Urological Research 6, 119-125 (1978)

Urological Research

ORIGINALS

Study of Three Urethral Pressure Recording Devices: Theoretical Considerations

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Accepted: January 6, 1978

Summary. Using a bladder-urethra model, 2 perfusion catheters (open side and open tip) were compared to the balloon catheter. The most accurate results were obtained using the balloon catheter. Based on the law of continuity and Bernouilli's law, the disadvantage of the open side catheter is due to the inconstant diameter of the sum of the side holes. Therefore, the measured pressure is not necessarily identical to the real pressure. The open tip catheter measures the opening pressure and the recorded pressure does not necessarily reflect the pressure at the site of the tip hole. The balloon catheter has elastic and plastic characteristics. Optimum results were obtained only with prestretch of the balloon and with calibration before and after each study. This catheter was the most complicated, but produced the best results and gave rise to the least irritation.

Key words: Open side catheter - Open tip catheter - Balloon catheter - Bladder-urethra model - Urethral pressure.

For as long as pressure recordings of the lower urinary tract have been performed, there has been discussion as to which type of catheter provides the most accurate results in recording urethral pressure. This study tested the 3 most commonly used catheters (Fig. 1):

A) The open side catheter, described by Brown and Wickham (2) which consists of 3 side holes that are arranged around the circumference (8 F) at intervals of 120°. The pressure is recorded against a constant perfusion.

B) The open tip catheter, first described by Beck and Heidenreich (1), which is a 14 F catheter with an end hole for urethral pressure recording.

C) The balloon catheter, described by Enhoerning (5) and modified by Drouin and McCurry (3), consists of a 4 channel catheter with 2 balloons for urethral pressure recording at 2 different levels: both latex balloons have a length of 1 cm, and an outer diameter of 13 F.

METHOD

In order to compare these catheters, a bladder-urethra model was constructed (6, 7) modifying the STARLING resistance (10) (Figs. 2A and B). A glass container represented the "bladder" and the "urethra". The "urethra" consisted of a latex tube 0.5 cm in diameter which ran through a second glass container. The pressures in the glass containers were regulated by the amount of water in each container. Additionally, the pressure in B could be mechanically altered and in spite of fluid loss a constant pressure rise in B was maintained.

After this "dynamic" study, a "static" study followed, in which the piston was removed and a constant pressure maintained in B while "urethral" pressure was altered by different levels of water in the second glass container (from 40 up to 60 cm H_2O pressure).

The "dynamic" study proved to be unsatisfactory, probably due to the inconstant distribution of energy inside the artificial urethra. The data showed a wide spread and were not reproducible, therefore all results are based on the "static" evaluation.

The 3 different types of catheters described were used for recording "urethral" pressures under these "static" conditions. Using the perfusion catheters, perfusion rates ranged from 2 to 5 ml/min. Using the balloon catheter, intraluminal pressures from 0 to 200 mmHg

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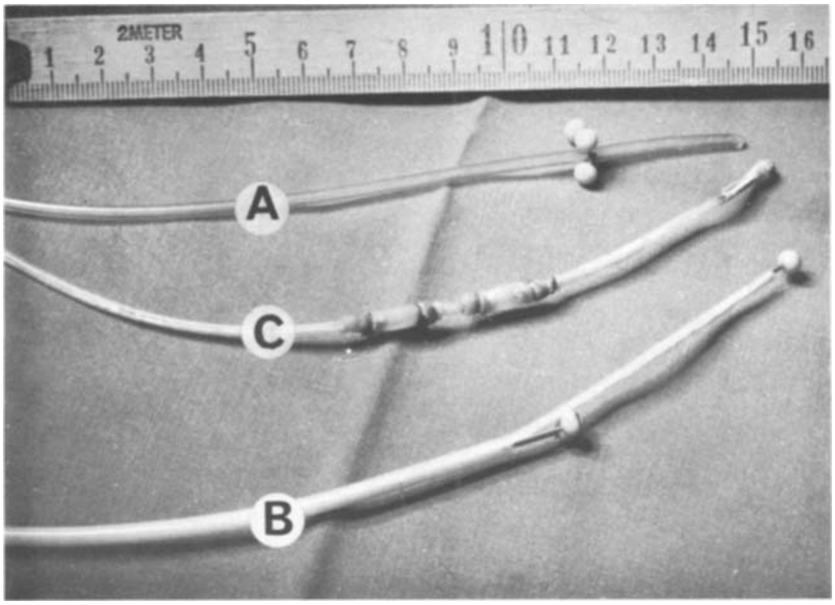

Fig. 1. Pressure recording devices: A) open side catheter (Brown, Wickham): 8 F perfusion catheter with 3 side holes of 1 mm in diameter and at 120° intervals; B) open tip catheter (Beck, Heidenreich): 14 F perfusion catheter with 2 recording tubes - for bladder and urethral pressure recording; C) balloon catheter (Enhoerning, Drouin and McCurry): 4 channel catheter of 13 F: 2 open channels for bladder filling and pressure recording; 2 channels with side holes, covered by latex balloons for urethral pressure recording at 2 different levels

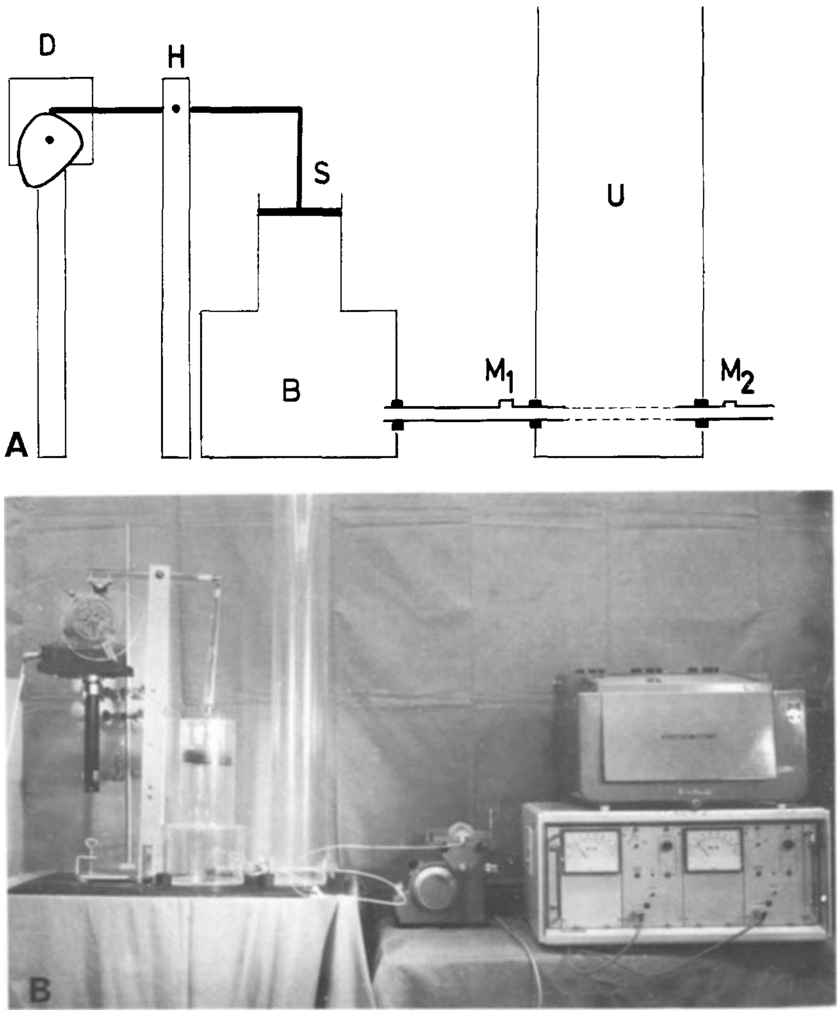

Fig. 2A and B. Bladder-urethra model: Container (U) with the latex tube as artificial "urethra". M1 and M2 are measuring points. B = artificial "bladder". The piston (S) may be depressed mechanically by an eccentric disc (D) via lever (H) to produce a continuous pressure increase in B despite the fluid loss through the artificial "urethra" were investigated. The optimum conditions were found to be:

1. Perfusion catheters: perfusion rate 5 ml/min.
2. Balloon catheter: intraluminal pressure 75 mm Hg.

Each study was repeated 5 times. The data, consisting of 1700 measuring points, were computerised and evaluated according to the following 3 criteria (Fig. 3):

1. the slope deviation
2. the standard deviation
3. the zero point shifting.

Deviations from the "ideal straight line", a 45° line summarising all measured points which are identical to the real - and in this model known - pressures, were evaluated.

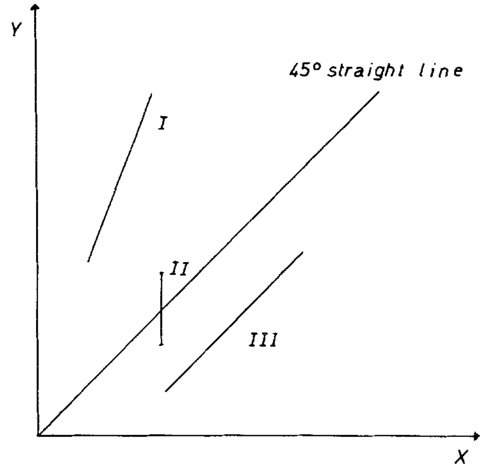

Fig. 3. Results obtained in comparison to the 45° "ideal straight line", which represents the ideal slope and no zero-point shifting. I: slope deviation, II: standard deviation, III: zero-point shifting

RESULTS

Table 1 shows that the best results were obtained using the balloon catheter. The theoretical considerations underlying these 3 recording catheters are therefore of interest.

Theoretical Considerations

The varying accuracy of the 3 catheters seems to be based on the fact that 3 different parameters were recorded.

A. Open Side Catheter. Two physical laws can be applied to this method:

I. The Law of Continuity states that under ideal flow conditions, the product of flow (v) and tube cross-section (F) is constant:

$$v \times F = \text{constant} \qquad (1)$$

II. The Bernouilli Law states that the sum of the kinetic and static pressure is constant, therefore it has to be equal inside the catheter and inside the urethra:

$$p_{static\ 1} + p_{kinetic\ 1} = p_{static\ 2} + p_{kinetic\ 2} \qquad (2)$$

The incompressible fluid has a constant density ϱ

The kinetic pressure is:

$$\frac{\varrho}{2} v^2 \qquad (3)$$

p_1 = urethral pressure (unknown)

p_2 = measured pressure

Table 1. Computerised results comparing the data obtained with the ideal straight line (using optimal conditions for each recording catheter)

Catheter type	Slope deviation (%)	Standard deviation (mmHg)	Zero-point shifting (mmHg)
Open side (perfusion: 5 ml/min)	1.24	± 2.03	- 0.94
Open tip (perfusion: 5 ml/min)	0.33	± 1.75	- 3.86
Balloon (inner pressure: 75 mmHg)	0	± 1.68	- 0.29

v_1 = outflow of the perfusion fluid (unknown)

v_2 = perfusion rate

F_1 = cross-section of the hole (or sum of the holes) (unknown)

F_2 = cross-section of the tube

h_L = pressure loss for a cylindrical tube

x = calibration function

Based on (1), it follows that:

$$v_1 \cdot F_1 = v_2 \cdot F_2 \qquad (4)$$

which gives:

$$v_1 = \frac{v_2 \; F_2}{F_1} \qquad (5)$$

From (2) and (3), we have:

$$\frac{\varrho}{2} v_1^{\,2} + p_1 = \frac{\varrho}{2} v_2^{\,2} + p_2 + h_L \qquad (6)$$

Substituting (5) in (6), we obtain:

$$\frac{\varrho}{2}\left(\frac{v_2 F_2}{F_1}\right)^2 + p_1 = \frac{\varrho}{2} v_2^{\,2} + p_2 + h_L \qquad (7)$$

Thus, the solution for (p_2) is:

$$p_2 = p_1 + \underbrace{\frac{\varrho}{2}\left[\left(\frac{v_2 \, F_2}{F_1}\right)^2 - v_2^{\,2}\right] - h_L}_{x} \qquad (8)$$

Based on this consideration it can be concluded that when x = zero, the recorded pressure (p_2) is equal to the real pressure (p_1). Therefore, the 2nd unknown factor - the cross-section of the hole (or the sum of the holes) (F_1) - can only be determined empirically by altering the perfusion rate (v_2) to reduce x to zero. h_L is valid for ideal conditions, i.e., $h_L = 0$. However, since the calibration factor (x) is never zero, the recorded pressure (p_2) is never equal to the real urethral pressure (p_1).

In this consideration (8), the viscosity of the perfusion, the roughness of the catheter-wall and the turbulences resulting from the entrance of the perfusion into the urethra which result in a pressure loss (h_L) are disregarded. To disregard h_L is correct under ideal conditions, but h_L must be considered when the perfusion leaves the catheter. Since the flow is likely to be laminar, the correct form of the Bernouilli equation is represented in Equation 7, in which h_L is quite large and may actually dominate the other terms. The formula for h_L demonstrates and dependence of the pressure loss on viscosity, roughness and tube diameter. For a cylinder, the pressure loss (h_L) is (see Eck (4)):

$$h_L = \frac{\lambda \cdot 1 \cdot \gamma \cdot v_c^2}{d \cdot 2g} \qquad (9)$$

in which

λ = dimensionless factor depending on roughness and viscosity

γ = specific weight

d = diameter of tube

g = acceleration due to gravity

1 = length of tube

v_c = critical velocity $= \dfrac{Re \cdot \vartheta}{d}$ (10)

ϑ = kinematic viscosity

Re = Reynold's number

By Re = 2320 (laminar flow) and a circular cross-section (see Eck (4)):

$$\lambda = 64/Re \qquad (11)$$

Based on (9), (10) and (11), we have

$$h_L = \frac{64 \cdot 1 \cdot v_c \cdot \vartheta}{d^2} \qquad (12)$$

It becomes clear from Equation 12 that by decreasing the diameter the pressure loss increases, resulting in another unknown parameter which determines the efficiency of the perfusion catheter. Figure 4 demonstrates that in the open side catheter the optimal perfusion rate was 5 ml/min. However, it has to be considered that in case of multiple side holes, one hole can be completely occluded by tissue. Therefore, it is never certain, in the event of pressure increase (p_2), whether this is due to the urethral pressure increase (p_1) or to a change in the cross-section of the hole or the sum of the holes (F_2 Equation 8) and the contributions of viscosity, roughness and the resulting turbulences are uncertain (Equation 12).

B. Open Tip Catheter. There is an essential difference between filling a rigid or an elastic system: in a rigid system, there is pressure and volume increase up to the point where the system is full. Further pressure increase however, does not change the volume, as can be seen in the pressure-volume diagram (Fig. 5). In an elastic system, the intraluminal pressure and volume increase in accordance with the wall elasticity up to the point where the elastic ability decompensates and further volume increase is no longer reflected by pressure rise. Instead, a fall in pressure is observed and further filling leads to rupture of the wall.

For the urethra, during a constant perfusion rate, pressure rises to the point where fluid drains into the bladder or externally. Subsequently, pressure drops and builds up again to the opening pressure. The frequency is proportional to the perfusion rate, which has to have a specific value for precise recording (Fig. 6). Because of the fact that

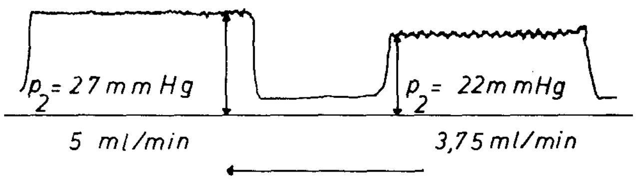

Fig. 4. Pressure recording using the open side catheter: urethral pressure (p_1) is 28 mmHg, the measured pressure (p_2) varies from 22 mmHg to 27 mmHg according to different perfusion rates. Best results were obtained using a rate of 5 ml/min

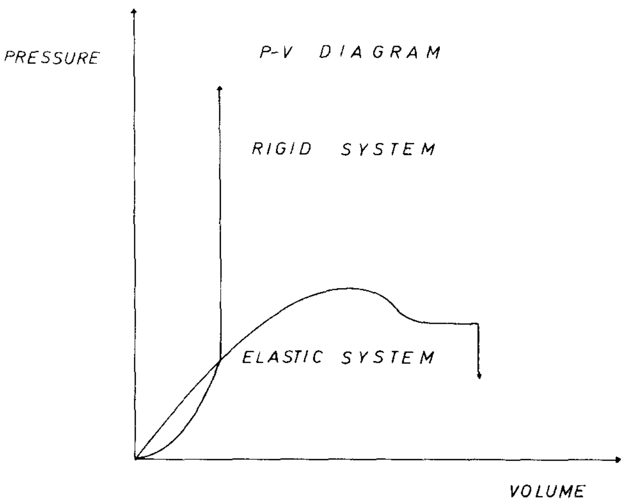

Fig. 5. Pressure-volume diagram in an elastic and rigid system: in a rigid system, perfusion leads to an increase of pressure and volume until the system is full. Further pressure increase does not change the volume. In an elastic system, volume and pressure increase in accordance to the wall elasticity up to a maximal point. Thereafter, pressure decreases until rupture of the wall occurs

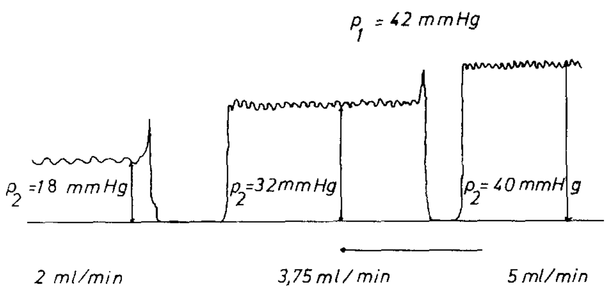

Fig. 6. Open tip catheter: opening pressure and its frequency at different perfusion rates. Frequency correlates with the perfusion rate. The most accurate pressure recording was obtained using a perfusion rate of 5 ml/min

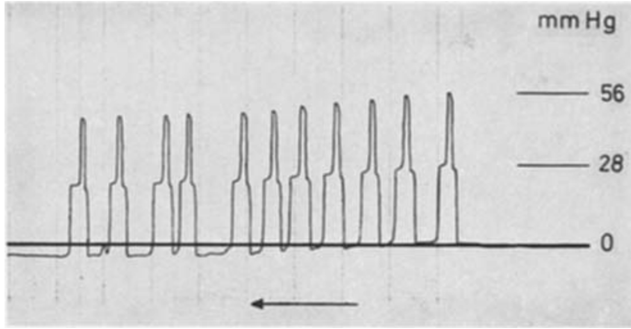

Fig. 7. Calibration curve using a balloon catheter: constant drop of the baseline after repeated pressure increase and release. Calibration must be done before and after each study

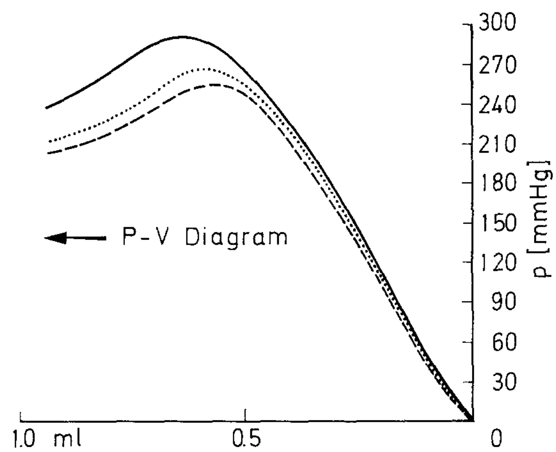

Fig. 8. Pressure-volume diagram using a balloon catheter: after repeated filling and emptying of the balloon catheter to the level of decompensation, a lower pressure rise is seen (dotted lines) as the material fatigues

fluid drains out of the urethra in the direction of the lower pressure gradient, it can be concluded that the site of the catheter opening does not necessarily record the urethral pressure at this specific level.

C. Balloon Catheter. Using the balloon catheter, 2 separate systems are involved:

1. the elastic tube (urethra) and
2. a water filled, closed system (the balloon) which has elastic and plastic characteristics. Pressure increase within the urethra is transmitted via the latex balloon and the incompressible fluid to the recording membrane.

Calibration studies showed very clearly that after some pressure changes, the baseline dropped (Fig. 7) due to continuous

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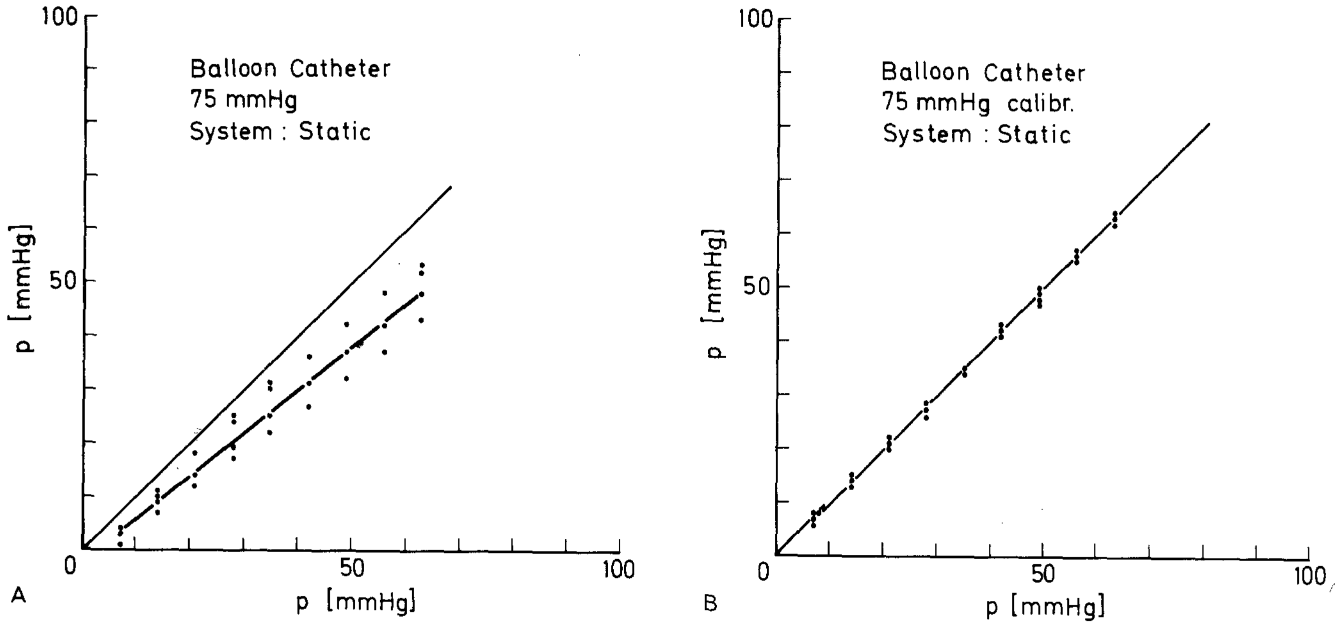

Fig. 9. Recording performed using a balloon catheter following prestretch to 75 mmHg intraluminal pressure: A) without calibration the results are very inconsistent (high standard deviation, slope deviation and zero-point shifting), B) same system with calibration: excellent results, no slope deviation and minimal zero-point shifting, almost identical to the 45^{o} ideal straight line

compression and decompression of the latex material. With each decompression the balloon stretched a little resulting in a small pressure drop. Therefore calibration has to be done before and after each study. Repeated filling of the balloon to the point where it decompensated (Fig. 8) and slackened (dotted lines) showed that the material fatigued and an identical fluid input was no longer reflected by an identical pressure increase.

The data obtained substantiated this observation: very inconsistent results were obtained without calibration while the results were optimum after calibration (Table 1). The figures also show that a "prestretch" - which was found to be best at 75 mmHg intraluminar pressure (calibrated to zero for later measurements) - improved the data obtained (Fig. 9A and B).

CONCLUSIONS

Using the open side catheter, the resistance of the urethral wall is measured at the level of the side holes. Temporary changes in the cross-section of the perfusion hole (or holes) leads to unpredictable changes in the recording device and alters the results. Only when the sum of the cross-sections is equal to the cross-section of the perfusion tube is the recorded pressure identical to the urethral pressure.

The open tip catheter records the opening pressure of the urethra, the pressure which is necessary for the perfusion fluid to drain out of the urethra. This pressure, however, is not necessarily identical to the pressure at the site of the recording tip.

Both of these techniques require a perfusate. Therefore, there is a further irritation in the system in addition to the mere presence of the catheter.

The balloon catheter records the real wall pressure of the urethra. However, exact calibration is necessary before and after each study to obtain good results. A pressure-volume diagram determines the optimum prestretch of the latex balloon. This device reduces urethral irritation, but it is more complicated to use.

The comparative study proved the advantages of the balloon catheter over the perfusion techniques (9). It became the method of choice in our department and has been used clinically in over 800 studies since 1976.

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