Urological Research 1, 15-21 (1973)

The Viscoelastic Behaviour of the Ureter during Elongation

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Summary. The viscoelastic behaviour of segments of ureters from dogs and guinea pigs has been studied by an ergometer. Elongation of the ureter produces a force, which may be ten times greater than the force of ureteric contractions, and which is proportional to the rate and magnitude of the stretch. Elongations of sufficient length and rate induce spontaneous contractions, the amplitude of which is proportional to the extent of the stretch after some cycles of elongation and shortening. The ureter shows hysteresis so that the loops of the force-length diagrams run in a clockwise direction. However, strain cycles of less than 4% L_0, and less than 0.07 Hz, provoke counterclockwise loops. The loops of the force-length diagram of the contractions also slope in a counterclockwise direction. The ureter behaves like a plasto-elastic body and adapts to strain. The plastic element is at least partly due to the musculature, since the deformation is reduced by continous stimulation of the ureter.

Key words: Ureter, viscoelasticity, smooth muscle, muscular properties, stress-strain.

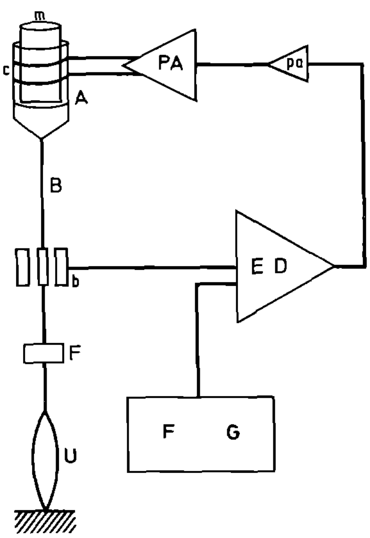
Unlike the bladder, there have been few investigations (2, 7) of the viscoelastic properties of the ureter, although knowledge of this behaviour is required for exact interpretation of its electromechanical relationships.

The present study is an analysis of the responses of the ureter to a series of passive mechanical stretches.

Material and Methods

The viscoelastic properties of the ureter were studied by means of an ergometer (Fig. 1, 4). In this apparatus, a segment of ureter (u) about 3 cm long, is suspended vertically; its lower end is fixed to a Perspex frame, and its upper end is tied to a light silver chain which is attached to strain gauge (F). The position of the strain gauge is controlled by an electro-magnetic ergometer made up of a vibrator (A) in which electric current passing through a coil determines the position of that coil in the field of a permanent magnet. The coil is connected to the strain gauges by a rod (B); an intermediate part of the rod serves as the moving part of a length transducer (b), thus measuring the position of the rod, and, accordingly of the coil.

The coil is fed by a power amplifier, the input of which is the pre-amplified difference between the output signal of the length transducer and the signal of a programmed function generator. Any difference between these two signals immediately results in a change in the position of the coil and then, of the upper end of the ureteric segment.



Sketch of the ergometer

A:Vibrator, m: magnet, c: coil, B: rod, b: length transducer, F: strain gauge, U: ureter, FG: programmed Function Generator, ED: Error detector, pa: pre-amplifier, PA: Power amplifier.

This circuit constitutes a negative feed-back loop through which the length of the preparation follows exactly the signal programmed in the function generator.

The imposed length changes (strains) and the forces evoked in the ureter (stress) are shown together as functions of time on a U-V recorder, and are also written as a stress-strain relationship on an X-Y recorder and an oscilloscope.

Various segments of ureters of dogs and guinea pigs were investigated. Since the ureter in vivo has no constant length, the reference length L_0 was taken as the length between the two ligatures when the ureter was straight and only under very light tension, i.e. the length beyond which any further elongation causes a marked increase in the passive tension.

Results

Changes of length imposed on the ureter in vitro (strains) evoke alterations (stress) in its tone or passive tension, and in its spontaneous active contractions (phasic activity). No qualitative differences were observed between the behaviour of ureters from dogs and guinea pigs, nor between different segments of ureters.

A - Linear stretching and shortening

a) Passive tension. Elongation of the ureter causes a steep rise of force (Fig. 1), which is slow at first and then becomes papid. The tension-time curve in concave upwards. When the ureter is maintained at the new length, the initial peak tension is not constant but declines, at first rapidly and then more slowly (stress relaxation or adaptation to strain). A steady-state tension at an imposed length is soon obtained with very small length increments. However, if the elongation is large, it takes a long time (many minutes) before an almost constant plateau is obtained where the steady-state passive tension is in equilibrium at the imposed length: in such cases there is a large difference between the peak tension and the final steady-state tension. Return to the original length (shortening) causes a fall in tension, which is stoep at first and slower

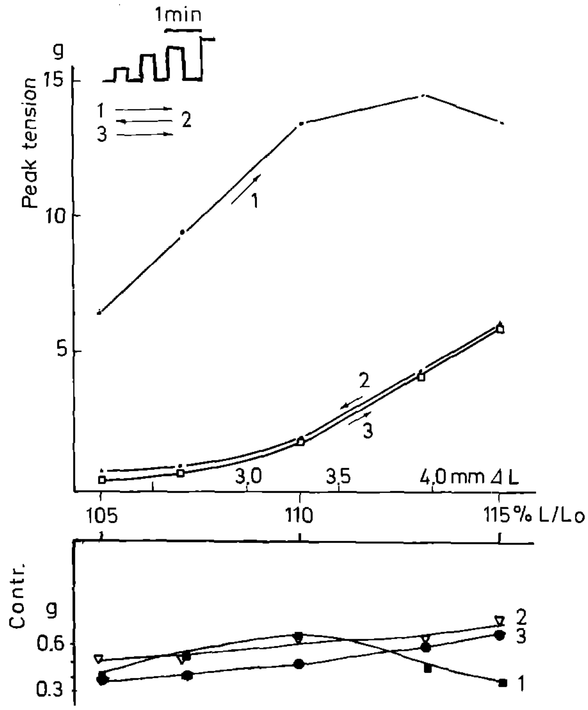


Fig. 2. Upper diagram: peak forces obtained during successive series of increasing (1 and 3) and decreasing (2) lengths. Lower diagram: amplitude of spontaneous contractions induced at each level of elongation during the same series of experiments

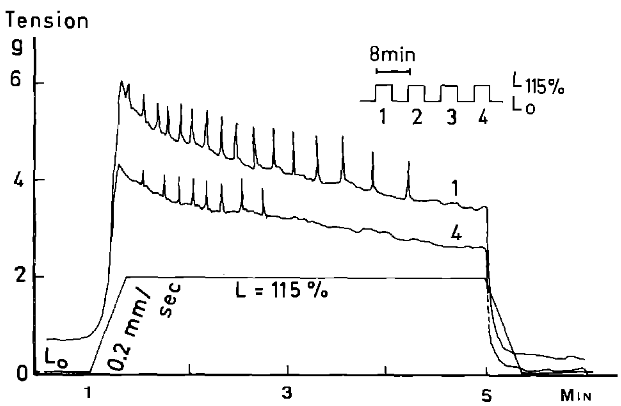


Fig. 1. Force developed during the first and fourth elongation of a segment of canine ureter 2.5 cm long (= L_0). Amplitude of elongation: 15% L_0; rate: 0.2 mm/sec; duration: 4 min

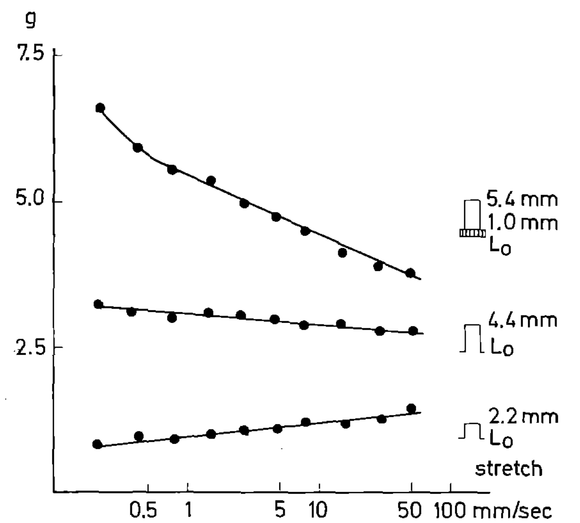


Fig. 3. Influence of rate of stretch on the maximum force. Guinea pig ureter with L_0 = 2.8 cm. Elongations of 2.2 mm, 4.4 mm and 4.4 mm after a previous constant elongation of 1 mm

afterwards. Despite identical speeds of elongation and shortening, the decrease of tension during shortening is always steeper than the increase during elongation (hysteresis).

The peak tension evoked by elongation is determined by several factors:

a) the magnitude of elongation: the greater the stretch, the greater the tension (Fig. 2).

b) the rate of elongation: a more rapid rate of stretch evokes a greater tension (Fig. 3).

c) previous stressing of the ureter (stretch history):

- if identical elongations and shortenings are repeated many times, the successivel peak and resting tensions gradually diminish (Fig. 1).
- if a series of elongations of increasing magnitude are repeated (Fig. 2), the peak tensions obtained during the first series are always disproportionally greater than those observed during subsequent series. The tension-length curve the initial series is usually convex with respect to the tension axis, but it becomes concave subsequently.

d) interference between the effects of the magnitude and rate of stretching. It the first elongation is very large, the effect of stress relation becomes so pronounced that the effect of even higher rates of elongation is masked by the decreasing tension (Fig. 3).

b) Effect of Passive Stretching on Active Contractions. If an inactive ureter is stretched and maintained at its new length, spontaneous contractions of increasing amplitude and decreasing frequency may be induced (Fig. 1). This reaction occurs after abrupt increases in length, as well as after slow elongation (0.2 mm/sec) provided that the increment is sufficiently great (more than 10% L_o).

The amplitude of spontaneous contractions and contractions induced by electrical or pharmacological stimulation is determined by the length imposed on the ureter. During the first of a series of passive, increasing elongations, the amplitude of the contractions increase up to an optimum length, after which they decreases. However the length at which the maximum amplitude of active contractions occurs, quickly shifts to greater lengths during repeated series of elongations, so that the greatest contraction soon coincides with the maximum length. From that moment the contractions are proportional to the length (Fig. 2).

It should be noted that the force exerted by an active contraction is largely (up to ten fold) exceeded by the passive tensions evoked by the stretch.

B - Sinusoidally Strains

a) High Amplitude Strains. Ureters respond to a sinusoidally strain of large amplitude (0.01 to 1 Hz) with an oscillating non-sinusoidal stress. The troughs of the stress curves are broad and their peaks are sharp. If stress and strain are recorded simultaneously as function of time (UV recorder), it appears that strain lags behind stress (phase lag), or, that stress "leads". The phase lag is small. The stress-strain loops have a non elliptical form and are skewed clockwise (Fig. 4): the tension measured during elongation is greater than that recorded during shortening (stress relaxation). Active contractions cause irregularities in the loops.

During successive cycles of sinusoidal strain of constant amplitude and constant rate, the stress-strain loops gradually shift towards lower tensions (Fig. 5). The progressive reduction in resting tension continues for a long time (e.g. in figure 5. for at least 90 cycles) and is faster at higher initial resting tensions. Simultaneously, the area enclosed by the loop diminishes progressively, because the decline of the ascending (elongation) limb of the loop is greater than that of the descending (shortening) limb. This denotes that equilibration at an imposed length occurs only gradually and slowly.

If the ureteric segment is stretched between repeated series of identical oscillating strains, the resting tension developed during the first of the subsequent series of elongations is disproportionally high, and its hysteresis, too, is very pronounced in comparison with succeeding loops.

There is marked dependence of the loop area on the magnitude of the elongations (Fig. 6). The shift to higher tension levels at larger stretches is particularly obvious for the second and subsequent cycles.

The area of the loop is also determined by the frequency of the oscillating strains, i.e. by the rate of the elongation, and it increases progressively with increasing rates of stretch. This should be expected in any viscoelastic process involving simple Newtonian viscosity. In the experiments in which successive series of stretches at increasing frequencies were applied to a segment of ureter which had

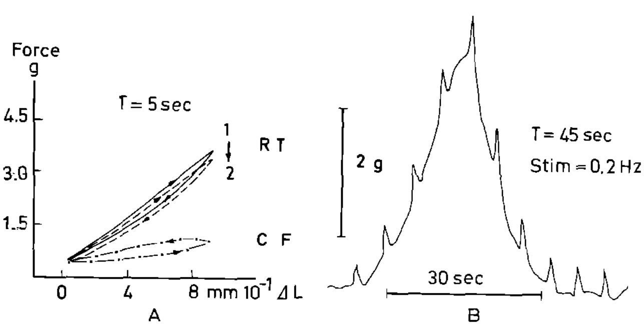


Fig. 4. A/Force-length loops during sinusoidal strains (period T = 5 sec; amplitude 5% L_o) and electrical stimulations (0.2 Hz; 50 V; 20 msec) of a ureteric segment from a dog. RT = resting tension; CF = force of contractions. B/Force-time curve during sinusoidal strain of 5% L_o and T = 45 sec. Electrical stimulation every 5 sec

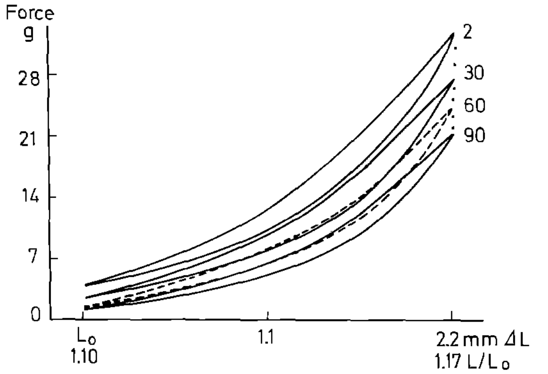


Fig. 5. Force-length loops of the 2nd, 3th, 60th and 90th cycle of oscillating strains at 0.07 Hz between 1.10 and 1.17% L_o. (L_o = 31 mm; dog ureter)

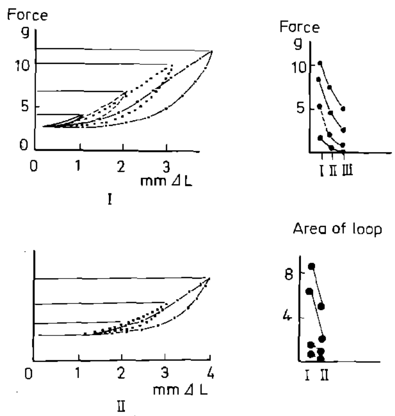


Fig. 6. Relation of force (g) and area of loop (g/min) to the magnitude of length changes during the three first successive cycles (I, II, III)

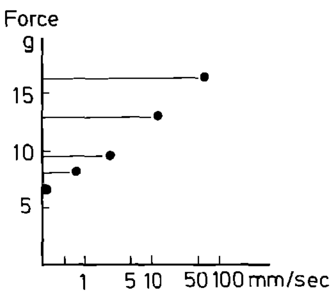


Fig. 7. Influence of rate of elongation on the tension developed. Amplitude of elongation: 109% L_o. Dog ureter

already been elongated, and in the experiments using high amplitude oscillatory strains, it was found that the loops were larger at lower frequencies. This behaviour is most probably due to pronounced stress relaxation, or to adaptation to imposed lengths during the entire period of the experiments (Fig. 8).

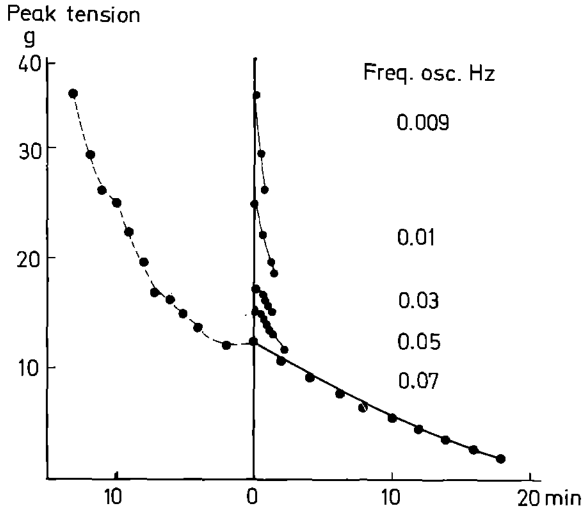


Fig. 8. Peak force developed during successive sinusoidal cycles at increasing frequency. The points symbolising the forces of cycles of the same frequency are connected by a solid line starting at time 0. In the left half of the figure the peak tensions are represented as functions of time, independent of the frequency of oscillations

b) Stimulation during oscillatory Changes in length. If the ureter is stimulated by single shocks at low frequency (0.2 to 1 Hz) during imposed oscillating changes in length, the amplitude of the induced contractions increases near the peak of the strain, and their amplitude for a given length is greater during the falling phase than during the phase of rising strain (Fig. 4B). If the amplitude of the contractions are shown in an active-force/length diagram (Fig. 4A), it will be seen that the direction of the loop is counterclockwise. Like stepwise increments in length, the maximum amplitude of the contraction does not coincide with the greatest elongation during the first set oscillating stresses but only during the subsequent cycles.

It has been described above that the tension developed by the ureter during successive oscillatory changes in length progressively diminishes. If, however, the ureter is continuously stimulated by a 50 Hz electrical current, the resting tension, instead of progressively declining, increases rapidly at first and thereafter more slowly (Fig. 9A). During such stimulation the width of the loops is increased as can also be seen in the tension-time recordings (Fig. 9B), in which the peak tensions increase more than the dips of the stress curves.

c) Low Amplitude Strains. If the amplitude of the oscillating stretches is kept very small (less than 4% L_o), so that the forces developed are of the same order (500 to 2000 mg) as those of active contractions, the stress-strain loops become more elliptical. Furthermore, if the duration of the sinusoidal strain at these low length changes is more than 15 seconds, the stress-strain loops tend

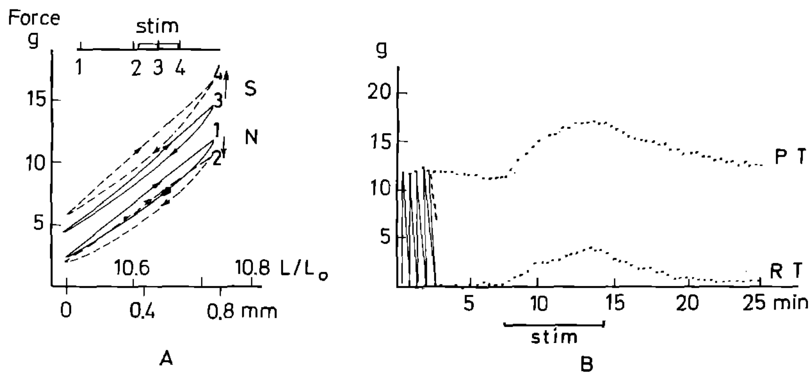


Fig. 9. Effect of stimulation at 50 Hz on the force developed during oscillating strains (period = 25 sec; amplitude between 1.05 and 1.07 L/L_0). Dog ureter. A/Force-length loops. Loops 1 and 2 without stimulation, loops 3 and 4 during stimulation. B/Force-time curves. The points represent the successive resting tensions (R. T.) and peak forces (P. T.)

to turn in a counterclockwise direction. If the stress and strain are recorded simultaneously as functions of time, it is clear that the stress peak comes after the strain peak, e. i. strain is leading.

It is also apparent that the tension evoked by the small sinusoidal stretches may, depending on their respective frequencies, interfere with the force of spontaneous contractions. The amplitudes of both tensions may be summated at the "resonant" frequency, and beats may occur if the frequencies almost match each other. In this way periodic waxing and waning may develop of the net force ultitely developed.

Discussion

The results obtained with stepwise changes of length and with sinusoidal strains are similar and complementary.

If an inactive ureter is submitted to a stepwise elongation, it resists by a force which progressively diminishes, even though the elongation is maintained (Fig. 1). The evoked tension is dependent on the rate (Fig. 3) of stretching. In cyclical strains of great amplitude or of high frequencies clockwise loops are observed: these loops are caused by stress relaxation (hysteresis), whereby the unstrained length increases and the stiffness (elastic modulus) decreases. The loop area is dependent on the frequency (Fig. 8) and on the number of cycles (Fig. 5). From this behaviour it may be concluded that the ureter is an organ with viscoplastic properties: the movements imposed on the ureter provoke a permanent deformation (plasticity) which is dependent on the velocity of the movements (viscosity). The permanent deformation is particularly obvious between the first and subsequent cycle of a series of elongations (Fig. 2).

As mentioned by Marechal and Casteels (5) such behaviour is not necessarily due to the contractile state of the smooth muscle, but is common to every plastic body. The contribution of the muscle cellsto the resistance to elongation can be differentiated by stimulating the ureter during or between the cycles: a "reset" on the length axis, i. e. disappearance of the effects of relaxation due to deformation, would signify that the plasto-elastic element resides in the musculature. In fact, the experiments show that during fast stimulation (Fig. 9) the tension increases instead of diminishing during succeeding sinusoidal strains; the increase is more pronounced during elongation than during shortening, so that the areas of the loops become larger. It is likely therefore that the contractile tissue of the ureter affects the plastic deformation. This implies that the elasticity of the ureteric wall alone cannot restore the ureter after elongation and that in clinical conditions, active contraction of the musculature are required to empty the ureter after distention and to restore the original state.

It should be noted, however, that stimulation never "resets" the tension evoked by the first elongation. This must mean that an irreversible reaction occured during the first significant stretch. It is common clinical experience that very dilated ureters rarely return entirely to normal. Before concluding that these experiments have shown an irreversible effect, it will be necessary to exclude possible damage to the ureter by examining the response to long lasting high frequency stimulation and studying the effects of powerful spasmogenic agents, e. g. histamine and barium chloride.

A counterclockwise loop was observed in the ureter during slow stretches of small amplitude. In these circumstances ureters contract with a force which is large enough to increase the overall stress although the strain is decreasing. The transition from counterclockwise to a clockwise direction of the force-length loops at small strains occurs at a frequency of 0.07 Hz, which is close to the value (0.08 Hz) found by Apter and Mason (2).

Spontaneous phasic contractions were mainly induced by large stretches (Fig. 1). Burnstock and Prosser (3) described phasic contractions induced by quick stretches (1 mm/sec) of 1 mm for each 12 mm length of ureter. The present experiments prove that much slower stretches also may induce contraction, provided that the elongation surpasses a critical value (about 10% L_o). This means that a bolus of urine entering the ureter may itself evoke a propagated contraction.

The active force of ureteric contractions induced by electrical stimulation is greater at decreasing than at increasing lengths (Fig. 4). This was also observed by Weiss et al. (7) in the ureter of the cat but is contrary to the relationship observed in arteries (6). No explanation can be given for this difference.

The phenomenon of waxing and waning of the amplitude at contractions can also be observed in vivo (Fig. 10). Displacements of the kidney by the respiratory movements of the diaphragm produce periodic stretching of the ureter, and if respiration has almost the same frequency as the spontaneous activity of the ureter there may be interference of the two forces. This may be one cause of false lisleading recordings of pressure waves in the ureter.

In the present experiments only changes in the length of the ureter have been considered. Despite the fact that in other experiments a good correlation has been found between contractions (longitudinal force) and intraluminar pressures (distentions and circular force components), investigation of the volume-pressure relationships is required to validate the results for a hollow organ such as the ureter.

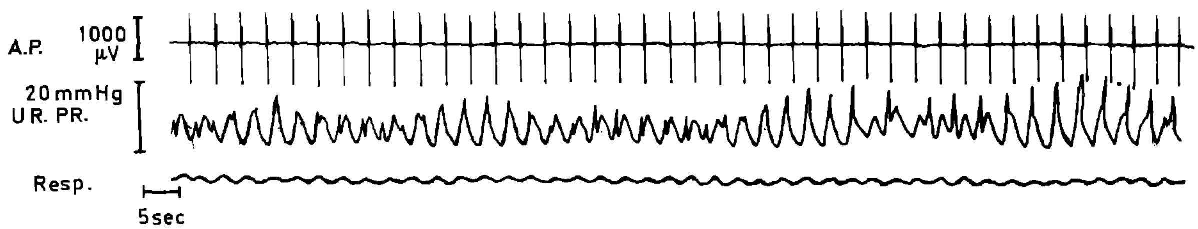


Fig. 10. Waxing and waning of the amplitude of the ureteric pressure waves (UR. PR.) caused by the almost synchronous frequencies of endogenous contractions (A. P. = extracellular action potentials) and respiratory movements (RESP)

It is striking that in both stepwise and oscillatory changes in length the maximum amplitude of spontaneous or induced contractions does not coincide with the maximum length during the first cycles of imposed changes, even though such a direct relationship is obtained during succeeding cycles. This fact denotes on one hand the inadequacy of ureteric contractions at great extensions, and on the other hand adaptation of the ureter to stretch. The reduced amplitude of the contraction at "overstretched" lengths may show a "rest" during subsequent cycles. Analogous behaviour has also been described in the bladder: with increasing stretch the contractile force passes through a maximum after which it diminishes (1), but the maximum shifts gradually to greater lengths as a function of the stretch history (4).

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