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Visco-Elastic Properties of the Bladder Wall

B. L. R. A. Coolsaet, W. A. van Duyl, R. van Mastrigt and A. van der Zwart

Departments of Urology and Biological and Medical Physics, Erasmus University, Rotterdam, and Department of Electrical Engineering, Technical University, Delft

Abstract. Stepwise cystometry is a new method proposed to analyse the visco-elastic properties of the bladder. It is based on a mathematical analysis of the pressure decay after a stepwise filling.

By assumption of a mechanical visco-elastic model of bladder tissue and a model of the geometry, the derived parameters are interpreted as elasticity and viscosity moduli.

Static cystometry is involved in this new procedure. From analysis by stepwise cystometry it is concluded that static cystometry attained by following a slow-filling procedure is unacceptable in studying elastic behaviour.

Key Words
Cystometry
Stepwise cystometry
Visco-elasticity
Exponential model

Introduction

To obtain a better understanding of the function of the urinary system in physiological and pathological conditions, it is necessary to know the mechanical properties of the bladder wall [1]. These properties influence the storage capacity and expulsion force of the bladder.

Objectives

The aim of our investigation is to find relevant parameters to describe quantitatively the dynamic and static behaviour of the bladder. By means of the results obtained, an attempt will be made to develop a procedure to determine clinically relevant parameters.

Definitions

Elasticity is that property of a material which gives a stress linearly proportional to the strain.
Thus:

$$S = \varepsilon \cdot E \qquad \text{(Hooke's law) (1)}$$

where: S = stress (N/m^2),
$\varepsilon = \frac{l - l_0}{l_0}$ = strain,
l = length of the material (m),
l_0 = unstretched length of the material (m),
E = elastic modulus (N/m^2).

Mechanically this can be represented by an ideal spring.

Viscosity is that property of a material which tends to oppose the rate of deformation of the stressed material. The stress is proportional to the rate of deformation. In formula:

$$S = \eta \cdot \dot{\varepsilon} \qquad \text{(Newton's law) (2)}$$

where: S = stress (N/m^2),
$\dot{\varepsilon} = \frac{d\varepsilon}{dt}$ = time-rate of strain (s^{-1}),
η = viscosity modulus (Ns/m^2).

Mechanically this can be represented by a dashpot.

Visco-elasticity is a combination of both [5] and is a property of most body tissues and of many other materials such as rubber and certain plastics.

Geometry

Measuring on the total bladder, it is necessary to have a model of the bladder geometry to determine the properties of the wall. If the bladder is idealized by a thin-walled sphere, then the Laplace formula would apply. This formula expresses tension as force per unit length:

$$T = \frac{pR}{2} \qquad (3)$$

where: T = tension (N/m),
p = pressure (N/m^2),
R = radius (m).

Because we want to consider changes in wall thickness, the Laplace formula is not applicable. In order to express tension as force per unit surface, the tension defined by the Laplace formula must be divided by wall thickness:

$$S=\frac{pR}{2d} \tag{4}$$

where: S = stress (N/m^2),
d = wall thickness (m).

Assuming tissue volume a constant we can set:

$$d \cdot 4\pi R^2 = V_t = \text{constant} \tag{5}$$

where: V_t = tissue volume (m^3).

Substituting of equation 5 into 4 yields:

$$S=\frac{3pV}{2V_t} \tag{6}$$

where: V = intraluminal volume (m^3).

The tissue volume can be measured after an experiment.

Methods

Experiments were done on mongrel dogs during continuous intravenous pentobarbital anaesthesia. The ureters were ligated to prevent reflux and efflux of urine. The pelvic nerves were connected to a Grass stimulator. Saline at body temperature was infused into the bladder through the outer canal of a double lumen catheter by means of a electronic controlled pump, which was developed for this purpose. The inner lumen of the catheter was connected to a pressure transducer. Intra-vesical pressure was recorded simultaneously with intra-luminal volume on a recorder and also punched on paper tape. These paper tapes were converted to punch cards which were fed to an IBM 360/65 computer for further analysis (fig. 1).

Measurements

The bladder wall is considered as a 'black-box' with an input and an output. In this case, the input is a strain (by means of a change in volume). The output is a stress, registered as pressure.

When a certain amount of fluid is introduced into the lumen of the urinary bladder, the intra-vesical pressure rises rapidly during filling. The

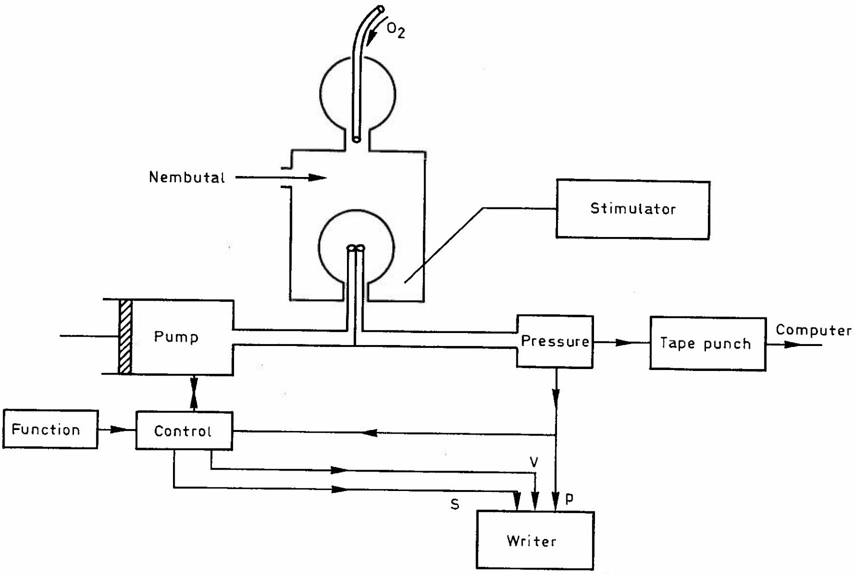

Fig. 1. Experimental set-up.

height and form of the pressure rise are, among other things, dependent on the rate of filling – that is, on the rate with which the bladder wall is strained.

If the rate of filling is infinite, the inflow function is called a mathematical step function. As soon as the filling is stopped, the pressure decreases in relation to time. This process is called 'adaptation', 'tension decay' or 'stress relaxation' (fig. 2). This phenomenon is also found in bladders *in vitro*, bladder wall strips, and rubber balloons (fig. 3). While tension decay can be described by a passive model and can even be found in 'dead' tissue and artificial materials, active mechanisms are not necessary to explain this phenomenon.

It can be understood from the rate dependency that the pressure rise would be steeper and higher in a small bladder than in a larger one when both are filled at the same infusion rate. Therefore, it is very difficult to draw conclusions concerning 'hypertonic' or 'hypotonic' bladder from the curves obtained by commonly used cystometry methods. This rate dependency also makes it possible to evoke a dynamic and analyzable response in that part of the cystometry curve where pressure is nearly constant during classical cystometry (fig. 4). In practice, an ideal step function cannot be

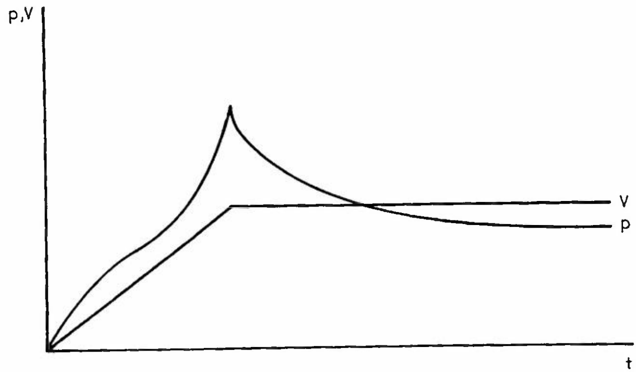

Fig. 2. Pressure decay in a urinary bladder.

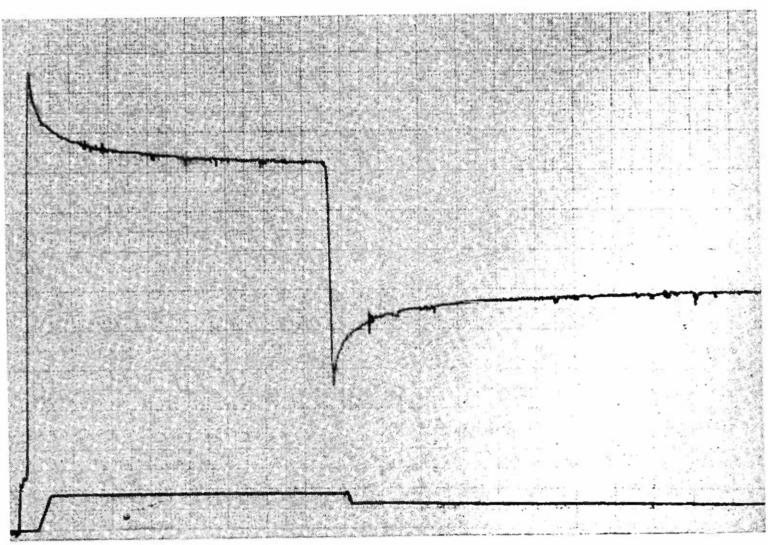

Fig. 3. Pressure decay in a rubber balloon.

realized because a certain volume cannot be infused in an infinitely short time. However, a steep ramp, i.e. a continuous fast filling of the bladder can be applied. When the rate of the ramp is known, the results can be converted to those of a step response.

In studying these converted results, the time dependency of the pressure was analyzed. When a semi-logarithmic plot of the pressure curve was made

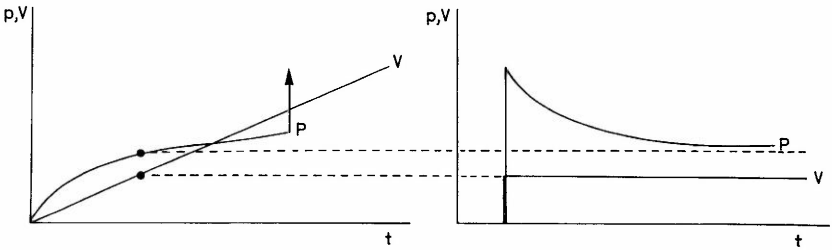

Fig. 4. Pseudo-static and dynamic pressure measurements.

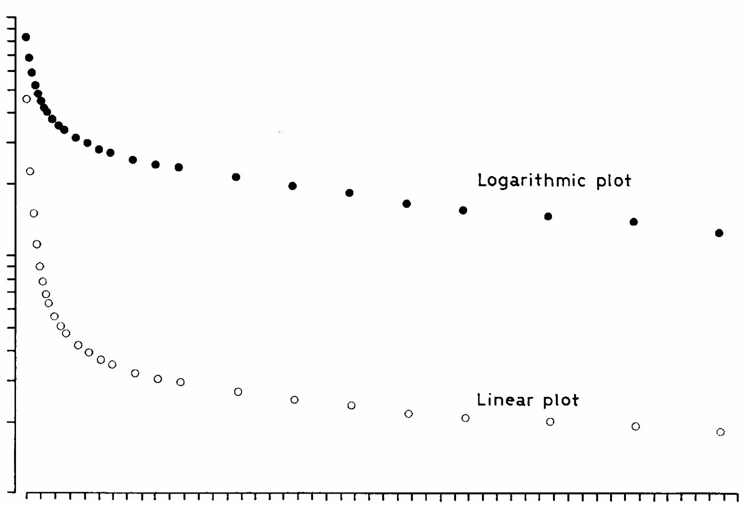

Fig. 5. Semi-logarithmic plot of pressure decay.

it was found that the pressure decay is not mono-exponential (fig. 5). Since application of a step function to a model consisting of elastic and viscous elements gives an output signal consisting of a sum of exponentials and a constant, we tried a mathematical model with two exponentials and a constant and a model with three exponentials and a constant. The models were fitted to the measurements according to a least-square fitting procedure, performed on a digital computer. The program used has been published by KIRKEGAARD [3]. It appears that the three-exponential model [4] is extremely sensitive to measurement errors. For clinical applications the two-

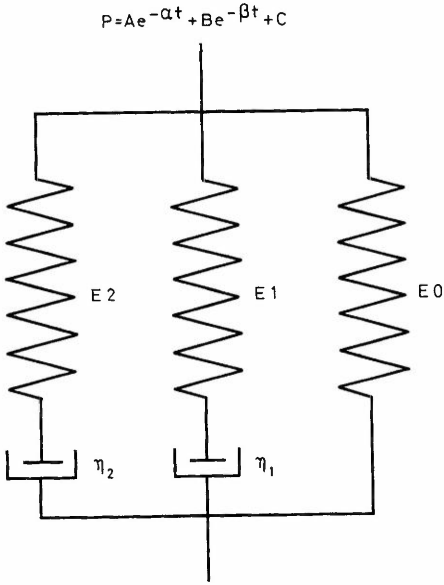

Fig. 6. Mechanical model of the bladder wall.

exponential model can be useful. The model can be translated into a mechanical model consisting of springs and dashpots (fig. 6).

A device has been constructed for quick analysis by electronic simulation. It projects a pressure decay curve on a screen together with a simulated curve consisting of two exponentials and a constant. By manually changing the parameter values, the simulated curve is adapted to the measurements so that the two curves coincide. We call the concept of filling the bladder with step functions and analyzing the results with a model of two exponentials and a constant *stepwise cystometry* [2].

Experimental Data

The reproducibility of the exponents was tested by applying a series of step functions on the same volume level in different animals, the experiments being done with opened abdomen (table I). With closed abdomen, however, the standard deviation and the difference between exponents of different dogs was greater (table II).

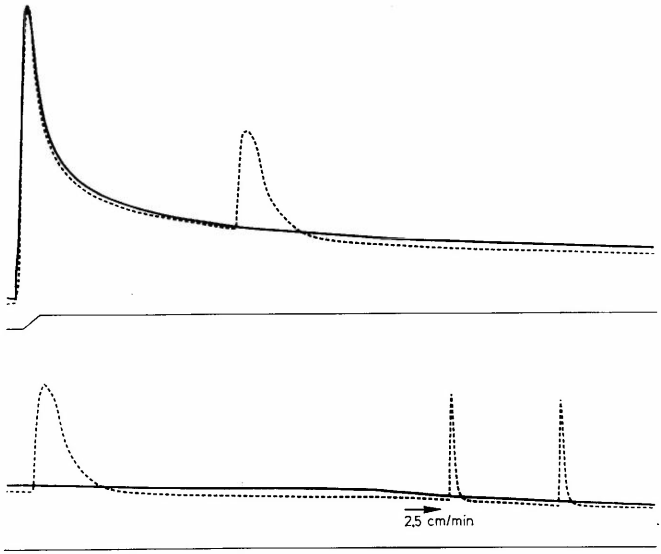

Fig. 7. Effect of superimposed contractions on pressure decay.

Table I. Exponents from experiments with opened abdomen

Dog No.	γ^1	δ	γ^2	δ	n
14	–0.16	0	–0.0045	0.0009	2
15	–0.11	0.01	–0.0045	0.0003	3
17^{V1}	–0.10	0.008	–0.0055	0.0004	3
17^{V2}	–0.095	0.01	–0.0053	0.0008	5

γ^1, γ^2 = Exponents (s^{-1}); δ = standard deviation; n = number of measurements.

Table II. Exponents from experiments with closed abdomen

Dog No.	γ^1	δ	γ^2	δ	n
15	–0.089	0.006	–0.0056	0.0006	4
16	–0.12	0.20	–0.008	0.004	2
17	–0.16	0.05	–0.004	0.002	2

γ^1, γ^2 = Exponents (s^{-1}); δ = standard deviation; n = number of experiments.

Table III. Exponents from experiments with and without superimposed contractions

Dog No.	γ^1	δ	γ^2	δ	n	
14	–0.12	0.006	–0.0039	0.0001	3	without superimposed contractions
15	–0.12	0.007	–0.0039	0.0003	2	
16	–0.14	0.008	–0.0085	0.0005	5	
15	–0.14	0.01	–0.0053	0.0004	2	with superimposed contractions
16	–0.16	0.04	–0.0194	0.01	4	

γ^1, γ^2 = Exponents (s^{-1}); δ = standard deviation; n = number of experiments.

Table IV. Exponents from experiments after 15 minutes of rest and five minutes after stimulation

Dog No.	γ^1	δ	γ^2	δ	n	
14	–0.16	0	–0.0045	0.0009	2	after 15 min rest
15	–0.11	0.01	–0.0045	0.0003	3	
14	–0.12	0.006	–0.0039	0.0001	3	5 min after stimulation
15	–0.12	0.007	–0.0039	0.0003	2	

γ^1, γ^2 = Exponents; δ = standard deviation; n = number of experiments.

When applying superimposed active bladder wall contractions by electrical pelvic nerve stimulation, it appeared that the pressure decay curve was nearly unchanged (fig. 7). Results of mathematical analysis are represented in table III.

Studying the influence of preceding conditions, exponents were measured in a series where volume input was applied after 15 min rest and another series 5 min after electrical stimulation of the pelvic nerves. Results are shown in table IV.

In order to examine the strain dependency of the parameters, several series of measurements were made with increasing volume levels. No trend could be seen in the exponents. The elastic moduli, however, showed a remarkably rising trend, as can be seen in the results of one of these experiments (fig. 8). Here E_0 represents the elastic modulus responsible for the static response of the system (fig. 6), i.e. the pressure which remains

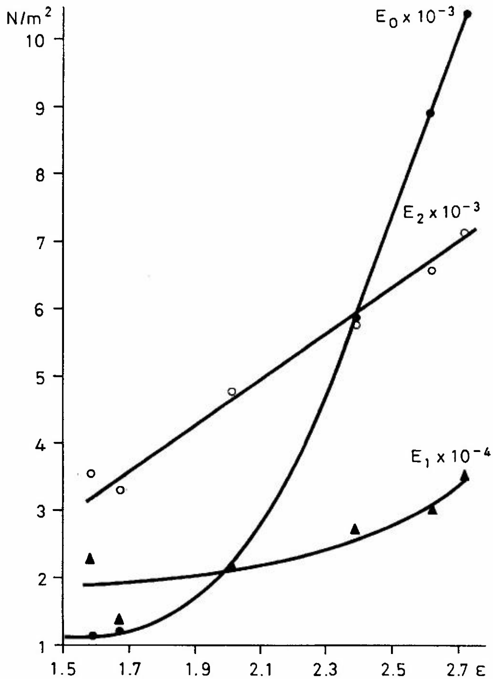

Fig. 8. Elastic moduli, dog 21. Two exponentials.

when the dynamic elements have come to rest. As can be seen in figure 8, E_0 is a non-linear function of ε. With the aid of the geometry model, the E_0 function can be computed from the *static cystometrogram*, which is obtained from the values of the constant in the multi-exponential model.

Besides the static cystometrogram, as may be derived from the proposed stepwise cystometry method, a pseudo-static cystometrogram can be obtained by two methods:

(1) Slow continuous filling of the bladder. With the aid of the model the error in measured pressure can be expressed in the rate of filling. Accepting an error of 15%, we obtain a filling rate of 0.5 ml/min which is clinically unacceptable.

(2) Stepwise filling of the bladder with increasing volume and registration of the pressure after a certain relaxation time. It can be shown from the exponents obtained that the error in measured pressure with a relaxation time of 15 min is approximately 15%.

Conclusions

In conclusion we hold that stress relaxation may be described by a model consisting of two exponentials and a constant. This model enables us to criticize the commonly used cystometry methods as far as visco-elastic behaviour is concerned. We therefore suggest *stepwise cystometry.*

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Request reprints from: Dr. B. L. R. A. COOLSAET, Douglaslaan 40, *B-2080 Kapellen-Antwerpen* (Belgium)