MAMMALIAN SMOOTH MUSCLE.—THE CAT'S BLADDER.¹

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METHODS.

THE use of the bladder as a means of studying the reactions of mammalian smooth muscle is not entirely new. Samkowy ¹ has investigated the influence of temperature on the bladders of frogs, cats and rabbits, and Capparelli ² has studied the same preparation in dogs and rabbits by means of plethysmographic tracings.

Theoretically the strongest objection to its use lies in the fact that in general direction its fibres are far from parallel. When, however, the viscus is suspended between two metal hooks and extended by a weight of twenty grams or more, its form is so elongated that this objection is almost ruled out; while the uniformity of the results obtained, the regularity in the response to a stimulus, and the fact that the whole muscle responds at once, seem to make the objection still more insignificant. As a decided advantage, the bladder may

¹ Read in abstract before the American Physiological Society, Dec., 1899: see This journal, 1900, iii, pp. xxv–xxvi.
be used either in situ, without any disturbance in circulation, or excised, without any direct injury to the muscle substance further than that necessitated by piercing at each end with a suspending hook.

Used in situ, the method of preparation is as follows: The cat is anaesthetized under a bell-jar with ether, stretched on its back on an animal holder of the usual form, and tracheotomized to facilitate the continued use of the anaesthetic. The abdomen is then opened in the middle line for a distance of six or eight centimetres from the symphysis pubis. The bladder is raised in the fingers and, if full, emptied by gentle pressure.

To obtain graphic records of the contractions of the bladder an arrangement of the form shown in Fig. 1 is used. This consists of a heavy iron standard which can be moved to a position close beside the animal board. To its rod are clamped horizontal bars carrying a second vertical rod which is thus brought to stand more directly above the animal. At the lower corner of the extension is an obliquely placed rod terminating below in a sharp spike; and at some distance above is a bearing for the long recording lever. The spike, about one centimetre in length, is run through from the ventral side in the middle line of the base of the bladder; the apex is drawn upward and pierced by a small hook which is, in turn, connected by an adjustable attachment with the short arm of the lever. The lever is directed at right angles to the circumference of the smoked drum, and its point rises and falls in a straight line, not in the arc of a circle.

By depressing the lower end of the spiked rod, the tissue below the point of fixation may be left so loosely relaxed that none of the
body movements, either of respiration or those of irregular origin, are communicated in the slightest degree to the recording lever. As an additional precaution, to avoid possible interference by intestinal peristalsis, it has been found best to empty the rectum by stripping it upward between finger and thumb; it should then be tied and clamped to the side of the abdominal opening. The electrical current used as a stimulus is applied through two wires, one leading to a binding post in the upper end of the oblique rod, and another, not shown in the figure, passing to the hook at the upper end of the bladder.

The advantage of this method of studying the responses of the bladder to stimulation lies chiefly in the absence of any sign of fatigue. The circulation being undisturbed it is possible to continue a series of observations for several hours without any appreciable change in the conditions. During the winter months, however, with the temperature of the room at 19° or 20° C., it is impossible to maintain the normal temperature in the exposed muscle, the resulting reactions being those of the viscus kept at 29° to 30° C. This is true even if the organ be surrounded by a casing packed with absorbent cotton kept warm by the frequent use of saline solution at body temperature.

To obtain records from the excised bladder the animal is killed with ether or curare, the abdomen is opened, and, the bladder being raised in the fingers, the urethra is cut across a few millimetres below the sphincter muscle. The urine is then expelled and the muscle transferred to a moist chamber. It is there suspended between an adjustable metal hook, insulated in the hard-rubber top of the chamber, and a second hook below, S-shaped and several centimetres in length, which in turn is attached to the long arm of the recording lever. The lever is a direct recording one exactly similar to that used with the bladder in situ. The electrical connections for this preparation are made by a binding-post attached to the hook in the top of the chamber, and a wire fastened to the lower, S-shaped, hook. The wall of the moist chamber is double, and the space of about two centimetres between the sides is filled with about 660 c.c.m. of water. The temperature within the chamber may be kept constant, or varied at will, by heating or cooling the water as desired.

Throughout the present research both the above methods have been freely used. Where the nature of the experiment was such that even a small amount of fatigue would interfere with the result, the
bladder was left in position in the living anesthetized animal. Otherwise the excised preparation was employed. Even with the latter the fatigue is very slight, and appears only after repeated stimulation. No differences have been found in the responses of the muscle under these different conditions. A bladder freshly exposed in the living animal reacts exactly as does one at the same temperature in the moist chamber. Nor does the nature of the result change if the animal be poisoned with curare, or if the bladder be excised until all nerve cells are dead.¹

**SPONTANEOUS MOVEMENTS.**

Occasionally on opening the abdomen of a freshly anesthetized cat the bladder will be found to be contracting and relaxing, apparently rhythmically, with a periodicity of about 45−50 seconds. This, however, is rare; in general the viscus is at rest. But spontaneous contractions occur very frequently after the muscle has been stimulated for some time.

Since Engelmann ² in 1869 published his work on the rabbit’s ureter, rhythmical spontaneous movements have been observed in other smooth muscle preparations in almost every case. Spontaneous contractions of the bladder have been described by Mosso and Pellacani,³ Ashdown,⁴ Sherrington,⁵ Langley and Anderson,⁶ Griffiths,⁷ and others. Sherrington has shown that the spontaneous contractions of the monkey’s bladder originate within its own substance. Using various preparations Engelmann,⁸ Sertoli,⁹ Bottazzi,¹⁰ and Straub¹¹ have maintained that the spontaneous activity is purely

¹ LANGENDORFF: Centralblatt für Physiologie, 1891, v, p. 131.
² ENGELMANN: Archiv für die gesammte Physiologie, 1869, ii, pp. 243-292.
³ MOSSO AND PELLACANI: Archives italiennes de biologie, 1882, i, pp. 97-128.
⁴ ASHDOWN: Journal of anatomy and physiology, 1887, xxi, pp. 299-324.
⁵ SHERRINGTON: Journal of physiology, 1892, xiii, pp. 625-772.
⁶ LANGLEY and ANDERSON: Journal of physiology, 1894, xvi, pp. 410-440.
⁹ SER TOLI: Archives italiennes de biologie, 1883, iii, pp. 78-94.
¹⁰ BOTTAZZI: Contributi alla fisiologia del teesuto di cellule muscolari, Firenze, 1897; Archives italiennes de biologie, 1897, xxvi, p. 443; 1897, xxviii, pp. 81-90; Lo sperimentali, 1897, ii, pp. 99-170; Archives italiennes de biologie, 1899, xxxi, pp. 63-68: 1899, xxxi, pp. 97-126.
¹¹ STRAUB: Archiv für die gesammte Physiologie, 1900, lxxix, pp. 379-399.
muscular, while Ranvier, Morgen, Schultz, and Barbéra have contended that it is of nerve cell origin. Rhythmical movements of the mammalian bladder are certainly present many hours after excision of the preparation, a fact which seems to leave no doubt as to their intrinsically muscular nature.

At times there is a regular sequence in the automatic movements of the bladder muscle, with the separate contractions of uniform size. More often they are irregular. Fig. 2 shows tracings obtained from spontaneously active preparations. The first, or upper curve (a) was obtained from a comparatively fresh muscle in a moist chamber at room temperature (20°C). The time intervals are ten seconds. The second line (b) shows the tracing from the same muscle twenty hours after excision, the conditions remaining unchanged in the interval, and the contractions being continuous. It will be noticed in both that the tracings show contractions which are symmetrical; the speed of contraction being approximately equal to the speed of relaxation. This form of curve has been pointed out by Sertoli in records obtained from the erector penis muscle, and Ducceschi's tracings from the pyloric end of the stomach have a similar form. Other observers, with non-mammalian preparations, have described the curve of spontaneous contraction as showing a relaxation phase very much longer in time than the phase of contraction. It is possible, then, that the symmetrical contraction is characteristic of mammalian smooth muscle.

1 Ranvier: Leçons d'anatomic générale sur le système musculaire, Paris, 1880.
2 Morgen: Untersuchungen aus der physiologischen Institut der Universität Halle (Bernstein's), 1890, ii, pp. 139-169.
3 Schultz: Archiv für Physiologie, 1897, pp. 322-328.
4 Barbéra: Zeitschrift fur Biologie, 1898, xxxvi, pp. 239-258.
5 Sertoli: Archives italiennes de biologie, 1883, iii, pp. 78-94.
6 Ducceschi: Archivio per le scienze mediche, 1897, xxi, pp. 121-189; Archives italiennes de biologie, 1897, xxvii, pp. 61-82.
Occasionally the sequence of large and small contractions gives evidence of being compounded of two or more regular rhythms, as in the cases reported by Bowditch, and later by Woodworth, for the frog's stomach preparation. The tracing of the first line in Fig. 3 shows very clearly the presence of two rhythms, one slightly slower than the other, the resulting record being produced by the interference of the two series of contractions working upon the lever at the same time. The second tracing shows a primary series, and a secondary series of smaller contractions at a slightly slower rate. The third, an apparently irregular curve, can be analyzed into two simple rhythms, the rates of which are indicated by the two horizontal series of dots above the recorded curve.

There is also some further evidence to support the view that this compounding of rhythms points to the occurrence of regular rhythmical contractions, with different rates in different parts of the viscus. For example, when a bladder at rest begins to show such spontaneous activity the first evidence of the disturbance is nearly always an almost perfectly uniform and rhythmical series, as though only one area were contracting. Such a tracing appears in the upper line (a) of Fig. 4. And again, where the bladder is kept under observation until all contractions cease, the last sign of spontaneous activity, corresponding probably to the last contracting area to die, is a faint but regular rhythmical series of contractions. The second line (b)

1 Bowditch: Report of the British Association for the Advancement of Science, 1897, pp. 809-810.
2 Woodworth: This journal, 1899, iii, pp. 26-44.
of Fig. 4 shows such a tracing obtained from an excised preparation after thirty-one hours.

There is thus a striking analogy between the spontaneously contracting bladder and the fibrillating heart, for if the heart be observed closely during fibrillation it will very often be seen that, while the whole mass appears to be moving irregularly, yet any particular small area of the surface, watched by itself, is contracting rhythmically. The irregular spontaneous contractions of the bladder are not normal, and possibly depend on the same or similar disturbances in nutrition or in conduction as those which may give rise to fibrillation in the mammalian heart. The graphic record, also, of the

![Tracings](image)

**Figure 4.**—Tracings showing (a) the first evidence of spontaneous activity in a newly excised bladder, and (b) the last, 31 hours later. Time intervals are 10 seconds. Original size.

movements of a fibrillating heart resembles the curves already shown for the bladder in spontaneous activity. Although the irregularities are much more numerous, there is occasionally an evidence of simple rhythm in the presence of an insistent beat larger than the others.

It is difficult to say what may be the purpose of automatic movements occurring normally in the living animal. It may be that such a type of activity enables the bladder to adjust its size more easily to the ever increasing amount of its contents. And it is possible that, stimulated to greater force by distention, the spontaneous movements serve to expel into the urethra the first few drops of urine which there arouse the desire to urinate, and start the reflex nervous mechanism for the emptying of the bladder.
The Single Contraction.

The bladder responds to mechanical stimulation, to stimulation by means of single induction shocks, to the making and the breaking of the constant current, and to the action of the constant current during the flow. It is also influenced by changes in temperature, though it is not clear whether this last result consists in an actual contraction, or is merely a change in tonic condition.

The graphic record of a single contraction, in response to a single induction current, presents the characters already described by earlier workers for other smooth muscle preparations. Fig. 5 shows the form of the contraction obtained from an excised bladder at body temperature on stimulating with a single break induction current of moderate strength. A latent period of about 0.25 second duration is followed by a relatively rapid rise of the lever, lasting typically five or six seconds. This is succeeded by a more gradual relaxation usually complete in about thirty-five seconds. The end of the relaxation, in particular, is very slow. Although there are variations in the size of the contraction the time of the whole process is regularly about forty seconds. To compare with this we have Sertoli's determination for the erector penis muscle of the dog, 90–120 seconds, and Lewandowsky's finding for the nictitating membrane in cats,—a contraction lasting from five to fifteen seconds, followed by a relaxation from three to eight times as long, variations occurring with the size of the contraction.1

1 SERTOLI: Archives italiennes de biologie, 1883, iii, pp. 78–94.
3 For other smooth muscle preparations see CAPPARELLI: Archives italiennes
With an increase in the strength of the stimulus, the height of the contraction increases up to a maximum. The curve in Fig. 6 shows the response to a series of single break induction currents with the secondary coil at 13.5, 13, 12.5, 12, 11.5, 11, 10.5, 10, 9.5, and 9 cm. from the primary. At 13.5 cm. the contraction is very small, but increases progressively until the coil is at 10 cm. Beyond that point there is no increase, the contraction being maximal.

**Summation of Contractions and Tetanus.**

If the excised bladder at body temperature be stimulated by means of two equal induction shocks of moderate strength, and separated by known intervals, it is found that when the interval is greater than about eight seconds, the result is shown in the form of two separate contractions. If the interval be less than eight seconds, however, summation takes place, and, as in striped muscle, the effect of the second stimulus is added to that of the first. The fusion of the two curves in the record of such a pair of contractions becomes more and more complete the shorter the interval. Fig. 7 shows a series of curves obtained in this way, with intervals varied from one to eight seconds, preceded by a single

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*References*

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contraction. It is found that at one second there is no apparent difference between the result of two stimuli and that of a single stimulus, except that the contraction is higher. With an interval of two seconds, however, a slight irregularity in the rising arm of the contraction curve can be detected, indicating the incomplete fusion of the two waves. As the interval is increased the separation is more evident, until at eight seconds summation fails. It is also to be observed that where there is no summation with the longest interval there is still an overlapping of the curves. To produce summation the second stimulus must fall either during the first contraction or early in the relaxation phase. The tracing shows also, as the result of temporary fatigue following such frequent stimulation of the viscus, a slight falling off in the height of the initial contraction.

If a series of equal stimuli be used, summation takes place in the same way. For the development of tetanus in smooth muscle see Engelmann: Archiv fur die gesammte Physiologie, 1870, iii, pp. 247-326; Capparelli: Archives italiennes de biologie, 1882, ii, pp. 291-302; Sertoli: Ibid., 1883, iii, pp. 78-94, who has found a single induction shock inefficient as a stimulus for the erector penis muscle; Pawlow: Archiv fur die gesammte Physiologie, 1885, xxxvii, pp. 6-31; Bottazzi: Archives italiennes de biologie, 1897, xxviii, pp. 81-90; Barber: Zeitschrift fur Biologie, 1898, xxxvi, pp. 239-258; Winkler: Archiv fur die
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an experiment in which the bladder at body temperature was stimulated with break induction currents of moderate strength, with varied time intervals between the currents. On shortening the interval, summation appears, and becomes more and more pronounced until, with an interval of one second between the stimuli, complete fusion occurs. Beyond this point, as shown in the last curve of the tracing, the result of stimulation increases as the interval between the stimuli decreases. The tetanus curve thus obtained appears to be exactly similar to that of striped muscle, except in time relations. In all cases after such prolonged stimulation the muscle is fatigued and relaxes very slowly.

There appears to be no period in the contraction of the bladder muscle, occurring either spontaneously or in response to an excitation, during which a stimulus is without effect. Ducceschi has observed a refractory period in the spontaneous rhythmical contractions of the pyloric end of the stomach. He records complete failure of response if the stimulus be applied during the phase of rising energy, and a variable result if stimulated during the first half of the fall.

THE EFFECT OF THE CONSTANT CURRENT.

Throughout the experiments upon the effect of stimulation by means of the constant current a battery of two small storage cells was used. It supplied a current of from four to five volts, and about three milliampères passed through the bladder suspended in the moist chamber.

Both the making and the breaking of the constant current act as stimuli and produce contractions, though the contraction in response to the make is generally of much greater extent than that following the break. This is in agreement with almost all previous experimenters, though the result of the breaking of the current has been variously described.

As to the disputed question whether the constant current, during its flow, acts as a stimulus, there can be no doubt as far as the bladder muscle of the cat is concerned. The effect of the flow of the

gesammte Physiologie, 1898, lxxi, pp. 357—398; WOODWORTH: This journal, 1899, iii, pp. 26—44; and STRAUB: Archiv für die gesammte Physiologie, 1900, lxxix, pp. 379—399.

1 Ducceschi: Archivio per le scienze mediche, 1897, xxi, pp. 121—189; Archives italiennes de biologie, 1897, xxvii, pp. 61—82.
current is often sufficient to obscure partially the break contraction. Fig. 9 gives a demonstration of this. To obtain the tracing, which is one of a large number, the current is made, allowed to flow for several seconds, and then broken. The result is a strong make contraction, succeeded by a period of very slow, imperfect relaxation, the true relaxation occurring only after the break contraction. That this tonic elevation, following the make contraction, is due to the flow of the current is proved by the second curve of the figure. Here the same current was made in the same way, but shut off gradually with a rheonome, avoiding both the influence of the flow and the break contraction.

If, again, with a bladder muscle at rest, the constant current be turned both on and off with the rheonome, there occurs a slight rise in tonus during the flow, though the electrical change is too gradual to produce either the make or the break contraction. Sertoli has described a tonic relaxation, with cessation of the spontaneous contractions of the erector penis preparation, during the flow of a weak constant current; Ducceschi has observed the same inhibition of spontaneous contractions in the pyloric end of the stomach; Ranvier has noted a slight inhibition of the movements of the frog's stomach preparation, and Winkler has occasionally observed a relaxation. This I have been unable to find in the bladder preparation. With the tonic contraction during the flow there is often a decrease in the size of the spontaneous movements, but not enough to be explained otherwise than by the temporary shortening of the whole muscle.  

1 Sertoli: Archives italiennes de biologie, 1883, iii, pp. 78-94.  
2 Ducceschi: Archivio per le scienze mediche, 1897, xxi, pp. 121-189.  
3 Ranvier: Lecons d'anatomic generale sur le systeme musculaire, Paris, 1880  
4 Winkler: Archiv fur die gesammte Physiologie, 1898, lxxi, pp. 357-398.  
5 Professor Theodore Hough, of the Massachusetts Institute of Technology, has told me, and kindly allows me to repeat, that he has observed this inhibiting
I have been unable to find any direct evidence of an antagonism between the make and the break excitations with the constant current. Winkler has described a relaxation as the result of breaking the current, but this result is probably only the failure of an evident break contraction, and a relaxation as the result of the mere stopping of the flow. Woodworth has observed relaxation on making the current in the frog's stomach preparation. Observations bearing on this question have been made by Engelmann and Capparelli, using mammalian preparations, by Biedermann, and by Woodworth, with the frog's stomach, who have found that the extent of the response to stimulation with the constant current varies, within limits, with the duration of the flow. Woodworth (loc. cit.) states that between the make and the break there must be a perceptible interval in order to get any response. And as the interval is increased, the response increases (p. 41). Woodworth advances this as a proof of the antagonism between the make and the break, and has demonstrated that it is not the result of varying the duration of the flow, by reversing the process, passing the current through the muscle, and stimulating by means of a break followed by a make. In this case the result varies directly with the duration of the pause in the flow.

This finding is fully confirmed by the reaction of the bladder muscle preparation, and is more clearly demonstrated than in the published tracings of those who have established the essential facts. In Fig. 10 two tracings from the bladder muscle are reproduced. The upper tracing shows the effect of making and breaking the constant current with a series of intervals of 1/2, 5, 1, 5, and 25 seconds. It will be noticed that with 1/2 second there is no response, and that the contractions increase in size up to the 5-second interval. The tracing at 5 seconds is higher than the one following, because, with that interval, there is summation of the make and break contractions. In 1/2 second there is no response, and that the contractions increase in size up to the 5-second interval. The tracing at 5 seconds is higher than the one following, because, with that interval, there is summation of the make and break contractions. In

effect the constant current upon the automatic contractions of the frog's stomach preparation. Prof. Hough's tracings show, during the passage of the current, a great decrease in the amplitude of the automatic movements.

1 WINKLER: Archiv für die gesammte Physiologie, 1898, lxxi, pp. 357-398.
2 WOODWORTH: This journal, 1899, iii, pp. 26-44.
3 ENGELMANN: Archiv für die gesammte Physiologie, 1870, iii, pp. 247-326.
5 BIEDERMANN: Elektrophysiologie, Jena, 1895.
6 WOODWORTH: This journal, 1899, iii, pp. 26-44.
the lower tracing of the figure the current is flowing, sufficient time having elapsed for the disappearance of the effect of the original stimulus. Then the current is cut off for intervals of \( \frac{1}{2}, 1, 5, \) and 10 seconds, as indicated in the record. The first produces no effect, and then, as the pause in the flow is lengthened, the response increases, the summated contraction at 5 seconds being again higher than the succeeding one. To prevent interference by fatigue, these experiments were made on fresh preparations, with the circulation intact. For the same reason the series was arranged with the weakest stimuli first. With the excised bladder at body temperature the result is exactly the same, except that it is found almost impossible to stimulate for so short a time that no response will result, this difference being due to the greater irritability of the preparation at 38° C. as compared with the bladder in situ at 30° C.

We have demonstrated the separate effects of both the making and the breaking excitations, and have shown that the effects may be summated. And it has been impossible to find any trace of relaxation as the direct result of stimulation by means of either the make or the break under any conditions. It is difficult, therefore, to accept an explanation for these results which postulates an antagonism between the two stimuli in their effect on smooth muscle.
THE INFLUENCE OF TEMPERATURE.

1. On the tone of the bladder muscle.—If the bladder muscle, enclosed in the moist chamber of a water jacket, be cooled, it is found to shorten considerably with the lowering of the temperature. At about 10° C. the shortening is complete. If the temperature be now slowly raised, relaxation appears almost immediately, but proceeds very slowly at first, and becomes more marked only when the temperature rises to about 15–19° C. The loss of tone then proceeds regularly to a temperature of about 40° C., that is, slightly above the body temperature. Above 40° C. shortening once more appears, and proceeds, slowly at first, then more rapidly, until the temperature of the moist chamber is raised to from 53° to 57° C. At this point the muscle apparently loses its irritability and dies. There follows then, whether the muscle be kept at that temperature or heated further, a distinct loss of tone often of considerable extent.

\[ \text{Figure 11. — The curve of tonic change, with temperature rising, as indicated, from 10° to 60° C. Time intervals 10 seconds. One-third the original size.} \]

In this stage the muscle is comparatively relaxed, and very soft. It is only when the temperature is raised to 69° C. that the first shortening of heat rigor is obtained.

Considering the whole process, then, from the standpoint of the condition of the muscle at the body temperature, it may be said that cold produces an increase of tonus, while heat gives first a slight relaxation, then a marked increase in tone. In relation to the condition of the muscle at a temperature slightly higher, however, the muscle may be said to contract for both heat and cold.

In the experiments from which these results have been obtained, every care was taken to make the changes in temperature slowly, so the bladder might have time to be fully warmed. And control experiments were made with small isolated strips of the muscle.

Fig. 11 shows the typical form of the curve of change of tone with a resting bladder. The temperature, beginning at 10° C., was slowly raised as indicated in the tracing. The record shows very clearly a maximum lengthening in the neighborhood of 40° C., and demon-
strates the loss of tone following the loss of irritability, in this case at 56°C.\(^1\)

The influence of changes in temperature upon the spontaneous contractions\(^2\) of the bladder muscle is also very marked. Entirely absent at 10°C., they appear early in the course of the


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first relaxation on warming, although at low temperatures they are feeble and very slow. As the temperature rises toward that of the body, the contractions become more frequent and are of greater extent. Beyond a maximum slightly below body temperature, further warming increases the rapidity and frequency of the movements, but diminishes their amplitude, until they disappear entirely with the loss of irritability at a temperature in the neighborhood of 55° C.

Where automatic contractions are present in the preparation, irregularities in the course of the tonus curve are introduced. This is the case in the record shown in Fig. 12. With the appearance of spontaneous activity the curve, instead of falling regularly to 40° C., as in the dotted line, shows a secondary rise. This is due to the fact that in such a condition some part of the bladder is always in contrac-

![Figure 13. Curve of change of tone with rising temperature, showing the variation produced by frequent stimulation. One-third the original size.](http://ajplegacy.physiology.org/)

...tion, the result being an apparent rise in tone which increases with the amplitude of the movements. And again, on raising the temperature beyond 40° C., when the contractions so diminish in amplitude that they no longer of themselves sustain the lever, there is an apparent secondary loss of tone. This form of curve is characteristic of such preparations, and in other respects is perfectly in accordance with the result shown in Fig. 11. Fig. 12 shows also the loss of tone following the rise to 54° C., and the true contraction of heat rigor, appearing at 60° C.

If the muscle be stimulated during the course of an experiment on the influence of temperature on the tone of the muscle, another characteristic variation from the true result is obtained. In Fig. 13 the progress of the change in tone is interfered with in the same way as in the case illustrated in Fig. 12, but for a different reason. The muscle was stimulated every few degrees, as indicated in the record,
with a single induction current, for the purpose of testing the irritability of the preparation. The variation is due to the after effect, or contraction remainder, following the application of the stimuli. As the temperature rises the effect becomes greater with the increase of irritability, and is particularly marked above 40° C. When the irritability begins to disappear the lever sinks back to its true course, and once more records the real condition of the muscle with respect to tone. The tracing is also of interest because it shows the final loss of tone which accompanies the permanent loss of irritability at about 57° C.

These irregularities are constant, and are dwelt upon because it is believed that in overlooking them and their cause very important errors are made in studying the influence of temperature.

2. On the form of the contraction. — The changes in the form of the contraction curve of smooth muscle, resulting from changes in temperature have already been described by various authors.\(^1\) With the cat's bladder the facts are in accordance with the results previously obtained. The first sign of irritability in response to a single induction current appears at a temperature of about 10° C. At 15° C. the contraction is slight and, in relation to its extent, very slow. The contraction at 20° C. is more active, the latent period is shorter, and the maximum height is earlier reached. As the temperature rises the latent period shortens progressively,\(^2\) and the height of the contraction increases to an optimum temperature of about 40° C. Above the optimum point the height decreases until irritability entirely disappears at, or about, 55° C. With the rise in temperature there is a steady increase in the steepness of the rise of the curve; and this depends only in part on the increased height of the contraction of certain temperatures, for there is also a progressive shortening of the time of the contraction phase. There is also, as the temperature rises, an increase in the steepness of the descent of the lever, particularly in


\(^2\) The latent period at 10° C. is 3.5 seconds; at 15° C., 2.5; at 20° C., 1.6; at 25° C., 0.75; at 30° C., 0.4; at 35° C., 0.3; at 38° C., 0.25; at 40° C., 0.2, from the averages of a number of determinations.
the early part of the relaxation. And, finally, the time of the relaxation process shortens considerably.

Fig. 14 is a reproduction of a series of actual curves obtained at various temperatures from 15°C. to above 50°C., under conditions otherwise uniform.

The variations in the height of the contraction must be considered in connection with the general variations in tone of the bladder muscle, already referred to. When the muscle is in a state of tonic contraction, the contractions resulting from stimulation are necessarily decreased in height, though the total shortening of the muscle may actually be greater than the height of the maximum contraction at 40°C., where the tonic relaxation is also greatest. The height of the contraction at any temperature cannot, therefore, be considered as an absolute index of the irritability of the muscle at that temperature.


Under the influence of an increase in weight the bladder elongates very considerably. The changes in length take place more slowly
than with striped muscle under the same conditions, but in other particulars the results are exactly similar. Fig. 15 demonstrates the elasticity of the bladder muscle. Beginning from a position of rest with a weight of 20 grams (including the lever), the first drop in the curve shows the extension following the addition of 20 grams to the weight. Each succeeding fall shows the effect of a further increment of 20 grams, the extension being progressively less in each case. When the total weight amounted to 120 grams, all the weights were removed with the exception of the original 20 grams, and the tracing shows in the final vertical line the recovery of the normal length. The total lengthening under the greatest weight amounted to 15 mm., fully 40 per cent of the original length of the viscus.

Fig. 16 is a reproduction of a record indicating the influence of the load on the height of the contraction. The first vertical line shows the height to which the lever rises with the usual load, 20 grams; the second, the response to a single induction shock with a load of 40 grams. Each succeeding line represents the relative height for an additional weight of 20 grams until 140 grams is reached. As with striated muscle, the contraction decreases in height in a roughly geometrical ratio. Within the limits of the experiment, the actual output of energy, in the form of work done, is greater the greater the weight.
THE DURATION OF IRRITABILITY; FATIGUE.

Sertoli, keeping his preparations for the greater part of the time at a low temperature, has found that the erector penis muscle may remain irritable for five, six, or even seven days. Various other observers have noted the extreme slowness with which smooth muscle dies under ordinary conditions. With the bladder muscle of the cat the duration of irritability at room temperatures is often as much as twenty-four to forty-eight hours, while one preparation, kept in an ice-box at 5–8° C., responded to the faradic current at the end of four days.

The bladder in situ, with the circulation intact, does not, in the course of any ordinary series of experiments, show any evidence of fatigue for very long periods. It does, however, show temporary fatigue if strong stimuli be repeated rapidly, as in producing tetanus. Even then recovery takes place within a short interval, the time varying with the extent of the stimulation, and the experiments may be proceeded with as before. It is impossible to completely reduce the contractility of a fresh muscle even under the most powerful stimulation.

With the excised preparation the facts are different. With ordinary use for two, or even three or four hours' experimentation, the muscle lasts extremely well, giving at the end of that time almost

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1 SERTOLI: Archives italiennes de biologie, 1883, iii, pp. 78–94.
as good reactions as at the beginning. But if the stimuli be repeated
too frequently, without allowing any sufficient pause for recovery,
the extent of the contraction will diminish, and there will be a
gradual lengthening of the time of each of the phases of the con-
traction. This change in the response is not always very apparent
within the limits of a small series of contractions, but appears if, for
example, the muscle be stimulated by means of induction currents,
each current falling just at the end of the relaxation following the
previous contraction. Fig. 17 shows portions of a fatigue curve ob-
tained under such conditions. At the end of each relaxation a new
stimulus was applied, until the bladder was almost completely ex-
hausted. The figure shows contractions numbered 2-17, 29-41,
55-63, 92-100, 121-128, and 149-154 of the series. In fatigue not
only is the height of the contraction diminished, but the curve is
lengthened materially. The lengthening is present in the latent
period, in the period of contraction, and in the period of relaxation
during which the lever returns to the base line. During a pause
in such a series of stimuli the muscle recovers considerably, though
if the series be a long one, particularly if the bladder has been stimu-
lated to tetanus, the re-
covery never gives a com-
plete return of the original
force of contraction.

Morgen ¹ has noted that,
with a frog's stomach prep-
aration fatigued by the re-
peated application of the
constant current, a re-
cov e r y o f t h e o r i g i n a l
efficiency may be obtained
by reversing the current.
This same peculiar result
is given by the bladder, as
shown in Fig. 18. In this
experiment the muscle
was stimulated in every case by means of a constant current lasting
two seconds. For the first six contractions the current was passed
from base to apex. Fatigue being evident, the current was then

¹ Morgen: Untersuchungen aus der physiologischen Institut der Universität
Halle (Bernstein's), 1892, ii, pp. 139-169.
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reversed, made to pass from apex to base, allowing no pause for recovery. The next contraction shows a great increase in force as compared with the last of the previous series. Fatigue again sets in, and recovery is once more shown on changing the direction of the current. This is repeated several times, each time with the same result.

It might be concluded from such a tracing that the explanation lies in a possible polar effect of stimulation with the constant current. Engelmann has observed that, with the rabbit’s ureter, the make current produces a contraction beginning at the cathode, the break at the anode. If, then, the effect of the make current being the stronger, stimulation produced fatigue only, or chiefly, in the cathodal region, reversal of the current would subject a new and comparatively fresh region to the influence of the stimulus. During the interval while this second area was being fatigued, the first would recover, and so on.

That this explanation does not hold good, however, is shown by clamping the bladder midway between the two electrodes, and recording the contractions of the anodal and cathodal regions separately. In this case, both regions respond in the same way. Both respond equally to the make, both to the break. And on stimulating to partial fatigue, both show recovery with the reversal of the current. Whatever the cause may be, it is in some way a property of the muscle in its entire length. The phenomenon is therefore still unexplained.

CONCLUSIONS.

The bladder, used either in situ or excised, supplies an excellent preparation for the study of the properties of mammalian smooth muscle.

Automatic movements are generally present, and show at times both simple and compound rhythms. A compound rhythm is produced when two or more areas of the muscle contract rhythmically at different rates.

The bladder responds to single induction currents, the make, break, and flow of the constant current, to mechanical stimuli and to changes in temperature. The response increases to a maximum with the strength of the stimulus.

1 Engelmann: Archiv für die gesammte Physiologie, 1870, iii, pp. 247–326.
The single contraction, appearing at about 10° C. and disappearing at about 55° C., shows a progressive shortening of all its phases with the rise in temperature, and a maximum height at 40° C.

Single contractions may be summated regularly, and, with an interval slightly less than two seconds, are fused to complete tetanus. There is no refractory period.

Unless the making and breaking of the constant current are separated by an interval of more than about ½ second no result is obtained. With longer intervals the contraction increases to a maximum both with the flow and with the pause in the flow of the current.

The make and break excitations show no antagonism and their contractions may be summated.

If the muscle be fatigued by stimulation with the constant current, reversal of the current gives a recovery of the original force in both anodal and cathodal regions.

With rising temperature the bladder shows a relaxation in tone from 10° C. to 40° C. From 40° C. to about 55° C. there is a tonic shortening, maximal with the loss of irritability at from 53° C. to 57° C. There appears, then, a relaxation, without rigor, persisting until the true contraction of heat rigor appears at 60° C.

With the rise in temperature spontaneous contractions appear, are maximal in amplitude below normal body temperature, and increase progressively in rate until they disappear with the death of the muscle at about 55° C.

The muscle shows perfect elasticity, and, with the increase in weight shows, within limits, an increased output of energy in the form of work done.

The bladder in situ lasts indefinitely, and shows at most only slight temporary fatigue. The excised bladder may be used for several hours, fatigues with repeated stimulation, but shows partial recovery. Spontaneous contractions persist for from twenty-four to forty-eight hours at room temperature; and the cooled muscle may maintain its irritability for as much as four days.