calculated error, and therefore Eq. (2) can be used to estimate the error caused by the slope of the wall.

Velocity Constant for Recording of the C.A.

Finally the c.a. recording was investigated with regard to the speed with which changes in c.a. could be registered. This was carried out in a 37 °C electrolyte containing fluid. The inner probe was placed in a cylindrical tube with a lumen just able to contain the probe, and then suddenly drawn out into an infinite lumen. This caused a sudden rise in display to the maximum value. The velocity constant of the c.a. measurement, defined as the time to reach 63% of the maximum amplitude, was in this manner found to be 0.057 s in an average of five measurements. The upper frequency limit for recordings with an error below 5% can be calculated as [8]:

$$f_0 = 1/2\,\pi \times t_{63} = 2.8 \text{ Hz.}$$

The Properties of the Balloon

Pressure of Inflation and Hysteresis

The PVC material is to a great extent without elasticity. The behaviour of the balloon when inflated is like a plastic bag, the inflation pressure being the pressure necessary for folding out the wall. The corresponding pressure from the outside is required when the balloon is to be deflated. These pressures were measured in a set-up with the balloon in 37 °C. Increasing and decreasing pressures in the balloon were generated from a level container at steps of 1 cm of water at a time. Fig. 5 shows that a pressure of 3–4 cm water is required to inflate the balloon to its maximum c.a. After this c.a. is reached there is a fast rise in pressure without any increase in c.a., indicating that the balloon is maximally distented. At falling pressures the c.a. is seen to be maintained almost at the maximum value although the pressure is reduced to zero. It takes a pressure of –5 cm H_2O to reach the minimum c.a. The distance between the two curves in Fig. 5 of 3–4 cm H_2O represents the hysteresis of the balloon.

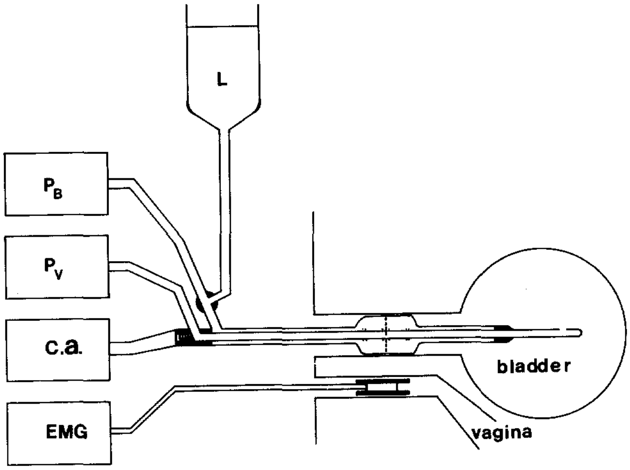


Fig. 6. Schematic set-up for measurements in the female urethra. Pressures are measured with Hansen manometers. C.a. is measured by means of the field-gradient principle. EMG is registered from surface electrodes in the vagina, using a DISA-recorder. *L*, level container; P_B, balloon pressure; P_V, vesical pressure; *c.a.*, cross-sectional area; *EMG*, electromyography

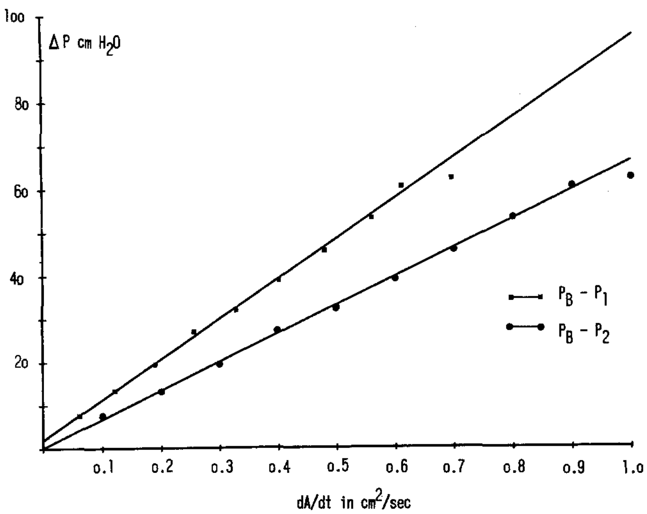


Fig. 7. Correlations between the speed of the change in c.a. and pressure gradients during 10 x 10 deflations of the balloon. $P_B - P_1$ is the gradient between the three way stop cock in Fig. 6 and the balloon, $P_B - P_2$ the gradient between the level container and the balloon

Pressure Recording in the Balloon

Velocity Constant

Pressure transmission in the system with the level container (Fig. 6) turned off was investigated and characterised by measuring the velocity constant, as described by Gabe [5]. The velocity constant $T_{63\%}$ was found to be 0.245 s, giving an upper limit of frequency for the pressure measurement of 0.65 Hz.

Pressure Recording at Changing C.A. in the Balloon

For clinical investigations with the probe the set up shown in Fig. 6 was used. The probe has two functions: infusion of saline into the balloon and pressure recording. The dimension of this infusion and pressure recording system is the inner c.a. of the outer catheter (0.038 cm^2) minus the outer c.a. of the inner catheter (0.020 cm^2) giving a lumen of 0.018 cm^2. This system is connected by the three way stop cock to a level container L and by a 2 m long manometer line to a pressure transducer (Hansen manometer, Simonsen & Weel, Albertslund, Denmark). When the c.a. of the balloon changes, saline is transported through the outer catheter. This means that there is a pressure gradient between the balloon and the three way stop cock ($P_B - P_1$) and the balloon and the level container ($P_B - P_2$). When the c.a. is changing the pressure in the balloon will be the pressure set by the height of the level container plus $P_B - P_2$. Therefore the relation between the speed at which c.a. changes, dA/dt, and the pressure gradient must be known.

A set-up to find this relation was made with the balloon in a pressure chamber. This made possible a sudden induction of a known pressure gradient between the balloon and the level container. Cross sectional area and pressure at the three way stop cock was recorded, and dt was measured for a value of dA of 0.2 cm^2, and dA/dt calculated. The pressure gradient was increased stepwise by 10 cm H_2O up to 100 cm H_2O. The results are shown in Fig. 7.

When the c.a. change does not exceed 0.6–0.7 cm^2/s, Fig. 6 can be used from recordings of dA and dt, to find the exact pressure in the balloon when it is inflated or deflated.

Discussion

The probe described makes possible recordings of related values of c.a. and intraluminal pressure in a biological tube, in this case the urethra. The range of the c.a. measurement is 0.07–0.79 cm^2. The range of the pressure induced is chosen to 0–150 cm H_2O for investigations in the urethra. These parameters make possible the evaluation of the urethra during distension.

Distensibility has been discussed in relation to the influence of the c.a. of the probe in pressure profile recordings [1, 10]. The clinical implication of urethral distensibility or compliance has only been mentioned briefly [6]. When pressure is plotted against c.a. the lower part of the curve is almost on a straight line which is characterised by the equation $y = \alpha x + k$, α being dP/dA, which can be used as a parameter for urethral stiffness or rigidity. When intraurethral pressure is considered equal to transmural pressure $1/\alpha$ = dA/dP is urethral compliance. k is the intersection of the line with the ordinate and denotes the pressure corresponding to a c.a. of zero.

By examining the pressure –c.a. relation of the resting urethra at increasing and decreasing pressures, the hysteresis of the urethra can be investigated. When recordings are done during contraction of the urethral closure muscles the contraction force can be expressed as work (volume multiplied by pressure with the unit erg) or as power (with the unit erg/s).

Of the factors influencing the measurements with the probe, the following are considered the most significant.

1. The Dimensions of the Probe

A minimum c.a. of 0.07 cm^2 is rather large and will influence the recorded closure pressure. This disadvantage is, however, compensated by the ability of the method to calculate the pressure at a c.a. of zero.

The c.a. measuring area of the inner catheter has a length of 1.2 cm (Fig. 2), and therefore the middle of this area has to be placed at least 0.6 cm from one end of the tube in which the recording takes place. If this length was to be reduced, the distance between the electrodes would have to be smaller, reducing the range of the c.a. measurement. The length of the c.a. measuring area of the inner catheter is thus a compromise between the wish to be able to record as close as possible to the end of the tube and to get a useful measuring range.

2. The Slope of the Wall

This source of error is thought to be the only one that really needs consideration when recording c.a. by means of the field-gradient principle in the resting female urethra with this probe. Pressure-profile recordings, no matter which technique has been used [2–4], show that there are great variations in the pressure along the longitudinal axis of the resting urethra. This means that the inflated balloon, especially when entering and leaving the high-pressure zone, very often will have a slope of the wall different from zero. If the change in pressure is uniform along the longitudinal axis, the maximum slope at which recordings can be performed will occur when electrode 1 in Fig. 2 (or 4) is in minimum c.a. and electrode 3 (or 2) in maximum c.a. This will give a slope of 20° and a value of R in Eq. (2) of 0.43 cm. According to Fig. 4 $(V_L^\circ - V_L)/V_L$ is 0.07.

If the pressure rise is very steep a situation could occur where electrode 1 and 2 are in a lumen which is almost zero and the lumen at 3 and 4 is at the maximum. This will give a slope of approximately 50° and the figures in Eq. (2) will be a = 1.17, R = 0.35 cm (d = 0.25).

$$(V_L^\circ - V_L)/V_L = 1.17^2 \times (0.25/0.35)^2 \times 3/2 = 1.05$$

This means, that an area of $0.35^2 \times \pi = 0.39$ cm^2 is recorded as 0.19 cm^2. This is theoretically the largest error in c.a. measurement the probe is able to make and denotes a very extreme situation.

A source of error in the c.a. measurements with this method would be variations in temperature of the electrolyte-containing liquid. To avoid this error all methodological measurements have been carried out in 37 °C. In recordings on volunteers this will cause an error when inflating large c.a.'s fast.

3. Pressure Measurement at Changing C.A.

When c.a. is changing in the balloon it is necessary to know the relation between dA/dt and the pressure gradients in the system, in order to know the true pressure in the balloon. This relation is a straight line as shown in Fig. 6.

Investigations on 30 volunteers have never shown values of dA/dt greater than 0.5–0.6 cm^2/s corresponding to a ΔP between the level container and the balloon of less than 60 cm H_2O, but c.a. changes faster than 0.7 to 0.8 cm^2/s will cause a change in the flow resulting in disappearance of the linearity. Figure 6 can thus not be used at faster c.a. changes than 0.7 cm^2/s.

References

1. Abrams PH, Martin S, Griffiths DJ (1978) The measurement and interpretation of urethral pressures obtained by the method of Brown and Wickham. Br J Urol 50:33
2. Asmussen M, Ulmsten U (1976) Simultaneous urethro-cystometry with a new technique. Scand J Urol 10:7
3. Brown M, Wickham JEA (1969) The urethral pressure profile. Br J Urol 41:211
4. Enhörning G (1961) Simultaneous recording of intravesical and intraurethral pressure. Acta Chir Scand (Suppl) 276
5. Gabe IT (1972) Pressure measurement in experimental physiology. In: Bergel DM (ed) Cardiovascular fluid dynamics, vol 1. Academic Press, London, p 12
6. Griffiths DJ (1980) Urodynamics, Chapter 2. Adam Hilger, Bristol, p 22
7. Harris JH, Therkelsen EE, Zinner NR (1971) Electrical measurements of ureteral flow. In: Boyarsky S, Tanagho EA, Gottschalk CW, Zimskind PD (eds) Chapter 34. Academic Press, New York, London, p 465
8. Steen-Knudsen O, Nissen-Petersen (1973) Om valg af måleapparatur. In: Pedersen J, Havsteen B (eds) Lægevidenskabelig Forskning, Chapter XI. FADL's Forlag, København, Århus, Odense, p 286
9. Mortensen S, Djurhuus JC, Rask-Andersen H, Frimodt-Møller C (1978) Urethral cross-sectional area measured by urinary stream impedance to HF electrical current. VIII ICS Meeting, Manchester. Pergamon Press, Oxford, p 151
10. Plevnik S (1976) Model of the proximal urethra: Measurement of the urethral stress profile. Urol Int 31:23
11. Rask-Andersen H, Djurhuus JC (1976) Development of a probe for endoureteral investigation of peristalsis by flow velocity and cross section area measurement. Acta Chir Scand (Suppl) 472:59
12. Rud T, Ulmsten U, Andersson KE (1978) Initiation of voiding in healthy women and those with stress incontinens. Acta Obstet Gynecol Scand 54:457

Dr. H. Colstrup
Department of Surgery D
Rigshospitalet
Blegdamsvej 9
DK-2100 Copenhagen Ø