STUDIES ON THE INNERVATION AND PHYSIOLOGY OF THE PELVIC PARTS OF THE ALIMENTARY AND URINARY TRACTS

A THESIS

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(Bishop, Garry, Roberts & Todd 1956a) and were published in a fuller form in the Journal of Physiology later that year (Bishop, Garry, Roberts & Todd 1956b). Some of the results of Part 4 were presented to the Physiological Society as a communication in September 1957, (Garry, Roberts & Todd 1957) and a fuller account of the contents of that section was published in the Journal of Physiology later (Garry, Roberts & Todd 1959). Some of the contents of this part were also read as a paper to the Urological Club of Great Britain in April 1961. The results of the experiments on urethral flow receptors contained in Part 5 were given in a communication to the Physiological Society in December 1960 (Murphy & Todd 1961). Finally the results of Part 3, the earliest part to be published, have now found their way into the most recent editions of standard taxtbooks of physiology published here and in the United States (Bell, Davidson & Scarborough 1961) and (Ruch & Fulton 1960), while the contents of Part 5 are being prepared for future publication.

GENERAL INTRODUCTION

The pelvic parts of the urinary and alimentary tracts have a common embryological origin from the cloaca and hence have a similar pattern of innervation and perform a similar function. Basically this function is two-fold: continence and evacuation. Most work in the past has been directed towards the second function - micturition and defaecation - although in terms of clinical experience problems of continence are equally important, particularly is this so as the average age of the population increases. Disturbances of evacuation and continence are common clinical problems in the practice of the geriatrician, the surgeon, the gynaecologist and the neurologist, yet our knowledge of the normal physiology of these processes remains incomplete. The study of patients offers a valuable approach but is unsuited to investigating the basic mechanisms involved. The alternative approach is that of experimental work on lower animals, bearing in mind that species differences exist and will complicate the transference of results.

In the late nineteenth and early twentieth centuries many papers dealing with this aspect of physiology were published. This period, when mechanical recording methods were used exclusively, culminated in the papers of Barrington on the bladder and urethra and those of Garry on the rectum and anal canal. Both of these workers emphasised the reflex basis of the physiology of the region and their work has since become the standard source of information on the subject. There are, however, a number of fundamental defects inherent in any method of recording based on mechanical principles when applied to these problems and these defects are discussed more fully in a later section. Little has been added to the results of Barrington and Garry since then and in recent years there has been a swing away from the study of physiological organisation at the level of the complete organ or system, towards its study at the level of the individual cell. One of the most striking advances which has accompanied this shift to a more fundamental approach to physiological research, is the development which has taken place in electronic recording methods, especially as applied to the study of nerve and muscle. It would seem that a profitable field for investigation exists in the application of these newer techniques to the problems of the pelvic viscera. A few studies of this sort have already appeared but many questions still remain to be answered.

So far as the reflex basis of micturition, defaecation and continence are concerned, there seem to me to be two likely applications: first, the study of the striated sphincter muscles of the anus and urethra whose proximity to the underlying smooth muscle sphincters complicates their study by mechanical methods and which form an important part of the effector side of the reflexes, and second, a study of the behaviour of the sense organs involved in the ingoing side of the reflex arc. In addition I believe that the most rational approach to most physiological problems is one in which experimental investigations are accompanied by parallel and complementary studies of the morphology of the elements involved. I have therefore carried out some histological studies of the sense organs and nerve trunks from which the recordings have been made.

PART I.

THE MUSCULATURE OF THE ANO-RECTAL AND URO-GENITAL REGIONS IN THE CAT, WITH A QUANTITATIVE HISTOLOGICAL STUDY OF THE PELVIC AND PUDENDAL NERVES

CONTENTS

A. THE MUSCULATURE AND NERVE SUPPLY OF THE ANO-RECTAL AND URO-GENITAL REGIONS IN THE CAT

1. Introduction

In contrast to human anatomy there exists no standard terminology for the anatomy of the cat. In view of the importance of this anatomy in the descriptions of operative and experimental procedures which follow, it seemed to be essential to make some study of the musculature and innervation in particular. To do this, I dissected a number of freshly killed animals of both sexes and compared the results with the descriptions given in the published works on cat anatomy.

There are two main works on the subject: those of Straus-Durckheim (1845) and of Reighard & Jennings (1925), but these do not agree closely, either in their description of structure or in the nomenclature used. Of the two, I have mainly used the nomenclature of Straus-Durckheim, because this terminology was subsequently used by Langley & Anderson (1895 & 1896), in their full and meticulous descriptions of the innervation of the pelvic viscera and because it approximates most closely to the nomenclature used by Sherrington.

2. The Musculature of the Ano-rectal Region and the Pelvic Diaphragm

An extensive literature exists on the anatomy, especially the surgical anatomy, of the ano-rectal musculature in man. Recent reviews include those of Milligan & Morgan (1934) and Gorsch (1955).

The human external anal sphincter is a band of striated muscle encircling the anal canal. The first accurate description of its attachments is that of Santorini (1710) and he seems to have been the first to have recognised its trilaminar arrangement. Holl (1889) offered the nomenclature which is now in established use, referring to its three components as subcutaneous, superficial and deep.

Confusion of terminology arises in the different descriptions of the anal sphincter in the carnivora. In the cat, Straus-Durckheim and Reighard & Jennings divide the striped muscle into an external and an internal anal sphincter. In order to keep the terminology in line with that of human anatomy, I use the term external anal sphincter to designate the entire striped muscle sheet - a sheet which can be divided into a superficial and a deep component. The superficial part of the external sphincter arises from a space about half a centimetre broad on the dorsal aspect of the fifth caudal vertebra, where it has some decussation with its fellow of the opposite side. It runs downward on either side of the tail as a band half a centimetre broad to surround the anus and decussate in the perineum, while its most superficial fibres are prolonged ventrally as the levator scroti or levator vulvae. According to Straus-Durckheim, there is also some decussation between the muscles of opposite sides between the anus and the tail. The muscle is often removed with the skin and its caudal prolongation especially, is often difficult to see. It corresponds to the 'external anal sphincter' of Straus-Durckheim.

The deep part of the external striped muscle is much more powerful and bulky. It forms a thick muscular collar for the anal canal, broader dorsad where it may be one and a half centimetres in width, and tapering as it runs ventrally encircling the anal canal and the anal pouches. This muscle corresponds to the 'internal anal sphincter' of Straus-Durckheim. It is fairly intimately attached to the underlying smooth muscle sphincter and in the female it is prolonged ventrally as the sphincter vaginae.

The true internal or smooth muscle sphincter, is described by most workers as a thickening of the circular muscle of the lower end of the rectum and is shown as such in diagrams. Such a thickening is not easily seen in dissections of the region, but its distinctive properties and the difference in its behaviour from that of the other parts of the large bowel muscle, justify its desciption as a separate entity. It corresponds to that part of the smooth muscle lying immediately subjacent to the external sphincter.

The pelvic diaphragm or levator ani muscle of the human is derived from the pubo-caudalis and ilio-caudalis muscles of the tailed vertebrates. These muscles, in the cat, are mainly flexors and abductors of the tail, but they have an indirect action on the rectum, that of lateral compression. The two muscles are incompletely separated.

The ilio-caudalis (Fig. I), arises from the internal aspect of the ilium at the antero-inferior border, between the iliac origin of psoas and the ischio-caudalis. It runs backwards and slightly inwards within the ischio-caudalis, applied to the side of the rectum and terminates in four broad tendinous strands which penetrate the longitudinal muscles on the ventral aspect of the vertebral column and are fixed to the mid-line of the 4th, 5th, 6th and 7th caudal vertebrae.

The pubo-caudalis (Figs. 1, 5 and 6), a direct continuation of the former, arises from the whole length of the pubic symphysis and its origin often extends to the anterior part of the ischium. It runs upwards and backwards surrounding the rectum and urethra, to be inserted together with its opposite number into the mid-line on the ventral aspect of the 3rd, 4th and 5th caudal vertebrae.

The ischio-caudalis (Figs. 1, 5 and 6) is a large thick muscle which arises by tendinous and fleshy fibres from the region of the ischial spine and runs medially backwards and upwards increasing in width, to be inserted into the whole length of the transverse and spinous processes of the first four caudal vertebrae.

A number of discrete smooth muscle bands are also found in this region. Recto-caudalis is a prominent band running from the upper and lateral parts of the rectum, where its fibres blend with the fibres of the pubo-caudalis. It runs upwards and backwards, forming initially a fine strand applied to the rectum which gradually detaches itself in the supero-median line. The two muscles of opposite sides join to form a cylindrical cord 2 to 3 mm broad, which passes backwards between the caudo-analis muscles and is inserted into the ventral aspect of the 6th and 7th caudal vertebrae. Its nerve supply is derived from the pelvic nerves and in man it is vestigial. The caudo-analis muscle, which is also smooth, arises from either side of the mid-line on the ventral surface of the 2nd and 3rd caudal vertebrae, where its posterior part is continuous with the caudo-cavernosus or caudo-vaginalis. It continues downwards and backwards enlarging as it goes and ends by joining the external anal sphincter, part of it being prolonged as the caudo-cavernosus or the caudo-vaginalis. It is covered laterally by the ilio-caudalis and the pubo-caudalis. It is not found in man and it may be absent in the cat also.

3. The Musculature of the Uro-genital System

The urethra of the male cat is made up of three distinct parts which are approximately equal in length (Fig. 2). The proximal urethra stretches from the bladder neck to the level of the prostate gland. It is the narrowest of the three parts and its wall consists of smooth muscle and elastic tissue. Between the prostate gland and the bulbo-urethral glands is the region of the external urethral sphincter described below, which contains striated muscle in its wall. The penile urethra traverses the corpus spongiosum and has virtually no muscle at all in its wall. The urethra in the female cat corresponds to the first two parts of the male urethra.

The external urethral sphincter or compressor urethrae muscle in the human, consists of striated muscle fibres which surround the membranous urethra between the upper and lower fascial layers of the uro-genital diaphragm. The neighbouring striated muscle fibres within the same fascial space, spanning the pubic arch and surrounding the external sphincter, are known as transversus perinei profundus. The human external sphincter cannot therefore correspond to the muscle of the same name in the carnivore, which consists of striated muscle fibres lying in the substance of the urethal wall (Fig. 4). McCrea (1926) and more recently Bors, Comarr & Reingold (1954) have described striated muscle fibres in the region of the human bladder neck and these may represent a structure analogous to the external urethral sphincter as described in the cat. According to Evans (1936) there is, in the cat, a small band of striated muscle surrounding the urethra at the level of the bulbo-urethral glands near the base of the penis, which probably represents the structure described in works of human anatomy as the external urethral sphincter. From a functional point of view it is probably reasonable to regard all striated muscle surrounding the urethra and having a sphincteric action on it as being the external sphincter.

The external sphincter muscle of the urethra in the cat consists of a layer of striated muscle fibres actually lying in the substance of the urethral wall surrounding the mucous coat. These fibres are basically circular in their arrangement but are more oblique in the outer layers, where the inter-twining bundles form a closely knit mass which is very difficult to tease (Fig.4). In the male cat, in which the muscle is most obvious, it forms a thick layer of red fibres stretching from the region of the prostate gland proximally, as far as the bulbo-urethral (Cowper's) glands lying at the base of the corpora cavernosa, where the fibres cease to form a complete ring and find attachment into the roots of the corpora cavernosa. In the female cat the muscle is shorter but broader and is confined to the distal third of the urethra (Fig. 3) where this canal is adherent to the vagina. As in the male, the fibres form a complete investment for the urethra but the most superficial are prolonged backwards onto the vagina to blend with the surface of its sphincter muscle coat.

According to Griffiths (1890), the external sphincter muscle shows variations in its state of development which parallel the functional state of the testicles. He claims that the individual muscle fibres are pale and shrunken in castrated animals.

Most authors, including Straus-Durckheim and Griffiths, are agreed that anatomically there is no discrete internal or smooth muscle sphincter of the urethra in either sex.

The fibres of the bulbo-cavernosus arise from the anterior half of the lateral aspect of the corpora cavernosa and run obliquely upwards and forwards to be inserted into the bulb of the penis by means of a median raphe. This muscle does not exist in the female. The ischio-cavernosus arises by tendon from the internal aspect of the ischium below the spine and is inserted into the base of the corpora cavernosa. The caudo-cavernosus consists of a fine band arising as two heads from the ventral surface of the first and second caudal vertebrae and runs downwards and backwards to be inserted into the corpora cavernosa. At its origin it blends with the caudo-analis and below it blends with the recto-cavernosus.

4. The Lumbo-sacral Spinal Cord and Plexus

The usual arrangement in the cat is seven free lumbar and three fused sacral vertebrae. Occasional animals are found with one more or one less lumbar vertebra. The spinal roots correspond and are named according to the vertebra below which they pass out (Fig. 7). I have followed the following procedure in verifying the identity of spinal roots post-mortem. I removed the spines and laminae from the entire lumbar and sacral parts of the vertebral column and identified Ll spinal root passing out beneath the first non-rib-bearing vertebra. I then counted down to the eighth post-thoracic spinal root and checked that it passed out through the first anterior sacral foramen.

There are a number of anatomical variations in the level of origin of the lumbo-sacral plexus from the spinal roots in the cat. Sherrington (1892) classified the different arrangements of the plexus into pre-fixed and post-fixed. Langley & Anderson (1896) described anterior, median and posterior forms of plexus. The greater the number of nerve fibres passing out by the more cranial roots, the more anterior is the plexus. The anterior form of Langley & Anderson corresponds broadly with Sherrington's pre-fixed type. I have followed the classification of Langley & Anderson because there is more information available about it with respect to the innervation of the pelvic viscera as opposed to the limb musculature.

Sherrington noted the muscles which responded on stimulation of the various ventral roots. He found closure of the anus on stimulation of fibres in Sl. mainly,

TABLE 1.

ROOTS OF ORIGIN OF BRANCHES OF THE PUDENDAL AND OF THE PELVIC NERVES

(after Langley & Anderson 1896)

ORIGIN OF	ANTERIOR FORM	MEDIAN FORM	POSTERIOR FORM
Genito-anal.	S1. Chief Origin S2. Small strand	S1. About 3/4 S2. About 1/4	S1. Small strand S2. Large strand S3. Large strand
Dorsalis Penis	S1. More than half S2. Less than half	S1. Two small strands S2. Chief origin	S2. Chief origin S3. Small strand
Perineal	S2. Sole origin	S2. Sole origin	S2. Large strand S3. Small strand
Pelvic nerve	S1. Small strand S2. Large strand S3. Small strand	S1. Small strand S2. Large strand S3. Rather large strand	S2. Less than half S3. More than half S3. More than half

in S2, frequently and in L7, sometimes. Langley & Anderson found the corresponding fibres in S1, mainly, in S2, usually and in S3, sometimes but never in L7. The results of stimulation experiments which I carried out in the course of recording from the sacral dorsal roots (Part 5) agree closely with Langley & Anderson - contraction of the external anal sphincter was produced by stimulation of any of the sacral ventral roots particularly S1, and S2, but was never seen on stimulating either the last lumbar or the first caudal ventral roots. I have included a table of Langley & Anderson's results on the roots of origin of the various nerves supplying the pelvic viscera in the different types of lumbo-sacral plexus because of their importance in relation to my own results. (Table I).

It is only quite recently that any new information has been added to the results of these early workers. Romanes (1951) localised the cell groups in the lumbo-sacral spinal cord of the cat from which the motor fibres to the plexus arise. Jefferson (1954), re-examined the question of fixation of the lumbo-sacral plexus in the cat and found that the older concept of anterior, median and posterior forms of plexus was oversimplified. Shifts of fixation could be en masse, but were not necessarily so, since sometimes the apparent fixation of the proximal and distal ends of the plexus were not the same. He counted the large fibres (over 7 μ) in the lumbar and sacral ventral roots in a series of cats and found that although the total number of fibres in any one root varied widely, the total number of fibres in the roots making up the plexus corresponded closely from cat to cat.

5. The Peripheral Nerve Supply to the Pelvic Viscera

A. The Pudendal Nerve. This nerve is formed from the first, second and third sacral roots and passes outward behind the piriformis and in front of the ischio-caudalis muscles, under cover of the attachment of the biceps femoris and the gluteus maximus muscles to the superficial spinal aponeurosis (Figs. 5 & 6). The perineal branch is given off at an early stage, while the main trunk passes backwards lateral to the ilio-caudalis, lying in the groove formed between pubo-caudalis and obturator internus. At the posterior border of the pubo-caudalis muscle it divides into the dorsalis penis (clitoris) and the genito-anal nerves. The branches are distributed as follows.

(1) Perineal. This is the finest of the branches and it arises exclusively from S2. It supplies sensory branches to the perineum and passes to the vulva or scrotum as the rami scrotales, which are motor to the dartos and sensory to the skin. (Figs. 5 & 55).

(2) Genito-anal. This forms a common strand with the dorsalis penis as far as the posterior border of the pubo-caudalis muscle although only connective tissue holds them together. It runs posteriorly from the point of division, applied directly to the side of the rectum, as far as the external anal sphincter. Approaching the sphincter it divides into five or six terminal branches, some of which enter the sphincter and supply it. Other branches run down to supply the sphincter vaginae, the recto-cavernosus and the bulbo-cavernosus and may send a few fibres to the external urethral sphincter.

3. <u>Dorsalis Penis</u>. This nerve runs ventrally to supply motor branches to the external urethral sphincter. Its main constituents, however, are sensory and vasomotor fibres to the urethra and to the penis or labia.

B. <u>The Pelvic Nerve</u>. The pelvic nerve in the cat supplies parasympathetic fibresto the pelvic viscera and it also acts as the ingoing pathway for the reflexes from the bladder and rectum. It arises from the first, second and third sacral roots and enters the pelvis between the sacro-caudal and ischio-caudal muscles, whence it runs on to the side wall of the rectum. After a short course it divides into two branches which end in conspicuous ganglia. From the cranial ganglion the fibres mix with those of the hypogastric nerve to supply the bladder and proximal urethra. The main outflow from the caudal ganglion is to the rectum and anus as the sacral colonic nerves. There is considerably variation in the arrangement of the pelvic plexus on the side wall of the rectum and numerous small ganglia are present on its main strands.

C. <u>The Sympathetic Nerve Supply</u>. The sympathetic nerve supply to the pelvic viscera is derived as described below. The spinal rami to the inferior mesenteric ganglia run from the sympathetic chain on each side and the inferior mesenteric ganglia themselves, usually four in number with inter-connecting strands, form a ring round the inferior mesenteric artery. A close network of fibres arising from the ganglia surrounds the inferior mesenteric artery and accompanies it to the gut - the so called lumbar colonic nerves. The two hypogastric nerves arise from the caudal pair of ganglia and run in the meso-colon in a caudal direction. Each hypogastric nerve divides into a ventral branch to the bladder and a dorsal branch which joins the pelvic nerve of the same side to form the pelvic plexus lying on the side wall of the rectum. Branches from this plexus then supply the lower bowel and internal anal sphincter.

[illegible].

In his early anatomical study, [illegible]
[illegible] apart the fibres of the pudendal nerve of [illegible]
[illegible] no accurate measurements or counts but he
[illegible] that the majority of the fibres were large [illegible]
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rhesus monkey and in some smaller animals [illegible]
[illegible] fibre-size distribution with the peak [illegible]
[illegible]. The largest fibres present [illegible]

The dorsalis penis branch of the pudendal nerve
[illegible] sheep was examined by Mitchell, [illegible]

B. A QUANTITATIVE HISTOLOGICAL STUDY OF THE PELVIC AND PUDENDAL NERVES IN THE CAT

I. Review of the Literature on the Histology of the Nerve Supply to the Pelvic Viscera

Some information is already available on the constitution of the pudendal and pelvic nerves. A number of reports have appeared over the past fifty years but it is not easy to correlate them and the resulting picture is fragmentary.

In his early anatomical study, Griffiths (1895a) teased apart the fibres of the pudendal nerve of the dog. He made no accurate measurements or counts but he reported that the majority of the fibres were large, about 12 µ in diameter, with a few groups of smaller fibres 2 to 3 µ in diameter.

A rather more detailed account was given by Häggquist (1938 & 1940) who, in the course of a survey of muscle nerves in relation to the function of the muscles which they supply, chose the external anal sphincter as an example of a muscle chiefly concerned in tonic contraction. He found that the small nerve twigs supplying this muscle in the rhesus monkey and in some smaller mammals too, had a uni-modal fibre-size distribution with the peak in the 3 to 4 µ range. The largest fibres present were about 9 µ.

The dorsalis penis branch of the pudendal nerve of the sheep was examined by Kitchell, Campbell, Quilliam & Larson (1955) at the level of its terminal twigs, at which level they presumed it to be almost entirely sensory. The fibre-size spectrum resembled that of the saphenous nerve of the sheep, a nerve of general cutaneous sensation, with its main peak in the 4 to 8 µ range, but in both sexes there was an additional peak which lay at 13 µ in the female and at 15 µ in the male. The authors considered that these peaks were associated with the presence of specialised receptors in the genital area.

The information available on the constitution of the pelvic nerves is more complete but the individual papers do not agree closely with one another. Once again the earliest report is that of Griffiths (1895a) who showed that, in contrast to the pudendal nerve, most of the fibres of the pelvic nerve in the dog were 2 to 3 µ in diameter with a small number of larger fibres up to 7 µ in diameter.

Langley & Anderson (1895f), whose papers are outstanding in this field, also used a teasing method but, unlike Griffiths, they actually carried out fibre counts on the teased preparations. They found that the pelvic nerve in the cat normally contains some 3500 fibres, of which 12 to 24 are 7 µ or more in diameter and several hundreds are 4 to 5 µ in diameter, the rest being smaller. They excised the sacral dorsal root ganglia and allowed the afferent fibres to degenerate. They concluded by this means that about a third of the fibres in the pelvic nerve, including most of the larger fibres, were ingoing.

There were apparently no further investigations of this sort until the work of Griffin, Griffin & Patton (1958) and since this work has not been published in full it is difficult to assess it adequately. These workers examined the pelvic nerve in the cat after sectioning it and staining it with osmic acid. They found that after it had been 'demotored' by section of the sacral ventral roots, some 6000 myelinated fibres remained which had a uni-modal distibution with the peak at 3 to 4 µ.

Schnitzlein, Hoffman, Tucker and Quigley (1961) studied the pelvic nerve of the male rhesus monkey using several different techniques. They examined transverse sections of the nerve with light microscopy after osmic acid and silver staining and they compared areas from these sections with similar fields viewed under the electron microscope. On the basis of these observations they estimated that the total fibre count was between 10,000 and 30,000, while more than half of these were less than 1 µ in diameter and twenty per cent of the total were too fine to be resolved using light microscopy. By means of degeneration studies which included sectioning the dorsal or ventral roots or sectioning the complete spinal root, they concluded that about half the total were preganglionic parasympathetic in origin and that more than a quarter were ingoing. Almost a quarter of the total fibres persisted after the sectioning of both dorsal and ventral roots in the sacral region and these, they decided, were probably sympathetic. It is not clear from this paper how these fibres reach the pelvic nerve, but presumably they must join it after it has entered the pelvis.

The wide differences in the figures given for the total fibre count of the pelvic nerve by different authors may reflect species difference to some extent but they are almost certainly much more the result of differences in technique. This question is dealt with more fully in the discussion at the end of this section.

The hypogastric nerve was examined briefly by Griffiths (1895a) and in a more detailed fashion by Langley & Anderson (1894). Both workers found it to be composed mainly of non-myelinated fibres with a small number of larger myelinated fibres.

2. Methods

(a) General review of the techniques used in fibre analysis

Since it has become established that a relationship exists between the diameter of nerve fibres and some of their functional attributes, the method of fibre analysis has become accepted as a useful method of investigating the peripheral nervous system. Several attempts have been made to correlate the fibre spectra of peripheral nerves with the various functional elements which they are known to innervate. Some attempts have been made to carry out such studies on the pelvic and pudendal nerves and these were reviewed in the previous section. In this section the value of fibre analysis is discussed and the errors involved in the technique are assessed.

The first attempts to measure fibre diameters in nerves were carried out by teasing apart the individual fibres in the nerve trunk. It is not, however, possible to get reliable quantitative information about the number of fibres of different sizes by this method and the standard modern method is to perform the measurements and counts on sections of the nerve. Analyses of the sources of error involved in the measurements have been made by Rexed (1944) and by Sanders (1947).

Three main histological techniques have been used in the past: the Weigert technique and its modifications, the Alzheimer-Mann-Häggquist (A.M.H.) method and the osmic acid method. The first of these is now rarely used because the staining of the finer myelinated fibres is unreliable as a result of the differentiation process involved. The A.M.H. method is preferred by many workers because it is simple and reliable but it suffers from the disadvantage that it causes a high degree of shrinkage of the tissues. Osmic acid, on the other hand, the oldest method of the three, is rather unpredictable in the depth of staining produced and in addition the penetration is poor, although this last is not a serious disadvantage with the small cat nerves. The main advantage of the osmic acid method is that it produces a minimum of distortion and shrinkage.

It was shown by Rexed (1944), that neither 10% formalin nor 1% osmic acid produced an appreciable alteration in fibre size compared with fresh material and he found no difference in size between nerves fixed in situ and nerves removed fresh and fixed later. He also found little difference between the fibre size spectra of the same nerve taken from different animals of the same species, provided the animals chosen were within a reasonable range of size. Fernand & Young (1951), on the other hand, found differences of thirty per cent in the number of fibres present in the corresponding muscle nerve in different rabbits as well as differences in the over-all fibre diameter.

Measurement of enlarged photographs is now generally preferred to measurement directly from the microscope slide because of the danger of counting the same fibre twice using the latter method. Various measuring devices are available but the use of a series of circles of known size inscribed on a transparent template as used in this investigation is probably one of the most accurate and certainly one of the simplest methods available.

(b) Method used for the excision of the sacral dorsal root ganglia in chronic survival experiments

The animals were large adult cats of both sexes which were free from disease or other abnormality. They were pre-medicated with 1/200 grain of atropine injected subcutaneously into the back of the neck and half an hour later were anaesthetised with intra-peritoneal Nembutal, as described in section 2, but in this case the trachea was not cannulated. A wide area of skin over the lower lumbar and sacral vertebrae was clipped and shaved and was swabbed with dilute Dettol solution. It was not found necessary to wear gloves or mask for the subsequent operation but otherwise full aseptic precautions were taken.

A mid-line dorsal incision was made from the spinous process of L5. to the base of the tail going through skin and superficial spinal aponeurosis and sterile towels were clipped to the edges of the wound. The dorsal vertebral muscles were removed on one side (the left) over L6., L7. and the sacrum. The laminae of the left side were then removed from L6. and L7. leaving the spinous processes intact but going as far laterally as the articular processes. The entire dorsum of the sacrum was next removed including the sacral spinous processes but not extending as far laterally as the articular processes. Bleeding was often profuse and difficult to control at this stage, and the most effective means of control was found to be the firm application of swabs soaked in warm saline. The extra-dural fat was then carefully picked out from between the roots and the cord retracted to the opposite side. The sacral roots were then identified by their size and by their position relative to the identifiable bony landmarks (Fig. 15 and Fig. 55).

One of the sacral roots was then picked up by its dorsal surface overlying the ganglion, using fine pointed forceps and the dural sheath was slit down the lateral surface with fine dural scissors. When the cut edges of the dura were pulled apart with the points of forceps a split could be seen on the lateral surface of the root indicating the natural line of division between the dorsal and ventral components. This split was enlarged proximally with the points of forceps and the dorsal root was cut across with scissors, well proximal to the ganglion. The cut end was then picked up in forceps and using a pair of fine scissors the two roots were separated distally to a point well beyond the distal tip of the ganglion. A binocular dissecting microscope was used during the separation of the dorsal and ventral roots. The ganglion and associated parts of the dorsal root were then removed.

When the three sacral dorsal roots on the left side had been dealt with in this way, the wound cavity was dusted with Bacitracin powder. The superficial spinal aponeurosis was then approximated to the interspinous ligament and was stiched to it. The skin wound was closed and an adhesive dressing applied. I ml of a Penicillin suspension (100,000 units) was given intra-muscularly and 50 ml of 5% glucose saline was injected into the lax subcutaneous tissue over the back of the neck. The animal gradually regained consciousness over the following 12 to 24 hours.

In all, some eight cats were dealt with in this way, four male and four female. Two died early; one during the operation and the other two days after it. Of the other six, none showed any permanent disability and all remained healthy until they were killed ten or twelve weeks after the operation.

Eccles & Sherrington (1930) who were the first to use this technique, examined the ganglia removed at operation histologically as a control of the completeness of removal. Their criterion of complete removal of the ganglion was the absence of ganglion cells from the distal tip of the piece of tissue which they had removed. This procedure, however, would not detect damage to the ventral root and such damage would be just as serious in the present investigation as would incomplete removal of the dorsal root.

For this reason I chose a different control procedure. When the animal was eventually killed the identity of the various roots was confirmed by their relation to the bony vertebral column as already described and the sacral roots on the operated (left) side were removed complete and were subjected to the same fixation and staining procedures as the peripheral nerves. The dorsal and ventral roots, distal to the point from which the ganglion had been removed, were then examined histologically; the ventral root for evidence of degenerating fibres and the dorsal root for evidence of incomplete degeneration (Fig. 19). In some cases a number of myelinated fibres of small diameter (1 to 2 μ) were seen in the dorsal root and these were probably regenerating sprouts. Such fibres could be seen in every case if the oil-immersion objective was used.

(c) Method used for the preparation of sections of nerve trunks and the construction of fibre-size histograms

The earlier animals used in this study were fixed by perfusion with formalin immediately after death and before the pieces of nerve were removed for histology. This procedure had the disadvantage that it hardened the tissues and made the dissection of the smaller nerve twigs technically difficult. In the case of the pelvic nerves in particular there was a danger of missing some of the branches altogether. I therefore decided that the possibility of damaging the unfixed nerve during dissection was less serious than the risk of missing part of the nerve. Formalin perfusion was therefore abandoned and the following scheme was followed.

The cat was anaesthetised with intra-peritoneal Nembutal and killed by bleeding. The nerves were dissected out as soon as possible after death in the fresh animal and the desired pieces (about 1.5 cm in length) were tied at each end with fine nylon thread and stretched lightly on small pieces of cardboard.

The steps from here to the stage of sectioning and mounting were carried out by the technical staff of the Physiology Department. Because the details of preparation are important in determining the degree of shrinkage produced and because of the importance of assessing this shrinkage in comparing the present results with those of other workers, the steps involved are indicated in detail.

1.	12% neutral formalin	overnight
2.	1% osmic acid	18 hours
3.	Distilled water	several changes
4.	10%, 20%, 30%, 40% alchohol (dehydration)	8 hours
5.	50% alchohol	overnight
6.	60%, 70%, 80%, 90% alchohol	8 hours
7.	Absolute alchohol	overnight
8.	Chloroform	3 hours
9.	Xylol	15 minutes
10.	Embed in wax.	

Sections 5 u thick were then cut from the blocks and mounted on slides. They were examined under the microscope to find a suitable specimen from each block, paying particular attention to evenness of staining, absence of tears and folds and clear separation of the individual fibres. The selected sections were photographed at an initial magnification of x250 on quarter plates, several quarter plates being required to cover each nerve. The plates were printed with a further x4 enlargement so that the final magnification of the prints was x1000.

The original section from which each print had been made was put under the high power objective of the microscope while the counting of the fibres in the prints was being carried out. Any doubtful fibres in the prints were re-examined on the original slide and by focussing up and down it was usually possible to decide whether any particular structure was a nerve fibre or not.

Fibre diameter was measured on the prints using a guage specially constructed for the purpose. This consisted of a piece of transparent celluloid (X-ray film from which the emulsion had been removed) on which were inscribed a series of circles ranging in diameter from I to 20 mm. The guage was placed over the fibre to be measured and the ring which gave the best fit to the outside diameter of the myelin sheath was selected. The fibres were entered into columns on paper and marked off on the prints at the same time. With practice, considerable speed and accuracy was developed, particularly with respect to the measurement of fibres which did not appear circular in the prints. In order to keep the subjective error to a minimum and constant level, all the counting was done by myself. The total numbers of fibres of different sizes counted were then calculated, the number of fibres of each size was converted to a percentage and the result expressed in the form of a histogram.

4. Results

Six cats survived the operation and were subsequently examined histologically. The results from two of these were rejected because the nerve specimens were over-impregnated and the detail of the finer myelinated nerve fibres was obscured. In addition, in one of these cats, some of the fine branches of the pelvic nerve were missed when the nerve was being dissected post-mortem. A third cat was rejected because the control sections indicated that the removal of the dorsal root ganglia had been incomplete. The remaining three cats, two male and one female, were found to be acceptable and complete counts were carried out on the pelvic nerve and the two main

TABLE 2.

NUMBER OF NERVE FIBRES OF DIFFERENT DIAMETERS IN BRANCHES OF THE PUDENDAL NERVE AND IN THE PELVIC NERVE

FIBRE DIAMETER μ	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
NERVE															
GENITO-ANAL (NORMAL)	-	20	85	89	77	97	164	162	149	160	103	52	15	6	5
GENITO-ANAL (DE-AFFERENTED)	-	2	4	15	17	36	64	106	130	142	106	71	21	11	4
DORSALIS PENIS (NORMAL)	57	214	532	497	176	96	133	112	104	52	39	27	-	-	-
DORSALIS PENIS (DE-AFFERENTED)	53	105	226	205	87	43	35	23	28	35	10	11	-	-	-
PELVIC (NORMAL)	353	817	1050	729	290	72	34	15	10	12	10	7	5	3	-
PELVIC (DE-AFFERENTED)	52	237	518	301	95	24	6	-	-	-	-	-	-	-	-

branches of the pudendal nerve. The results were similar in all three animals. The results of one of these, a male cat, are given in detail in this section in the form of Table 2 and Figs. 12, 13, 14 and 15.

3. Discussion

This investigation of the pudendal and pelvic nerves was undertaken to provide information about the morphology of the nerve trunks which form the pathways of the defaecation and micturition reflexes. It was intended to be a supplement to the results of the experimental sections of this thesis (Sections 3, 4 and 5) rather than a general study of the constitution of motor and sensory nerves, although some information of a general nature does emerge. I have therefore concentrated on the larger myelinated fibres (2 μ and over) which can be seen with the ordinary microscope under high power and have not used the oil-immersion objective or the electron microscope as others have done nor used histological techniques designed to demonstrate unmyelinated fibres. Although my results do include fibres of 1 μ and 2 μ, there is reason to believe that the figures obtained for the counts of fibres of this size do not approximate to the true totals. This matter is particularly relevant in the case of the pelvic nerve and it is discussed further in that connection.

The results presented (Table 2 and Figs. 12, 13 and 14) confirm that the pudendal nerve is a mixed somatic nerve. Gross dissection shows that the genito-anal branch is principally the motor nerve to the external anal sphincter but that it also carries fibres for the recto-cavernosus and bulbo-cavernosus muscles. It therefore corresponds quite closely to the inferior haemorrhoidal nerve of human anatomy. Histological examination shows that only a small proportion of its fibres are ingoing and these are chiefly of small diameter (Fig. 12).

Häggquist (1940) described two fibre systems in motor nerves: a system of "coarse" fibres associated with endings of the "en plaque" type on "white" muscle fibres, which was chiefly concerned with phasic movements and another system of "fine" nerve fibres associated with "en grappe" endings on "red" muscle fibres, which was chiefly concerned in tonic contraction. He found that the nerves supplying the sphincter ani externus muscle in the monkey resembled those supplying the facial muscles in having a uni-modal fibre-size distribution with a peak at 4 u and no very large or very small fibres. These nerves were made up exclusively of fibres of the fine tonic system.

Fernand & Young (1951) examined the fibre-size distribution of a wide range of motor nerves to limb and trunk muscles and found that they could be classified into two groups: (1) the bi-modal group, which included the limb and extra-ocular muscles, in which the spectrum contained large fibres (up to 24 μ) and showed two distinct peaks and (2) the uni-modal group the spectrum of which contained no large fibres (none over 14 μ) and which had a single peak between 8 and 12 μ. They found that the infra-hyoid muscles, the diaphragm and the facial muscles belonged to this group. They considered that muscles of the uni-modal group had certain characteristics in common, they exerted little tension and did not assist in maintaining posture against gravity but they shortened considerably during contraction. These muscles were therefore isotonic rather than isometric in their action. Fernand & Young also considered that such muscles had little or no proprioceptive supply and contained few or no muscle spindles. The absence of annulo-spiral endings and γ-efferents thus explained the absence of large fibres and small fibres respectively, from the spectrum, all the myelinated fibres being of a single type - somatic extra-fusal. They concluded that such fibres were smaller than those to limb muscles because of the smaller amount of afferent information reaching the anterior horn cell.

The histogram of fibre-size distribution of a de-afferented motor nerve to a limb muscle shows two peaks (Eccles & Sherrington 1930). The larger peak is in the α range (about 12 μ) and corresponds to the motor innervation of the extra-fusal muscle fibres, the smaller peak is in the γ range (about 6 μ) and is due to the motor innervation of the intra-fusal muscle fibres of the muscle spindles.

The results of the present study show that the cat genito-anal nerve, particularly when it has been de-afferented, has a fibre-size spectrum with a uni-modal distribution which has its peak in the 8 to 10 μ range and has few fibres larger than 12 μ or smaller than 5 μ. This agrees with Häggquist's findings in the monkey although the actual value found for the peak diameter differs considerably in the two investigations. This difference is not necessarily a significant one and is probably due to a combination of species difference and difference in histological technique. Häggquist used his own A.M.H. method which is known to cause a greater degree of shrinkage than the osmic acid method.

The present results show that the genito-anal nerve also fits clearly into Fernand & Young's group of unimodal muscle nerves, but on the other hand the external anal sphincter does not show all the other attributes of this group. It does in fact contract isotonically rather than isometrically but it is not free from proprioceptive innervation. It can be shown histologically to contain spindles (Section 6) and can be demonstrated experimentally to have a proprioceptive discharge (Section 5). Neither the spindles nor the discharge differ demonstrably from those associated with limb muscles. The true significance of the unimodal distribution is therefore still not clear although it seems likely that the nerve fibres supplying the extra-fusal muscle fibres of the external anal sphincter are of smaller diameter than the corresponding nerve fibres in limb muscle nerves. The muscle fibres of the sphincter themselves are smaller (50 μ) as compared with the biceps femoris (75 μ) (Garry 1934b).

The dorsalis penis nerve in the cat seems on naked eye dissection to be chiefly sensory, supplying the coverings of the penis, the glans and the anterior urethra. In the female the corresponding nerve supplies the clitoris, the vulva and the urethra. In both sexes it also sends some motor fibres to the external urethral sphincter and in the male to the pubo-cavernosus. In addition it contains a vasoconstrictor outflow to the penis and it is joined in the distal part of its course by specific vasodilator fibres which have passed out in the pelvic nerves (nervi erigentes) and which are responsible for the erection of the penis. Kitchel, Campbell, Quilliam & Larson (1955) examined small twigs of this nerve in the sheep, taken as far distally as possible at a level where the nerve was thought to be purely sensory. In the ewe, the spectrum was similar to that of a general cutaneous nerve such as the saphenous, being uni-modal in its distribution with a maximum at 6 to 8 µ. In the ram, an additional peak was found in the larger fibre-size range at 14 to 16 µ which they associated with specialised genital receptors. Probably the difference between the numbers of large fibres in the two sexes, reflects the difference in size between the penis and clitoris.

In the present investigation the dorsalis penis (or clitoris) nerve was taken proximally, close to its origin from the main pudendal trunk, at which level it was still a mixed nerve with some motor and many vasomotor fibres present. No difference could be detected between the two sexes in the cat at this level. The present results confirm that the dorsalis penis is mainly a sensory nerve with a typical unimodal fibre-size distribution and has a peak at 3 to 4 µ with large numbers of smaller fibres which are probably vasomotor.

The perineal branch is seen on gross dissection to have a purely cutaneous distribution, it is sensory and vasomotor and is motor to the smooth muscle of the dartos. It was not examined histologically.

The pelvic nerve, on the other hand, is a visceral nerve. It carries the pre-ganglionic parasympathetic sacral outflow and also contains visceral afferent fibres. Langley & Anderson (1895f) estimated it to contain 3,500 myelinated fibres most of which were small in diameter and a third of the total were ingoing. They stated that most of the larger fibres were sensory.

The present results agree broadly with this early analysis although the proportion of ingoing fibres was found to be about half of the total. The normal nerve contains between 3,000 and 4,000 myelinated fibres when counted under the high power of the microscope. Both normal and de-afferented pelvic nerves have uni-modal fibre spectra with the peak at 4 µ, while the normal nerve has a small but significant number of larger fibres up to 14 µ. All the fibres over 7 µ in diameter are ingoing.

Two recent reports on this subject apparently differ significantly from this picture. Griffin, Griffin & Patton (1958), found that the cat pelvic nerve contained up to 6,000 myelinated fibres after section of the sacral ventral roots, when examined under oil-immersion. Schnitzlein, Hoffman, Tucker & Quigley (1960) estimated that the total number of fibres in the pelvic nerve of the rhesus monkey varied between 10,000 and 30,000 when silver staining and electron microscopy were used, more than half of these were less than 1 µ in diameter, while the finest non-myelinated fibres (20% of the total) could not be resolved at all using light microscopy even under ideal conditions.

It seems that any histological technique which depends on light microscopy will only reveal a proportion of the total present and since these very small fibres constitute the majority, the actual technique which is used can be expected to affect the total count significantly. Some lower limit of size must therefore be defined in order to give the results some meaning. Even the conventional distinction between myelinated and unmyelinated fibres is not a hard and fast one. All nerve fibres are surrounded by a membrane containing radially orientated lipid molecules and tangentially arranged protein molecules (Sjöstrand 1953), and these two components are arranged to form a concentrically layered structure. In mammalian nerve fibres which exceed 1 to 2 μ in diameter there is enough lipid to cause the sheath to blacken in osmic acid and such fibres are conventionally termed myelinated. It follows that the distinction between myelinated and unmyelinated nerve fibres is an arbitary one and does not rest on any fundamental physiological property. In addition it depends upon the degree to which the osmic acid is taken up, which is itself a variable phenomenon. Even in ideally impregnated osmic acid preparations, large numbers of fibres can be seen under oil-immersion which are not visible under high power and in which the blackened lipid layer is barely visible.

It was for this reason that in the present investigation I decided, as stated at the beginning of this discussion, to count only those fibres which were visible in photographs enlarged to one thousand times supplemented by the high power of the microscope and to disregard the many fine fibres which can be seen only under oil-immersion. This difference in technique probably accounts for the discrepancy which exists between the total fibre counts obtained for the pelvic nerve by myself and the two groups of authors mentioned above. Under the conditions just defined, the cat pelvic nerve contains 3,000 to 4,000 myelinated fibres of which about half are ingoing.

4. Summary

The musculature of the ano-rectal and uro-genital regions of the cat are described, attention being paid to the differences between the morphology of this region in lower animals and in man. The nerve supply to the pelvic viscera is described and the commoner variations are discussed.

The results of a quantitative fibre analysis of the pelvic nerve and the branches of the pudendal nerve are given. The pelvic nerve was found to contain 3,000 to 4,000 myelinated fibres of which approximately half are ingoing. The fibre-size spectrum is uni-modal with the maximum number of fibres in the 3 to 4 µ range. The normal nerve contains a few large fibres up to 14 µ while all fibres over 7 µ are ingoing.

The genito-anal branch of the pudendal nerve contains mainly outgoing fibres. The de-afferented nerve has a uni-modal spectrum with the maximum number of fibres in the 8 to 10 µ range. The dorsalis penis nerve is mainly sensory but has a large number of outgoing fibres in the 3 to 4 µ range and a smaller number 8 to 10 µ in diameter.

The significance of these results is discussed.

PART 2

METHODS USED IN THE EXPERIMENTAL INVESTIGATIONS

CONTENTS

A number of objections can be raised to all the above techniques based on mechanical principles. First, the size and positioning of the balloons must be critically arranged to record the response of the rectum or the anal canal, without the activity of the one influencing the balloon lying in the other. Second, these methods record the behaviour of the anal canal as a whole and do not differentiate between the responses of the striated and smooth sphincter muscles. These two muscles may respond similarly but will not necessarily do so.

Garry (1933a & b) approached this problem by eliminating the response of the external sphincter. This he did either by cutting the pudendal nerves or by giving sufficient Curare to paralyse the muscle. Of these two, the Curare method is the less satisfactory as the striped external sphincters are amongst the muscles in the body most resistant to Curare and the dose levels which are necessary to paralyse them are not without effect on the autonomically innervated pelvic viscera. Langley (1911) and Barrington (1915) both reported a lowering of bladder tone and a partial reversal of the response of the bladder to pelvic nerve stimulation after the administration of Curare. The procedure of cutting the pudendal nerves is probably less open to objection but it is clumsy in that the bulk of the over-lying mass of striated muscle obscures the response of the smooth muscle and more important, the cutting of the pudendal nerves eliminates most of the afferent impulses from the anal region which may play a significant part in the reflex picture.

The third and most important objection to mechanical recording methods is that the balloon or fluid used must itself act as a foreign body within the anal canal and presumably therefore act as a source of reflex stimulation.

Finally, all recording techniques using balloons require some medium to transmit the signal from the balloon to the display unit. Of the two substances most commonly used for this purpose, water introduces considerable friction into the recording system, while an air filled system is subject to error resulting from alteration in laboratory temperature.

The problem of studying the urethral sphincters is somewhat similar although here there is less difficulty in distinguishing between the responses of the two sphincters since, in the cat at least, the external sphincter is separated from the bladder neck where the main smooth muscle action is thought to be localised, by about one centimetre of proximal urethra.

Fagge (1902) used a small rubber balloon lying in the urethra and this method of recording was chosen as recently as 1959 by Girado & Campbell. Most workers, however, have used resistance to fluid flow. Barrington (1915) allowed a stream of fluid to flow along the urethra from a fixed pressure head and noted any change in the rate at which the drops issued from the external meatus when he stimulated the nerves supplying the urethra or distended the bladder. In chronic experiments, he estimated urethral resistance in terms of the pressure required when applied to the anterior abdominal wall, to force fluid along the urethra. Langworthy, Drew & Vest (1940), measured the resistance by means of a cannula tied into the urethra, or by a needle passed into the bladder through the anterior abdominal wall. Several of the earlier workers, including Elliot (1907), and Giannuzi & Nawrocki (1863), measured resistance in terms of the urethral opening pressure.

Methods similar in principle to these have been applied to human subjects. Simons (1936) and Bors (1948) have both described instruments known as sphincterometers which are designed to measure the activity of the urethral sphincters. Simon's instrument consists of a water-filled balloon tied on a urethral catheter, while Bors' instrument measures the resistance offered to the retrograde flow of liquid into the bladder. Such instruments are in routine use in some urological clinics.

Most of the objections to the use of mechanical recording methods which were discussed in connection with the anal canal apply also to the urethra. In particular the objection raised to the introduction of extraneous reflex stimuli is relevant to these methods which involve the flow of a liquid along the urethra or the compression or distension of the bladder.

Electronic methods of recording represent a new approach to these problems and avoid many of the objections. Electromyography as a method of recording is frictionless and does not involve extraneous reflex stimulation since, using needle electrodes, it is not necessary for any foreign body to lie within the anal canal or urethra. It is a more sensitive indicator of muscle activity than mechanical methods and it is particularly suited to the problem of the sphincter muscles, since the electrical discharge of the striated muscle consisting of discrete and relatively high voltage action potentials is easily recognised and recorded whereas, using standard condenser coupled amplifiers, smooth muscle is without recordable electrical activity.

Electromyography has been criticised as a method on the grounds that inactive muscles may show signs of activity by conduction from adjacent active muscles. Thus Forbes & Barbeau (1927), using uninsulated silver electrodes, recorded action potentials from gastrocnemius when the nerve to tibialis anterior was stimulated. Denny Brown (1949) concluded that if a muscle was discharging intensely, its activity could be picked up from inactive muscles fifteen centimetres away. Adrian (1925 a, b & c), however, found that with electrodes of small surface area a selective field was sampled and the activity recorded was mainly determined by those fibres lying in a straight line between the two electrodes. Gellhorn & Johnson (1950), found that electrical activity induced in muscles by stimulation of the cerebral cortex was always sharply localised even when maximal.

The exposed area of the electrodes is probably the critical factor. I have used fine needle electrodes insulated in such a way as to present a minimal conducting surface and I find that with these, a single motor unit can be picked up from a very localised area within a muscle. On stimulation of the peripheral end of the cut pudendal nerve the muscle action potential can be recorded from the surface of the sphincter muscle but it is not seen in the record obtained from the ischio-rectal fat immediately adjacent to the active muscle.

Rather surprisingly there is only one reference in the literature to the subject of electrical recording from the external anal sphincter in animals; Beck (1930), though there are three reports concerning studies made on human beings; Newman (1949), Floyd & Walls (1953) and Kawakami (1954). There are no references to recording from the urethral sphincter in animals although Evans (1936) recorded motor activity from the pudendal nerve in the cat. There are a few reports of electromyographic studies on the human urethral sphincter; Newman (1949) performed electromyography on the anal and urethral sphincters in women, and Frankson & Petersen (1953 & 1954) recorded from the bladder wall, internal urethral sphincter and urethral striated muscle, in human patients.

Information about the ingoing pathways from the pelvic viscera and the afferent side of the micturition and defaecation reflexes has in the past been gained largely by indirect methods. Most experimental workers have investigated the nature of the adequate stimulus by observing the effector side of the reflex arc in animals. Clinical workers have approached the same problem by applying various stimuli to the viscera in man and recording the conscious sensations produced. Investigation of the ingoing reflex paths by electronic recording from the sensory nerves involved allows the sense organs to be studied directly. This method has been used by Talaat (1937) to study the bladder and urethra, by Iggo (1956) to demonstrate stretch receptors in the bladder wall and by Chennels, Floyd & Gould (1960) to study the sensory innervation of the anal region.

B. METHODS USED IN THE PRESENT INVESTIGATION

1. Experimental Animals

In all the experiments involving the study of reflex activity, decerebrate cats were used. This was done principally because many of the reflexes being studied were found to be abolished by quite shallow anaesthesia. It is an additional advantage that it is possible to leave the decerebrate animal unattended for short periods, as is often necessary when working single-handed, whereas the anaesthetised animal requires constant supervision.

Criticism of the use of decerebrate preparations for this work is perhaps justifiable, since decerebration, involving as it does the complete elimination of all impulses arising in the higher parts of the brain, produces drastic changes in the degree and distribution of tone, the complete picture being that of decerebrate rigidity. It would be reasonable to suppose that decerebration might produce some change in the tone of the external sphincters and indeed it might even be arguable that the resting tone recorded from the decerebrate animal might not exist in the intact animal. Nevertheless such a tone has been recorded in conscious intact human beings and it can also be recorded almost unchanged in the acute spinal cat.

For recording from sensory nerve fibres, anaesthetised cats were used. These were found to be more resistant to trauma and to the haemorrhage involved in the subsequent rather heroic dissection than were decerebrate or spinal animals. The anaesthetic used was

Nembutal (Abbot) which was administered intra-peritoneally in an initial dose of 45 mg/Kg body weight. Subsequent maintenance dosage was regulated to the level of reflex response observed from the preparation.

Because of the wide range of experimental procedures carried out and because of the fact that several procedures were carried out on any one animal, it is not possible to enumerate the number of animals used for each procedure in detail, but a summary of the number of animals used in each section of the thesis is given below.

Purpose for which used		Number of cats
Analysis of the motor and sensory components of the pudendal and pelvic nerves, after dorsal root section	(Section 1)	8
Electromyography of the external anal sphincter	(Section 3)	30
Electromyography of the external urethral sphincter.	(Section 4)	49
Recording from sensory fibres in the sacral dorsal roots	(Section 5)	33
	TOTAL	120

In addition many of the above cats were subsequently used for histological studies and a number of cats were used specifically for this purpose.

2. Method of Decerebration

The animal was placed in a glass sided box and anaesthetised with ether blown into the box by bubbling air through ether in a wash bottle. When the cat's respiration became deep and regular it was removed from the box and anaesthesia was maintained by dropping ether onto the toe of a sock which was held over the animal's face. The skin was then incised in the mid-ventral line of the neck, the strap muscles were separated by blunt dissection and the trachea exposed and cannulated. The level of anaesthesia was subsequently controlled by means of an anaesthetic tin which gave a controllable mixture of ether and air.

The common carotid artery was next tied on both sides, taking care that the vagus nerve was not included in the ligature, after which the animal was turned into the prone position and supported in a head clamp. The scalp was incised from above one eye to behind the ear of the opposite side and the temporalis muscle was removed by blunt dissection from the lateral aspect of the skull on one side. A hole was then trephined in the bony vault and enlarged by bone nibblers until it could comfortably admit the index finger. The edges of the open diploic space were blocked with plasticine. The vertebral arteries were next temporarily occluded with the thumb and middle finger of the left hand, while with the right hand the dura was incised and removed from over the opening in the bone. A piece of the underlying cerebral cortex was removed and the remainder of the cerebral tissue turned forward, so that the dorsal aspect of the brain-stem was clearly visible. The brain-stem was then transected between the superior and the inferior colliculi and the remaining cerebral tissue was removed. Any loose blood was sucked out and pieces of Gelfoam were placed over the bony sella turcica. The cranial cavity was then filled with warm Ringer solution which was immediately sucked out again with a suction pump, thus compressing the Gelfoam onto the collapsed vessels of the circle of Willis and ensuring haemostasis. If this procedure did not produce almost immediate haemostasis, moderate pressure was applied with the index finger in a downward direction over the region of the sella for a few minutes.

If at any time during the decerebration the respiration stopped, artificial respiration was applied by blowing through a tube designed to fit onto the tracheal cannula., The animal's temperature was maintained by a heating plate on the operating table.

3. Method of Exposure of the Pudendal, Pelvic and Sympathetic Nerves

The course and relations of these nerves in the cat are described in Section I and illustrated in Figs. I, 2, 3, 5 and 6. .

In order to expose the pudendal nerve, an incision was started above and between the two easily palpable bony prominences (tuber ischii and greater trochanter) and was continued vertically downward for two inches. At the level of the tuber ischii, a vein was found which runs down the postero-lateral aspect of the thigh and plunges between the gluteus maximus, in front, and the biceps femoris, behind. This intra-muscular space was opened and the sciatic nerve followed dorsally to where it emerges between the piriformis and ischio-caudal muscles. The pudendal nerve was then found, lying on the posterior aspect of the sciatic nerve and running posteriorly between the obturator internus and pubo-caudal muscles, to its point of division into genito-anal and dorsalis penis branches.

The pelvic nerves were approached by Barrington (1915) along the anal canal, and by Elliot (1907) from behind the rectum. It was found, however, that the most effective exposure could be obtained using a ventral approach as described by Garry (1933 a). The symphysis pubis was split in the mid-line and the two halves separated. By blunt dissection dorsally, on either side of the rectum, the pelvic nerve could be found emerging from between the sacro-caudal and ischio-caudal muscles and splitting up to form the pelvic plexus on the side wall of the rectum.

Elliot (1907) approached the lumbar sympathetic outflow through an incision in the left flank which allowed an extra-peritoneal exposure of the hypogastric nerves. This procedure was also followed by Garry. In the present experiments I approached the lumbar outflow ventrally through the greater sac of the general peritoneal cavity. I felt that the disadvantages of opening the peritoneum and handling the abdominal viscera were offset by the greater simplicity of this approach and the wider access which it afforded.

Sectioning the pudendal nerve is a simple procedure once the nerve trunk has been adequately exposed. Complete interruption of the pelvic nerve is more difficult to ensure because the main trunk breaks up into a large number of very fine branches immediately after entering the pelvis and the nerve is accompanied by quite a large branch of the middle rectal artery. It is best, therefore, to isolate the main trunk with its accompanying vessel as near to its roots of origin as possible and to divide it between ligatures.

Destruction of the lumbar sympathetic outflow involves two distinct processes and here again care must be taken to ensure complete interruption of the nerve strands. First, the hypogastric nerves are isolated in the mesocolon where they are sectioned and removed along with the inferior mesenteric ganglia. The inferior mesenteric artery is then stripped of all surrounding connective tissue and the fine nerve strands which run in close association with its adventitia (the lumbar colonic nerves) are destroyed using the points of fine forceps.

4. General Lay-out of the Apparatus

The experiments were all carried out within a cage of wire mesh screening. The operating table, the pre-amplifiers and the pen-recorder, were all within the screening, while the power-packs, the oscilloscope with the camera attached and the pre-amplifiers were outside. A small "slave" cathode-ray tube was installed in the cage and was visible while dissection was being carried out. Fig. 16 is a general view showing some of the apparatus.

5. Amplifiers and Stimulators

In the majority of the recording experiments only one pre-amplifier was used, but in those experiments where the external sphincters of the urethra and anus were studied simultaneously, two were used. These amplifiers were similar in pattern, each consisting of two symmetrical channels providing balanced input and output with rejection of in-phase artefact. The stimulator used was a battery-operated transistorised unit giving square wave pulses of variable frequency, length and duration.

6. Apparatus for Recording and Displaying the Results

All records were made from electrical signals, either as an ink trace written by a pen-oscillograph or as a photograph of the oscilloscope screen.

The input leads, which were of screened co-axial cable, were attached to the recording electrodes by means of crocodile clips or by a Plessey plug and were fed into a balanced-input, condenser-coupled pre-amplifier within the screening cage. From here the signal was fed through a further amplifier of conventional design to a double-beam display unit mounted on a rack outside the cage, and this in turn operated a "slave" unit within the cage. A Cossor camera was mounted on the double-beam instrument and this was used to make the records where only two signal lines were needed, for example in the nerve recording experiments. Two types of time marking were used for the photographic records, the output from a crystal time-ruler or from a clockwork system giving half second pulses. One or other of these was displayed on the second beam of the oscilloscope, superimposed on the signal already on this beam.

In experiments where several simultaneous records were required, for example in the electromyography experiments, an Ediswan four-channel pen-recorder was used. This instrument writes four signals simultaneously in ink on a moving paper strip and has a separate amplifier with a gain control for each of the four channels. It was found that for the purpose of the present experiments, the paper speeds available with the standard Ediswan instrument were usually too fast. A Palmer electric kymograph, giving a wide range of drum speeds, was therefore mounted sideways on a specially made metal frame and was used to provide slower paper drive. (Fig.17.)

7. Electrodes for Stimulation and Recording

The recording electrodes used for electromyography were made from fine entymological pins. These were soldered at the head end to lengths of fine varnished copper wire. They were then dipped in a high resistance insulating varnish and baked according to the manufacturer's instructions for one hour at 110°C. The free end of the wire was soldered to an insulated tag-strip and the head of the pin was embedded in a block of sealing wax or "Araldite". A fine piano-wire spring connected the sealing wax block to the tag-strip and helped to spring the electrodes into position and to maintain them there.

Two varieties of this basic design were used. For recording from the anal sphincter it was found most convenient to have both pins attached to the same tag-strip and embedded in the same block with the separation of the tips fixed at about 3 mm. In the experiments on the urethral sphincter a separate tag-strip and spring was used for each pin. This arrangement allowed greater flexibility for placing the electrodes in the confined space available and it also allowed the inter-electrode distance to be altered. In both cases the tag-strips were mounted on rigid brass rods and the rods were held in moveable ball and socket joints. The different types of recording electrode used are shown in Fig. 18.

The electrodes used for recording from nerve strands were made from two lengths of platinum wire bent to form hooks and these were soldered to lengths of insulated copper wire. The copper wires were enclosed within a piece of brass tubing and the soldered junction covered with sealing wax so that only about half an inch of the platinum wire was exposed. The insulated copper wires were attached either to a tag-strip or to a co-axial cable junction and the brass tubing was attached to the cable screening. This type of electrode was also used for stimulating nerves when only a short period of stimulation was required, for example in Section 5 when stimulating the ventral roots.

When it was desired to stimulate a nerve for a longer period during the course of an experiment, the nerve was cut and the end implanted in fluid electrodes. In particular this method was used in the experiments on the effect of stimulating the hypogastric and pudendal nerves on the sphincter mechanisms of the urethra and the experiments on the effect of pudendal nerve stimulation on the bladder.

These electrodes were a small version of those described by Garry & Wishart (1951) and consisted of two cylindrical chambers of perspex separated by a thin rubber diaphragm, with a silver terminal in each chamber. The nerve was cut and a thread tied to the cut end. This thread was led through the rubber diaphragm using a fine straight needle. Both chambers were filled with fluid from a syringe and the distal chamber was plugged. The electrodes were small enough to be inserted and stitched into a space in the tissues and the wound closed over them. They are shown in Fig. 19.

In early experiments Mammalian Ringer solution was used as the fluid medium but it was found, as was previously reported by Brown & Garry (1932), that the nerves did not retain their sensitivity for the duration of a long experiment in this fluid and the animal's own serum was found to be more effective. This was prepared by withdrawing 3 to 5 ml of blood from the external jugular vein early in the experiment and centrifuging down the cells in a tapered tube.

8. Apparatus for Distension of the Rectum and Anal Canal

Two rubber balloons, mounted "in tandem" on separate metal holders, as described by Garry (1933 a), were used for distension of the rectum and anal canal; examples of these are shown in Fig. 20. The rectal balloon was made from a condom which was tied over the end of a holder consisting of a thin metal tube about six inches long with a series of perforations at one end opening into the central cavity. The anal canal balloon was mounted on a shorter metal holder which rode over the rectal balloon holder so that the two balloons were independently moveable and could be independently inflated. The position of the rectal balloon could be varied by moving it through the anal balloon holder so that to and fro or rotatory movement of the rectal balloon could be performed without stimululating the anal canal. When in use the balloon holders were clamped to the metal rod framework which supported the animal and the balloons were lubricated with vaseline. On a number of occasions soap jelly was used for this lubrication and this substance was found to have an augmentative effect on the activity of the external anal sphincter, which was sometimes an advantage.

The system used for inflating the balloon is shown in Fig. 24. A two gallon petrol can was used as an air pressure reservoir and was pressurised by means of hand bellows. The reservoir was connected to the two balloons independently by means of a series of glass two-way taps, while a separate mercury manometer was used to measure the pressure in each balloon. A record of the pressure within the balloons was made with the electronic transducer manometer.

9. Apparatus for Filling the Bladder or perfusing the Urethra

The urethral cannulae were made from silver plated brass and had smoothly rounded closed ends to facilitate their introduction (Fig. 24). For simultaneous recording of bladder pressure and bladder volume changes, the cannula used had two separate channels each connecting with the exterior through a separate series of side perforations.

A single channalled cannula of similar pattern was designed for perfusion of the urethra but in practice fine polythene tubing, open at the end, was found to be more satisfactory. The cannula was connected to the reservoir and the manometer by thick-walled polythene tubing so that the system was of minimum distensibility and volume displacement.

In some of the earlier experiments, a constant pressure device of the type described by Ferguson & Garry (1954), consisting of a horizontally mounted flat spiral of tubing was used for delivering fluid to the bladder or urethra. This was later found to be unsuitable on account of its high resistance to flow and a tendency for the column of fluid to break up into sections. A simple reservoir made of perspex was found to be suitable. Its dimensions were such, that the change in head of pressure resulting from the flow of fluid in or out was relatively small and in the circumstances quite acceptable.

The reservoir had three openings ; one at the top, one at the base and one at the side, (Fig. 39). It was filled through the opening at the top and at other times this opening was connected to the float volume recorder by a system of air-filled tubes. The side opening was left open to allow air to escape while the reservoir was being filled and was closed off at other times. A syringe adaptor with a three-way tap was interposed in the tubing system between the reservoir and the volume recorder so that the volume of the system could be adjusted, by adding or withdrawing air with a syringe. This method was also used to calibrate the volume-change records.

The reservoir was mounted on the carriage of a Palmer stand which could be raised and lowered between 0 and 40 cm to allow the bladder to fill or empty. The height of the reservoir was recorded by a system of pulley wheels which operated a potentiometer connected across a 4 volt battery supply. This apparatus is shown in Fig. 39 & Fig. 40.

10. The Measurement of Volume Change

Changes in the volume of the bladder contents, or the total volume of flow along the urethra, were measured by a modified float volume recorder built from transparent celluloid (Fig. 21). Floats of different capacities were used to vary the sensitivity of the instrument. A side arm of brass wire was soldered to the spindle at the axis of rotation of the float, so that movement of the float caused the end of this wire to travel along a trough filled with a conducting fluid of suitable specific resistance. The cross sectional area of this trough was small but uniform and it was filled with glycerine to which saline was added until the resistance across the cell reached a suitable value such as 20 KΩ. Two metal electrodes were inserted, one in each end of the trough and a d.c. potential was connected across them from a dry battery. This d.c. potential varied from 2 to 12 volts according to the sensitivity desired. A 1MΩ potentiometer was connected across the cell and this was adjusted to balance the bridge, while the signal was led off from the sweep terminal of the potentiometer. The sensitivity of the whole instrument could be varied by altering the capacity of the float, the voltage across the cell, or the gain of the amplifiers into which the signal was fed.

II. The Measurement of Pressure

The pressures developed within the viscera were recorded by means of an electronic transducer manometer, (Fig. 22 & Fig.23). The original version of this instrument was designed and built by Dr. T.D.M. Roberts of this department.

The essential component is the RCA 5734 mechano-electric transducer valve which was rigidly mounted in a brass block. This is a triode which is designed for use in converting mechanical movement into an electrical signal. In this instrument, it was used as a diode with the grid and cathode common. The anode of the valve is extended as a pin protruding through the metal diaphragm which forms the base of the valve. Angular displacement of this pin produces a change in the total impedance of the valve. A desirable deflection of the tip is about 5 μ, which, with a d.c. voltage of 240 volts, gives an output signal of 6 volts.

The instrument was constructed by milling a slot out of the centre of a brass block and this slot was connected by holes drilled at each end of the block, to projecting metal tubing. The slot was covered by a glass diaphragm consisting of a number one microscope cover slip, sealed down with sealing wax. The chamber so formed was filled with water for use and the transparent cover slip allowed any bubbles to be seen and to be washed out. The lever connecting the diaphragm to the anode pin is of stiff metal and is thermally insulated by a fibre sleeve to minimise expansion effects. The RCA 5734 is connected in a bridge circuit which is first balanced by adjusting the potentiometers and the output is fed into a high impedance voltmeter, such as a cathode-ray tube, or the amplifiers for the Ediswan pen-recorder. The high tension supply, 240 to 300 volts, is derived from dry batteries and a 6 volt transformer is used to step down the mains voltage for thevvalve heater.

PART 3

THE PHYSIOLOGY OF THE EXTERNAL ANAL SPHINCTER

CONTENTS

A. REVIEW OF THE LITERATURE ON THE CENTRAL CONTROL OF THE ANAL SPHINCTERS AND THEIR REFLEX RESPONSES

The earlier work on this subject has been extensively reviewed by Garry (1934 a & b) and I have found these reviews a valuable source for many references to these early papers. There were a large number of early studies on the anal sphincters, many of which duplicated one another and added little to the total information already accumulated. Most of these investigations were concerned with localising the area in the lumbo-sacral spinal cord which acts as a centre for the tone of the anal sphincters and as a reflex centre for defaecation. Several workers also described rhythmic contractions of the anal sphincters in animals with isolated lumbo-sacral cords. At the same time a number of reports appeared which suggested that the external sphincter did not show loss of tonicity nor degenerate when its motor nerves were cut and in addition it was reputed to be resistant to the action of Curare. As a result of these reports, the belief arose that the external anal sphincter had certain properties unique amongst the striated muscles of the body.

Some of the earlier writers made statements about the functions of the anal sphincters which were largely unsubstantiated by experimental results. Müller (1838) believed that the anal sphincters played a purely passive part in defaecation, being forced open by the passage of the faeces. He attributed the major role in the process to the abdominal muscles and the diaphragm. Valentin (1847) believed that the smooth muscle internal sphincter acted as a detrusor during defaecation while the striped external sphincter relaxed.

Marshal Hall (1836) was the first to study the problem experimentally. He found that when the lumbosacral cord of the turtle was isolated, the tone of the anal canal remained intact and a touch stimulus applied to the peri-anal skin caused contraction of the anal sphincters. In such a spinal preparation considerable pressure was required to force fluid outwards past the sphincters but destruction of the isolated segment of cord abolished both the tone and the reflex responses. He obtained similar results working on the decorticate horse. Budge (1858) also noted that the tone of the anal canal was dependent on the integrity of the lumbo-sacral cord and he concluded that the effective centre was in the lumbar region. He emphasised the role of the pelvo-caudal muscles which surround the anal canal as auxiliary sphincters and was able to stop the flow of water through the anal canal by direct stimulation of these muscles.

By selective cutting of the sacral nerve roots in the dog Giannuzi & Nawrocki (1863) localised the outflow to the sphincters to the second and third sacral roots. They regarded the tone of the anal sphincters as being only partly reflex in origin and they postulated that the centre for the anal sphincters lay in the caudal part of the fifth lumbar segment. They found that the anal sphincters could support a pressure of 40 cm H_2O during life but this resistance fell to 18 cm H_2O on cutting the pudendal nerves and remained at this level after the death of the animal. Masius (1867 & 1868) concluded that the ano-spinal centre was sacral and he found that transection of the spinal cord at a higher level increased both the tone and the defensive contractions of the anus.

Goltz & Freusberg (1874) produced chronic spinal dogs by transection of the spinal cord and reported contraction of the anus when the anal mucous membrane of these animals was stimulated. A finger inserted into the anal canal led to a series of rhythmic contractions of the anus at a rate of about twenty per minute and these contractions could be inhibited by any nocuous stimulus. These chronic spinal dogs were able to expel any foreign body which was introduced into the rectum. Ott (1879) described rhythmic contractions similar to those reported by Goltz & Freusberg, appearing some hours after high spinal transection in dogs and cats. He localised a centre in the thalamus which was inhibitory to the ano-spinal centre.

The first clinical report, Gowers (1877), showed that in a patient with damage to the sacral roots the external anal sphincter was paralysed while the internal smooth muscle sphincter showed varying tone and could be relaxed by irritation of the rectal mucosa. This relaxation was sometimes followed by a period of rhythmic contractions. Unfortunately it is not possible to decide from the description given the exact nature of the lesion in this case.

The findings of Goltz & Ewald (1896) are difficult to explain and seem to have been responsible for many of the statements which appeared subsequently, implying that the external sphincter had special properties. These workers found that in 'cordless' dogs, in which all the somatic muculature had atrophied, the sphincter remained undegenerated and still responded to stimulation of the pudendal nerve. They also found that the sphincter could not be paralysed by Curare. They claimed that defaecation was carried out normally in these cordless animals.

The results of Arloing & Chantre (1897 & 1898) are in many ways similar to those of Goltz & Ewald and their investigation was in fact stimulated by the papers of these workers published in the previous year. Arloing & Chantre found that degeneration of the external anal sphincter was minimal after section of both pudendal nerves and even after an interval of two years the muscle still responded to stimulation through the skin. They reported that the response of the external sphincter to stimulation through the pudendal nerve differed from the normal response of a striated muscle to stimulation of its motor nerve, in that the contraction produced was slow and feeble, the critical frequency of stimulation required to produce a sustained tetanus was lower and the latent period of the response was longer. The behaviour of the muscle was in fact, they decided, more in keeping with the properties of smooth muscle than of striated muscle. Direct electrical stimulation of the muscle fibres themselves, however, produced a typical striated muscle response. It is difficult to explain these results, particularly so since they have not been substantiated by subsequent workers.

It is also difficult to explain the results of Elliot & Barclay Smith (1904) who reported that destruction of the lumbo-sacral cord in cats relaxed the external sphincter but did not cause loss of excitability or atrophy whereas the same procedure in rats did not even relax the anal canal. It seems likely that in the rats, the closure of the anus was due to the internal smooth muscle sphincter, supplied by the inferior mesenteric ganglia.

A further group of anomalous findings concern the response of the external anal sphincter to the action of Curare. Frankl Hochwort & Frölich (1904) found that the muscle had a high threshold to this substance, being little effected by dose levels which paralysed the limb musculature. Goltz & Ewald (1896) believed it to be totally resistant, as did Magnus (1911), but on the other hand several workers including Dale (1906) and Garry (1934a) were able to produce neuromuscular block using Curare.

The investigations of Garry (1933 a, b & c and 1934) on the physiology of the anal sphincters are the fullest and most authoritative yet published. He reinvestigated the behaviour of the external anal sphincter with respect to the effect of denervation and Curare and he concluded that there was no justification for regarding the behaviour of this muscle as in any way unique, but that it should rather be regarded as an extreme example of a "red" muscle. In addition he worked out the reflex behaviour of this muscle in detail in a manner complementary to the studies of Barrington on micturition.

Garry found that movement of a deflated balloon within the anal canal, either to and fro or rotatory, relaxed the canal and brought on contraction of the somatic musculature with the development of the defaecation posture. Distension of the anal canal without movement had little effect, while the introduction of a foreign body from without caused a series of twitch like contractions of the anus. This relaxation of the canal in response to movement within it persisted after pudendal nerve section and depended on the integrity of the lumbar outflow. It was presumably, thus, a phenomenon of the internal sphincter. When cocaine was applied to the anal mucous membrane, the canal relaxed and movement within it now caused contraction. Garry also found that distension of the rectum did not cause the anal canal to dilate, whereas movement of a deflated balloon within the rectum was a potent stimulus. This response was abolished by the application of cocaine to the rectal mucous membrane but was still present after the administration of Curare or section of the pudendal nerves. He examined the external anal sphincter histologically and found that it was of typical "red" muscle appearance, with fibres of small diameter rich in sarcoplasm having typical motor endings. He found that section of the pudendal nerves led to degeneration of the muscle fibres but that this was slower than in most striped muscles. The threshold to Curare was also higher than in limb muscles but no higher than in the diaphragm and he concluded that there was therefore no justification for regarding the properties of the striated external anal sphincter as in any way unique, as had been previously suggested.

In the most comprehensive clinical report on the subject yet published, Denny Brown & Robertson (1935) applied the multiple balloon technique to the study of the control of defaecation in man. They reported that voluntary control over defaecation in man depends wholly on the external sphincter, the internal sphincter acting only in reciprocity with the muscle of the rectum. They claimed that the external anal sphincter in spinal man did not show tonic contraction but contracted reflexly as part of the mass reflex and it also contracted reflexly in synergy with the rest of the abdominal muscles, to resist a rise in intra-abdominal pressure. This result is in contradiction to that of Head & Riddoch (1917) who claimed that the external anal sphincter was the first muscle in the body to regain its tone on recovery from spinal shock. The explanation of this difference probably lies in the variable interpretation which can be put upon the results of mechanical recording methods and balloon recording in particular and serves to emphasise the fact that it is not possible to disentangle the roles of the two superimposed sphincters by such methods.

Amongst other clinical workers, Gaston (1948 a & b) and Goligher & Hughes (1951) have studied the physiology of the anal sphincters from the point of view of their function in the maintenance of faecal continence. Gaston found that a sudden rise in intra-rectal pressure resulting from the inflation of a balloon or from the passage of faeces or flatus from the colon into the rectum, caused a contraction of the external anal sphincter. This reflex was absent in spinal man but was present in the normal subject during sleep or during light anaesthesia. Goligher & Hughes reported similar results and concluded that this was a reflex phenomenon occurring at a subcortical level and that it was important for the maintenance of faecal continence.

Kühn (1950) in a study of twenty five men with chronic high spinal transections, found that fourteen of them were able to initiate reflex defaecation by digital stretching of the external anal sphincter and that this stretching was often associated with some vague sensation such as abdominal aching or sweating over the upper part of the body. A nocuous stimulus applied to the legs or genital area during the course of reflex micturition caused contraction of the anal and urethral sphincters. He noted that anal sphincter tone fell during contraction of the bladder.

This same interaction between bladder and anus was reported by Denny Brown & Robertson (1933)in man and was investigated experimentally by Semba, Mishima & Date (1956) in chronic spinal dogs. They found that the rhythmic contractions of the external anal sphincter which these animals showed were abolished by any sudden rise in intravesical pressure whether produced by distension or compression of the bladder. Such a rise in bladder pressure also caused inhibition of the colon, followed by a contraction which outlasted the stimulus by several minutes.

Only a few reports of electromyographic studies of the striped external anal sphincter muscle can be traced despite its reputedly anomalous behaviour and its relative accessibility.

Beck (1930) used steel needle electrodes which he inserted at the muco-cutaneous junction to a depth of 4 mm, making his recordings with a string galvanometer. He studied the effects of distension of the anal canal in seven dogs and in one man. During both contraction and relaxation of the sphincter, he found that action potentials were recorded, but when the muscle fibres remained at constant length the action currents gradually subsided and sometimes completely disappeared. These findings he interpreted as an example of a true 'ratchet' tone mechanism. It is difficult to interpret Beck's results in terms of the modern concept of striated muscle function.

Newman (1949) recorded electrically from the external sphincters of the anus and urethra in unanaesthetised women, using concentric needle electrodes. He found that there was no electrical activity in either muscle when the subject was at rest. Coughing, or attempts to raise intra-abdominal pressure by contraction of the anterior abdominal wall muscles, or voluntary contraction of the sphincters themselves, all led to increased activity, while a passive increase in intra-abdominal pressure produced by the observer did not do so. Attempts to void were preceded by twitches of both sphincters. The electromyographic records which are included in his paper show only slow base-line shifts with no discrete action potentials. Details of the equipment and the method of recording used are very scanty, so that the results as a whole are difficult to evaluate. The paper of Floyd & Walls (1953) is more impressive than either of the two previously described. They studied seven human subjects using surface electrodes applied to the peri-anal skin. The external sphincter showed a tonic discharge throughout the waking hours, which became minimal during the hours of sleep. Raised intra-abdominal pressure was always accompanied by an increased discharge, except when this was associated with an effort at defaecation, in which circumstance sphincter tone was reduced.

Kawakami (1954) studied human subjects under light narcosis using needle electrodes. Like Floyd & Walls, he found a continuous low frequency electrical activity in the muscle. This could be reduced by a conscious attempt at defaecation; quite easily if the rectum was full, but only with difficulty if it was empty. He found that the tonic discharge could be reflexly modified by various procedures, such as cutaneous reflexes from the skin of the perineum and anterior abdominal wall.

Bishop, who worked along with me in 1956, has published a further paper on this subject since her return to the United States. (Bishop 1959). She finds that the ingoing fibres which are responsible for the tonic motor activity, almost all pass in by S2. dorsal root, whereas the ingoing fibres responsible for phasic activity pass in by all three sacral dorsal roots. Variations in the osmotic pressure and pH of the colonic contents, outside a certain range, influence the level of external anal sphincter tone.

It can be seen from the foregoing review that our knowledge of the reflex behaviour of the anal sphincters is derived from a large number of observations, both experimental and clinical, in which mechanical recording techniques were used. Those electromyographic studies which have so far been published have been limited in scope and a full electromyographic study of the behaviour of the external sphincter has not yet been reported.

B. DISSECTION AND ARRANGEMENT OF EQUIPMENT FOR ELECTROMYOGRAPHY OF THE EXTERNAL ANAL SPHINCTER

The cat was placed on its side or in a few cases was supported upright in a system of brass rods and the hair was shaved from the peri-anal region. A vertical skin incision was then made one inch lateral to the anus and concave towards it and the skin was reflected inwards taking care to preserve cutaneous nerve twigs. The ischio-rectal pad of fat was then carefully removed leaving the boundaries of the muscle and the surrounding structures clearly exposed. The skin edges formed a pool over the exposed muscle which was filled with warm liquid paraffin. The recording electrodes were placed so that their points were resting lightly on the surface of the sphincter.

For investigating the reflexes, the rectal and anal canal balloons were inserted either through the anal canal or through a colostomy opening and were connected to the pressure reservoir and to the mercury and electronic manometers. In the earlier experiments no pressure reservoir was used and the balloons were inflated directly by hand bellows. All the signals were displayed on the Ediswan pen-recorder. A diagram of the arrangement is shown in Fig. 24.

C. EXPERIMENTAL RESULTS

1. Tone in the External Anal Sphincter

With the exception of one animal in which the anal glands were infected and the external sphincter was barely visible, a steady tonic discharge could always be recorded from the surface of the muscle in the decerebrate cat when the animal was at rest and the anal canal was empty. This tone persisted throughout the duration of each experiment and showed no sign of waning with time. In a few cases slight twitching of the muscle was visible, but typically no sign of activity could be seen with the naked eye, although the anal canal was held closed. With the points of the recording electrodes close together on the surface of the muscle and arranged so that the tips were parallel to the general line of the muscle fibres, it was often possible to record the activity of a single motor unit (Fig. 25A). Such a unit would discharge regularly at a frequency of about 12 impulses per second, for a period of several seconds or minutes at a time and would often alternate periods of activity and periods of silence. This behaviour suggests that some form of rotation of motor units takes place.

A single unit of this sort would respond to an augmentative stimulus with an increase in discharge frequency up to a value of about 30 impulses per second. Variations in the discharge frequency of single units did not, however, give a faithful picture of changes in the activity of the muscle, since the discharge was increased principally by recruitment of additional motor units. These same two factors, changes in the number of active units and changes in the discharge frequency of individual units, are involved in the reduction in activity which accompanies inhibition of the muscle. They are well shown in Fig. 29 where inhibition of the resting discharge was produced gradually.

In general, however, no attempt was made to record from single units. A more useful indication of activity was obtained by having the electrode tips some 3 mm apart and recording the combined discharge of several motor units. Fig. 25B is an example of a resting tonic discharge recorded in this way. When the pen-recorder is used at the lower paper speeds, individual spikes are not distinguishable from one another. Variation in overall amplitude rather than variation in frequency is shown in the pen records and this was found to be the most useful indication of the changes in muscle activity which occurred in the reflex experiments. On the other hand, comparison of the level of sphincter tone over long periods of time is difficult by this method, especially if the differences looked for are slight, since the same electrode placement cannot usually be maintained if operative procedures are being carried out.

With this reservation, there was noticed a slight but definite increase in resting sphincter discharge after destruction of the lumbar sympathetic outflow and after transection of the spinal cord at the lower thoracic level. The tone remained at an unchanged level after section of the pelvic nerves and it was completely abolished after the pudendal nerves had been cut.

Spinal anaesthesia of the lumbo-sacral cord with 1% procaine hydrochloride solution, injected intra-thecally at the lumbo-sacral junction, abolished all activity from the muscle, although the tone of the sphincter disappeared somewhat later than did the knee jerk. Full general anaesthesia with ether or with intra-venous Pentobarbitone also abolished the activity but the application of a 5% Cocaine solution or a 4% Xylocaine solution to the mucous membrane of the colon, or of the anal canal, did not alter the level of the tonic activity of the external anal sphincter.

2. Augmentation of the Tonic Discharge.

Stroking or pinching the peri-anal skin or the visible part of the anal mucous membrane caused a sharp burst of activity which was visible to the naked eye as a twitch of the muscle (Fig. 26). This reflex, known as the anal reflex, is present in man and is used in routine neurological examination as a test of the integrity of the sacral roots and the sacral spinal cord. An attempt to insert a cotton wool bolus or a blunt instrument into the anal canal from the exterior, caused a strong contraction of the sphincter, although this contraction was followed by a period of reduced discharge while the object traversed the anal canal, before the resting discharge was re-established (Fig. 28). Both these reflexes were present after section of the spinal cord at the lower thoracic level, after section of the pelvic nerves and after section of the lumbar sympathetic outflow.

The inflation of a balloon within the anal canal led to powerful rhythmic contractions of the external sphincter and at the same time the animal assumed the characteristic defaecation posture, with flexing of the tail, arching of the back and contraction of other somatic muscles to assist in the expulsion of the balloon to the exterior. It was impossible to keep a balloon inflated within the anal canal for more than a few seconds under these circumstances and the movement involved complicated the process of recording from the sphincter. Movement of a deflated balloon within the anal canal caused an increased discharge but with less tendency for other somatic muscles to be involved. In some cases the background discharge seemed to be reduced for short periods but no sustained reduction of activity was seen, the response being primarily augmentative. Stretching of the sphincter muscle, without simultaneously stimulating the mucous membrane, was produced by dorsiflexing the tail to which the posterior part of the muscle is attached or more elegantly by inserting sutures into the most anterior and posterior parts of the muscle ring and applying traction to them. These procedures caused a sustained but regular increase in the discharge without involving neighbouring somatic muscles.

In many cases, inflation of a balloon within the colon caused a distinct increase in the discharge from the sphincter before inhibition developed (Fig. 32) and there was evidence also that surface receptors in the colonic mucosa could influence the level of the discharge. Thus the application of an irritant substance to the mucous membrane of the colon or anal canal - the soap solution used to lubricate the balloons in some of the earlier experiments - caused a sustained increase in the tonic discharge to the muscle.

A nocuous cutaneous stimulus applied to the limbs or elsewhere caused a brief burst of activity in the sphincter. This response was more marked if the site of stimulation was near to the perineum. Raising the intra-abdominal pressure by pressing over the anterior abdominal wall or by obstructing the tracheal cannula at the height of inspiration and allowing the animal to expire forcibly against resistance, caused an increase in the discharge.

3. Inhibition of the Tonic Discharge

The tonic discharge could be inhibited by inflating the colon with air through a colostomy. This procedure is free from some of the objections which might be raised against the introduction of balloons but does not allow the effects of different pressures or the effects of distension at different sites to be investigated. Distension of a balloon within the colon reduced the discharge or abolished it completely, depending on the pressure used (Figs. 30 and 31). During the period that the balloon remained inflated within the colon, reflexes which normally produced an increase in the discharge, such as the anal reflex, were absent. The balloons were introduced either through the anus or through a colostomy opening in the caecal region. When the balloon was deflated the period of inhibition of the discharge ended immediately and there was often a burst of increased sphincter activity. This 'rebound' phenomenon was a constant feature of the response after ligation of the spinal cord above the lumbar region. (Fig. 36).

The position of the balloon was important in determining the nature of the response to distension. Inhibition was most easily produced by distension of the distal colon but in most cats distension as far cranial as the caecum was effective although usually a higher pressure was needed in the cranial region. The actual level of pressure needed to produce complete silence in the sphincter varied between 10 and 80 mm Hg, but accurate measurement of the effective pressure was made difficult by the fact that in many cases active contraction of the colon wall took place as a reflex response to distension. When the balloon was inflated from the pressure reservoir, as in the later experiments, and the tap to the reservoir was then closed, the effect of this reflex contraction could be seen as a pressure rise superimposed upon the reservoir pressure. Active contraction produced in this way was a more effective stimulus to sphincter inhibition than was passive distension. Thus, although it was difficult to obtain an accurate value for the pressure required to produce complete silence in the external sphincter, it was found that a lower pressure was necessary to produce inhibition when applied to the anal end of the colon than when applied to the caecal end, and similarly a lower pressure was required with a large balloon than with a smaller one. It was also found that a lower intra-colonic pressure was effective after destruction of the lumbar sympathetic outflow. The rate of application of the distension did not seem to be a significant factor in determining the response of the external sphincter.

Distension of the colon was not associated with the somatic spread of activity to limb and tail muscles which make up the complete defaecation response, unless part of the balloon lay within the anal canal. If the balloon lay entirely within the colon it could be maintained distended for periods of over two minutes and inhibition of the sphincter discharge continued until ultimately either activity gradually returned to the sphincter (Fig. 34), or a 'defaecation' response set in (Fig. 29). When the colon was distended to a pressure just above that necessary to produce inhibition of the external sphincter and was maintained at this level, inhibition of the external sphincter slowly passed off and electrical activity returned to the muscle over a period of minutes (Fig. 34). If the pressure was significantly above this level the discharge did not reappear and the usual termination was the expulsion of the balloon through the anal canal. As the balloon traversed the anal canal the defaecation posture already described was assumed and the return of activity to the sphincter was preceded by rhythmic contractions of the muscle (Fig. 24). On rare occasions records were obtained from the sphincter during spontaneous normal defaecation in the absence of balloons and showed a similar pattern of response. Towards the end of the act, as the faeces were traversing the anal canal, periods of inhibition alternated with periods of strong contraction of the muscle.

Simple distension of the colon was not the only effective stimulus for eliciting inhibition of the external anal sphincter. Movement of a deflated balloon or of a swab tied over a balloon holder within the colon led to inhibition of the external sphincter (Fig. 33). No means of recording or of measuring such movement was developed. Even under these circumstances, however, it is possible that some tension may have developed in the wall of the colon, since the colon could be felt to contract and grip the balloon holder as the movement was carried out.

It was noted that complete inhibition of anal sphincter discharge accompanied spontaneous micturition. To investigate this effect, simultaneous recordings were taken from the anal and urethral sphincters in a number of cats. It was found that either distension of the colon with a balloon or distension of the bladder with fluid could inhibit both sphincters (Figs. 35 & 54) and there was no detectable difference between the two sphincters either in the pressure threshold necessary to produce a response or in the latency of the responses - the sphincters behaved as though they were part of the same muscle mass. No attempt was made to record intra-colonic pressures during distension of the bladder but it was noted that while the colon was being distended with a balloon a slight rise in bladder pressure occurred, which was due to the balloon in the colon pressing on the bladder. On no occasion was contraction of the bladder seen.

After the application of a 5% solution of cocaine hydrochloride to the mucous membrane of the colon, the discharge from the sphincter was unaffected but it was no longer possible to inhibit it either by inflation of a balloon or by movement of a balloon within the colon. It was not found possible to remove one of the inhibitory responses and to leave the other one intact by applying cocaine, but it was noted that complete inhibition of the anal sphincter still accompanied spontaneous micturition. In no case was there a suggestion of any central effects due to absorption of cocaine and the pudendal nerve continued to function normally.

4. The Nervous Paths

Isolation of the lumbo-sacral part of the spinal cord by extra-dural ligation at or above the level of L2, did not impair the tonic activity of the external sphincter muscle which was recordable as soon as the ether anaesthesia had worn off and as soon as the knee jerk had returned. In most cases the tonic activity of the sphincter seemed to be somewhat increased after such interruption of the cord and in some cases the spontaneous rhythmic contractions of the external sphincter described by several of the early workers were seen (Fig. 37). The discharge could be inhibited as before and a rebound phase of post-inhibitory activity was frequently seen (Fig. 36).

Destruction of the lumbar sympathetic outflow left the tonic discharge unimpaired and in most cases it seemed to be enhanced. This tonic discharge to the external sphincter could still be inhibited by distension of the colon and at a lower pressure than before.

After division of the pelvic nerves the discharge was unchanged in amplitude but distension and movement within the colon were now ineffective even with distending pressures of over 100 mm Hg (Fig. 38). In one cat, distension remained effective and examination showed a small twig of pelvic nerve still intact.

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D. DISCUSSION

The external anal sphincter in the cat is composed of red muscle fibres of small diameter rich in sarcoplasm. The average diameter of the muscle fibres of the sphincter is 50 μ, compared with 75 μ in the biceps femoris. These are the histological features in skeletal muscles which are associated with the maintenance of prolonged tonic contraction. Häggquist (1940) found that the nerve supplying the sphincter was made up exclusively of fine fibres with "en grappe" endings. This arrangement he considered to be concerned with tonic rather than phasic activity. The electro-myographic findings conform to what one would expect from a muscle having these histological features; a steady discharge was observed with the animal in a resting posture and in the absence of any direct stimulation.

Denny Brown & Robertson (1935), on the other hand, on the basis of digital palpation and balloon recording, came to the conclusion that the tonic closure of the anal canal in man was maintained by contraction of the smooth internal sphincter and that the chief function of the external sphincter was rapid contraction to prevent incontinence. The external sphincter, they believed, could not contract tonically because it fatigued easily. Newman (1949) came to a similar conclusion on the basis of electromyographic studies on women, but the records which he shows are unlike the electromyographs of other workers and the results are difficult to interpret.

One could object that in the present series of experiments, nociceptive impulses resulting from trauma at the skin incision and from the exposed tissue, generated an abnormal tonic activity. On the other hand, the discharge continued at an unchanged level after the initial dissection for as long as the animal survived - in some cases for several days - and it showed no signs of waning with time. The level of the discharge was not directly related to the amount of trauma involved; additional trauma had no effect. One could also object that the tone observed was a result of the disturbance in the function of the nervous system produced by the decerebration. This objection is less easily answered since anaesthesia abolishes the tone and it would be technically difficult to record from intact unanaesthetised cats. On the other hand, Floyd & Walls (1953) and Kawakami (1954) both observed a continuous tonic discharge in normal conscious human beings without anaesthesia or surgical interference. The former used surface electrodes and the latter needle electrodes.

Tone in the external anal sphincter is unique among the muscles of the body which have so far been studied, for even in those muscles most concerned with posture, (soleus) which are in tonic contraction while the erect posture is maintained, certain alterations in posture, for example sitting, result in an instant cessation of discharge without an accompanying willed relaxation.

Sphincter tone, like striated muscle tone elsewhere in the body, is reflex in nature, with the afferent impulses which give rise to it passing in by the sacral dorsal roots. Garry (1934b) found that the anal canal became patulous when the sacral dorsal roots were cut.

Bishop (1960) confirmed that the external sphincter had no recordable electrical activity after the dorsal roots had been cut. The present results confirm that the tone is central in origin and that it is abolished by general or spinal anaesthesia. The source of the impulses which drive this tone is not immediately obvious. The tone persists after section of the thoracic spinal cord, the lumbar sympathetic outflow, or the pelvic nerves, either singly or all together and indeed the spinal cord and the sympathetic paths seem to carry impulses which are inhibitory to the tone in the intact animal. The afferent stimulus for the tone must therefore pass in mainly by way of the pudendal nerves, but since these nerves are also the route for the motor outflow, this fact cannot easily be confirmed. Local anaesthesia of the anal and colonic mucous membranes does not alter the level of the tone, so it seems likely that proprioceptors within the sphincter muscle itself may be concerned. This problem is fully dealt with in the discussion to section 5 of this thesis.

Little need be said about the increase in discharge which was observed when the peri-anal skin was stimulated or a foreign body was introduced into the anal canal from the exterior. These findings confirm electromyographically, what had previously been described by many workers and conform to expected behaviour. The finding of an increased discharge when the anal canal was distended by a balloon is in agreement with Denny Brown & Robertson (1935) although in the decerebrate cat, as opposed to the spinal man, such stimulation calls forth the coordinated action of tail muscles, abdominal muscles and limb muscles, which make up the defaecation posture. Such stimulation of the anal canal will occur in the intact animal, only when the faeces are actually traversing the canal and the response of the sphincter(:) rapid contractions, alternating with periods of relaxation, results in the expulsion of the balloon and so will presumably have a similar action on the faecal masses.

Distension of the colon, to a degree insufficient to inhibit the external sphincter, causes a significant increase in the activity of the muscle. Gaston (1948) found that any sudden rise in intra-rectal pressure in man, such as that resulting from the passage of faeces or flatus from the colon into the rectum, caused a contraction of the external sphincter. This response was absent in spinal man but was present in the normal subject during sleep or while under light anaesthesia. Goligher & Hughes (1951) concluded that this was a reflex phenomenoh occurring at a subcortical level. They found that the reflex was important for the maintenance of faecal continence; the initial contraction was reflex but it was soon followed and reinforced by voluntary sphincter contraction. The decision as to whether faeces or flatus is present is a conscious one. Todd (1959) emphasised the importance of the sensitivity of the anal canal in this connection and the necessity to preserve not only rectal sensation but anal sensation also, in any operative procedures on this region, if continence is to be retained.

Distension of the colon of adequate degree and movement within it, both elicited inhibition of the external sphincter. Garry (1933b) was doubtful if simple distension could be effective as the stimulus, since he did not find relaxation of the anal canal in the cat on distension of the colon. This was probably because he used a water manometer and the pressure levels produced in this way were too low to be effective. The pressures used in the present series, 10 to 60 mm Hg, are probably not excessive, since Goligher & Hughes (1951), and Nathan & Smith (1953), had to use pressures ranging from 40 to 150 mm Hg in the rectum in man, to evoke the desire to defaecate. It is commonly stated that in man the desire to defaecate is fugitive. This may well be so, since in the cat, when the pressure in the colon was maintained for over two minutes, either the discharge to the external sphincter recommenced or defaecation movements set in. Inhibition of the external sphincter could always be produced by distension of the caudal region of the colon and usually such inhibition could be produced by distension of the colon as far cranial as the caecum. In man, according to Goligher & Hughes, the desire to defaecate is evoked only when the rectum is distended, whereas distension of the colon itself causes colic. There is probably a true species difference, in that the whole colon of the cat, a carnivorous creature, corresponds functionally to the more caudal portions of the large intestine in man.

Since distension of the colon failed to evoke inhibition of the sphincter when the pelvic nerves were cut, it seems that the ingoing pathway for this reflex lies in the pelvic nerves. This viscero-somatic reflex, therefore, corresponds to Barrington's fifth micturition reflex (Table 3). On the other hand, section of the sympathetic outflow allowed the reflex to be elicited with greater ease. The mechanism by which this effect is produced is not clear, but section of the sympathetic nerves is known to lower the threshold for the reflex contraction of the bladder in response to distension with fluid (Barrington) and of the colon in response to distension with a balloon (Garry) and thus a given distending pressure might be expected to lead to the development of a greater tension in the wall of the colon afrer the sympathetic outflow has been destroyed. This seems the most likely explanation.

In Section 4 of this thesis, the argument is advanced that the fourth micturition reflex of Barrington; flow along the urethra causing inhibition of the external urethral sphincter, does not exist. In the case of the anus, however, there does seem to be evidence, in Fig. 28, for example, for the existence of a corresponding reflex involving the anal sphincter and the anal canal. Stimulation of the peri-anal skin and distension of the anal canal itself, cause motor responses. It is therefore difficult to obtain a prolonged period of inhibition in response to movement within the anal canal, without these motor responses being superimposed upon it. Nevertheless, in Fig. 28, after the initial sphincter contraction when the thermometer was being inserted, there is a period when the sphincter discharge is reduced significantly below the resting tonic level. In the intact animal this reflex would not be required to produce sustained inhibition of the external sphincter but only to reinforce already existing inhibition, since movement through the canal would only take place during defaecation, when the tension receptors in the wall of the colon were already stimulated. Sphincter inhibition under these circumstances would not be confined to striated muscle. Garry (1933b) showed that movement within the anal canal brought about relaxation of the internal anal sphincter even after the pudendal nerves had been cut, therefore centripetal impulses pass in both pelvic and pudendal nerves.

Distension of the bladder inhibited the anal sphincter. This was observed clinically in spinal man by Denny Brown & Robertson (1935) and was further reported by Semba, Mishima & Date (1956) in chronic spinal dogs. In fact the two external sphincters respond together in both augmentative and inhibitory reflexes, as though they formed a single muscle mass. There is no difference between the responses of the two muscles either in latency or in threshold. It seems likely that the motor neurons supplying the two muscles form a single pool in the spinal cord.

It would perhaps be possible to number the individual component reflexes of defaecation, in a manner similar to that used by Barrington for the reflexes of micturition. Such numbering is apt to obscure the normal coordinated sequence of events. Probably a truer physiological picture is given by a description which recognises just two stages. In stage one, distension of the colon and movement within the colon send impulses along the pelvic nerves to the lumbo-sacral region of the spinal cord which acts as a centre. Then, motor impulses to the colon, and inhibitory impulses to the internal anal sphincter pass out by the pelvic nerves, while the external anal sphincter relaxes owing to inhibition of its motor neurons. In stage two, movement occurs within the anal canal. During this stage the ingoing impulses run in the pelvic and pudendal nerves and the centre again is in the lumbo-sacral cord. Outgoing motor impulses pass by the pelvic nerves to the colon to maintain contraction and continuing inhibitory impulses in the pelvic nerves maintain the relaxation of the internal anal sphincter. The relaxation of the external anal sphincter persists, since not only is tension still high in the wall of the colon, inhibiting any possible motor response to distension of the anal canal, but the movement taking place within the anal canal will act to reinforce the already existing inhibition of the striated sphincter. At the close of this second stage, the relaxation of the external sphincter is interrupted by phases of strong contraction which expel any faecal masses from the anal canal.

The receptors lying in the anal region are described in detail in Sections 5 and 6 of this thesis. On the basis of the above scheme, however, the chief receptors responsible for the initiation of reflex defaecation are those lying in the wall of the colon. Little definite can be said about the precise location, the nature and the characteristics of these receptors, since they have not been demonstrated by direct electrical recording. Iggo (1957) has however demonstrated tension receptors, similar to those he has described in the bladder, lying in the upper parts of the alimentary canal with their ingoing fibres in the vagus. Presumably similar receptors are present in the distal parts of the gut. Receptors which initiate the feeling of fullness and the desire to defaecate and which are essential for the maintenance of faecal continence in conscious human beings, must lie in the wall of the rectum (Gaston 1948 a & b, Goligher 1951).

There is also some evidence for the existence of receptors in the mucosa of the large bowel, sensitive to stimulation other than tension, though the evidence for these is less complete than for the tension receptors. Thus, movement of a deflated balloon within the colon is an adequate stimulus to sphincter inhibition, while this response is abolished by the application of cocaine to the rectal mucous membrane. The value of this last piece of evidence is largely reduced by the fact that the application of cocaine abolishes the inhibitory response of the sphincter to distension of the colon as well as that to movement and the fact that cocaine is rapidly absorbed from most mucosal surfaces. On the other hand Bishop (1959) showed that the composition of the colonic contents influenced the level of the external sphincter tone and Goligher & Hughes (1951) showed that the injection of an irritant solution into the submucosa of the lower rectum in man was followed by a sensation of distension akin to that accompanying normal defaecation.

E. SUMMARY

An electromyographic study of the external anal sphincter of the decerebrate cat shows that this muscle has a continuous low grade tonic discharge in the absence of any direct stimulation. This tone is not affected by section of the pelvic nerves or by local anaesthesia of the anal or colonic mucous membranes. It is somewhat increased by section of the spinal cord above the lumbar region, or by destruction of the lumbar sympathetic outflow. General or spinal anaesthesia abolishes the tone.

Stimulation of the peri-anal skin or of the anal mucous membrane causes contraction of the external sphincter. Distension of the colon to a degree insufficient to inhibit the discharge to the sphincter increases this discharge. Any increase in intra-abdominal pressure, whether actively or passively produced, if it is not accompanied by a 'defaecation' response, causes an increase in the tone. Distension of the anal canal leads to powerful rhythmic contractions of the external sphincter.

Distension of the colon or movement within the colon of a deflated balloon inhibits the resting discharge. The response to distension is more easily produced at the anal end of the colon than at the caecal end. It is more easily produced after destruction of the lumbar sympathetic outflow but it is abolished by section of the pelvic nerves or by the application of cocaine to the mucous membrane of the colon.

The external anal sphincter is inhibited during spontaneous micturition or during distension of the bladder.

The possible significance of these results is discussed and a scheme for the reflex basis of defaecation and faecal continence is outlined.

PART 4

THE PHYSIOLOGY OF THE EXTERNAL URETHRAL SPHINCTER

CONTENTS

A. REVIEW OF THE LITERATURE ON THE PHYSIOLOGY OF THE URETHRA AND THE REFLEX BASIS OF MICTURITION

Reviews of the earlier work have been published by Fearnsides (1927), Gruber (1933) and Langworthy, Kolb & Lewis (1940).

None of these reviews goes fully into the physiology of the striated urethral sphincter or into the sensory neurophysiology of the bladder and urethra. Much of the previous work concerns the relation of the sympathetic and parasympathetic nervous systems to the function of the bladder, or the localisation within the central nervous system of the centres controlling micturition. In this review I have not attempted to deal fully with all aspects of micturition, but have concentrated on the physiology of the urethra with special emphasis on the external sphincter muscle and on the reflex basis of micturition. In the historical introduction to part 5, I have discussed the literature dealing with the sensibility and the sensory innervation of the lower urinary tract.

Many of the earlier workers were concerned with the localisation of the spinal roots controlling the bladder and the urethra. Valentin (1847) showed that stimulation of the peripheral ends of the cut lower lumbar and upper sacral spinal roots in rabbits, dogs and cats, caused contraction of the bladder. He believed that the initiation of micturition was brought about by the voluntary relaxation of the external urethral sphincter.

Budge (1864) reported unilateral contraction of the bladder on stimulation of the third and fourth sacral ventral roots and bilateral contraction on stimulation of the first, second and third sacral dorsal roots. These results on stimulation have been confirmed by many workers.

Other workers have been concerned with the localisation of the spinal centre for the bladder and urethra. Masius (1867) found that in animals with isolated lumbo-sacral cords, urethral resistance was greater than normal, but it fell markedly when the isolated segment of cord was destroyed. He located a centre for urethral tone in the sacral cord, just cranial to the ano-spinal centre. Similarly, Ott (1879) by sectioning the spinal cord, located a 'vesico-spinal' centre, between L6 and L7, which was actually a centre for urethral tonicity. Like the corresponding ano-spinal centre this is normally inhibited by impulses arising in the region of the upper part of the crura cerebri.

The relative importance of the smooth and striated muscle sphincters of the urethra was estimated by Courtade and Guyon (1895) in the dog. The external sphincter was the stronger and could support a pressure of 70 cm H_2O, whereas the bladder neck (internal sphincter) could only hold back 15 cm H_2O. Simons (1936) came to a similar conclusion about the relative strengths of the two muscles in man. Simons' sphincterometer, with which he investigated the physiology of the human urethral sphincters, consisted of a water filled balloon at the end of a catheter. He found that the internal sphincter could not be voluntarily contracted or relaxed, but when under normal tonus it supported a pressure of 12cm H_2O. The external sphincter was also less under voluntary control than is generally supposed but was more powerful and was able to support a pressure more than twice as great. Bors (1948) used another type of sphincterometer which differed from Simons' instrument, in using a stream of liquid instead of a balloon to assess sphincter tone. It gave similar results but the figures obtained for sphincter tone were consistently higher than those obtained using Simons' instrument.

Many workers have investigated the effect of the peripheral nerves on the tone of the urethral sphincters and upon the resistance which these muscles offer to the passage of fluid along the urethra. Gianuzzi & Nawrock (1863) working in Claude Bernard's laboratory, showed that the resistance of the urethral sphincter mechanism in the dog was reduced after section of the nerves supplying the urethra, presumably both pelvic and pudendal nerves, but that no great fall occurred in the resistance of the denervated urethra on the deqth of the animal. They found urethral resistance to be greater in the male animal than in the female and believed that it was related to the length of the urethra. Von Zeissl (1893) also estimated urethral resistance in terms of opening pressure. He found that parasympethetic stimulation caused urethral relaxation independently of bladder contraction and that sympathetic stimulation increased the resistance to flow. He supported the theory of crossed innervation which holds that the autonomic nerves have opposite effects on the detrusor and smooth muscle sphincter.

Stewart (1899 & 1900) on the other hand, claimed that stimulation of the peripheral end of the cut pelvic nerve did not cause dilation of the urethra and a similar result was obtained by Fagge (1902) who used a balloon lying in the urethra as his recording device, rather than measuring opening pressure for fluid, as the other workers did. Fagge was sceptical of the crossed innervation theory and thought it was an over-simplification of the true picture, a view which is widely held today. Elliot (1907) in a series of carefully designed and controlled experiments re-examined these questions and found that sympathetic nerve stimulation produced contraction of the smooth muscle of the proximal urethra in the male cat, as did intravenous adrenaline, while stimulation of the pelvic nerve led to a slight and transient relaxation.

In 1915 Barrington published the first of his notable series of papers on micturition in which he described some experiments upon the effect of the peripheral nerves on the tone of the urethral sphincters. Using female cats anaesthetised with ether he found that stimulation of the hypogastric nerves or the pudendal nerves, caused an increase in urethral resistance. In both cases the effect was transient and flow recommenced while the stimulation was still being applied. In acute experiments he investigated the tonic effects of these nerves by cutting them while fluid was flowing through the urethra, noting any change in the rate of flow. Hypogastric nerve section led to a transient increase in flow, pelvic nerve section to a permanent decrease in flow, pudendal nerve section to a permanent increase in flow, while thoracic spinal transection had no permanent effect on the flow. In chronic experiments he assessed urethral tone by the resistance felt to the manual expression of urine by pressure applied through the abdominal wall. Pudendal nerve section caused, in this case, a marked fall in resistance, while section of the sympathetic and pelvic nerves produced little change. Spinal transection craniad to the lumbar cord increased the resistance for several days, while the section of the sacral dorsal roots increased it permanently. Division of both pudendal nerves in surviving animals invariably produced some incontinence.

Langworthy and his colleagues (1933-1940), in a series of experiments on cats using anaesthetised and decerabrate animals, estimated urethral resistance in terms of the intra-vesical pressure required to force fluid along the urethra. Measurement was made by means of a needle inserted into the bladder through the anterior abdominal wall. Male cats had a higher urethral resistance than females and in both sexes resistance fell on active vesical contraction or parasympathetic stimulation. Stimulation of the peripheral end of the cut pudendal nerve led to a series ofrhythmic contractions of the external sphincter end of the perineal muscles, which led to the expulsion of any fluid in the urethra and raised the urethral resistance, In contrast to the result of Barrington, they found that section of the pudendal nerves in surviving animals never produced incontinence of urine and subsequent estimation of the urethral resistance over a period of weeks showed that it had not altered. Stimulation of the parasympathetic nerve supply in the sacral roots increased urethral resistance in the male cat only and this they attributed to tumescence of the penis. Sympathetic stimulation increased the resistance, especially in males and this increased resistance was localised to the region of the verumontanum at the junction of the prostatic and membranous parts of the urethra. Section of the sacral dorsal roots led to an increase in the resistance to flow along the urethra and this they attributed to oedema of the urethral mucosa.

The most recent investigation of this aspect of the subject, is that of Girado & Campbell (1959) who, working with anaesthetised and decerebrate cats in which the external urethral sphincter and all other striated muscles were paralysed by a muscle relaxant, described the response of the urethral smooth muscle to nerve stimulation and to drugs. They concluded that the tone of the smooth muscle of the urethra is non-neurogenic because it was not affected by nerve section, but was reduced by autonomic blocking agents.

In addition to the many investigations on the effects of the sympathetic and parasympathetic nerves on the urethra in animals , there have also been a few observations on this subject in man. Learmonth (1930) in his review of the effects of stimulating the autonomic outflows on the urinary tract in man, stated that stimulation of the sympathetic pathways contracted the bladder neck. Bucy, Huggins & Buchanan (1937) on the other hand, repoeted contraction of the human urethra in the region of the external sphincter, when the sympathetic nerve supply was stimulated but they were unable to tell whether smooth or striated muscle was responsible.

Although the pudendal nerve is motor to the external sphincter and is sensory to the urethra, several workers have produced evidence that its integrity is not essential for micturition. In his first paper (1915), Barrington reported that when both pudendal nerves had been cut in cats, they remained continent at rest, but when jumping or otherwise straining, urine escaped in spurts. Langworthy, Kolb & Lewis (1940) stated, on the other hand, that section of the pudendal nerves in cats did not produce even stress incontinence. Dennig (1926) found that micturition in various animals was unaffected by section of both sympathetic and pudendal nerves. In the clinical field Wertheimer & Michon (1928) cut the pudendal nerves in women for painful conditions of the vulva and reported no incontinence or other urinary disturbance. This finding has since been confirmed by many workers.

A related observation is that of Lapides, Sweet & Lewis, (1955) who found that patients, totally paralysed by the injection of muscle relaxants, had no incontinence and were able to pass urine normally, although the cessation of the act was delayed. Simple pudendal block produced similar results. Elliott (1954) as a result of studies on incontinent and post-prostatectomy patients, concluded that the external sphincter always acted as an auxiliary to the internal sphincter and had no tonic action.

Many workers have studied micturition from the point of view of its reflex basis. Goltz (1874) gave a detailed description of micturition in chronic spinal dogs. This involved the passage of large volumes of urine at a time and hence was a co-ordinated act and not simply an overflow from a full bladder. The process could be initiated by stimulation of the perineum or the anterior abdominal wall and hence was presumably reflex in nature. He also described a rhythmic fluctuation in the urinary stream of these animals which was similar to the rhythm which he had described in the anal sphincters of spinal animals and this also could be inhibited by nocuous stimulation.

A later paper by the same author (Goltz & Ewald, 1896), is more difficult to fit into the general picture. These workers excised the spinal cord below the thoracic level in dogs and found that after a period of retention with overflow, a stage of spontaneous periodic micturition resulted, which, they believed, was similar to that developing after simple spinal transection above the lumbar region. It is not certain from the details given, however, that bladder contraction was actually taking place in these animals, and it is difficult to imagine that any contraction was possible.

The earliest experimental study of micturition in man is that of Mosso & Pellacani (1882) and this paper is outstanding amongst the others of that period. These workers produced graphic cystometric records in human subjects as well as animals, with simultaneous recording from the bladder, abdominal wall and chest. They demonstrated that the bladder could hold widely differing volumes at approximately constant pressure and they showed that reflex bladder contraction could result from emotional stimuli. They also showed that in dogs ; micturition was unaffected by section of the sympathetic nerve supply to the bladder and urethra but stimulation of these same sympathetic nerve trunks caused the bladder to contract.

Another full and careful investigation of this period is contained in the papers of Griffiths (1890 and 1894, a & b) whose observations covered the anatomy of the parts concerned and some study of the fibre constitution of the relevant nerve trunks, as well as experimental physiological observations. Griffiths stated that stimulation of the peripheral end of the cut pudendal nerve caused the striated muscles of the perineum and urethra to contract in an orderly sequence from proximal to distal and so to expel urine from the urethra. Stimulation of the central end of the cut pudendal nerve led to a slight bladder contraction if the organ contained only a small volume of urine, but if a large volume was contained, it led to a contraction followed by a prolonged period of relaxation. He found, that neither section of the hypogastric nerves, nor section of the pudendal nerves affected urethral resistance. After the death of the animal the resistance fell to a low value. Griffiths emphasised the importance of physical factors, such as surface tension, in the maintenance of urinary continence.

Guyon (1900) described in detail the reflex response of the bladder to distension in curarised dogs and showed that the reflex was abolished by pelvic nerve section but was not affected by section of the sympathetic nerves. This reflex came to be known as Guyon's reflex and later it became Barrington's first micturition reflex. Shattock (1908) found that the application of cocaine to the bladder mucosa caused a temporary urinary retention due to the abolition of this reflex response of the bladder wall to stretch.

In 1921, Barrington subdivided the process of micturition into five reflexes. He added a sixth in 1931 and a seventh in 1941. These reflexes are here presented in tabular form, (Table 3), because of their relevance to the subject matter of this thesis. His conception was based on studies of the pressure and volume of fluid in the bladder and of the resistance to flow along the urethra. It can be seen from Table 3, that two of these reflexes the fourth and the fifth, have as their effector organ the external urethral sphincter and that neither of these reflexes passes cranial to the lumbar region of the spinal cord. Those reflexes which have the detrusor muscle as

TABLE 3.

MICTURITION REFLEXES IN THE CAT ACCORDING TO BARRINGTON :

THE TERMINOLOGY IS THAT OF BARRINGTON.

REFLEX	THE STIMULUS	INGOING PATH	"CENTRE"	OUTGOING PATH	RESPONSE OF THE EFFECTOR
1	Distension of the bladder	Pelvic nerves	Hind-brain	Pelvic nerves	Contraction of the bladder
2	Running water through the urethra	Pudendal nerves	Hind-brain	Pelvic nerves	Contraction of the bladder
3	Distension of the proximal urethra	Hypogastric nerves	Lumbar cord	Hypogastric nerves	Slight transitory contraction of the bladder
4	Running water through the urethra	Pudendal nerves	Sacral cord	Pudendal nerves	Relaxation of the urethra
5	Distension of the bladder	Pelvic nerves	Sacral cord	Pudendal nerves	Relaxation of the urethra
6	Distension of the bladder	Pelvic nerves	Sacral cord	Pelvic nerves	Relaxation of the plain muscle of the urethra in its proximal third
7	Running water through the urethra	Pelvic nerves	Sacral cord	Pelvic nerves	Contraction of the bladder

their effector, the first and second, have a reflex centre in the hind brain at the level of the upper part of the pons. Barrington's papers form the basis of our present day concept of the reflex basis of micturition and they represent the most important single contribution to our knowledge of the physiology of the urinary tract.

Denny Brown & Robertson (1933) studied the process of micturition in three normal men. They recorded simultaneously the behaviour of the detrusor and the sphincters. By placing catheters at different levels in the urethra they found that they could dissociate the response of the two sphincter muscles. They also recorded the behaviour of the perineum and of the anterior abdominal wall and the pressure within the rectum. They found that when the subject attempted voluntary micturition, the first detectable event was a bulging of the perineum. Detrusor contraction preceded the opening of the internal sphincter and this in turn preceded the opening of the external sphincter. At the end of micturition, or when an attempt was made to arrest micturition while it was in progress, the external sphincter contracted sharply and the internal sphincter gradually contracted some time later. They also found that the external sphincter was capable of voluntary closing but could not be opened voluntarily. The introduction of fluid into the posterior urethra produced no sensation and was quite ineffective as a stimulus to bladder contraction. As a result of this observation they were doubtful of the presence of Barrington's second and fourth micturition reflexes in man. In spinal man stimulation of the sole of the foot led to a powerful contraction of the external sphincter which immediately stopped the stream and was followed by relaxation of the vesical detrusor. This paper is the basis of many of the current textbook accounts of the process of micturition in man.

Langworthy, Drew & Vest (1940) studied the effect of varying the intra-urethral pressure on the urethral resistance in decerebrate cats. When the intra-urethral pressure was raised gradually, there was at first no flow, and later when flow started it was at first spurting in character and was associated with spasmodic contraction of the external urethral sphincter and the perineal muscles. At still higher pressures there was a continuous flow. When the pressure was gradually reduced, the spurting flow recurred, but both the irregular flow and the closure of the urethra occurred at lower pressures than when the pressure was being raised. A somewhat similar phenomenon was reported in male dogs by Huggins, Haymond & McCarrol (1934) who found that distension of the membraneous urethra in these animals produced a rhythmic contraction of the external urethral sphincter and perineal striped muscles which they called urethral clonus. They considered this to be the normal mechanism of ejaculation.

Nathan (1952) studied some of the micturition reflexes in men. He measured bladder pressure while moving a cystoscope within the urethra, while dilating the urethra with the bag of a Foley catheter, and while irrigating the urethra with saline. In no instance did the subject experience a desire to micturate or was a reflex rise in bladder pressure recorded. He concluded, that there was no evidence for the existence in man of Barrington's second and fourth reflexes (bladder contraction and sphincter relaxation in response to movement within or perfusion of the urethra). Previously, Nathan & Smith (1951) had reported that in a percentage of men a desire to micturate was produced when the tip of a catheter was traversing the membranous urethra, but in no case was this accompanied by any response from the vesical wall.

As was stated in part 2, electrical recording methods offer certain advantages over mechanical recording methods in the study of the external urethral sphincter and especially of its reflex behaviour. A number of workers have used such methods to investigate the reflex basis of micturition.

The earliest investigation of the urinary tract by means of electrical recording, was made by Evans (1936), who recorded efferent activity in the nerves supplying the bladder and the urethra in cats. Twigs of the pelvic nerve passing to the bladder fundus and the proximal urethra, showed a similar pattern of discharge -- a constant outflow of impulses when the bladder was in a state of moderate contraction and this outflow disappeared if the pressure in the bladder was suddenly reduced. He was forced to conclude that this discharge was motor to the bladder wall and inhibitor to the region of the internal sphincter. The external sphincter was kept in a state of tonic contraction by a stream of impulses passing out in the pudendal nerves and these impulses disappeared completely when bladder pressure reached a critical level. Evans recorded the total activity in the nerves and did not attempt to obtain records from the individual nerve fibres nor to record sensory discharges, nevertheless his paper must be regarded as being outstanding considering the simple equipment which he used.

Newman (1949) recorded electrically from the external urethral sphincter in women and concluded that the muscle was not in a state of tonic contraction when the subject was at rest. Voluntary increase in intra-abdominal pressure, coughing, or voluntary attempts to contract the sphincter, produced activity in the external urethral sphincter, but the application of pressure to the abdominal wall by the observer did not do so. Attempts to void urine were preceded by spasmodic contractions of the muscle. The details given of the recording technique used in this investigation are incomplete and the records included, are not convincing. It is difficult to decide how much reliance can be put on its results, especially since they disagree with those of most of the other workers.

Frankson & Petersen (1953), under direct endoscopic observation, inserted needle electrodes into the bladder wall and internal sphincter of normal human subjects. They recorded irregular bursts of activity superimposed on a continuous low voltage fluctuation from the bladder wall when they filled the bladder with fluid. Before micturition there was no electrical activity in the bladder wall but irregular bursts of activity were recorded from the internal sphincter. When micturition began, electrical activity disappeared from the internal sphincter and appeared in the bladder wall. The same authors (1955), recorded electrically from the striated muscle of the human male urethra. They found a continuous resting tone which was increased on coughing or voluntary contraction.

The mechanism whereby voluntary control is exercised over micturition has been the subject of theories by many authors, but the true picture is still not clear. Goltz (1874) proposed a scheme which was subsequently accepted by other authors and which appeared in the textbooks for many years. According to this theory, distension of the bladder increased the amplitude of rhythmic contractions of the bladder, until at the height of one of these contractions, urine was forced into the posterior urethra where it irritated the mucuous membrane and led to a sensation "the Harndrang", which produced a desire to micturate. This sensation was either consciously repressed and the external sphincter voluntarily contracted to maintain continence, or the abdominal muscles contracted to reinforce the vesical contraction and assist in evacuating the bladder contents. This scheme is comparable to the scheme for the maintenance of faecal continence which was proposed by Gaston (1948) and by Goligher & Hughes (1951).

At least one argument against it is the fact that Denny Brown & Robertson (1933) and Nathan (1951) both reported that the introduction of fluid into the posterior urethra did not give rise to a desire to micturate nor indeed to any sensation.

Several alternative schemes have since been suggested. Haller (1878), for example, considered that micturition was initiated by the diaphragm which contracts as part of the inspiration which precedes the voiding of urine. Le Gros Clarke (1883) believed that voluntary relaxation of the external sphincter was responsible for the initiation of micturition. Neither of these authors produced any experimental evidence for their suggestions. Rehfisch (1897) believed the internal sphincter in the human to be under voluntary control since when a catheter was passed up the urethra to lie within the external sphincter muscle and hold it open, urine did not escape until the subject tried to urinate. This finding has since been confirmed by several authors but it does not necessarily mean that the internal sphincter can be relaxed voluntarily. Fearnsides (1927) in his review suggests a scheme of events taking place in normal micturition which invokes the external sphincter only to stop the stream. Learmonth (1930), claimed that there was voluntary control over the internal urethral sphincter and that this was important in voluntary micturition. Müller (1931), on the other hand, stated that willed micturition could only be started by voluntary relaxation of the external sphincter and that this event started the autonomic reflexes which carried the process through to completion. The question is still not settled, but the most widely accepted view is probably that of Denny Brown & Robertson, who found that the external urethral sphincter was capable of voluntary closing but could not be opened voluntarily, while the internal sphincter could neither be contracted nor relaxed by the action of the will.

B. DISSECTION AND ARRANGEMENT OF APPARATUS FOR RECORDING FROM THE EXTERNAL URETHRAL SPHINCTER

To expose the urethra,a mid-line ventral incision was made in the skin of the anterior abdominal wall, from a point just above the pubic crest, to a point overlying the lower border of the pubic arch. The underlying fat was removed and the gracilis and adductor longus muscles were separated in the mid-line, to expose the whole length of the pubic symphysis. The tendon of the rectus abdominis was then detached from the pubic crest and the cartilage of the pubic symphysis was incised, taking care not to damage the underlying structures. The pubic bones were drawn apart and the underlying fat, which was often considerable in amount, was removed using blunt pointed forceps. The anterior borders of the pubo-caudal muscle which arises from the posterior border of the pubic symphysis was detached and the whole length of the urethra, from the bladder neck distally, was then clearly visible together with the rectum and the pelvic plexuses. The wound cavity was filled with warm liquid paraffin and the muscle recording electrodes were sprung into place on the surface of the external sphincter muscle.

When the reflexes from the bladder to the urethra were being studied, a small opening was made in the wall of the proximal urethra between the bladder neck and the external sphincter. The twin-bore cannula was passed into the bladder and tied in, so that no fluid could pass from the bladder to the urethra. One limb of the cannula was connected to the fluid reservoir which was mounted on an adjustable stand and could be raised or lowered between 0 and 40 cm above the level of the bladder. A pulley system operating a potentiometer was used to record the height of the reservoir. The volume recorder was connected to the air-inlet of the reservoir and so gave a record of the changes in bladder volume. The second channel of the cannula was connected by tubing of minimum volume displacement to the transducer manometer, which thus recorded intra-vesical pressure. A pressure standard of 40 cm H_2O was used to calibrate the records.

All four traces, bladder volume change, bladder pressure, height of reservoir and electrical activity of the external sphincter, were displayed simultaneously, together with a time trace, on the Ediswan pen recorder. The arrangement of apparatus used for studying the reflexes from the bladder to the external urethral sphincter is shown in figs. 39 & 40.

When the reflexes from the urethra were being studied, a single bore cannula was tied into the proximal urethra and directed distally, although the tip was not allowed to extend as far as the external sphincter. A twin-bore cannula was passed into the bladder as before so that bladder volume could be controlled and bladder pressure recorded if desired. The single-bore cannula was connected through a three-way tap to a second fluid reservoir and the height of this reservoir could be set at any level between 0 and 60 cm above the level of the urethra. Pressure in the urethra could be raised gradually by raising the reservoir with the tap open, or suddenly by first raising the reservoir and then opening the tap. When the tap was opened, fluid flowed distally along the urethra and escaped from the external meatus. In these experiments the volume recorder was used either to record changes in bladder volume or to record flow along the urethra.

C. EXPERIMENTAL RESULTS

1. The Sphincter Mechanisms of the Urethra

In the present investigation the reflex behaviour of the internal sphincter mechanism was not studied, but some information was obtained about the capacity of this muscle to close the urethra. The behaviour of the urethral sphincter muscles was studied in terms of the resistance offered to the flow of fluid along the urethra. Two measurements of this resistance can be made : first, the opening pressure which was measured as the height to which the reservoir was required to be raised before flow along the urethra started and second, the pressure needed to maintain flow after it had started. This latter pressure was found to be lower than the opening pressure in the cat with intact urethral innervation, in the cat with pudendal nerves cut, in the cat after spinal anaesthesia and in the recently dead cat. The term resistance is used to mean the opening pressure.

In cats in which both pudendal nerves had been cut and in which the tone of the internal sphincter presumably remained intact, the opening pressure was about 30 cm H_2O for male cats. The opening pressure of the female urethra tended to be about 10 cm H_2O lower than that of the male urethra. This difference was presumably related to the shorter length of the urethra in the female. In neither sex did a significant change in resistance follow spinal anaesthesia, produced by intrathecal injection of 1 ml of a 1% procaine solution, at the sacral level. On the death of the animal, the resistance fell after the initial perfusion to 5 cm H_2O or less, being slightly higher in the male than in the female, though it was difficult to obtain a definite level since changes in the physical state of the urethral wall continued for some time after the death of the animal.

Section of the hypogastric nerves in cats in which the pudendal nerves had previously been cut, did not alter the opening pressure. Stimulation of the peripheral end of the cut hypogastric nerve, while fluid was flowing along the urethra from a reservoir above the bladder, stopped the flow (fig. 41 D) and the optimum frequency of stimulation for producing this effect was 50/ second. The increase in resistance produced in this way was less than that produced by stimulation of the pudendal nerves and the effect developed more slowly and disappeared more slowly when stimulation ceased. In addition, the effect was more easily fatigued and ceased in one to two minutes even though stimulation was maintained. This effect of hypogastric nerve stimulation upon urethral resistance was significant only in male animals.

Measurements of urethral resistance in animals with intact pudendal innervation were complicated by the powerful reflexes which developed (fig. 47) as the intra-urethral pressure was raised. The results were thus unsatisfactory. Investigations of the strength and nature of the external sphincter mechanism by stimulation of the pudendal nerves, proved more useful. Stimulation of the peripheral end of one pudendal nerve, at frequencies of 20/ second or above, in animals in which both pudendal nerves had been cut, led to a marked increase in urethral resistance. If this procedure was carried out while fluid was flowing, the flow immediately stopped (fig. 41 B).

This effect was strong in both sexes and particularly so in the male where pressures up to 200 cm H_2O were resisted, pressures well above those normally developed in the cat bladder. There appeared to be no significant difference between the strengths of the responses obtained when both nerves were stimulated and when only one nerve was stimulated. Stimulation at low frequencies, 1 to 10/ second, led to rhythmic contractions of the external sphincter. These were associated with powerful ejection of spurts of fluid from the external meatus, the sphincter acting as a urethral emptying mechanism, but stimulation at these frequencies did not affect the total volume flowing along the urethra from a reservoir, in a given period of time. If the stimulation frequency was gradually and progressively increased while fluid was flowing along the urethra from a reservoir, the rate of flow was not significantly affected until the frequency reached that necessary for tetanic contraction of the external sphincter, normally 15 to 20/ second. When this frequency was reached the flow stopped immediately (fig. 41 C).

It should be emphasised that the condition of synchronous maximal contraction of all the motor units in the muscle which is produced in this way, will be very different from the normally occuring condition of asynchronous partial tetanus. This condition is seen in the electromyographic records obtained from decerebrate cats with intact pudendal innervation where the maximum resistance offered by the external sphincter, reflexly elicited, rarely exceeds 30 cm H_2O (fig. 47). On the other hand there is evidence that the sphincter acts as a tap also under these conditions. When the activity of the sphincter is reflexly inhibited, there is a marked drop in urethral resistance and if a perfusing pressure is being applied to the urethra at this time, flow along the urethra starts with characteristic suddenness (fig. 52). At the same time it can be seen from this same figure, that when the inhibitory state is passing off and activity is returning to the external sphincter, it does so in the form of rhythmic bursts and the sphincter in addition to stopping flow acts as an emptying mechanism in a manner similar to its behaviour during stimulation of the pudendal nerves at subtetanic frequencies.

2. Tone in the External Urethral Sphincter

When the external urethral sphincter is exposed with a minimum of operative trauma, the urethral wall still being intact and no foreign body lying in the urethra, a continuous tonic discharge of low frequency and small amplitude can be recorded from electrodes placed on the surface of the muscle. As in the case of the external anal sphincter, a discharge from single units could be recorded with suitable placing of the electrodes (fig. 42 A), but in general a discharge showing the activity of several motor units was more suitable. Changes in activity were judged by changes in the overall amplitude of the discharge and to some extent also by changes in the frequency of the combined discharge of several motor units.

As in the case of the external anal sphincter, the level of the discharge did not change with time in the course of an acute experiment. The discharge was abolished by moderately deep general anaesthesia and by spinal anaesthesia at the sacral level, but it persisted after section of the pelvic nerves. It was still present and usually increased after section of the spinal cord (fig. 46) or after destruction of the lumbar sympathetic outflow. Here again a potentially painful cutaneous stimulus, especially if applied to the perineal region, caused a brief burst of activity, while pressure applied over the lower anterior abdominal wall caused a sustained increase in discharge. Mechanical stimulation of the urethral wall or the peri-urethral tissue from the exterior with a probe, caused a brief burst of activity, though the most potent augmentative stimulus was one applied to the interior of the urethra. This is more fully dealt with later.

3. Reflexes from the Bladder to the External Urethral Sphincter

The resting discharge from the external urethral sphincter is of low frequency when the bladder is empty but as the bladder begins to fill there is an increase in the frequency of the discharge. This increase is best seen in fig. 44 but can be seen also in fig.43. The increase produced in this way is never vary marked and never large enough to cause a visible contraction of the muscle. On the other hand, it was observed in the majority of cases and would seem to be a real response, presumably reflex and probably analogous to the initial increase in anal sphincter discharge seen on rectal distension (fig. 32).

Intra-vesical pressure does not rise in a linear fashion with increasing bladder volume. It shows an initial rise in the early stages of filling and remains more or less constant for a period thereafter (fig. 43). When a certain degree of filling is reached two marked responses take place, both take several seconds to develop fully : I. sphincter activity decreases and then ceases entirely (Barrington's fifth reflex) and 2: Bladder pressure rises sharply and exceeds the filling pressure leading, with the system used here, to the return of fluid to the reservoir (Barrington's first reflex).

In most cases the response of the external sphincter and the response of the bladder appear to start at about the same time (fig. 44) and in some cases the sphincter response follows that of the bladder, but often, as in fig. 43, the reduction in sphincter activity clearly precedes the rise in bladder pressure, in this case by over 20 seconds and complete inhibition of the sphincter discharge develops while the volume of the bladder is increasing, but during a period when the intra-vesical pressure remains constant.

When the outflow from the partially filled bladder to the reservoir is closed, so that change in volume of the bladder is not permitted, then the detrusor muscle often exhibits a series of spontaneous isometric contractions, first described by Mellanby & Pratt (1940). The isometric contractions are also accompanied by reduced sphincter activity (fig.45), and in this case the reduction develops during a period of constant bladder volume and rising intra-vesical pressure.

If the spinal cord is transected by extradural ligation at the lower thoracic level, the tonic discharge returns to the external sphincter as soon as the effect of the ether administered during the ligation has passed off and is in most cases of a greater amplitude then before spinalisation. Reflex contraction of the bladder in response to filling is however abolished at least for the duration of an acute experiment ; indeed Barrington (1921) found that this reflex was still absent thirty five days after section of the cord. Nevertheless, filling of the bladder, after isolation of the lumbo-sacral cord, is still accompanied by reduction of sphincter activity in the complete absence of bladder contraction, although this reduction is less marked than in cases where bladder contraction takes place, possibly because of the lower intra-vesical pressures developed.

4. Reflexes from the Urethra to the External Urethral Sphincter

If an attempt is made to force fluid distally along the urethra, by gradually raising the level of a reservoir connected to a cannula lying in the proximal urethra, when the bladder is empty or contains only a small volume of fluid, a progressive increase in the activity of the sphincter is produced (fig.47) and the sphincter 'guards' against the escape of fluid. For convenience in the subsequent discussion this response is referred to as the Urethral 'guarding reflex'. Actual flow along the urethra is not essential for this response since an appreciable increase in electrical discharge takes place before flow has started (fig. 47) and a considerable increase in discharge can be produced by sudden distension of the urethra after it has been tied off distally (fig. 50). A similar augmentive reflex can be produced by mechanical stimulation of the interior of the urethra with a solid foreign body. Thus, the movement of a metal cannula or a smooth piece of polythene tubing to and fro within the urethra (fig. 48A) is accompanied by an increase in sphincter discharge. So also is the inflation of a small condom rubber balloon lying in the urethra beneath the external sphincter (fig. 48B). In a few experiments the urethra was slit up its ventral surface and so converted into a narrow strip of tissue covered with mucous membrane. In these cases light mechanical stimulation of the exposed mucosal surface with a fine probe was an effective stimulus to increased discharge. It was not possible to decide whether stretch of the urethral wall or mechanical stimulation of the mucosal surface is the more effective stimulus in the production of these reflexes - it would seem that both types of stimulation are effective.

Pressures in excess of 50 cm H_2O can force fluid along the urethra past the powerfully contracted external sphincter (fig. 47) and in such an experiment, if the pressure is now gradually reduced, fluid continues to pass along the urethra at pressures which are significantly less than that needed to start the flow. This behaviour is not, however, associated with any true inhibition of the discharge to the external sphincter, the muscle is still very active. The gradual diminution in the activity of the sphincter which uccurs after flow has started coincides with a progressive reduction in the perfusion pressure, due to lowering of the fluid reservoir during this period. The reduction in the activity of the sphincter is due to a reduction in the sensory drive rather than to an inhibitory reflex in response to flow.

On the other hand, flow along the urethra or distension of the urethra, does not augment the activity of the sphincter if the tone of the muscle has been abolished as a reflex response to distension of the bladder (fig.50). If the urethra be distended at intervals during filling and subsequent emptying of the bladder, the augmentive response of the external sphincter to the distension of the urethra disappears when the bladder is comparatively full and reappears again as the bladder empties. It follows from this that when Barrington's fifth reflex is in action (dilation of the urethra in response to distension of the bladder) the passage of fluid along the urethra can no longer cause contraction of the external sphincters.

If the bladder is no longer empty but contains a sufficient volume of fluid to allow it to contract and to develop pressure, then running fluid along the urethra evokes a sustained contraction of the bladder (fig.51) (Barrington's second and seventh reflexes). The actual volume of fluid in the bladder necessary to allow these reflexes to occur, varies quite widely from cat to cat and seems to depend chiefly on the level at which the brain stem is transected. In some cats, the necessary volume of fluid in the bladder approaches that at which reflex contraction of the bladder takes place without further stimulation, but in many cats a small volume of fluid is adequate, 5 to 10 ml being enough.

This contraction of the bladder detrusor in response to the passage of fluid along the urethra develops more slowly than the guarding burst of activity in the sphincter. Under these circumstances there is at first an increase in sphincter activity which later disappears completely as the bladder contracts, to be replaced by a period of complete electrical silence in the muscle. As the bladder finally expels its contents intra-vesical pressure falls and activity returns to the sphincter, at first intermittently and later as a sustained contraction as the guarding reflex reasserts itself.

These features are well seen in fig.51, in which the bladder is gradually filling from the reservoir in the first (left) part of the record. When the urethra is distended on the first occasion there is insufficient fluid in the bladder to allow it to contract and the sphincter responds with a guarding burst of activity. By the time the second urethral distension takes place some 30 seconds later, the volume in the bladder has increased sufficiently to allow it to contract and the combined response of augmentation and of inhibition of the external sphincter is seen. As the bladder empties the sphincter discharge reappears, at first intermittently as bursts of activity alternating with periods of silence and later as a continuous discharge.

In fig.52, a similar experiment is seen. In this case neither bladder pressure nor volume is shown, but instead flow along the urethra and the intra-urethral pressure (actually the pressure recorded from a side tube close to the urethral cannula), are shown. The intra-urethral pressure rises steadily at first as the reservoir is raised, but there is no flow along the urethra since contraction of the external sphincter increases correspondingly. When the sphincter activity is inhibited as a result of contraction of the bladder, fluid suddenly starts to flow along the urethra, reaching its maximum rate of flow immediately and intra-urethral pressure falls suddenly as soon as the flow starts. Here again the first sphincter activity to reappear after inhibition is rhythmic in nature and these contractions lead to corresponding rises in intra-urethral pressure and to rhythmic expulsion of spurts of fluid from the external meatus. Spontaneous micturition in the intact cat terminates with a similar series of expulsive contractions.

If bladder contraction in response to flow along the urethra is prevented, or if the reflex effect of tension in the bladder wall is otherwise eliminated, the only response to flow along the urethra is increased activity of the external sphincter. Abolition of the effect of bladder wall tension can be achieved in several ways :- by spinalisation, by cutting the pelvic nerves, by removing the bladder, or simply by emptying the bladder completely. In any of these circumstances if a high perfusion pressure is applied suddenly to the urethra, the augmentation of the activity of the external sphincter is rhythmic and the fluid excapes from the external meatus, if it escapes at all, in spurts (fig.49).

Experiments were made on four cats, to determine if the effect on the bladder of contraction of the external sphincter produced by stimulation of the peripheral end of one of the pudendal nerves, was similar to the effect of flow along the urethra with reflex sphincter contraction. One pudendal nerve was cut and the peripheral end of the cut nerve was inserted into a fluid electrode, the other pudendal nerve remaining intact. Electrical stimulation of the peripheral end of the cut pudendal nerve, causing tetanic contraction of the external urethral sphincter, was accompanied by bladder contraction (fig. 53 A & B). The intra-vesical pressure developed in this way, was often greater than the intra-vesical pressure developed as a result of reflex bladder contraction in response to filling the bladder. It could be initiated as this reflex contraction in response to filling, was passing off (fig. 53 C & D). It could be shown that this was a reflex effect due to impulses passing inward by the intact pudendal nerve, since it was abolished if this nerve was cut.

5. Reflexes from the Rectum to the External Urethral Sphincter

Distension of the colon with a balloon inhibits activity in the external urethral sphincter as well as in the external anal sphincter (fig. 54). Bladder pressure may rise slightly during the distension since the balloon in the colon inevitably presses on the bladder, but the bladder wall does not contract, and the rise in pressure which results is not by itself enough to affect sphincter tone. Inhibition develops in both external sphincters simultaneously as though they were part of the same muscle.

D. Discussion

There are two sphincter mechanisms in the urethra ; one based on smooth muscle and one on striated muscle. For many years these have been referred to as the internal sphincter and the external sphincter respectively, because of the positions which they occupy relative to one another in man. Neither in man nor in the cat is a complete separation of the two types of muscle possible on the basis of their position. Bucy, Huggins & Buchanan (1937), reported a contraction in the position of the external sphincter in man on stimulation of the sympathetic nerve supply to the urethra, which was presumably due to smooth muscle activation. If the terms internal and external sphincter are to be retained, and they now seem to be well established in common use, they are probably best used to mean the smooth muscle and the striated muscle of the urethra irrespective of their position.

There is no internal sphincter in the cat, in the sense of a discrete or localised smooth muscle thickening such as is represented in diagrams ; all anatomical workers are agreed on this. Evans (1936) regarded the smooth muscle of the bladder neck as the functional internal sphincter since urine is normally held at this point. Barrington (1915), who assessed changes in the internal sphincter activity in terms of changes in urethral resistance after section of the pudendal nerves, used the term internal sphincter to refer to all the smooth muscle of the urethra.

Histologically, this extends from the bladder neck throughout the one and a half centimetres of the proximal urethra, as far distally as the prostate gland. It is in this sense that I shall use the term.

The external sphincter in the cat is a region of striated muscle fibres lying in the urethral wall, which extends from the prostate to the Cowper's glands and so cannot be the strict analogue of the human external sphincter which encircles the membranous urethra between the upper and lower layers of the fascia of the uro-genital diaphragm. The relationship between the external sphincter muscles in man and the cat was discussed more fully in section I. There is evidence that they perform similar functions in the two species.

Several investigators have attempted to assess the relative strength of the two sphincter mechanisms. Amongst them Courtade & Guyon (1895) in the cat and Simons (1936) in the human. Both found the external sphincter to be the stronger.

Attempts to estimate the strength of the external sphincter are complicated by the complex pattern of reflexes produced. In the present investigation the strength of the external sphincter was estimated during maximal contraction produced by stimulation of the pudendal nerve and during reflexly elicited contraction.

Stimulation of the pudendal nerve at tetanic frequencies shows that the external sphincter can act as an effective and powerful urethral closing mechanism, able to hold back pressures up to 200 cm H_2O. The statement of Langworthy, Drew & Vest (1940), that stimulation of the pudendal nerve produced no significant change in urethral resistance, can only be explained by assuming that subtetanic frequencies were used. The condition of synchronous maximal contraction of all the motor units in the muscle produced in this way, will differ markedly from the normal condition of asynchronous partial tetanus of the motor units and probably a contraction capable of producing such a resistance does not occur normally. When gradually increasing perfusion pressures are applied to the urethra, the external sphincter responds with the guarding reflex. The resistance produced by contraction of the muscle elicited reflexly rarely exceeds 80 cm H_2O and a figure of 50 cm H_2O is more usual for the female. These values are considerably above the normal range of bladder pressures except during bladder contraction. There is evidence also that the sphincter acts as a tap under conditions of normal reflex contraction, since, when normal sphincter tone is reflexly inhibited, a marked fall in urethral resistance develops and flow starts with characteristic suddenness.

The main functions of the external sphincter then is to act as a tap ; increased sphincter activity causing an increased urethral resistance, decreased activity causing a fall in resistance. Evidence was also found to show that the tap effect is not a fully graded one, but is in a sense an all or none effect, the activity being either just enough to prevent flow of urine or completely absent to allow maximum flow.

Stimulation of the pudendal nerve at subtetanic frequencies has little effect on the rate of flow of fluid along the urethra, but causes twitch-like contractions of the external sphincter and the other striated uro-genital muscles. The result is powerful expulsion of fluid from the external meatus in spurts. These spurts can propel the jet of fluid a distance of 20 to 30 cm. Although stimulation of the cut end of a pudendal nerve is by no means a physiological occurrence, the effect approximates quite closely to the situation which occurs when activity is returning to the external sphincter after a period of reflex inhibition. Under these circumstances the first activity which returns to the sphincter is a series of brief contractions involving also the other perineal musculature and causing emptying of the urethra. It was suggested by Langworthy, Drew & Vest, that this behaviour might represent the reflex basis of ejaculation, but it seems more likely that these contractions also serve to empty the urethra at the end of micturition, especially since they are seen in both sexes.

Although it is widely accepted that the external sphincter is the stronger of the two urethral closing mechanisms, there are many reports suggesting that it is not essential to continence under conditions of rest. Barrington's cats, in which he had divided both pudendal nerves, were continent at rest, but on jumping or otherwise straining, or if quite light pressure was applied to the anterior abdominal wall, the urine escaped in jets. Langworthy also cut the pudendal nerves in cats and reported no incontinence, but urine was more easily expressed manually. Wertheimer & Michon (1928) cut the pudendal nerves in women for painful conditions of the vulva and found only a slight stress incontinence. Lapides, Sweet & Lewis (1955) found that when all striated muscle was paralysed with relaxants, patients were able to start and stop micturition voluntarily, but cessation of the stream was delayed. They remained continent.

The concept arises then, of the external sphincter acting as a mechanism for rapid and powerful increase in urethral resistance to prevent excape of urine under conditions tending to produce stress incontinence and stopping the stream and emptying the urethra at the end of micturition. We shall later consider how the reflex behaviour of the muscle fits this picture.

In this investigation, the reflex behaviour of the internal sphincter was not analysed, since electromyography in this context seems to offer no advantage over the mechanical recording methods used by Barrington in his classical and meticulous researches and there seemed little to be gained from duplicating Barrington's original experiments. Frankson & Petersen (1953), did in fact succeed in recording electrical activity from the smooth muscle of the human bladder neck, but the activity recorded consisted of slow potential changes which had no obvious relation to the mechanical events taking place. Probably intra-cellular recording offers the only satisfactory way of studying smooth muscle activity electrically, but in contrast to striated muscle, the relation between electrical activity and mechanical behaviour is complex. Evans (1936) found that the electrical discharge recorded from fine filaments of the pelvic nerve passing to the detrusor and bladder neck showed identical patterns and he was forced to conclude that the impulses had a motor effect at one site and an inhibitory effect at the other.

The present finding that sacral spinal anaesthesia does not significantly alter the resistance offered by the smooth muscle and elastic tissue of the urethra, tends to support the contention of Girado & Campbell (1959) that the smooth muscle tone of the urethra is non-neurogenic in nature. The inhibition of this tone, reported by Barrington in response to distension of the bladder (the sixth reflex), must be due to active inhibition produced by the pelvic nerves. This constant 20 to 30 cm H_2O resistance, is above the normal range of intra-vesical pressure at rest in the absence of bladder contraction or overdistension and thus is adequate to explain the maintenance of continence in the absence of external sphincter activity. This tone may not be entirely due to smooth muscle since there is elastic tissue present in the urethra. Pennington & Lund (1960), described a dense ring of elastic tissue in the distal prostatic and membraneous urethra of man.

Stimulation of the peripheral end of the cut hypogastric nerves leads to a moderate and transient increase in urethral resistance in male cats. This result is in agreement with the findings of earlier workers from Von Zeissl onwards. No attempt wqs made to determine whether this effect was due to smooth muscle contraction as Elliot (1907) maintained, or to swelling of the mucosa in the region of the verumontanum as Langworthy claimed. The fact that the effect is transient and is not significant in female animals seems to support Langworthy. On the other hand, Learmonth (1930) and Bucy, Higgins & Buchanan (1937) reported visible contraction in the bladder neck and in the external sphincter regions respectively on stimulation of the pre-sacral nerve in humans at operation. Whichever mechanism is involved, it seems unlikely, in the cat at least, that this represents an important sphincter mechanism.

The present experiments indicate that the external urethral sphincter in the cat is in a state of tonic activity with the animal at rest, which seems to be similar in most respects to the tonic activity of the external anal sphincter. The question of the tone being an artefact produced by decerebration may be again raised, but a similar discharge was recorded from within the human urethra by Frankson & Petersen (1955). As in the case of the anal sphincter the source of the afferent stimulation for the tone, assuming it to be reflex in nature, is not clear. The fact that the tone is of low grade when the bladder is empty and increases during the early stages of filling suggests that some at least of the afferent stimulation passes in by way of the pelvic nerves from the bladder and the bladder neck, but the fact that the tone is little affected by section of the pelvic nerves indicates that this is not the only source. Reflexes from the urethra passing in by the pudendal nerves, are the most effective means of augmenting the discharge. Presumably some of the stimulation to maintain the tonic discharge passes inward by this route also.

The increase in tone produced by bladder filling is never very great. It does not lead to visible contraction of the sphincter. On the other hand, it will be effective in reinforcing the internal sphincter in its function of maintaining continence at rest, because intra-vesical pressure remains low. Evans & McPherson (1959) found that the early stages of bladder filling enhanced limb tone and limb reflexes. The increased discharge recorded from the external sphincter may thus be only a special example of a generalised raising of the striated muscle tone of the body.

The experiments shown in figs. 43 & 44, illustrate directly the inhibition of the external sphincter which accompanies distension of the bladder. Barrington had inferred the existence of this inhibition from indirect observations such as changes in urethral resistance or changes in the rate of flow of fluid in the urethra. In addition, the more accurate timing of events which electromyography allows, makes it possible to correlate the behaviour of the sphincter with that of the bladder and gives some information about the nature of the receptors in the bladder wall which are responsible for this reflex. Barrington believed that bladder volume was the critical factor in determining the onset of the micturition reflexes. Other workers, however, have suggested that bladder pressure was more closely related. The present experiments show that the bladder wall receptors responsible for sphincter inhibition are stimulated when volume changes without change in pressure. They are also stimulated when pressure rises during a phase of constant volume. They respond during active bladder contraction and, in the acute spinal cat, during passive distension of the bladder in the absence of contraction. It can be seen from this, that neither bladder volume nor bladder pressure alone, can be the critical factor in the stimulation of these receptors. Tension receptors in series with the contractile elements in the bladder wall would respond under all these conditions and the presence of receptors of this sort has been demonstrated by Iggo (1956) by direct recording from filaments of the pelvic nerves. Receptors in every way similar to these are known to exist in the upper levels of the alimentary canal. Nathen (1951) observed that the desire to micturate was evoked in man when the bladder wall was stretched and also when the bladder contracted. It is unlikely that two separate sets of stretch receptors exist in the bladder wall, so presumably the same receptors are responsible for reflex bladder contraction in response to bladder filling as are responsible for sphincter inhibition.

The main point at issue between the present findings and those of Barrington, concerns the response of the external urethral sphincter to the passage of fluid along the urethra - the fourth micturition reflex (Table 3). Barrington believed that independently of any other factor, the flow of urine along the distal urethra reflexly brought about relaxation of the external sphincter, both pathways being in the pudendal nerves. The present results, on the other hand, indicate that stimulation of the urethral receptors, whether by distension with fluid, by inflation of a balloon, by movement of a foreigh body or by the flow of fluid, always leads to an increase in the discharge from the external sphincter. On no occasion was an inhibition of the external sphincter seen, apart from that due to stimulation of the tension receptors in the bladder wall. In other words, passage of fluid into the urethra has first to cause contraction of the bladder, the second micturition reflex, then the increased tension in the bladder wall brings about inhibition of the sphincter by the fifth reflex. The present results confirm the existence of the second and fifth reflexes in the cat but on no occasion was the fourth reflex, as described, seen. The apparent effect of the fourth was found to be due to a combination of the other two. If this is the case, it is difficult to understand why Barrington thought that the fourth reflex persisted after section of the spinal cord or after section of the pelvic nerves, since either of these procedures will eliminate the bladder response. In his original paper on this topic, Barrington (1921) did indeed state that section of the spinal cord or pelvic nerves modified the response in exactly the same way, the flow through the urethra becoming a series of rhythmic spurts instead of a steady stream, but it could still be maintained at pressures less than that needed to start the flow. This rhythmic sphincter contraction in response to flow, after pelvic nerve section, was seen in the present investigation also and it was mentioned by Langworthy, Drew & Vest (1940). A comparison of the electromyographic picture of fig. 49 with that of fig. 51 shows that the response is certainly not inhibitory. The effect of bladder wall tension can be eliminated in several ways ; by cutting the pelvic nerves, by emptying the bladder completely, by sectioning the spinal cord or by removing the bladder. In all these cases the only response to stimulation of the urethra was increased sphincter activity.

The main evidence on which Barrington based his belief in the existence of an independent fourth reflex, with both pathways in the pudendal nerves, was the observation that when a gradually increasing pressure of fluid was applied to the distal urethra, a greater pressure was required to start the flow than to maintain the flow once it had been started. The present results show that this effect can be due to more than one cause and that it does not neccessarily indicate that inhibition has taken place. Such behaviour has been shown to exist both in conditions of high sustained external sphincter activity, in the absence of external sphincter activity after spinal anaesthesia, and even in the recently dead cat. The fact that external sphincter activity does in fact diminish somewhat in the first of these conditions, may be taken as a consequence of the reduced sensory drive corresponding to the reduction in the perfusing or distending pressure which is taking place at this time.

Several earlier workers have been doubtful of the existence of the fourth reflex and some have described external sphincter contraction in response to flow through the urethra, but the urethral guarding reflex as such has not previously been described nor its significance appreciated. Langworthy, Drew & Vest (1940), for example, noticed that as they perfused the urethra of decerebrate cats and the pressure in the urethra rose, the perineal muscles contracted spasmodically and the fluid escaped in spurts. They also found that sudden increases of pressure in the urethra evoked spasm of the perineal muscles although such responses could not be elicited when the bladder was full. Denny Brown & Robertson (1933), stated categorically that the presence of fluid in the posterior urethra in spinal man could not cause relaxation of the external sphinctdr. Evans (1936) reported that attempts to force fluid distally along the urethra caused an increased resistance. Nathan (1952) came to the conclusion that there was no evidence for the existence of either the fourth or even of the second micturition reflex in man.

As was stated in the section dealing with experimental results, the second and seventh reflexes in the cat -- contraction of the bladder in response to perfusion of the urethra -- can only be elicited when there is adequate fluid in the bladder. Under normal circumstances, in the intact animal, these reflexes would not be expected to initiate contraction of the bladder but only to maintain and reinforce q contraction already present. Denny Brown & Robertson (1933) and Nathan (1952) could find no evidence for their existence in man. The present results in the cat, however, agree with those of Barrington and similar effects have been demonstrated by Langworthy, Kolb & Lewis (1940). The cat would thus seem to have reflexes which are not present in man.

When the external sphincter is already in a state of relaxation due to distension or contraction of the bladder, the augmentative guarding reflex can no longer be elicited. This is a significant finding since it means that when the bladder is contracting and forcing fluid along the urethra past the relaxed sphincter, the guarding reflex is inhibited, and the external sphincter cannot contract to interrupt the stream. Instead, the passage of fluid along the urethra reinforces the already existing bladder contraction and ensures that it carries on to complete emptying of the bladder. Thus, in the competition for the final common path, the inhibitory reflex is prepotent and the relaxation of the sphincter represents a true central inhibitory process similar to the inhibition found in limb muscle reflexes.

It was shown by Denny Brown & Robertson (1933) that the external urethral sphincter is capable of powerful voluntary contraction and that such a contraction is the first detectable event at the end of micturition or when the subject tries to arrest micturition while in progress. It would seem reasonable from this that a reflex may exist by which contraction of the external sphincter inhibits any contraction of the bladder which is in progress and such a reflex might also be expected to reinforce the effect of the guarding reflex in the maintenance of continence. Experiments were therefore carried out to see if contraction of the external sphincter in the absence of flow along the urethra could lead to inhibition of the bladder. The result, however, was bladder contraction which was often more powerful than that which resulted from distension of the bladder and it could certainly be produced at smaller bladder volumes. It is difficult to think of any useful role for this response, in the mechanism of either continence or micturition.

The lower urinary tract has two main functions ; the maintenance of continence during the continuous passage of urine into the bladder and the periodic emptying of the bladder. In the past, experimental workers have concentrated on the second of these functions, micturition, almost to the exclusion of the first. In spite of this, it seems that the maintenance of continence is no less important than the other and certainly incontinence is a larger clinical problem than is retention of urine. Barrington's seven reflexes all lead to amptying of the bladder and none is described which would help to retain urine. If these reflexes were the complete picture, then continence would be an unstable state and any trifling external stimulus might trigger off the whole reflex micturition process. This, however, is not the case. Continence is not a purely voluntary function. It is maintained during sleep even at high degrees of bladder filling and since unconscious patients much more commonly show retention of urine than incontinence, continence must presumably have a reflex basis also.

Perhaps a series of reflexes could be described, complementary to those of Barrington, whose function is to retain urine. The present investigation suggests two reflexes of this kind :-

1. Early degrees of bladder filling cause a moderate increase in external sphincter discharge, and

2. An attempt to force fluid along or into the urethra causes a powerful guarding contraction of the external sphincter, the strength of which is graded to the level of the perfusing pressure.

We are still far from understanding the complexity of the reflexes which control micturition, still further from understanding the factors determining the nice relationship between urinary continence and micturition. So far as we can see at the moment, from Barrington's original work, from the papers of other workers and from the results of the present investigation, the sequence is as follows.

As the bladder fills from the ureters, intra-vesical pressure does not rise in a linear fashion with bladder volume. After a slight initial rise, pressure remains fairly constant at a level of about 10 to 15 cm H_2O over a wide range of increasing bladder volume. (Tang & Ruch 1955 and Langley & Whiteside 1951). This is a purely physical effect since it is seen in the dead bladder and even in a rubber balloon (Osborne 1909 and Kesson 1913). The resistance offered by the urethral smooth muscle and elastic tissue is about 20 to 30 cm H_2O, so continence at rest is easily maintained. At greater degrees of bladder filling intra-vesical pressure will eventually begin to rise, but reflex micturition normally occurs before this stage. In addition, at the higher degrees of bladder filling there is some increase in the activity of the external sphincter and should any circumstance produce a sudden rise in intra-vesical pressure forcing fluid from the bladder into the proximal urethra, the external sphincter responds with a powerful reflex guarding contraction which holds back fluid. According to this scheme the external sphincter functions as the mechanism for producing rapid and powerful increase in the urethral resistance to prevent stress incontinence but is of little importance in maintaining continence at rest. The internal sphincter plays the complementary role of maintaining continence at rest and it maintains a moderate urethral resistance for long periods with no tendency to fatigue.

Although intra-vesical pressure remains practically constant during filling, the tension in the bladder wall rises steadily with increasing radii of curvature and if we assume then that the feline bladder is spherical, an assumption which is quite a close approximation to the truth, then the relation between wall tension, intra-vesical pressure and bladder volume is a simple one given by the Laplace equation $T=\frac{1}{2}PR$., where T is the tension in the bladder wall (G/cm), P is the intra-vesical pressure (G/cm^2) and R is the radius of curvature of the bladder in cm.

When a critical tension develops in the bladder wall the micturition reflexes come into action. These probably operate in two stages. In stage I., stimulation of the tension receptors in series with the contractile elements in the bladder wall inhibits the existing tonic contraction of the striped muscle of the external urethral sphincter through a centre in the sacral cord. The ingoing path is in the pelvic nerves. This is Barrington's fifth reflex and it may come into play even before the following reflex. Stimulation, presumably of the same receptors in series with the contractile elements in the bladder wall, initiates, through a centre in the hind brain, contraction of the detrusor muscle of the bladder. Both ingoing and outgoing paths are in the pelvic nerves. This is Barrington's first reflex although it is referred to in the older literature as Guyon's reflex.

About the same time stimulation again acting somewhere in the bladder causes reflex relaxation of the plain muscle in the wall of the proximal urethra -- the internal sphincter. Both paths are again in the pelvic nerves, but the centre is in the sacral cord. This is Barrington's sixth reflex.

In stage 2., urine flows along the urethra, but since Barrington's fifth reflex is now in action, this flow no longer elicits the guarding reflex and instead the flow of urine along the urethra maintains and perhaps reinforces the contraction of the bladder to ensure complete evacuation. Two reflexes play a part : Barrington's seventh reflex, with both paths in the pelvic nerves and a centre in the sacral cord and his second reflex with the ingoing path in the pudendal nerves, the centre in the hind brain and the outgoing paths in the pelvic nerves.

These reflexes continue in action while the bladder is expelling its contents. Then, although the muscle in the bladder wall is still active, as the volume of the bladder contents is reduced, the area of the wall will also diminish and there will come a point when the contractile elements have shortened as much as they can. A further reduction in wall area now relieves the tension on the receptors and removes the stimulus. The reflex drive is thus cut off and both the activation of the bladder wall and the inhibition of the external sphincter subside. Since the re - reptors in the urethra are still active at this stage, they will produce reflex contraction of the external urethral sphincter now that the inhibition has been removed. This external sphincter contraction is at first intermittent and then tonic. It empties the urethra and allows bladder filling to recommence.

E. SUMMARY

The relative strength of the two urethral sphincters in the cat was assessed. The external or striated muscle sphincter is the more powerful. Tetanic contraction of this muscle produced by stimulation of the pudendal nerves enables the sphincter to hold back pressures of up to 200 cm H_2O, although the maximum reflexly produced contraction is only about half as strong as this. The tone of the internal smooth muscle sphincter enables it to withstand a pressure of about 30 cm H_2O, and this resistance is not significantly affected by spinal anaesthesia. Stimulation of the hypogastric nerves produces a moderate but easily fatigued increase in urethral resistance though this effect is significant only in the male sex.

An electromyographic study of the external urethral sphincter in decerebrate cats, shows that this muscle has a continuous tonic discharge of small smplitude in the absence of direct stimulation. As in the case of the external anal sphincter, this tone is not affected by section of the pelvic nerves but is somewhat increased by destruction of the lumbar sympathetic outflow. It is abolished by general or spinal anaesthesia.

Early stages of bladder filling produce a moderate increase in the discharge to the external sphincter. An attempt to force fluid into or along the urethra in either direction leads to a powerful contraction of the muscle and this has been termed the guarding reflex.

Higher degrees of bladder filling produce inhibition of the external urethral sphincter (Barrington's fifth reflex). The critical factor for this response is tension in the bladder wall. Like the corresponding reflex from the rectum this response is abolished by section of the pelvic nerves. It is still present, after section of the spinal cord above the lumbar region. It is still present and it occurs at smaller bladder volume after destruction of the lumbar sympathetic outflows.

The existence of Barrington's second micturition reflex (contraction of the bladder in response to flow along the urethra), is confirmed. The existence of his fourth reflex (relaxation of the external sphincter in response to flow along the urethra), is denied, the apparent effect being due to a combination of the second and fifth reflexes.

Contraction of the external urethral sphincter produced by stimulation of the peripheral end of one pudendal nerve, reflexly causes bladder contraction.

The possible significance of these findings is discussed and a scheme for the reflex basis of continence and micturition is proposed.

PART 5

THE PHYSIOLOGICAL RESPONSES AND FUNCTIONS OF SENSORY UNITS IN THE ANAL REGION AND THE URETHRA

[illegible] results

(1) The physiological [illegible] anal [illegible]

(2) The physiological [illegible] of the urethra.

(3) Central [illegible] and [illegible] in the [illegible] the region

Discussion

Summary

CONTENTS

A. HISTORICAL REVIEW

1. The Sensibility of the Rectum and the Anal Canal

The sensibility of the pelvic viscera has been studied in two ways. Experimental physiologists, working on animals, have drawn conclusions about sensibility from the study of the reflexes, while clinicians have enquired into the conscious sensations aroused. The information, provided by these methods, about the sense organs present in this region, is indirect. The most direct method of studying the physiology of sense organs is the technique of single fibre nerve recording originally developed by Adrian, but this technique has only once been applied to the ano-rectal region and has only been applied to a limited extent to the uro-genital region. Although the experiments described in this section deal mainly with the sensory function of the pudendal nerves, because of the close interaction of the pudendal and pelvic nerves in the reflex behaviour of the pelvic viscera, it is impracticable to discuss the sensory function of one nerve without at the same time considering the other. This short review therefore deals with some of the more important papers on the afferent pathways, the sensibility, the nature of the adequate stimulus for the reflexes and the histology of the sense organs.

The Afferent Pathways

From a study of the pain of visceral disease, Head (1893) concluded that the sensory fibres from the human rectum pass inward by the second, third and fourth sacral dorsal roots. This was confirmed by Rankin & Learmonth (1930). Both the pudendal and the pelvic nerves carry afferent impulses which give rise to the desire to defaecate, but it was reported by Barrington (1915) that cats with both pelvic nerves cut, still showed signs of a desire to defaecate when the rectum was full, and he decided that the main pathways for the desire to defaecate, lay in the pudendal nerve. The spinal pathway involved in defaecation in man was localised by Nathan & Smith (1953) to a strip of the spinal cord running from the lateral horn to the periphery. The lateral parts of this strip are mainly afferent and the medial parts mainly efferent.

The sensibility and the adequate stimulus for the reflexes

The first systematic study of the sensibility of the lower alimentary canal in man was carried out by Hurst (1911) and described by him in the Goulstonian lectures for that year. He found that the colon and the rectum were insensitive to tactile or thermal stimulation, or to chemical stimulation with alcohol or acids. Distension of a balloon in the colon above the pelvi-rectal junction produced a sensation of abdominal discomfort while below this level it produced a desire to defaecate. The pressure required to produce the sensation of a desire to defaecate varied from 50 to 100 mm Hg but was relatively constant for each individual, although a somewhat lower pressure was required near the anal canal than was required at the uppee end of the rectum. Local pressure applied directly to the rectal wall, however strong, was never effective and Hurst concluded that this sensation was a muscle sense in the wall of the gut. Irritation applied to the rectal mucosa could increase motility, but could not produce sensation.

On the other hand, Garry (1934), working on cats, showed conclusively, that there were receptors in the rectal wall sensitive to the movement of a solid body over the rectal mucosa and that these receptors were capable of causing a reflex dilation of the anal canal. The application of cocaine to the rectal mucosa abolished this response. Garry found that distension of the rectum was not effective as a stimulus, but this was possibly because he used a water manometer as a distending agent and the pressures developed in this way were inadequate. This result was in agreement with that of Templeton & Lawson (1931) who were unable to induce defaecation in unanaesthetised dogs by inflating balloons at different levels of the colon and rectum. Garry's findings also agree with those of Alvarez (1929), who found that the human colon was unresponsive to distension.

Goligher & Hughes (1951), however, confirmed the observation of Hurst that distension of the human rectum within 10 to 15 cm of the anus led to a sensation of fulness which was associated with a desire to pass wind or to defaecate. This sensation was accompanied by contraction of the external anal sphincter. Distension of the colon, cranial to the pelvi-rectal junction however, caused abdominal colic. They showed that the rectal sensation was carried by nerve fibres, which travelled centrally in the pelvic splanchnic nerves while the colonic sensation was carried by fibres passing centrally in the sympathetic pathways. They emphasised the importance, in sphincter saving resections of the rectum, of preserving six to eight centimetres of the ano-rectal stump with its parasympathetic innervation intact, in order to avoid incontinence of faeces.

Another aspect of the sensory basis of faecal continence was emphasised by I.P. Todd (1959), who stressed the importance of the special sensitivity of the anal mucous membrane in making the distinction between faeces and flatus. He recommended that this mucous membrane should be preserved if at all possible in sphincter saving operations. The sensitivity of the anal mucous membrane was tested clinically by Duthie & Gairns (1960), who found that all the modalities represented in normal skin were present here also, in many cases with increased sensitivity.

The histology of the sense organs

There are a number of studies of the histology of the sense organs of the ano-rectal region. Duthie & Gairns (1960), examined human biopsy and post-mortem material and found a wide variety of specialised end organs in the anal canal but could find none in the rectal mucosa. Sotelo (1954), on the other hand, reported nerve endings in the mucosa and in the muscular wall of the rectum in human foetuses and in the distal colon of kittens. Walker (1959) using gold chloride staining, reported finding muscle spindles in the external anal sphincter of the cat, while Chennels, Floyd & Gould (1960) have confirmed this observation and have succeeded in recording the afferent discharge from these. The cutaneous innervation of the cat was studied by Winkelman (1959) using silver staining and methylene blue. He found that the basic arrangement of the nerve plexuses corresponded to that found in human skin. The peri-anal skin in the cat contained Pacinian corpuscles and smaller lamellated end-organs.

2. The Sensibility of the Bladder and the Urethra

As in the case of the lower alimentary canal, both experimental and clinical methods have been used to study sensibility.

The afferent pathways

The first evidence localising the ingoing pathways from the lower urinary tract was produced by Head (1893). He showed that ulcerative lesions of the vesical mucosa were accompanied by pain referred to the distribution of the third and fourth, and occasionally of the second sacral roots. The pain which accompanied prolonged over-distension of the bladder was different in quality and was referred to the skin supplied by the eleventh and twelfth thoracic and first lumbar roots. He showed that the prostatic urethra was supplied by both the tenth, eleventh and twelfth thoracic roots and the first, second and third sacral roots. Head & Riddoch (1917) showed that a patient whose sacral cord had been destroyed, but whose sympathetic pathways were still intact, could appreciate distension and emptying of his bladder. It was shown by Riddoch (1921) that not only the pain of bladder distension, but also the pain associated with stimulation of the trigone was carried by nerve fibres running inward by way of the sympathetic pathways.

The sensibility

Moore (1924) carried out a systematic investigation of vesical sensibility. He found that tactile stimulation was poorly recognised and very poorly localised and he concluded that the bladder was insensitive to tactile stimulation unless this was firm enough to produce local deformation of the surrounding structures. All sensations were poorly localised on the dome and lateral walls although left and right could usually be distinguished. The base of the bladder was more sensitive, the trigone still more sensitive and the posterior urethra was the most sensitive of all. Application of local heat was better recognised than local cold. This last finding was later confirmed by MacDonald & Murphy (1959), who showed that normal patients had a definite but crude sensibility to warmth or cold in the bladder, the pathways being in the pelvic nerves. Nathan (1956), on the other hand, found that warmth could be perceived only in the distal urethra and not in the bladder. This could be shown if the sensation of heat was tested through a supra-pubic tube rather than through a urethral catheter.

Nathan (1956) also described the various sensations associated with normal micturition and his paper is the most authoritative statement on the subject of the sensibility of the urinary tract. The normal sensation of the desire to micturate is associated with tension receptors in the bladder wall which send impulses along fibres lying in the pelvic nerves. There is also a sensation that micturition is imminent, felt in the perineum. This sensation is urethral in origin and can be produced in a patient with a supra-pubic cystostomy, by blowing air or running fluid through the urethra. The ingoing pathway is by way of the pudendal nerve and the dorsal columns of the spinal cord. The sensation that urine is passing has three components :-

a. an awareness of the opening of the sphincter musculature
b. a feeling of something passing along the urethra, and
c. a thermal sensation. There is also some proprioceptive sensation from the perineal muscles at the beginning and end of micturition. Urethral sensation is less marked in women than in men and all modalities are carried in the

pudendal nerves. Pain and temperature pass craniad in the spino-thalamic tracts while touch and sphincter proprioception pass in the dorsal columns.

Electro-physiological studies

The first investigation of the urinary system, using electrical recording was that of Talaat (1937) and since this is the only electro-physiological study of the sensory innervation of the urethra, it is reviewed in some detail. Talaat recorded the afferent discharges from the nerves supplying the bladder and urethra but his recordings were taken from the complete nerve trunks with the sheath intact. They therefore represent the combined discharge of many sensory units and provide little information about the individual sense organs.

Talaat found that when the bladder was empty, the pelvic nerves showed an irregular centripetal discharge with a frequency of about five impulses per second and bursts of impulses coincident with each heart beat. Filling of the bladder, unless very gradual, caused an initial burst of impulses which faded gradually over a period of five minutes. A discharge could also be recorded from the pelvic nerve when the bladder was contracting, but the sense organs which responded to active contraction were not the same as those which responded to passive distension, since the receptors responding on contraction were often rapidly adapting and those sensitive to distension always adapted slowly.

Nerve twigs from the pelvic nerve supplying the urethra of the female cat, like those supplying the bladder, showed a constant but faint resting discharge. Distension of the urethra produced only rapidly adapting responses in the pudendal and pelvic nerves, but a few slowly adapting responses to distension were recorded from the hypogastric nerves at pressures over 100 cm H_2O. When saline was made to flow along the urethra, there was a maintained centripetal discharge in the pudendal nerves which started at the onset of flow and reached its maximum in about five seconds. The direction of flow was immaterial. Flow along the urethra produced no discharge in either the pelvic of the hypogastric nerves.

The only other electro-physiological investigation of the afferent nerve supply of the urinary system is that of Iggo (1955) and this is a much more impressive paper than Talaat's largely because of the more refined technique which Iggo used. He was able to dissect small twigs of the pelvic nerve supplying the bladder and to obtain single fibre preparations from these. Iggo demonstrated stretch receptors in the bladder wall which were stimulated during passive distension of the bladder and also during active contraction, whereas Talaat had stated that different sense organs responded in these two conditions. He also reported (Iggo 1956), a single receptor, with its axon in the pelvic nerve which responded to flow through the urethra, its frequency was proportional to the rate of flow and its maximum discharge frequency was about 300 impulses per second.

The paper of Kuru & Kamikawa (1960) is probably best considered also under the heading of electro-physiological investigations, although it is difficult to assess the importance of its results. These workers recorded action potentials from the previously delimited vesico-constrictor and vesico-relaxer centres in the medulla. Filling of the bladder produced both increase in discharge frequency and decrease in discharge frequency in the units recorded from both centres, while contraction of the bladder was associated with reduction in the discharge frequency recorded from both centres. It is not clear, however, whether these impulses are ingoing or outgoing or even that they are concerned with the urinary system.

The histology of the sense organs

Several workers, among them Klentjens & Langworthy (1938) and Langworthy & Murphy (1939), using either metallic impregnation or methylene blue staining, have described what they have taken to be sensory nerve endings in the wall of the bladder. As with such structures in smooth muscle elsewhere in the body, their identity as sense organs is rather doubtful and such papers have added little to the physiological picture.

Another report of rather uncertain significance is that of Gerbetzoff & Grieten (1956). These workers used a technique designed to demonstrate cholinesterase histochemically in the tissues. They claimed that they could distinguish between intra-fusal and extra-fusal muscle fibres with this method, on the basis of the distribution of cholinesterase in the motor end plates. They found that the external urethral sphincter of the guinea pig was rich in intra-fusal fibres and therefore, presumably rich in muscle spindles. They did not however, demonstrate muscle spindles or even sensory nerve endings.

Garry & Garven (1957) described a variety of organised nerve endings in and around the urethral wall of the cat.

B. METHODS

1. Dissection for Recording Impulses from the Pelvic Viscera in the Sacral Dorsal Roots

The first attempts to record afferent impulses from the pudendal nerves were unrewarding because there was too much movement when the rectum and anus were distended. In addition only a short length of the pudendal nerve was accessible and in the confined space of the ischio-rectal fossa the procedure was technically difficult. It was therefore decided to record from the sacral dorsal roots. In this way movement artefact was avoided, a longer length of nerve was available for dissection and the almost complete absence of sheath or perineurium simplified the procedure. All the muscles supplied by the sacral plexus were, as far as possible, denervated by a dissection of the sacral plexus which left only the genito-anal, the dorsalis penis and the pelvic nerves still intact. Considerable confusion was caused in the first experiments by impulses arising from receptors in the joints and muscles at the base of the tail, especially when the anal canal was distended. This difficulty was later overcome by removing the tail and its associated muscles. Disarticulation was carried out at the sacro-caudal junction, leaving the anal canal and its sphincters with the distal colon, freely exposed from the dorsal surface (fig.55). This exposure allowed the sensory units which were being studied to be accurately localised by exploration with a blunt probe while the resulting discharge was observed. The rectum and anal canal could be examined by this dorsal approach, while a combined approach could be made to the urethra round the side of the rectum and ventrally through the gap between the separated ends of the pubic symphysis.

The procedure followed in the dorsal root experiments can now be described in some detail. The cat was anaesthetised with Nembutal, given by intra-peritoneal injection and the trachea was cannulated. The urethra was exposed as already described in section 4. and an opening made into it just below the bladder neck. A polythene tube was then passed into the bladder and through the same opening another was passed into the urethra and directed distally and both tubes were tied in. The pubic symphysis was then propped open with a piece of cork and the space between the ends was packed with cotton wool soaked in paraffin.

The cat was then turned into a prone position and supported in a system of rods and blocks. The back was shaved and a mid-line dorsal incision was made from the fifth lumbar spine to a point overlying the first inch or so of the tail. The skin was reflected laterally and so also was the superficial spinal aponeurosis (lumbar fascia), after it had been detached from the tips of the spinous processes. The long muscles covering the dorsal aspect of the lumbar vertebral column were next dissected free, from the level of L5. to the base of the tail, leaving the laminae and spinous processes exposed. The skin was now incised between the anus and the base of the tail and this plane of separation was continued forward between the tail and the rectum, severing the attachments of the various muscles as close to the tail as possible. These muscles are pubo-caudalis, ilio-caudalis, ischio-caudalis, caudo-cavernosus and recto-caudalis. The lateral longitudinal vein of the tail was clamped on each side and the tail removed by disarticulation of the sacro-caudal junction, cutting across the cauda equina. Profuse bleeding usually occurred from the anterior caudal artery, but this was quickly clamped and tied. The sacral and lower lumbar spinous processes were now removed with bone nibblers. A pair of fine bone nibblers was then inserted into the gap between the sacrum and the seventh lumbar vertebra and the dorsal laminae were removed as far cranially as the fifth lumbar. The dorsal aspect of the sacrum was then removed and the bone edges trimmed as far back as the bases of the articular processes. The extra-dural fat and the connective tissue were removed taking care not to damage the dura. The edges of the skin wound were now stitched to a brass ring which was clamped to the framework holding the cat and the pool so formed was filled with liquid paraffin which was maintained at 38°C. The dura mater was next incised in the middle line from the level of L5, to the level of S3, using fine scissors with the tips turned up to avoid touching the underlying cord. The edges of the cut dura were held up in fine forceps and were stitched back to the surrounding muscle using a fine curved needle. The individual spinal roots were separated with watch-makers' forceps and glass hooks. A provisional decision was then made as to the identity of the various roots and the ventral and dorsal components of the roots were separated using blunt ended glass hooks.

The ventral roots from L7. to S3, were cut across on both sides as near to the cord as possible and the peripheral cut end of each root in turn was laid over platinum wire electrodes and stimulated with pulses of I msec duration, at low frequency. A note was taken of which muscles responded in each case and if any muscle other than the sphincters responded, further dissection was undertaken to complete the denervation. At the end of the experiment the identity of the roots was verified post-mortem as described in section I.

2. Procedure for Recording from the Dorsal Root Fibres

Recording was carried out on the dorsal roots corresponding to the ventral roots which had caused contraction of the urethral and anal sphincters when stimulated.

The discharge recorded from the twigs initially pulled off the dorsal roots, usually consisted of the response of several sensory units and it was not possible to analyse this discharge without further subdivision of the strand. This subdivision was carried out beneath the surface of the paraffin. The instruments used for the subdivision are shown in fig. 56 and included fine watchmakers' forceps, finely ground needles sealed into glass rods, and small hooks drawn from glass tubing and flamed at the ends to ensure that no sharp edges remained.

The early stages of the subdivision were carried out using the fine forceps. The cut end of the twig was lifted with the points of two pairs of forceps and the twig was split longitudinally by pulling the two pairs apart. With practice , quite fine strands could be split this way. This method was found to give better results than other methods which were tried using needle points and glass hooks, although the condition of the forcep points was critical and these had to be sharpened frequently on a small oil stone. It was never found satisfactory to touch with instruments, the part of the nerve which was later to lie in contact with the recording electrodes, so during the teasing only the extreme end of the twig was touched.

The later stages of the subdivision were carried out with the aid of a binocular dissecting microscope. This was mounted on a massive movable stand, which was completely separate from the operating table. The stand was fitted with fine adjusting screws by means of which movement of the instrument in any desired direction could be produced. The microscope was also fitted with a focussing spotlight so arranged that the field remained illuminated when the instrument was moved.

At the beginning of an experiment the oscilloscope sweep speed was adjusted to give the appearance of a single line on the screen. At this sweep speed, several action potentials could be seen on the screen simultaneously, even at low discharge frequencies. A strand was pulled off the dorsal root which was being examined and laid across the recording electrodes. It was found that winding the end of the strand round one of the electrode blades ensured a more stable contact and did not damage the constituent fibres of the strand. The various stimuli -- distension and movement within the anal canal and distension and perfusion of the urethra -- were then tried and if no response was obtained, the nerve was moved to a new position on the electrodes and the same procedures repeated. If this failed to produce a response and if the twig was still of considerable size, it was split and the procedure repeated on the resulting smaller twigs.

In most cases, however, the response obtained consisted of the discharges of a number of sensory units and in order to obtain records for analysis, the twig had to be broken down until a single fibre preparation was left. The term single fibre preparation, is applied to a twig which contains only one active unit under the conditions of the experiment, although several sensory axons may be contained in it. Twigs which were not completely single fibre in their discharge patterns, but which contained two or three active units, were often suitable for recognising the units involved, but not for analysing their behaviour in detail.

In some cases a twig which was too small for further subdivision was found to contain several active units. In this case, stroking the length of the nerve lying between the two blades of the electrodes sometimes reduced the number of active units present, though in a purely random way and by this method single fibre preparations could occasionally be produced.

The aim of all these methods was to obtain a preparation which gave a single unit discharge in response to the application of a standard stimulus, with a reasonable action-potential to noise ratio and with no action potentials from other units coming in to confuse the record. In these respects, larger twigs usually gave a higher action-potential to noise ratio, but were more prone to interference from other units.

On each occasion that a sensory unit was found to be sensitive to one of the applied stimuli, it was subsequently localised by touching with a blunt ended probe. The suspected area was explored with the probe until a region was found where light pressure produced an increase in the discharge already present. With experience, it was usually possible to localise quite accurately the receptor of the unit which had previously been isolated and studied. In this respect the sound produced by the monitoring loud speaker was usually more helpful than the discharge visible on the screen. As a routine, also, the ventral root corresponding to the dorsal root being studied, was placed on metal stimulating electrodes so that the effect of motor stimulation on any units isolated, could be observed.

A detailed record of all the sensory units isolated in this way was kept, to give information on the relative frequency of the different types of receptor.

C. EXPERIMENTAL RESULTS

1. The Pudendal Sensory Innervation of the Anal Canal

When twigs from the sacral dorsal roots were laid on the recording electrodes, after all branches of the sacral plexus except the pudendal nerves had been cut, background activity of small amplitude of undetermined origin but consisting of the combined discharges of several sensory units was usually present. In addition there might be one or more units which responded to mechanical stimulation of the anal region. Two methods of stimulation were used as a routine -- touching the peri-anal skin and mucous membrane with a probe and inflation of a balloon lying in the anal canal. If more than one active sensory unit was present, an attempt was made to divide the strand so that a single fibre preparation of each sensory unit was isolated and the receptors could be classified on the basis of their response to the stimuli. In all these cases the sacral ventral roots were first cut so that the sensory discharges were the responses from the receptors themselves, uninfluenced by reflex activity or by tonic motor innervation. It was not possible, however, to give an accurate evaluation of the relative frequency with which the different types of sense organ are distributed in the anal region, since the recording method detected only a proportion of the sensory units present in the roots and tended to emphasise those having a higher spike voltage.

The majority of impulses from the anal region arise in receptors lying in the peri-anal skin and in the underlying fascia. These receptors are sensitive to light touch, respond to movement of hairs and in addition, those lying nearest to the anal mucous membrane are stimulated when the anal canal is distended. The sensitivity of this region to temperature and pin-prick was not investigated as there is no reason to believe that the sensitivity of the perineal skin differs from that of the hairy skin elsewhere in the cat.

On distension of the anal canal two types of response were observed. The first, which shall be referred to as the rapidly adapting type of response, consists of a brief burst of two to six impulses during the period of inflation of the balloon and a similar burst as the balloon is deflated. No discharge is recorded while the balloon is maintained in a steady state of distension. A discharge of this sort is shown in fig. 57D. To and fro, or rotatory movement of a deflated balloon in the anal canal, leads to a totally irregular and intermittent discharge from receptors of this type. A similar response is given when the same receptor is stimulated by probing and such sense organs could be quite accurately located in this way. They were found to lie in and around the external anal sphincter, in the surrounding ischio-rectal fat and in the mucous membrane of the anal canal.

The second type of discharge seen on distension of the anal canal will be referred to as the slowly adapting response (figs. 57A & B). This consists of a sustained and basically regular discharge of impulses which continues for as long as the distension is maintained and in which the discharge frequency varies with the degree of distension. Local pressure with a probe stimulated the sense organs responsible for this type of discharge and caused a similar sustained discharge. By this means the receptors could be localised and were found to lie in close association with and probably within the substance of the external anal sphincter. Many of these sensory units were isolated as single fibre preparations and a number of these were studied in detail. All had a similar pattern of response.

Most of those examined showed a continuous resting discharge with the animal supported in a prone position as described above, and with nothing lying in the anal canal to act as a stimulus (fig. 58 A). This resting discharge varied between five and fifteen impulses per second and when the frequency fell below five impulses per second, the discharge became irregular and often showed alternating periods of activity and periods of silence. The resting discharge was present whether the sacral ventral roots were intact or cut. In some cases, slow rhythmic contractions of the smooth muscle of the colon could be observed passing along to involve the internal sphincter. These contractions caused the anal opening to show rhythmic narrowing and dilation with a periodicity of about thirty seconds. The frequency of the slowly adapting sense organ discharge from the overlying striated muscle sphincter, followed this movement, showing a rise during contraction and a fall during relaxation.

The question of whether or not the slowly adapting receptors really have a tonic discharge with the animal at rest, is not easy to settle. It was not possible to identify the anal receptors with certainty in an animal with the tail still attached, or to distinguish these from receptors in the joints and ligaments at the base of the tail. In preparations in which the tail had been removed and the skin stitched to a brass ring, it is possible that the external sphincter was under abnormally high tension due to stretching of the skin and muscle, so producing a resting sensory discharge which was not present in the intact animal. On the basis of inspection alone, however, the sphincter appeared to be under lower resting tension when it was detached from its normal dorsal origin on the caudal vertebrae and was suspended from the brass ring by the skin.

A rise in intra-abdominal pressure brought about passively by manual pressure on the anterior abdominal wall, or actively, by obstructing the tracheal cannula during the start of expiration, led to an increase in the discharge from the sphincter. The insertion of a foreign body into the anal canal from the outside, or the stretching of the anal opening with forceps, also increased the discharge.

Distension of the anal canal by inflating a balloon, led to a sharp increase in the frequency of the discharge which reached a peak during the first second and then gradually decayed over a period of about twenty seconds to reach a steady value characteristic for each distending pressure. (fig. 57 A & B). The time course of this adaptation process was similar in all receptors of this kind studied and is well shown in fig. 58, in which the impulse frequency was plotted against time.

This and similar diagrams were constructed in the following way. At appropriate points in time, either at half second or at quarter second intervals, measurements were made of the time intervals between successive impulses and the average was used to derive the frequency of the discharge at this point. The frequency was plotted to the nearest whole number of impulses per second.

The time taken for the adaptation of the discharge to a steady value, varied somewhat from unit to unit and depended on the rate of application of the distending pressure and on the pressure actually used, but there was usually little change in frequency after ten seconds. In fig. 58 E, (adaptation to 40 mm Hg), adaptation still seems to be going on, though to a very slight extent after twenty seconds, whereas in fig. 58 B (adaptation to 10 mm Hg), there is no further change in impulse frequency after five seconds.

Fig. 58 also shows that there is a relation between the magnitude of the distending pressure and the frequency of the final adapted discharge. This relation is better seen in fig. 59 in which the two quantities are plotted one against the other for two different slowly adapting units from the external anal sphincter. It can be seen that the relationship is approximately linear. Presumably the actual stimulus to which the sense organ responds is the tension in the muscle ring, although the use of a balloon as a distending agent, while convenient in many respects does not allow accurate assessment of the tension developed in the muscle and no attempt was made to estimate it. Fig. 60 shows samples of the discharges recorded from such a sensory unit at different pressures after a twenty second interval to allow adaptation to take place.

When the pressure distending the anal canal was released the discharge frequency fell abruptly to a value below that of the previous resting discharge and usually fell to zero. Thereafter it gradually rose again to the normal resting frequency. This sequence of events during inflation and deflation, easily recognised when heard on the loudspeaker, enables the slowly adapting unit to be distinguished from a background of other units. Fig. 61 shows a graphic plot of frequency against time, for such a cycle. The unit in this case shows a 'resting discharge' of 20 impulses per second, although, this will not be a true resting discharge since a deflated balloon was lying in the anal canal while the discharge was being recorded. When a distending pressure of 40 mm Hg was applied at the rate of 10 mm Hg per second the frequency rose to 50 impulses per second. Here the degree of adaptation which occurred was slight because of the slow rate of distension. When the balloon was rapidly deflated, the discharge frequency fell abruptly to zero and gradually returned to the original level of 20 impulses per second over a period of three to four seconds.

The maximum frequency attained by the discharge is reached very shortly after the maximum pressure is developed and is largely a function of the rate of application of the pressure, the more rapid the application, the higher the frequency. Figs. 57 A & B show the discharge recorded from the same unit during the distension of the anal canal, with a pressure of 30 mm Hg at two different rates and fig. 62 shows a similar experiment plotted graphically. In the response represented by the continuous line, the pressure was applied at the rate of 60 mm Hg in half a second and the peak discharge frequency rose to 70 impulses per second. In the response represented by the dotted line, the pressure was applied at 10 mm Hg per second and the peak discharge frequency rose to 37 impulses per second. In both responses, the frequency adapted to the same value of about 33 impulses per second during the next 10 seconds.

When a sensory unit was isolated as a single fibre preparation, the corresponding ventral root was placed on a second pair of electrodes and stimulated with single pulses of 1 msec duration and varying voltage. Stimulation of the ventral root led to contraction of the external anal sphincter, which was more marked on the side being stimulated. If a steady distension was being applied to the anal canal at the same time, the contraction of the external sphincter was accompanied by a pause in the discharge recorded from the sensory fibre (fig. 63 A). In some cases, at higher voltages of stimulation, the result was a burst of impulses or a burst followed by a pause. In all the units examined, the pause was the main response and could always be obtained if a suitable stimulating voltage was chosen (fig. 63 B & C). Stimulation of the corresponding ventral root on the same side with 1 msec pulses at a frequency sufficient to produce tetanic contraction of the external sphincter, abolished the afferent discharge completely. In fig. 57 C, the ventral root was stimulated at 16 per second and the voltage was gradually increased from zero. There was an initial slight increase in the discharge rate followed by complete abolition of the discharge for the duration of the tetanus.

Receptors in every way similar to those found in the anal sphincter were present in the sphincter vaginae and could be localised to that muscle ; they were not anal receptors being stimulated by vaginal distension.

2. The Pudendal Sensory Innervation of the Urethra

As in the case of the anal region, most of the impulses arising on stimulation of the urethral region arise in cutaneous sense organs. Rapidly adapting sense organs sensitive to touch were common in the skin of the glans penis, the prepuce and the vulva of the female. Some of these impulses may have originated in the genital corpuscles of the region and may be concerned in sexual reflexes.

When the urethra was tied off and then distended with fluid from the proximal end, rapidly adapting discharges were found closely resembling those found on stimulation of the anal region. The discharge consisted of a brief burst as the pressure was released, but there was no discharge during maintained distension. The spikes making up discharges of this type were often of large amplitude and were easily picked out from background activity. These receptors were not sensitive to flow along the urethra unless the flow was very rapid or fluctuating, when they would discharge briefly if the flow started or stopped, or changed suddenly in rate.

In no case did low pressure distension of the urethra evoke a sustained discharge comparable to that from the slowly adapting anal stretch receptors. In a few cases, usually at pressure in excess of 100 mm Hg, a sustained discharge was seen, but this pressure was almost certainly well above the pressure normally developed in the urethra. This high pressure may have stimulated receptors lying in neighbouring structures. It was not found possible to localise accurately the source of discharges of this kind.

A constant rate of flow of fluid along the urethra was produced by tying a fine polythene cannula, directed distally, into the proximal urethra and connecting the cannula through a tap to a reservoir of fluid at a fixed height above the urethra (usually 60 cm). When the tap was opened, the fluid ran along the urethra and escaped from the external meatus. The rate of flow was measured with a volume recorder connected to the air-inlet of the reservoir as described in section 4. A steady stream of fluid along the urethra was accompanied by a sustained but totally irregular discharge in the dorsal root fibres. The duration of the discharge corresponded closely to the period of the flow (figs. 64 A & B and fig. 67) and there was often an increase in the discharge rate when the flow started and stopped. Stimulation of the corresponding ventral root with single pulses, which produced twitches of the external sphincter, had little effect on the discharge in the dorsal roots (figs. 64 A). When, however, the frequency of stimulation was increased sufficiently to give tetanic contraction of the external sphincter, the discharge in the dorsal root fibre disappeared for the period that the flow was stopped and reappeared when flow restarted (fig. 64 B and fig. 67).

Fig. 65 A is a portion of the discharge recorded during steady flow along the urethra from a reservoir 60 cm above bladder level and shows the characteristic irregularity of the discharge. It can be seen that there is no underlying rhythm in this case, in contrast to the slowly adapting discharge from the stretch receptors in the anal canal.

The frequency of the discharge was found to vary with the rate of flow along the urethra. To investigate this, the reservoir was set at different heights above the urethra, while the volume of fluid which escaped from the external meatus and the average discharge frequency were measured over the same period. The result of such an experiment is shown graphically in fig. 68. With driving pressures up to 60 cm H_2O, the discharge varied between 5 and 20 impulses per second. It can be seen also that there is a certain minimum driving pressure and therefore a certain minimum flow rate below which the urethra remains closed.

A much faster rate of flow could be produced by blowing air along the urethra with a syringe. The passage of the air produced sound and was therefore presumably turbulent. It was accompanied by a very high frequency of discharge (80-100/ sec) in the flow receptors, and the discharge became more regular at the higher frequencies (fig. 65 B). Simple distension of the urethra in the absence of flow, caused only two or three impulses in these units during the application of the distension and a similar response was found to local stimulation with a probe. The sense organs could be localised by probing and were found to lie in the substance of the urethra itself.

The 'flow-receptor' units always had a low spike voltage and so were difficult to distinguish from the background activity. This, together with the absence of any basic regularity in their discharge, made their isolation as single fibre preparations technically difficult. They were more easily found in male animals than in females, possibly due to the greater length of the male urethra. They were most abundant in the region of the external sphincter.

3. Centripetal Impulses in the Pelvic Nerves and Impulses Arising from Somatic Structures in the Pelvis on Distending the Bladder or the Rectum

Attempts were made to record from the ingoing fibres of the pelvic nerves as they travelled in the sacral dorsal roots and this involved attempts to denervate the sacral plexus further, so that only the pelvic nerves remained uncut. To do this, all visible branches of the plexus including the pudendal nerves were cut. The sacral ventral roots were then stimulated and extensive dissection carried out to cut nerves wherever skeletal muscle contraction was seen. It was not found possible to carry out a full denervation of this kind although the combined dorsal and ventral approach to the pelvic viscera as used in all the nerve recording experiments already described, provided excellent access and visibility for this purpose.

Distension of the bladder and especially of the rectum was accompanied by sustained slowly adapting discharges of the muscle spindle type. These were subsequently identified as coming from the skeletal muscles of the pelvic disphragm, the pubo-caudalis, ilio-caudalis and ischio-caudalis ; and from the muscles of the side wall of the pelvis, obturator internus and piriformis. These muscles are innervated by short branches arising from the roots of the sacral plexus just after the roots leave the anterior sacral foramina and before they emerge from the greater sciatic foramen. These branches are not shown in the usual representations of the sacral plexus (fig. 16) and it was not found possible to eliminate them completely.

D. DISCUSSION

The results in section 5 confirm, by direct electrical recording, the accepted view that the pudendal nerves carry ingoing impulses from the anal and urethral regions. Several different types of sensory unit are represented in these regions and many of these must play a part in the afferent side of the reflexes described in sections 3 and 4. The method of electrical recording from individual sensory units is, however, essentially a sampling method by means of which only a percentage of the sensory units in a given nerve trunk can be studied. It is also a method which tends to emphasise receptors whose discharge is composed of action potentials of high voltage, so it is possible that some receptors with low voltage discharges may not have been detected.

The sense organs lying in the pari-anal skin are — presumably those concerned in the augmentative anal reflex. These touch sensitive end-organs are present in the skin itself and in association with hairs. Both histologically and experimentally the peri-anal skin of the cat seems to be similar in its sensory innervation to the general pattern of the hairy skin elsewhere.

The receptors in the anal mucous membrane are among those stimulated by movement of a balloon or of faeces in the anal canal. Movement of a balloon in the anal canal was shown by Garry (1933b) to cause reflex contraction of the smooth muscle of the wall of the colon, while the results of part 3 of this thesis show that such movement can also produce bursts of activity in the external anal sphincter, alternating with periods of silence, but not a true sustained inhibition.

These same receptors in the anal mucous membrane will also give rise to conscious sensation which is important in the maintenance of faecal continence. The clinical investigations of Duthie & Gairns (1960) confirm the finding of Hertz (1911) that all normal modalities of sensation are represented, apparently with increased sensitivity, in the mucous membrane of the human anal canal. Todd (1959) stated that the sensitivity of the human anal canal enables a distinction to be made between faeces and flatus and that the ability to make this distinction is an important factor in the maintenance of faecal continence.

It would seem unlikely that the receptors in the peri-anal skin and mucous membrane contribute significantly to the reflex resting tone of the external anal sphincters. These surface receptors do not discharge spontaneously, but only on stimulation, while local anaesthesia of the anal canal produces no recordable change in the level of the resting discharge to the external anal sphincter. On the other hand, the application of soap to the anal mucous membrane produces irritation which is associated with a prolonged and significant augmentation of the discharge. Thus, although surface afferents from the anal region can reflexly alter the discharge, they do not normally contribute to the resting tone.

The sensory innervation of the external anal sphincter has been found in this work to conform to the basic pattern of the sensory innervation of skeletal muscle as described by Matthews (1933). He classified the sensory units which he found in the cat soleus into four groups, A1, A2, B, and C. The slowly adapting stretch receptors present in the external anal sphincter were found to belong to the A group although the distinction into A1, and A2 on the basis of their response to motor nerve stimulation was not so clear cut as Matthews' description suggests. This agrees with the finding of Harvey & Matthews (1961), who state that the division of the endings in soleus into A1, and A2 on the basis of their response to motor nerve stimulation is not valid. It can however, be said with confidence, that any discharge which shows a pause on motor nerve stimulation must arise in a stretch receptor lying in parallel with the extra-fusal muscle fibres, that is to say, in a muscle spindle.

In section 3 it was shown that the external anal sphincter shows a continuous resting motor discharge which persists after section of the pelvic nerves and after destruction of the lumbar sympathetic outflow. The tone is unaffected by local anaesthesia of the anal mucous membrane, but is, however, reflex in origin since it is abolished by sacral dorsal root section. The fact that a proportion of the anal sphincter stretch receptors show a 'resting' tonic discharge with the anal canal empty, suggests that these receptors are at least in part responsible for the afferent stimulation for the tone of the external anal sphincter. It is possible, however, that the resting sensory discharge may be an artefact, produced by the alteration in skin tension which results from stitching the skin to a brass ring after removing the tail. On the other hand, the muscle does not appear in these circumstances to be under increased tension and in the intact animal the superficial part of the sphincter is suspended from the caudal vertebrae and seems to help in supporting the weight of the more distally situated of the pelvic viscera. Matthews found that 30% of the A endings in the soleus muscle showed a spontaneous discharge when the muscle was detached from its insertion and hence was under no tension.

It was found in the present enquiry that an increase in intra-abdominal pressure, actively or passively produced increases the sensory discharge from the sphincter, whereas in the decerebrate cat a similar increase in the intra-abdominal pressure increases the motor discharge. It is under conditions of increased intra-abdominal pressure that accidental escape of faeces is most likely to occur. The anal sphincter in these circumstances, therefore, plays a role comparable to that played by the external urethral sphincter in preventing stress incontinence of urine. It seems then, that the external anal sphincter shows a stretch reflex similar to that shown by limb muscles, in that increase in the passive tension of the muscle increases the sensory discharge from the muscle spindles lying in it and this reflexly increases the discharge to the extra-fusal fibres of the muscle. The stretch reflex which is the basis of tone in limb muscles, depends on the development of passive tension in the muscle and this usually involves both ends of the muscle being attached to bone. The deep part of the external anal sphincter has no such attachments since it forms a thick collar round the anal canal but increase in intra-abdominal pressure will tend to open the anal ring and so increase the passive tension in the muscle. The stretch which provides the stimulus for the resting tone of the sphincter, is produced by the normal intra-abdominal pressure resulting from the abdominal wall muscles contracting against the weight of the abdominal viscera.

The muscle spindles in the external sphincter may have another function. Matti (1909) found that even a very imperfect repair of a ruptured external anal sphincter, cured incontinence of faeces in man and this cure was not explicable on the basis of the mechanical effect of the repaired external sphincter. He concluded that the presence of even a few fibres bridging the gap in the external sphincter allows tension to be developed in this muscle which reflexly stimulates the internal sphincter to contract. Garry (1933 C) produced supporting evidence for this hypothesis from experimental work on cats. Thus the afferent discharge from the external sphincter depending on the integrity of the skeletal muscle ring not only maintains the tone of the external anal sphincter but that of the internal sphincter also. This sensory discharge is therefore of considerable impodtance in the maintenance of faecal continence.

No discharges corresponding to the B group of Matthews were found. These are thought to originate in the Golgi tendon organs and to be responsible for the autogenic inhibition which occurs in the clasp knife reaction of limb musculature. No sign of tendon can be seen in the external sphincter either with the naked eye or histologically and no tendon organs were found when the muscle was examined by nerve staining techniques. The anal sphincter does not show a clasp-knife reaction.

Rapidly adapting discharges arising from receptors in and around the sphincter were found on distending the anal canal. These correspond to the C discharges of Matthews and were quite rare in the soleus, whereas in the external sphincter they were easily found. This may be because the sphincter is surrounded by the fat of the ischio-rectal fossa which can be shown histologically to contain lamellated receptors of the Pacinian corpuscle type.

On moderate distension of the urethra after it had been completely cleared of surrounding tissue, no sustained discharges were found although such discharges were looked for in all thirty three cats examined. This finding agrees with Talaat (1937) who recorded from whole nerves and who found no sustained discharges from either the pudendal or pelvic nerves with pressures up to 100 cm H_2O, although he did find a few sustained discharges from the hypogastric nerves at pressures over 100 cm H_2O. The only discharges recorded on moderate distension of the urethra in the present enquiry were rapidly adapting in nature. These were similar in their behaviour to the rapidly adapting discharges recorded from the anal region and only a few of these responded during steady flow along the urethra, although most responded to the starting or stopping of flow, or to a sudden change in the rate of flow. These receptors may play some part in the guarding reflex which helps to maintain continence although it is unlikely that a significant degree of urethral distension is ever produced normally.

The normal stimulus to the urethra is the flow of urine. This is the stimulus for three of Barrington's reflexes and it gives rise to conscious sensation in man (Nathan 1956). Talaat (1937) reported that the flow of water through the urethra of the cat produced a greater increase in the discharge recorded from the whole pudendal nerve trunk than did distension of the urethra, but he could obtain no information about the individual receptors. There is indeed no previous report of a mechano-receptor sensitive to flow, apart from a single observation made in passing by Iggo (1956), the details of which I have since verified by personal communication. He found a single receptor in the proximal urethra with its axon passing inward by the pelvic nerve, which discharged at frequencies of up to 300 impulses per second when fluid was made to flow along the proximal urethra into the bladder.

The demonstration by electrical recording, in the present enquiry, of receptors which discharge when fluid flows along the urethra, is complementary to the findings in part 4 of this thesis, where it was shown that flow along the urethra causes contraction of the external urethral sphincter. It was also shown in part 4 that if the bladder contains enough fluid, this flow causes it to contract. It seems a reasonable assumption that the flow receptors represent the beginning of the ingoing side of these two reflexes. The flow receptors, however, do not discharge spontaneously, and so cannot be responsible for the tonic motor discharge to the external urethral sphincter.

The mode of stimulation of the flow receptors is not clear but it presents an interesting problem. They responded to a constant mechanical deformation produced by distension, in a manner similar to other rapidly adapting receptors, with a burst of impulses during the initial application of the stimulus, but showed no discharge during the constant deformation. The nature of the discharge which accompanied an apparently steady flow of fluid, suggests that the stimulus is applied in the form of a continuously changing deformation. Such a condition could result from the presence of turbulence in the flow of fluid along the urethra. If the flow along the urethra is laminar*, the mechanical deformation produced will be constant and will consist of a shearing force parallel to the mucosal surface. It is difficult to see how a stimulus of this sort could give rise to the totally irregular discharge pattern recorded from the flow receptors. At higher velocities, however, laminar flow breaks down into turbulent flow. If flow in the urethra is turbulent the effect produced will be that of an irregular coarse vibration producing a constantly changing mechanical stimulus and it is probably that turbulence in the flow of urine represents the normal mode of stimulation of the flow receptors.

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* *The term laminar flow is applied to a flow pattern in which the fluid may be divided into parallel layers which flow past one another with different velocities. As a result of internal friction (viscosity) the more rapidly moving layer tends to drag the neighbouring layer along with it and thus accelerates it and similarly the slow layer tends to retard the faster. The velocity profile is thus parabolic, the individual particles of the fluid follow parallel rectilinear paths and the values of velocity and pressure at a given point are constant in time. In laminar flow the velocity of efflux is proportional to the pressure difference (Poseuille's law). At higher velocity, however, laminar flow breaks down into another state termed turbulence. In this condition the velocity of efflux is no longer proportional to the pressure difference, the value of velocity and pressure at a given point are no longer constant in time but oscillate about mean values and the paths of individual particles are no longer rectilinear but are random leading to continual intermixing.*

It is of interest in this connection that Hunt (1961) has reported that Pacinian corpuscles in the periosteum of the tibia in the cat, are sensitive to rapid mechanical stimulation in the form of a sinusoidal vibration over a range of frequencies from 90 to 600 vibrations per second. These Pacinian corpuscles are larger than the 'cucumber shaped' endings described later but have a similar lamellated structure.

The relationship of the various factors concerned in the onset of turbulence is complex even under standardised laboratory conditions. Basically the onset of turbulence is determined by the value of a dimensionless quantity called the Reynolds Number (Re), which can be calculated for simple conditions with rigid walled tubing of uniform bore. It is not possible to predict on theoretical grounds, however, whether or not flow in the urethra will be turbulent because of the many complicating factors present. Irregularities in the wall and constrictions of the lumen will tend to bring the critical value for Re down to quite low levels and will therefore tend to increase the possibility of at least local turbulence.

The impulses which arise on distension of the bladder and rectum in the skeletal muscles of the pelvic floor and walls may contribute to the normal sensation of fulness arising in either of these organs. There is little doubt, however, that the greater part of this sensation arises in the walls of the viscera and passes inward along the pelvic nerve. The additional skeletal muscle discharge on distension may be important in those patients who have had a substitute rectum or bladder constructed from colon or ileum.

The sensory innervation of the colon enables distension to be appreciated only when very high pressure is present and the sensation produced is that of colic, the impulse passing centrally by the sympathetic pathways. Both Goligher and Hughes (1951) and Nathan (1956) report that such patients often develop a spurious form of rectal or vesical sensation, which both groups of workers suggest may originate in neighbouring pelvic structures. The patient can learn to interpret and make use of this sensation although it does not contribute to the reflex maintenance of continence or of evacuation. The results of the present investigation indicate that distension of the bladder or rectum can give rise to impulses which have their origin outside these organs. These impulses may well contribute to the sensation which Goligher & Hughes and Nathan have observed in their patients.

E. SUMMARY

Using a 'single fibre' recording technique, afferent discharges from single sensory units in the anal and urethral regions of the anaesthetised cat have been recorded from the sacral dorsal roots.

Surface receptors from the peri-anal skin and the anal mucous membrane give rise to the majority of the responses from the anal region. These are sensitive to light touch and in the case of those in the peri-anal skin to movement of hairs, Two types of response are seen on distending the anal canal with a balloon ; a rapidly adapting response and a slowly adapting response. The rapidly adapting response consists of a brief burst of impulses during inflation or deflation of the balloon, but no discharge during sustained distension of the anal canal. This type of response comes from endings in and around the external sphincter and in the ischio-rectal fat. The slowly-adapting (stretch receptor) response consists of a sustained regular discharge which persists while distension is maintained with exaggerated changes in frequency during inflation and deflation. The steady adapted frequency varies with the distending pressure, while the peak frequency is a function of the rate of application of the pressure. Responses of this sort originate in sense organs lying in the substance of the external anal sphincter. Many of these receptors have a resting discharge in the absence of distension.

Distension of the urethra in either sex produces only rapidly adapting responses. In addition receptors are present which respond to the flow of fluid along the urethra

from a steady pressure head. The 'flow receptor' discharge consists of a sustained but basically irregular train of impulses which corresponds closely to the period of flow. The average discharge frequency varies with the rate of flow. The highest discharge frequencies are produced by blowing air along the urethra. These receptors respond to distension of the urethra, as rapidly adapting discharges of small spike height. The endings responsible lie in the urethral wall.

Distension of the rectum or bladder leads to sustained discharges from striated muscles of the pelvic diaphragm and the side wall of the pelvis.

It is suggested that the stretch receptor discharge from the anal sphincter is largely responsible for the resting tonic discharge to the sphincter and perhaps also for reflexly maintaining contraction of the internal anal sphincter, while the rapidly adapting discharge from the anal region is responsible for the reflexes which result from movement within the anal canal.

It is further suggested that the flow receptors normally respond to the irregular vibration which results from the development of turbulence in the flow of urine along the urethra and that these receptors are concerned in the reflexes which result from the flow of urine along the urethra.

PART 6

THE HISTOLOGICAL STRUCTURE OF THE SENSE ORGANS IN THE ANAL CANAL AND IN THE URETHRA

CONTENTS

A. HISTOLOGICAL METHODS

The histological techniques used in the nerve fibre analysis have already been described in section I. To study the morphology of the sensory nerve endings in the anal and urethral regions several other techniques were used. Paraffin sections, in some cases serial sections, were prepared by conventional methods by the technical staff and the sections were stained with haemalum and eosin and by the Masson method. These methods are suitable for demonstrating the general morphology of the region and the distribution of the sense organs, but are not suited to a detailed study of the structure of the end organs. For this purpose a combination of the conventional methods and the metallic impregnation techniques, designed to be specific for nervous structures, was used. Two metallic impregnation techniques were used :- The Bielschowsky-Gros silver diamine ion method and the gold chloride method of Gairns. In the first of these methods the pieces of tissue are fixed in 12% neutral formalin for some days, following which thick sections, 15 µ to 20 µ, are cut with the freezing microtome and impregnated by the silver diamine ion method. The details of this method are described by Garven & Gairns (1952).

The modified gold chloride method of Gairns (1930), was found to be the most generally useful method. It has the advantage of not requiring any special equipment and so can be carried through very conveniently by an experimental worker along with the experimental work. For this reason the technique is described in some detail.

1. Small pieces of sphincter muscle or of mucous membrane were dissected from the recently killed cat and

cleared of fat or any other tissue. These were placed in a mixture of one part formic acid and three parts freshly filtered lemon juice, and left in darkness for ten minutes.

2. The pieces of tissue were removed and dried between the folds of a clean towel, transferred to 1% gold chloride and returned to the dark for a further 10 minutes. At the end of this time the tissue was dried as before.

3. The tissue was next placed in 25% formic acid and left in darkness for 24 hours, at the end of this time it was removed and dried again. It was then placed in glycerine and left exposed to daylight for several days.

Apart from the glycerine all reagents were used in the minimum quantity sufficient to cover the tissue. The presence of too much gold chloride can lead to over-impregnation of the tissue.

To search for receptors, a small piece of tissue was placed on a slide under a coverslip with a small amount of glycerine and gradually teased to separate the various elements present and to produce a preparation transparent enough to allow the sense organs to be clearly seen. Pressure applied over the cover-slip was helpful in the early stages of the process, and after examination under the low-power objective the suitably stained areas were separated using mounted needles and fine scissors and were transferred to fresh slides. By repetition of this treatment, the pieces of tissue under examination was gradually reduced in size until a suitable preparation of a sense organ and its supplying nerve fibre was obtained, with the detail of its structure unobscured by other tissues. Tissue removed from almost every cat used for sensory nerve recording (section 5) was treated by this method.

In addition to its simplicity, the gold chloride method has the advantage that it produces a whole mount preparation of a sense organ as opposed to a section, and this is helpful in the study of structure. Its main disadvantage lies in the fact that the impregnation is unpredictable and much of the tissue treated is unsuitable for the demonstration of nerve endings. For this reason only a proportion of the nerve endings present in any one piece of tissue will be found and attempts to estimate the relative distribution of the different types of receptor will be inaccurate.

B. RESULTS

The anal canal of the cat is lined with stratified squamous epithelium showing no keratinisation. At the upper end of the canal there is an abrupt transition to the columnar epithelium lining the large bowel, while at the lower end the transition to the keratinising epithelium of the peri-anal skin is more gradual. Many nerve fibres could be seen branching in the subepithelial connective tissue, but no organised sensory nerve endings were found in or near the anal mucous membrane. In suitably impregnated silver preparations, however, fine nonmyelinated nerve endings could be seen running up to the lowest layer of the epithelium. No nerve endings were seen in the colonic mucous membrane, while in the hairy peri-anal skin only peri-trichial endings and undifferentiated nerve endings were found.

Discrete bundles of striated muscle fibres run in the loose connective tissue almost up to the lowest layers of the epithelium of the anal canal. These form the most superficial part of the external anal sphincter. Lamellated sense organs of the Pacinian corpuscle type were found lying between these bundles and also in the connective tissue planes of the deep part of the external sphincter (fig. 71). These varied from 200 to 500 μ in transverse diameter.

Muscle spindles were found in the external anal sphincter in both sexes. The gold chloride method was the most satisfactory for studying these though in many cases only part of the spindle was stained. Eleven muscle spindles, however, were found almost completely stained and of these, two were complex spindles, with spiral and spray endings (fig.70), while the other nine were simple spindles with spiral endings only (fig. 69). Muscle spindles were also found in the sphincter vaginae.

The external urethral sphincter muscle was studied in a large number of cats of both sexes, but no muscle spindles were found. The teasing part of the gold chloride method was more difficult to carry out on this muscle than on the anal sphincter because of the much tougher consistency of the urethral sphincter and the interweaving arrangement of the fibres.

A variety of lamellated end organs were found in and around the wall of the urethra. These varied from large Pacinian corpuscles lying in the peri-urethral connective tissue which were up to 500 µ in transverse diameter (fig.72) down to small 'cucumber shaped' endings lying in the urethral mucosa which were about 30 µ in transverse diameter, (figs. 74, 75, 76 & 77), with intermediate forms in the muscle layers and the deeper parts of the mucosa, 100 to 300 µ in diameter, (fig. 73). The larger Pacinian corpuscles and those intermediate in size, were similar in structure to lamellated sense organs found in other sites in the cat. They were most common in the region of the prostate and Cowper's glands where the urethra changes direction and a section of the urethra taken at one of these sites sometimes showed several sense organs. Apart from the flexures, the lamellated sense organs were most easily found in the external sphincter region and were rare along the proximal urethra.

The small 'cucumber shaped' endings were found only in the most superficial layers of the urethral mucosa in which they lay immediately under the epithelium. They were usually situated at the summits of the folds which develop in the urethral mucosa when the urethra is empty. They were found in groups of two to five endings (figs. 74 & 75) with the long axis parallel to the direction of flow of the urine.

In teased preparations of the urethral mucosa stained with gold chloride, the small lamellated end organs could be seen entire (fig. 77). They could be seen to have a darkly stained central portion continuous with the supplying nerve fibre, and this was surrounded by a paler staining zone of granular cytoplasm. This in turn was surrounded by five or six lamellae of flattened cells, concentrically arranged. The whole structure was about 30 μ in transverse diameter and was about 250 μ in length.

C. DISCUSSION

In the present investigation a definite correlation was not attempted between the experimentally recorded sensory nerve discharges and the histologically demonstrated sense organs. To establish this correlation it is necessary to localise the source of the discharge very accurately to a small piece of tissue and to remove this piece of tissue from the living animal while continuing to record the discharge as long as possible. The removed tissue must then be examined histologically and shown to contain only one type of sense organ. This technique can rarely be carried out successsfully on more than one occasion in each animal, and later the result may be found to be indecisive since more than one end organ may be found in the tissue removed. In addition, metallic impregnation techniques, which are the most suitable for demonstrating nervous structures, are notoriously capricious in their reaction and the failure to demonstrate a particular sense organ in a piece of tissue, does not necessarily imply that such a sense organ is absent. For these reasons no attempt was made to carry out experiments along the above lines and therefore, the association between the discharges and the end organs must be presumptive.

The most satisfqctory association is that between the slowly-adapting discharge produced by stretching the external anal and vaginal sphincters and the muscle spindles demonstrated in these muscles. The time course of the adaptation curve of these discharges is similar to that of muscle spindles in soleus (Matthews 1933), while the finding of a pause in the discharge on motor nerve stimulation, indicates that the receptor lies in parallel with the muscle fibres, and makes the identification of the discharge with the muscle spindle virtually certain.

Barker (1948), using the classification originally proposed by Ruffini (1898), described three types of muscle spindle on the basis of the sensory endings which they contained. The simple spindle contains a single annulo-spiral ending, the intermediate type contains an annulo-spiral ending and a single ending of the spray type, while the complex spindle has two or more spray endings in addition to the annulo-spiral ending. He found that the simple type outnumbered the complex type by about three to one in the skeletal muscles of the cat. In the present enquiry both simple and complex spindles were found in the external anal sphincter. Two were complex and nine simple. This limited number does not permit a decision as to their relative abundance in this muscle. Little is known of any differences in function between the two types.

The various organised sense organs, lamellated endings of the Pacinian corpuscle type, which were found in and around the external anal sphincter are presumably responsible for the rapidly adapting type of discharge seen on distending the anal canal. Gray & Malcolm (1951) showed that Pacinian corpuscles in the mesentery of the cat were sensitive to rapidly applied mechanical deformation, to which they responded with a single impulse or a brief burst of impulses in a rapidly adapting fashion. This result has been confirmed by other workers and the earlier report by Adrian & Umrath (1931) that Pacinian corpuscles in the toe pad of the cat responded to the application of a steady pressure with a sustained discharge, is now regarded as being in error. It seems reasonable to believe that all receptors with the same basic lamellated structure behave as rapidly adapting mechano-receptors.

The absence of specialised nerve endings from the anal mucous membrane of the cat in this investigation, contrasts with the findings of Duthie & Gairns (1960) in man and there is probably a species difference since the same histological techniques were used in the two investigations. The rapidly adapting receptors in the anal region are probably responsible for the reflexes produced by movement in the anal canal.

In view of the report by Gerbetzoff & Grieten (1956) that the external urethral sphincter in the rabbit and guinea pig is rich in 'intra-fusal' muscle fibres, the failure to demonstrate muscle spindles in the external urethral sphincter of the cat in the present investigation seems surprising. This is especially so, since the external sphincters of the anus and urethra share a common embryological origin and a common nerve supply and since spindles are present in the external anal sphincter. On the other hand, Gerbetzoff & Grieten made the distinction between intra-fusal and extra-fusal muscle fibres on the basis of a difference in the distribution of cholinesterase in the motor end plates of the two types of fibre as revealed by a histochemical method. On no occasion did they actually demonstrate muscle spindles. To assess the significance of their result, I examined the external urethral sphincter of the guinea pig, with the gold chloride method. This was the muscle which they had reported as containing the largest number of 'intra-fusal' muscle fibres of all, but no muscle spindles were demonstrated.

The external urethral sphincter is a difficult muscle to tease. Unlike the external anal sphincter, where the muscle fibres lie parallel to one another, it is composed of interlacing bands of muscle fibres running in all directions and forming a rough cohesive mass. It is difficult to see how muscle spindles could be under resting tension or how a receptor of variable length could play a useful role in this situation. No discharge of the muscle spindle type could be recorded from the urethra of the cat either in the present investigation or in that of Talaat (1937).

It is not clear, then, which receptors could act as the source of the afferent stimulation for the reflex tone of the urethral sphincter since no receptors were found in the urethral region which had a sustained discharge. On the other hand, reflexes which cause contraction of the anal sphincter, such as the anal reflex, also cause contraction of the urethral sphincter and the two muscles behave as part of a single muscle mass when inhibition occurs. It may be that the resting afferent discharge from the spindles in the anal sphincter drives both muscles.

A variety of end organs of the lamellated type were found in and around the wall of the urethra. These vary from large end-organs of the Pacinian corpuscle type lying in the peri-urethral connective tissue, to the small 'cucumber' endings with only five or six surrounding lamellae, lying in the urethral mucosa immediately beneath the surface epithelium. There were also other receptors intermediate in size and form lying in the urethral wall, especially in the muscle layers. As already stated, it is likely that all receptors of this basic pattern behave as rapidly adapting deformation receptors and it seems probable that those furthest out from the lumen respond to sudden distension of the urethra or to any sudden marked change in the rate of flow. The small 'cucumber shaped' endings probably respond to the vibration effect produced by turbulence in the flow of urine. These small endings are situated at the summits of the mucosal folds with the long axis parallel to the direction of flow where they will be most exposed to any local turbulence. It may be significant that the greatest concentration of lamellated receptors of all sizes is in the regions of the prostate and bulbo-urethral glands, that is at either end of the external sphincter where variation in the calibre and direction of the urethra occur and where conditions wuld be most favourable to the development of turbulence.

The function of lamellated sense organs in the body has for long been a matter for conjecture. They are found in many sites :- in the mesenteries and in retro-peritoneal fat depots, in the peri-anal and genital regions, in the foot pads, along the course of large blood vessels (Roberts 1955), in fascial planes, in the periosteum, and in the deep seated abdominal viscera. Small end organs, apparently identical in structure with the 'cucumber shaped' endings of the urethral mucosa, have been described in the capsule of the cat knee joint by Boyd (1954) and have been positively identified by him as the source of a rapidly adapting type of discharge in the articular nerve, using the procedure outlined at the beginning of this chapter. Although the stimulus response relationship of lamellated endings is now well known and the mechanism by which the action potentials are generated has been closely studied, it has rarely been possible to ascribe to these endings a specific role in the economy of the body, apart from supposing them to be concerned in vascular reflexes, in postural reflexes or in deep sensation. On the other hand, well defined reflexes are described for which the normal stimulus is flow along the urethra (Barrington's second and seventh micturition reflexes and the urethral guarding reflex described in this thesis).

If it is accepted, as is suggested in this discussion that the 'cucumber shaped' endings are responsible for the flow receptor discharge and that the flow receptor discharge is responsible for these reflexes, this will be one of the first instances in which it has been possible to ascribe a specific physiological role to such end organs.

D. Summary

The histology of the sense organs in the anal and urethral regions was investigated using gold and silver impregnation techniques supplemented by conventional staining methods.

Typical muscle spindles of simple and complex types are present in the external anal sphincter and in the sphincter vaginae. Lamellated end organs of the Pacinian corpuscle type are found in the ischio-rectal fat, in the subcutaneous tissue and within the external sphincter. No specialised end organs were found in or under the anal mucous membrane, nor in the mucous membrane of the colon.

Pacinian corpuscles lie in the connective tissue which surrounds the urethra and in the outer parts of the striated muscle of the external urethral sphincter. Small lamellated 'cucumber shaped' endings lie in the mucosa of the urethra immediately under the surface epithelium and particularly at the tips of the mucosal folds. These have a basic lamellated structure but with only five or six lamellae. No muscle spindles were found in the external urethral sphincter.

It is suggested that the muscle spindles present in the external anal sphincter are responsible for the slowly adapting stretch receptor discharge seen on distension of the anus and that the small lamellated endings in the urethral mucosa are responsible for the flow receptor discharges.

GENERAL SUMMARY

The experiments described in this thesis represent an attempt to study the role of the pudendal nerve and the structures which it supplies in the mechanisms controlling evacuation and continence. The problem was approached from several directions. First the morphology of the striated sphincters and other related muscles was studied by gross dissection and conventional histological techniques. Then the morphology of the pudendal nerve was investigated in relation to its function by means of a quantitative study of its fibre size distribution. The motor function of the pudendal nerve and the outgoing side of the reflexes in which it participates were investigated by electromyography, while its sensory function was studied by direct electrical recording from the individual nerve fibres. Finally the structure of the relevant sense organs was studied using neurohistological techniques. The results of these varied investigations form a complete whole. The results of the individual sections have been summarised in detail in the text and at this stage I shall only attempt to select those aspects of the findings which seem to me to be most significant.

One of the most striking features of the results is the similarity which they indicate between the behaviour of the external sphincters of the anus and of the urethra. This similarity is not surprising in view of the common embryological origin of the two muscles. From these results the concept emerges that the external sphincter muscles guard against the escape of rectal or bladder contents during periods of high intra-abdominal pressure and during periods when the rectum and bladder are very full. Although both external sphincters have a low grade tonic activity when the animal is at rest, they are not essential for the maintenance of continence at rest ; this is the function of the smooth muscle internal sphincters. An extension of this concept of the function of the external sphincters as guardians of continence during activity, is the realisation that a number of reflexes exist, the effect of which is to maintain continence. The idea that the maintenance of continence is based on a series of reflexes complementary to those described as the basis of defaecation and of micturition, has not, I think, been emphasised before.

The results of the nerve recording experiments are complementary to the results of the electromyographic experiments. The findings described in connection with the flow receptor discharges are of interest because of the light they throw on the functions of lamellated sense organs.

Although the results fall together neatly, I am well aware of the wide gaps which still remain to be filled. In particular an investigation, using electronic recording methods, of the reflex behaviour of the smooth muscle internal sphincters and of the sensory function of the pelvic nerve would probably be worth while.

It is tempting to think of the results of experimental work on animals in relation to the clinical problems of surgery and medicine but it is not certain how valid such a direct transference of results would be in this case since significant species differences exist. Two of the most striking of these differences are the absence of reflex bladder contraction after chronic spinal cord transection in the cat and the apparent absence in man of Barrington's second and seventh micturition reflexes as found in the cat. These differences, however, should not be allowed to obscure the fundamental similarity of the processes in the two species.

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STUDIES ON THE INNERVATION AND PHYSIOLOGY OF THE PELVIC PARTS OF THE ALIMENTARY AND URINARY TRACTS

by

JOHN KIRKLAND TODD

VOLUME II.

ILLUSTRATIONS

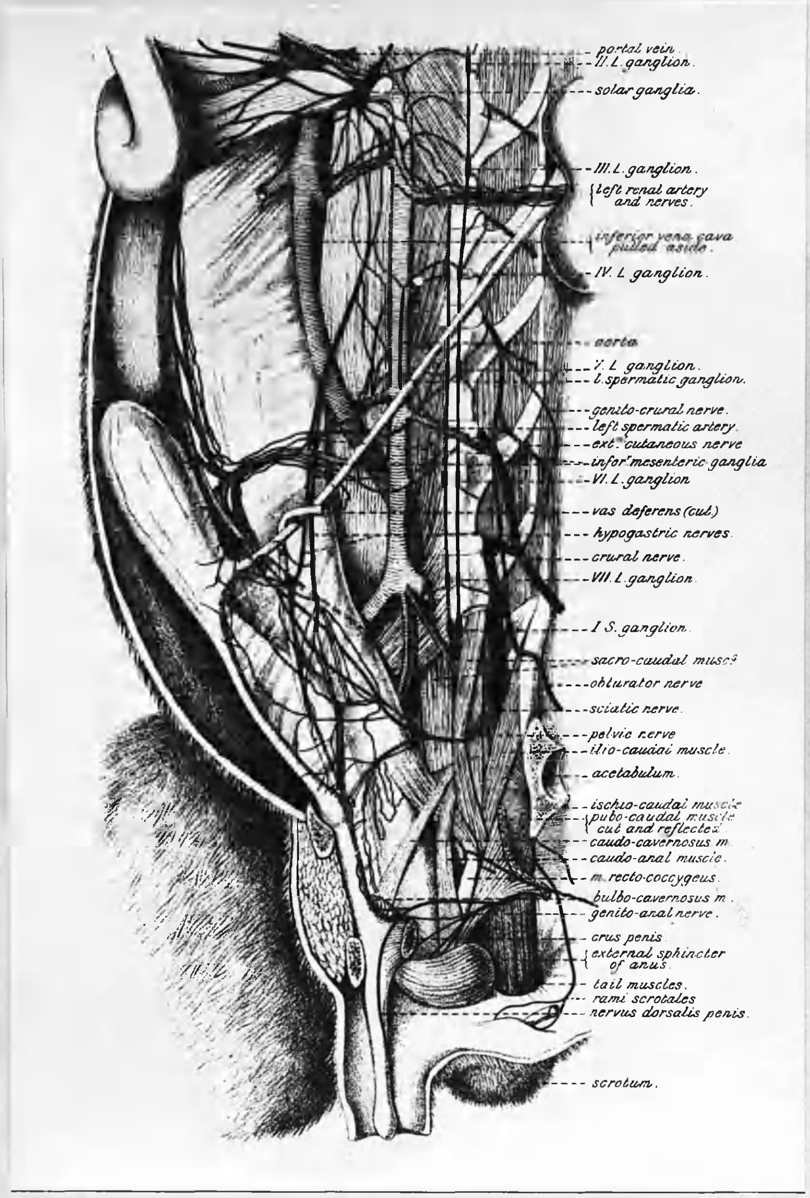

Fig. 1. A drawing of a dissection of the lower abdominal and pelvic viscera of a male cat to show the lower urinary and alimentary tracts with their nerve supply.

(From Langley & Anderson 1896)

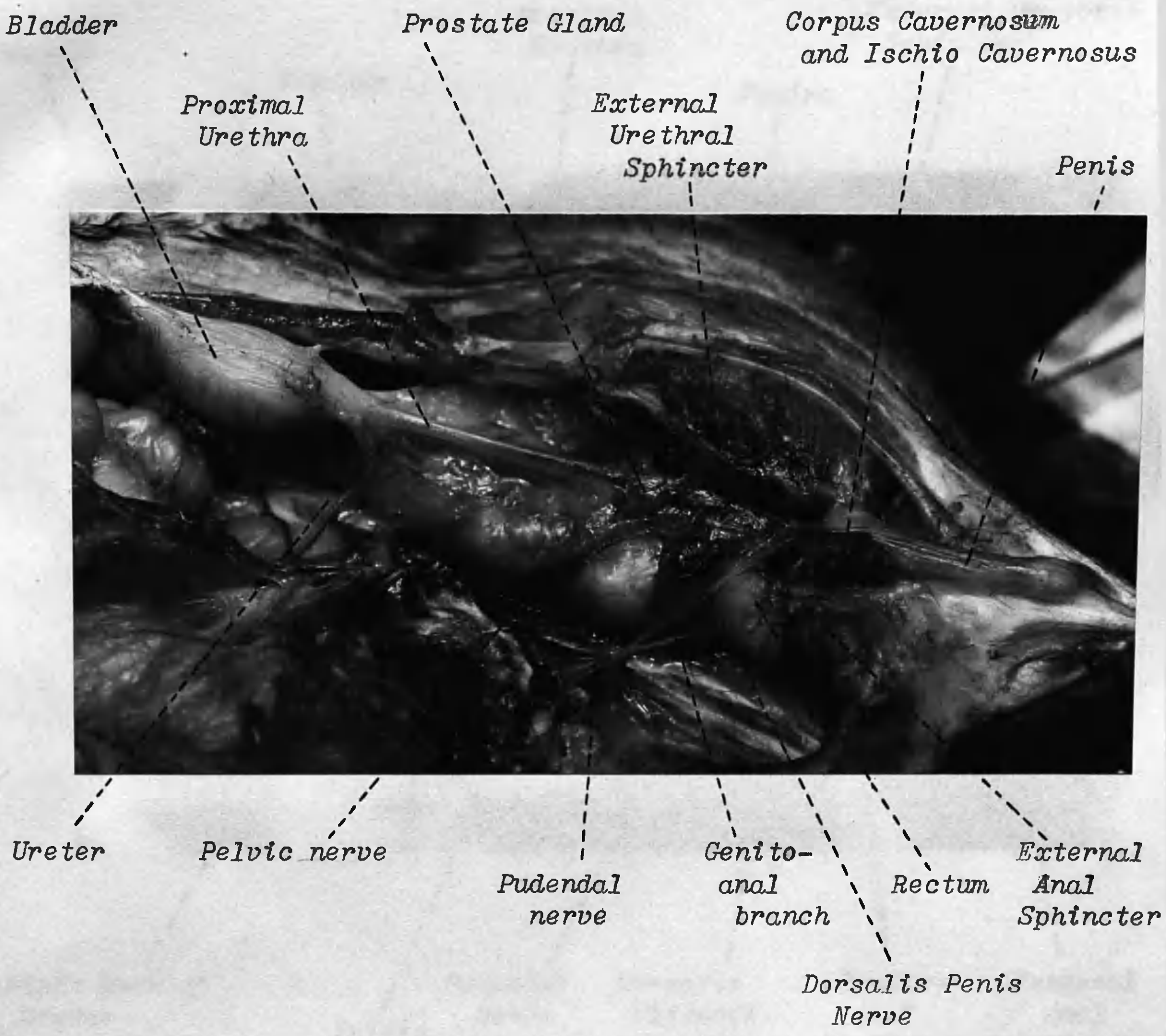

Fig. 2. A dissection of the pelvic viscera of a male cat seen from the front. The symphysis pubis has been split and separated. The anterior part of the right wall of the pelvis has been removed to expose the lower urinary and alimentary tracts. The three parts of the urethra can be clearly seen, together with the external sphincters of the anus and urethra. Note also the pelvic nerve running across the side of the rectum and the pudendal nerve dividing into dorsalis penis and genito-anal branches.

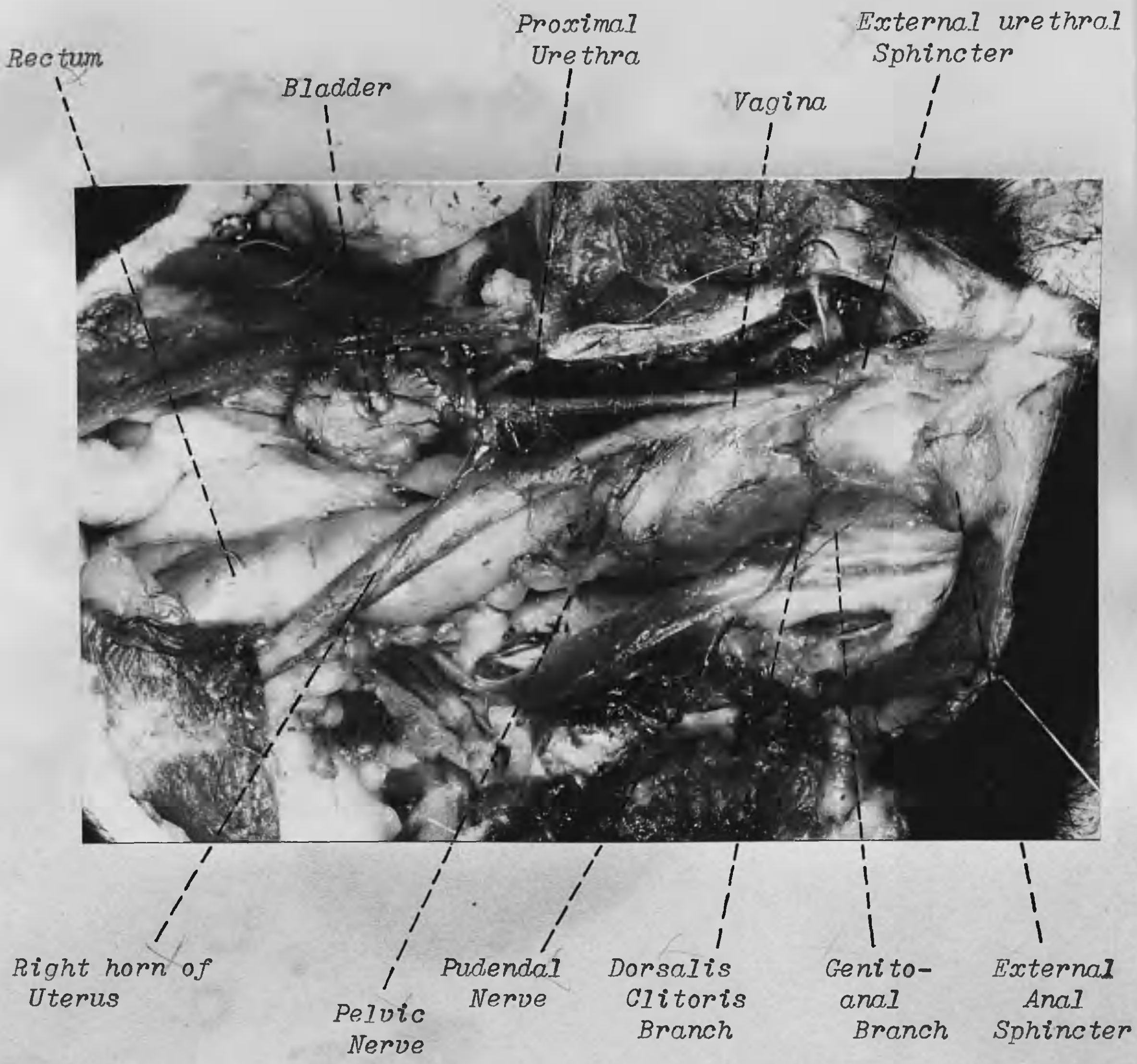

Fig. 3. A dissection of the pelvic viscera of a female cat seen from the front. The symphysis pubis has been split and separated. The anterior part of the right wall of the pelvis has been removed to expose the lower urinary and alimentary tracts. The two parts of the urethra can be seen. Note the close relation of the distal parts of the urethra to the vagina. Note also the pelvic nerve running across the side wall of the rectum and the pudendal nerve dividing into dorsalic clitoris and genito-anal branches.

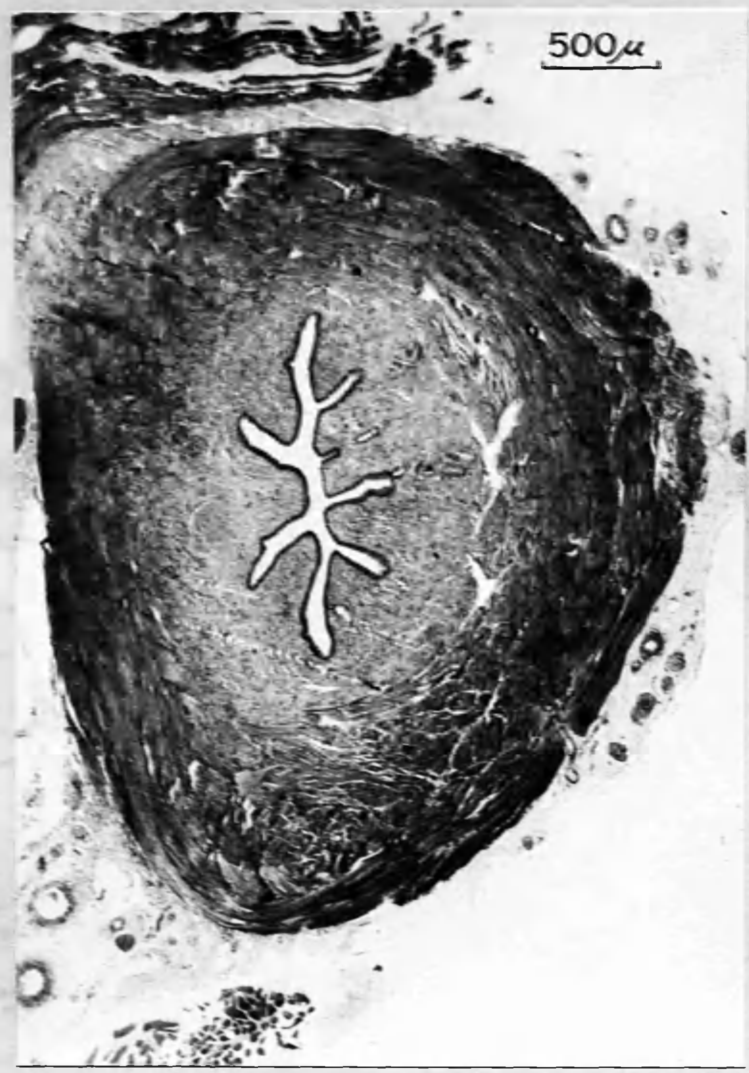

Fig. 4. A transverse section of the urethra of a male cat, taken at the level of the external urethral sphincter and stained with haemalum and eosin. Note the striated muscle fibres in the outer part of the urethral wall which constitute the external sphincter.

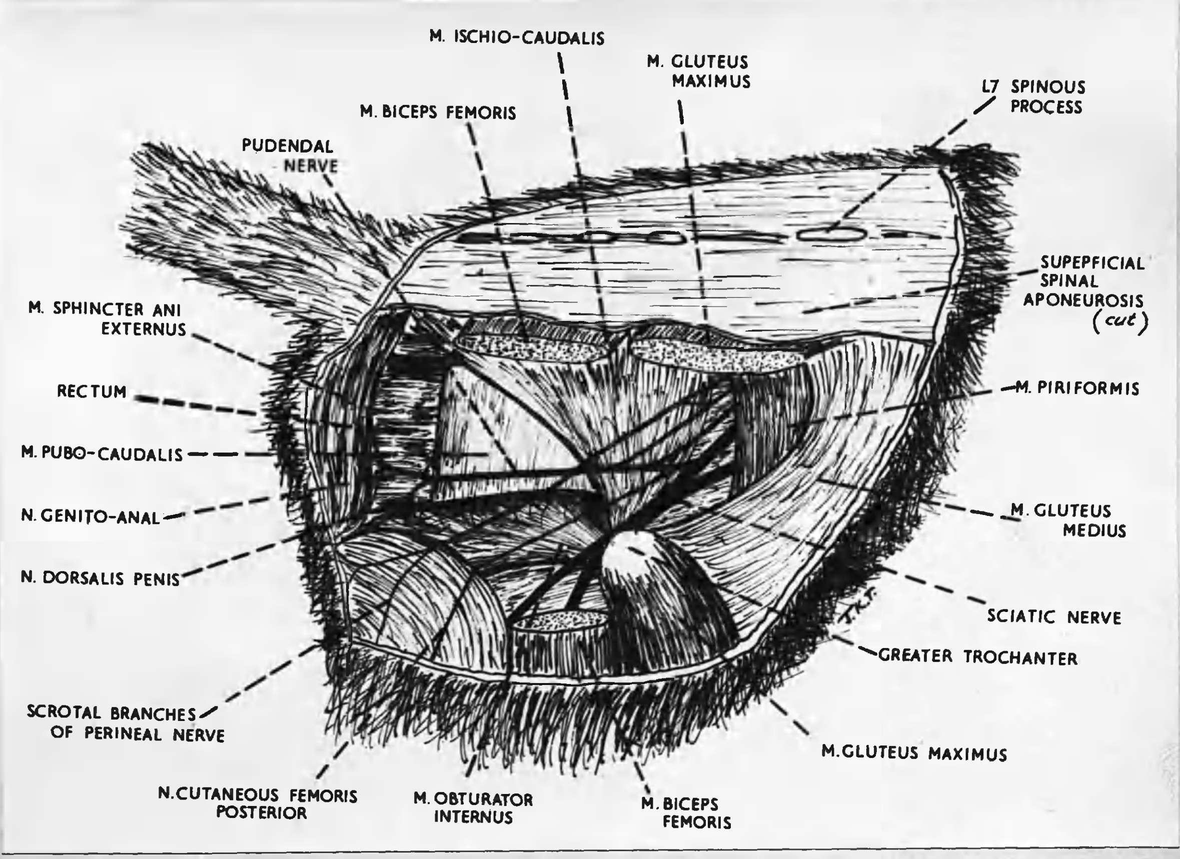

Fig. 5. *A drawing of a dissection of the lateral aspect of the gluteal and anal regions of a cat, showing the lumbo-sacral plexus in situ.*

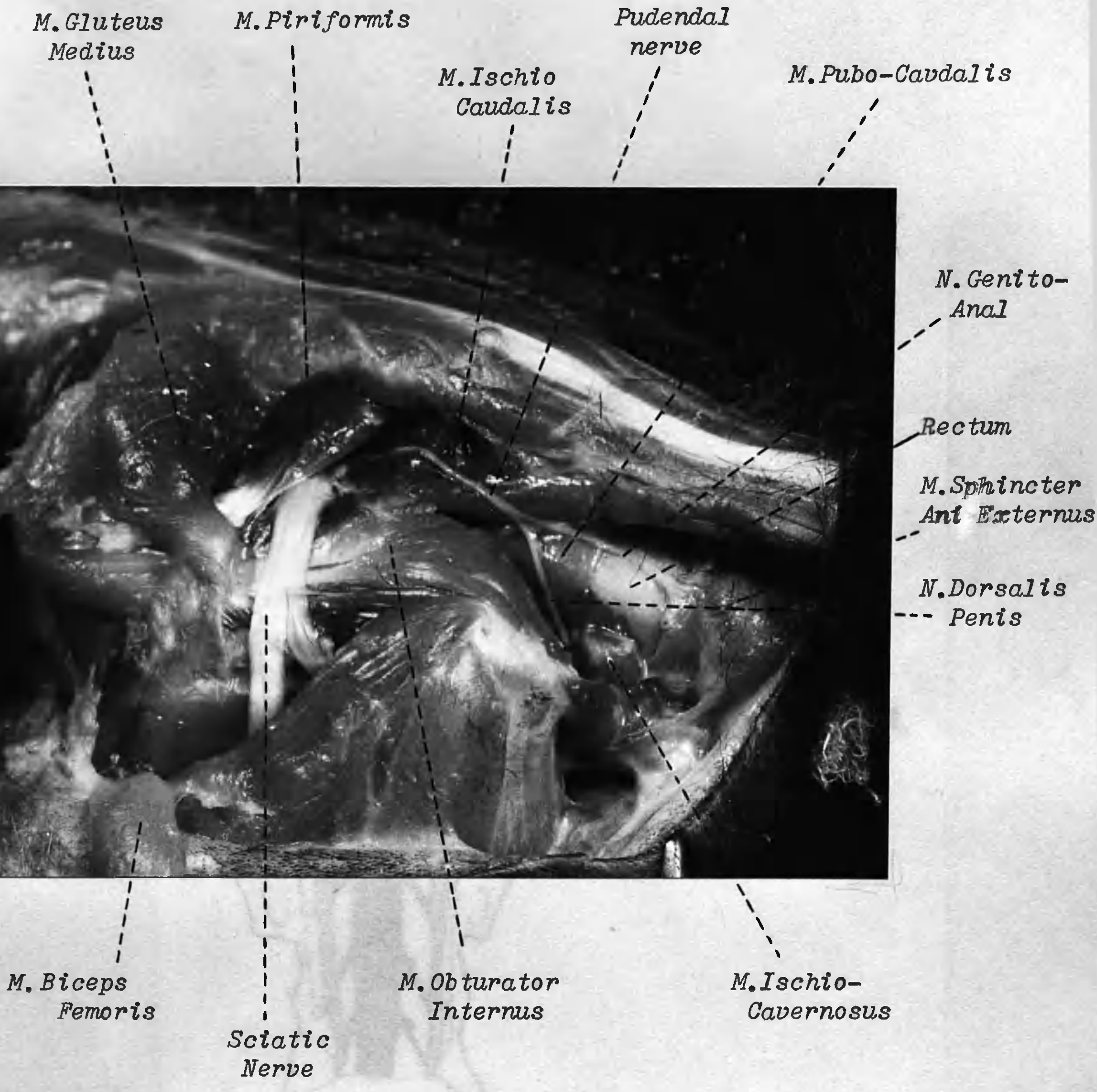

Fig. 6. A dissection of the gluteal and anal regions of a male cat seen from the left side, showing the external anal sphincter and the relations of the pudendal nerve.

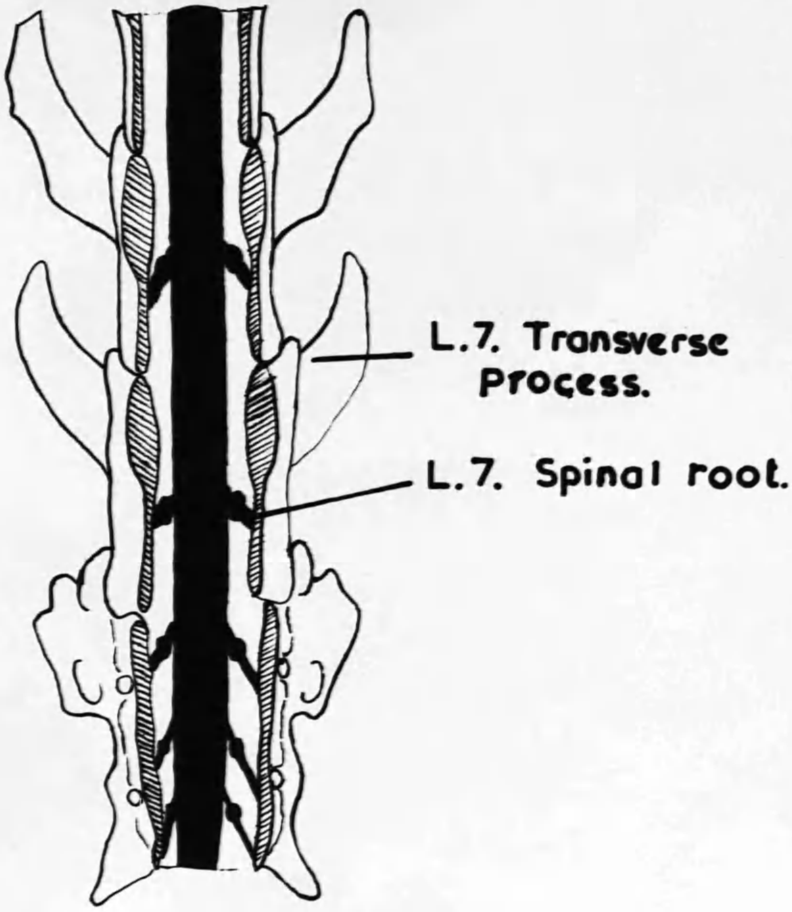

Fig. 7. *A diagram of the dorsal aspect of the lower lumbar and sacral vertebral column of the cat, with the dorsal laminae of L6, L7 and the sacrum cut away to show the relation of the spinal roots to the corresponding vertebrae.*

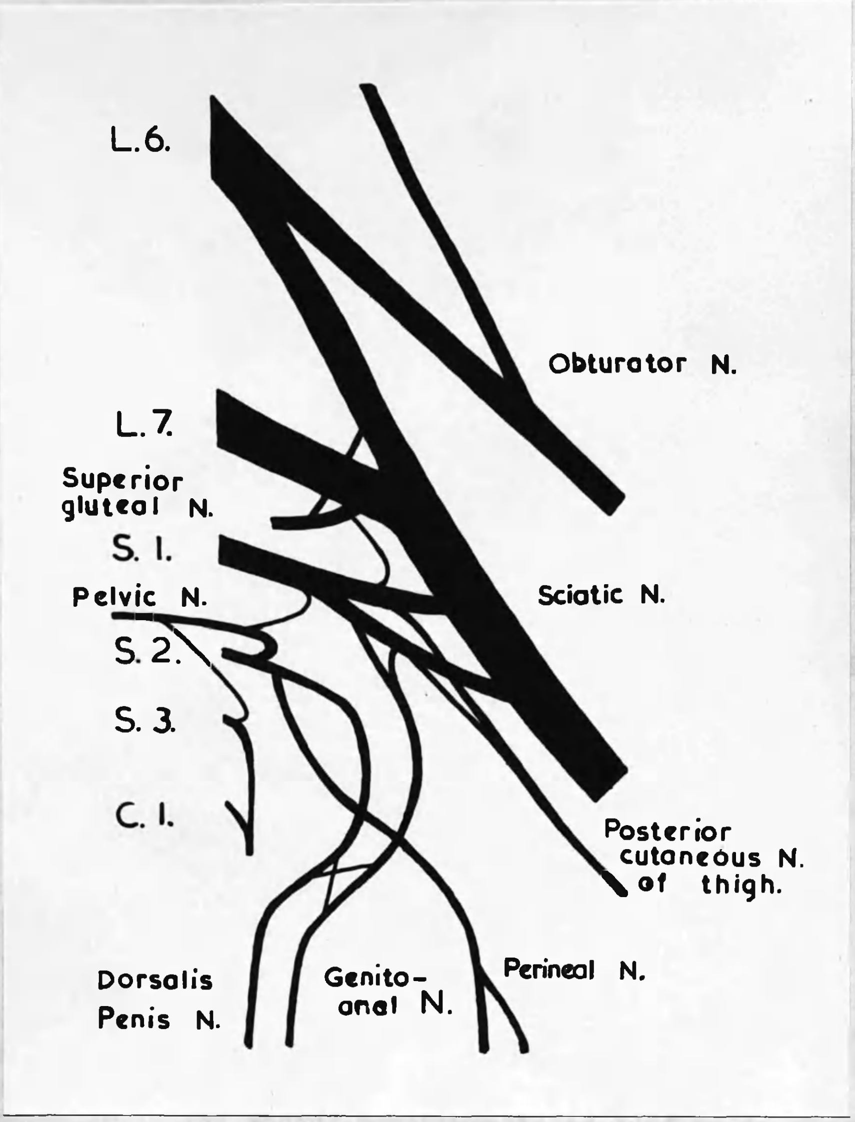

Fig. 8. A diagram of the lumbo-sacral plexus of the cat. This arrangement corresponds to the median fixation of the plexus as described by Langley & Anderson (1895f).

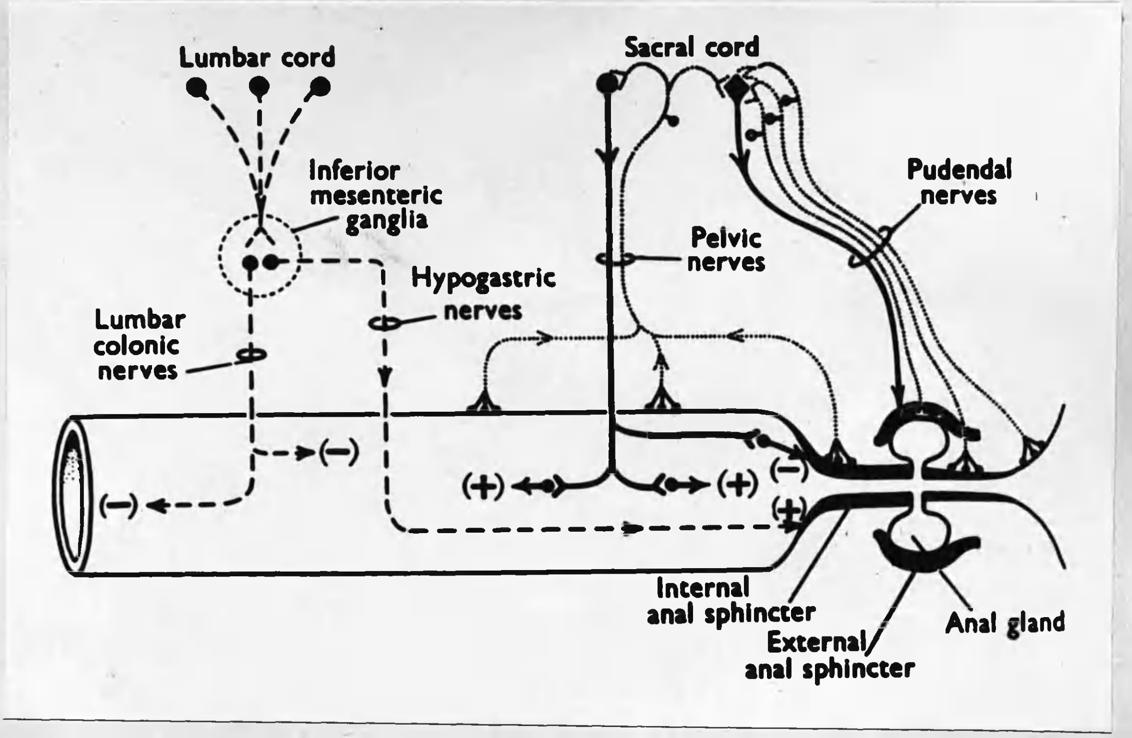

Fig. 9. A schematic representation of the innervation of the distal colon and anal canal in the cat. The lumbar sympathetic outflow inhibits the colon and is motor to the internal sphincter. The sacral parasympathetic outflow in the pelvic nerves is motor to the colon and inhibits the internal anal sphincter: ingoing fibres from the tissues surrounding the anal canal and from the wall of the colon run in the pelvic nerves. The pudendal nerves innervate the external anal sphincter: ingoing fibres from the circumanal skin, from the tissues surrounding the anal canal and from spindles in the external anal sphincter run in the pudendal nerves.

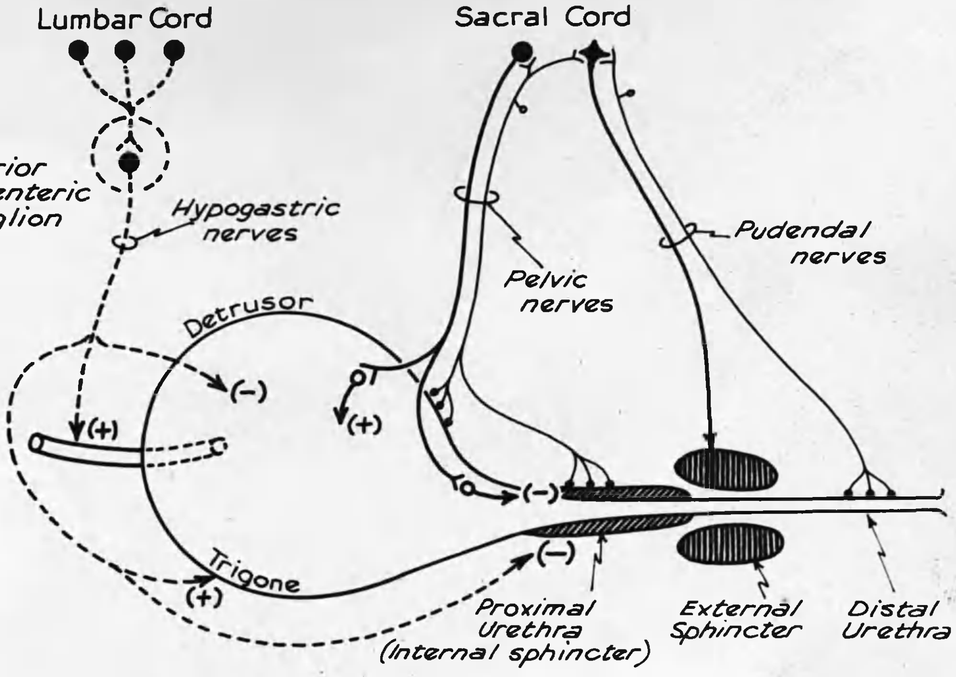

Fig. 10. A schematic representation of the innervation of the bladder and urethra in the cat. The lumbar sympathetic outflow inhibits the detrusor muscle of the bladder wall and is motor to the trigone and the internal sphincter. The sacral parasympathetic outflow in the pelvic nerves is motor to the detrusor muscle and inhibits the internal urethral sphincter: ingoing fibres from the proximal urethra and the wall of the bladder run in the pelvic nerves. The pudendal nerves innervate the external urethral sphincter: ingoing fibres from the skin around the external urinary meatus and the wall of the urethra run in the pudendal nerves.

Fig. 11. The second sacral spinal root on the left side, from a cat in which the sacral dorsal root ganglia of the left side had been excised twelve weeks previously. The three bundles in the upper part of the figure are the degenerated dorsal root (distal to the ganglion) and the two bundles below are the ventral root.

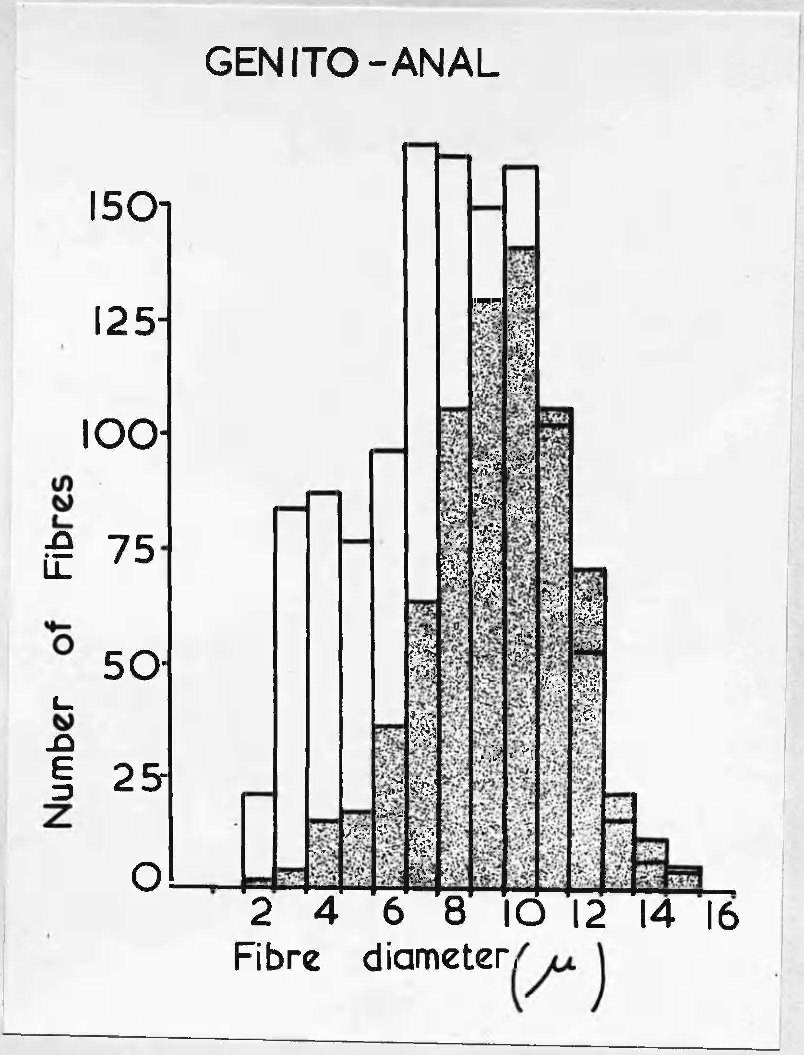

Fig. 12. *Fibre-size histograms of the genito-anal branch of the pudendal nerve of a male cat. The stippled columns represent the de-afferented nerve. The clear portions of the column show the numbers and diameters of the fibres disappearing on removal of the sacral dorsal root ganglia.*

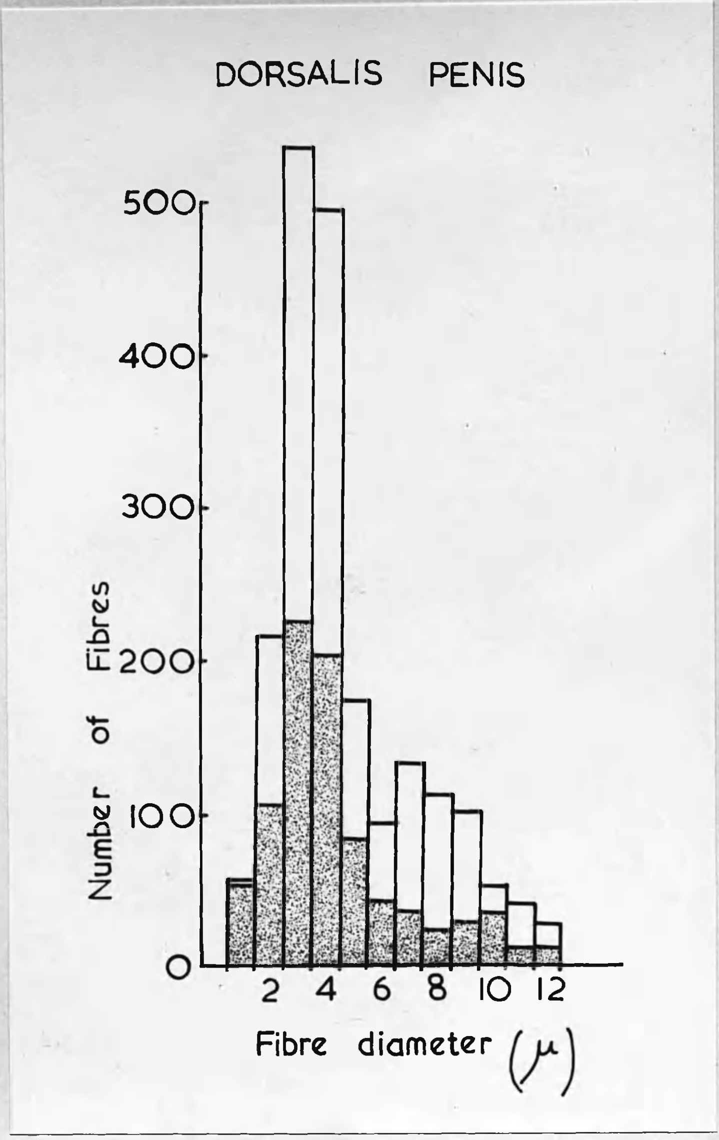

Fig. 13. Fibre-size histograms of the dorsalis penis branch of the pudendal nerve of a male cat. The stippled columns represent the de-afferented nerve. The clear portions of the columns show the numbers and diameters of the fibres disappearing on removal of the sacral dorsal root ganglia.

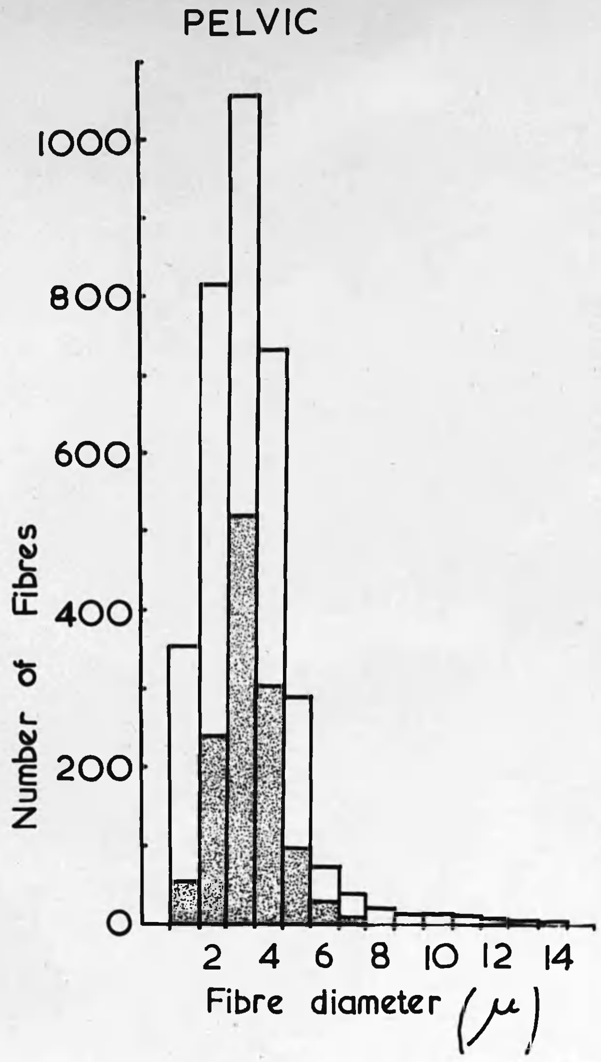

Fig. 14. Fibre-size histograms of the pelvic nerve of a male cat. The stippled columns represent the de-afferented nerve. The clear portions of the columns show the numbers and diameters of the fibres disappearing on removal of the sacral dorsal root ganglia.

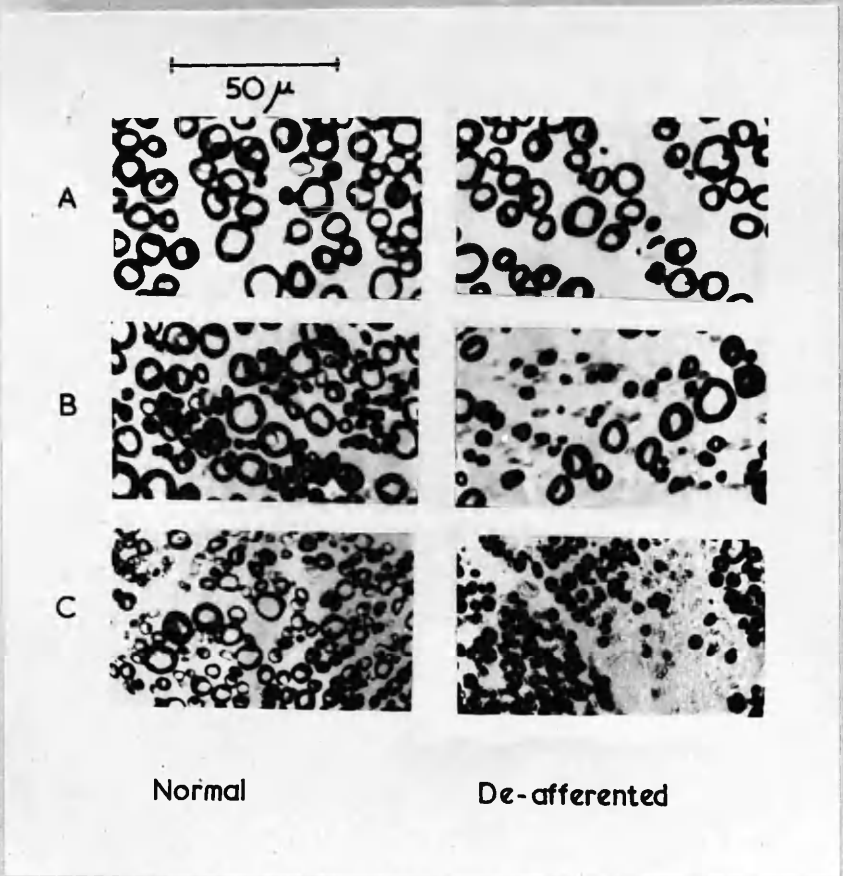

Fig. 15. Sample areas from the enlarged photographs used in the construction of the fibre-size histograms shown in Figs.12, 13 and 14. The samples in the right column are from the de-afferented nerves. The controls on the left are from the opposite side of the same animal.
(A) genito-anal branch; (B) dorsalis penis branch;
(C) pelvic nerve.

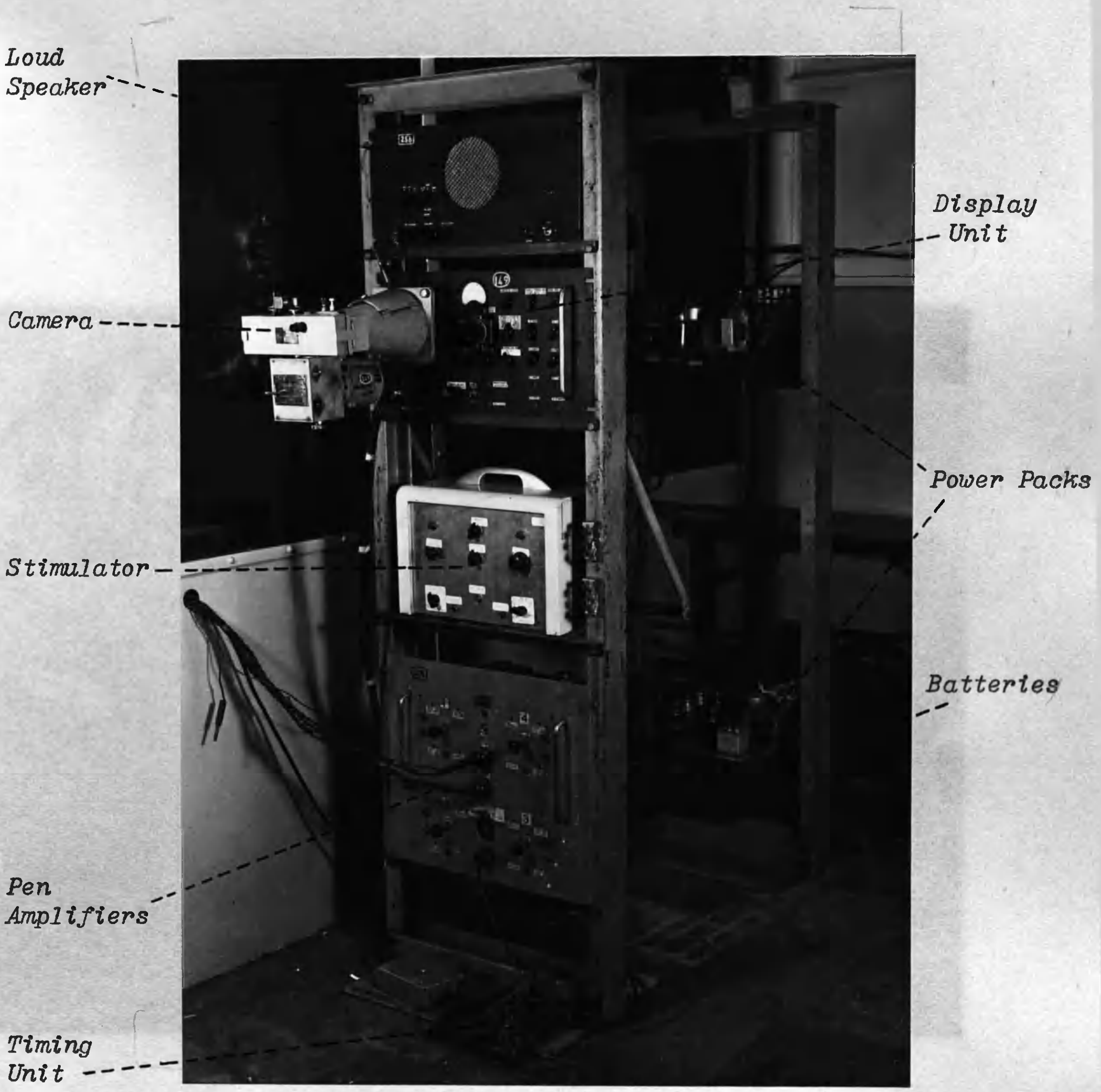

Fig. 16. A general view of the apparatus standing outside the wire screening. The following can be seen:- loud-speaker, double-beam display unit with camera mounted, stimulator, pen-amplifiers, timing unit, power packs and batteries.

Fig. 17. The Ediswan pen-recorder with the Palmer electric kymograph used to drive the paper.

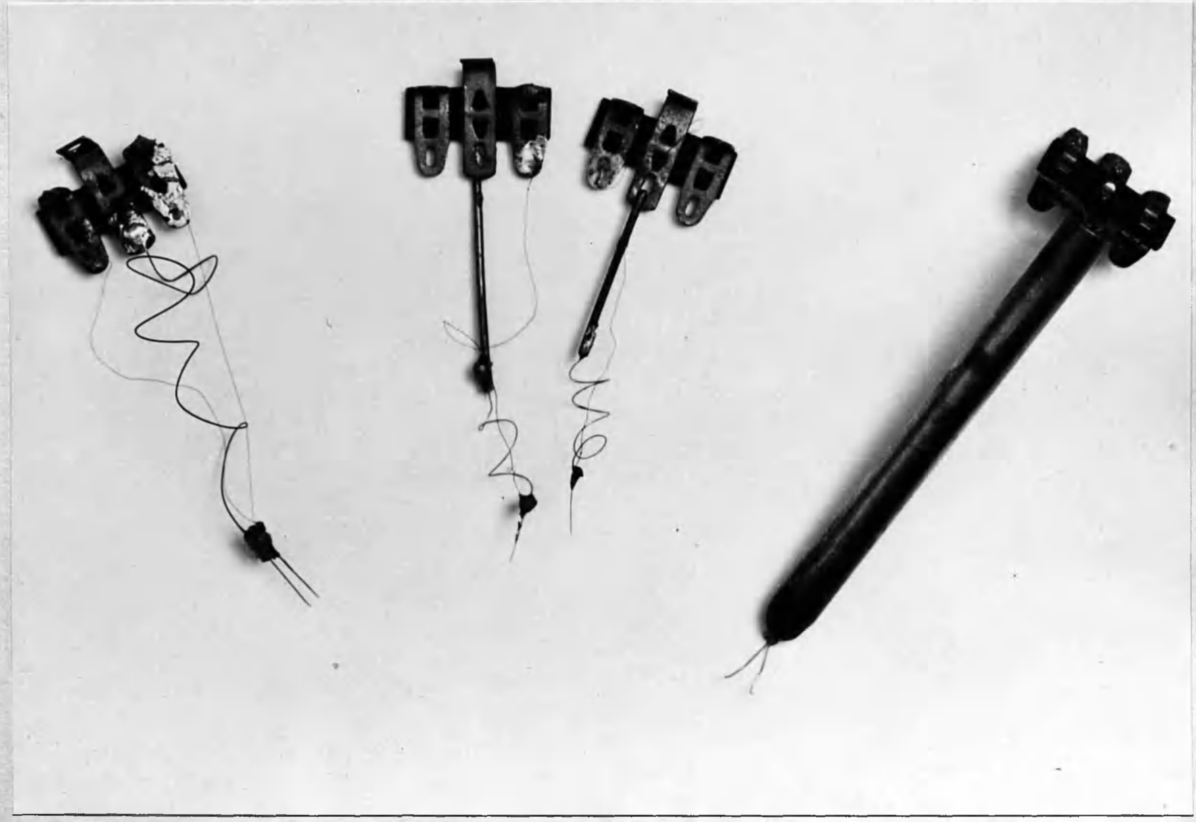

Fig. 18. The different types of recording electrodes used. On the left bi-polar muscle recording electrodes, in the centre a pair of uni-polar muscle recording electrodes and on the right the electrodes used for recording from nerve fibres.

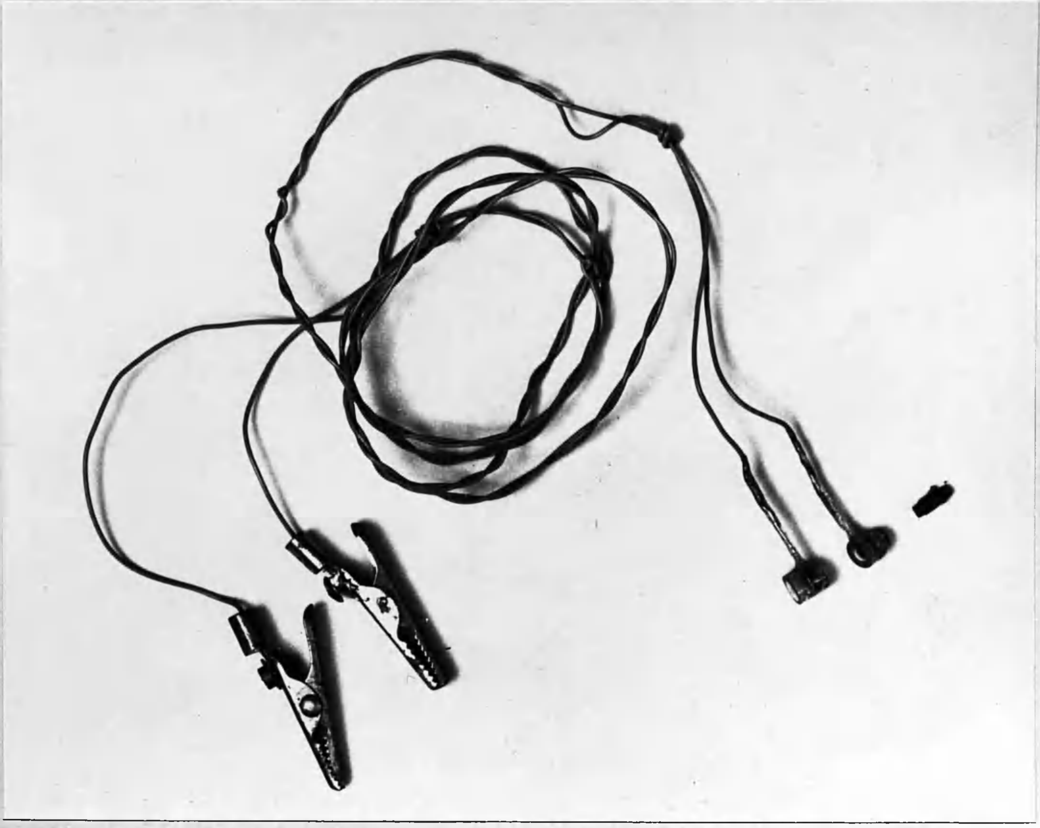

Fig. 19. The miniature fluid stimulating electrodes.

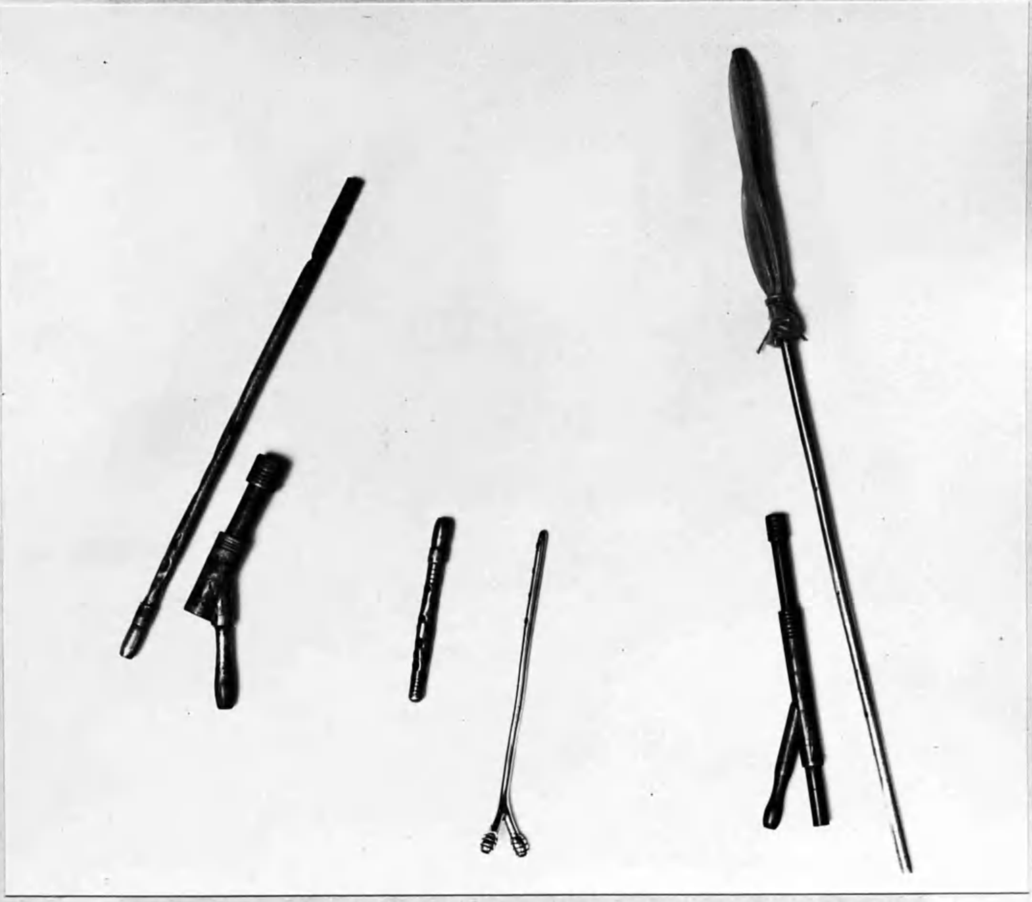

Fig. 20. Balloon holders and cannulae. From left to right:- tandem balloon holders, a small balloon holder used on the end of a rubber tube, a twin-channel urethral cannula and a second longer set of tandem balloon holders with a balloon tied on.

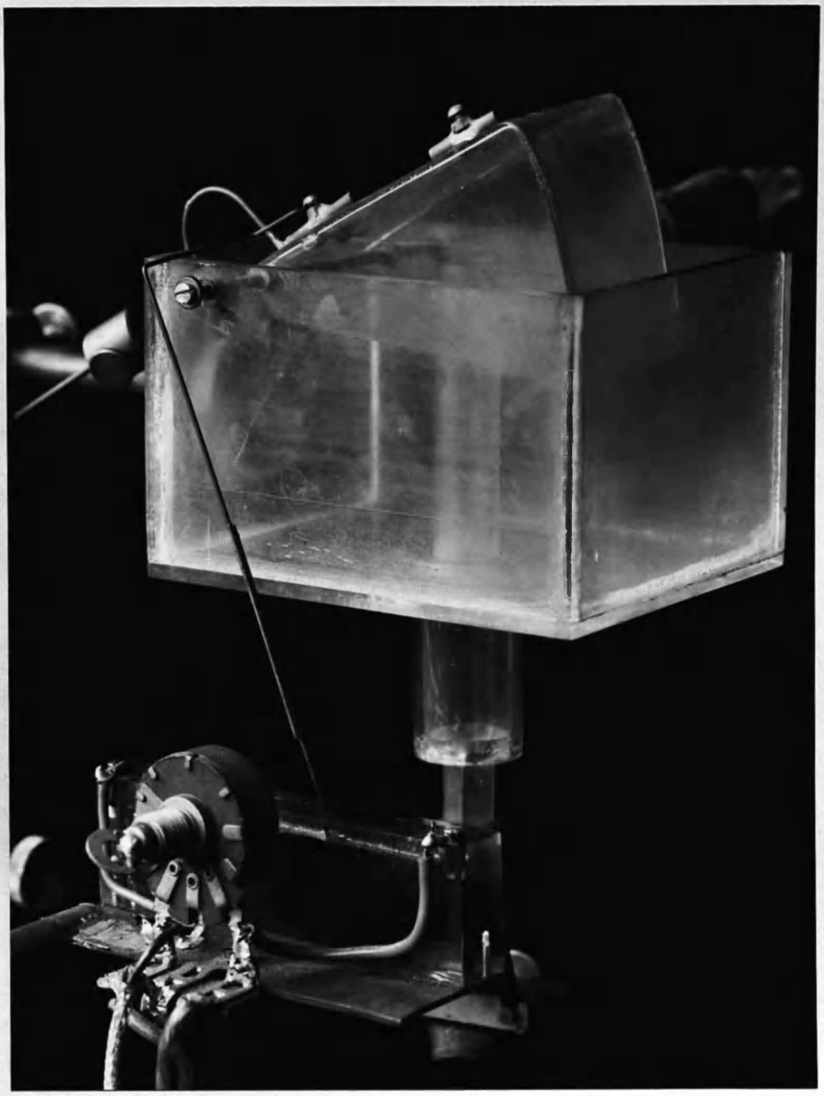

Fig. 21. The volume recorder in close up, showing the float with the side arm moving in the glycerine-saline trough.

Fig. 22. The electronic transducer manometer.

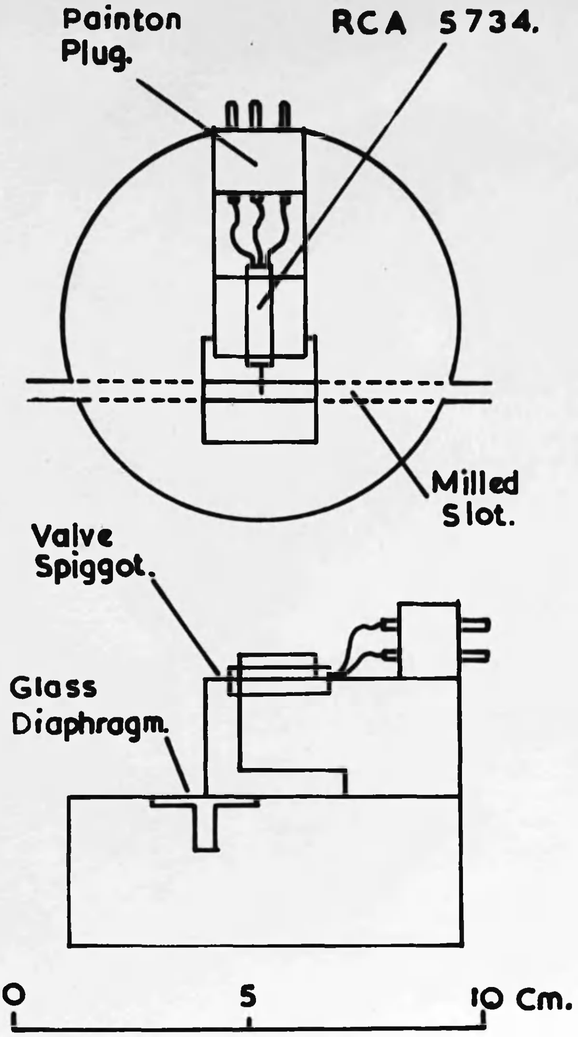

Fig. 23. A scale diagram showing the construction of the transducer manometer.

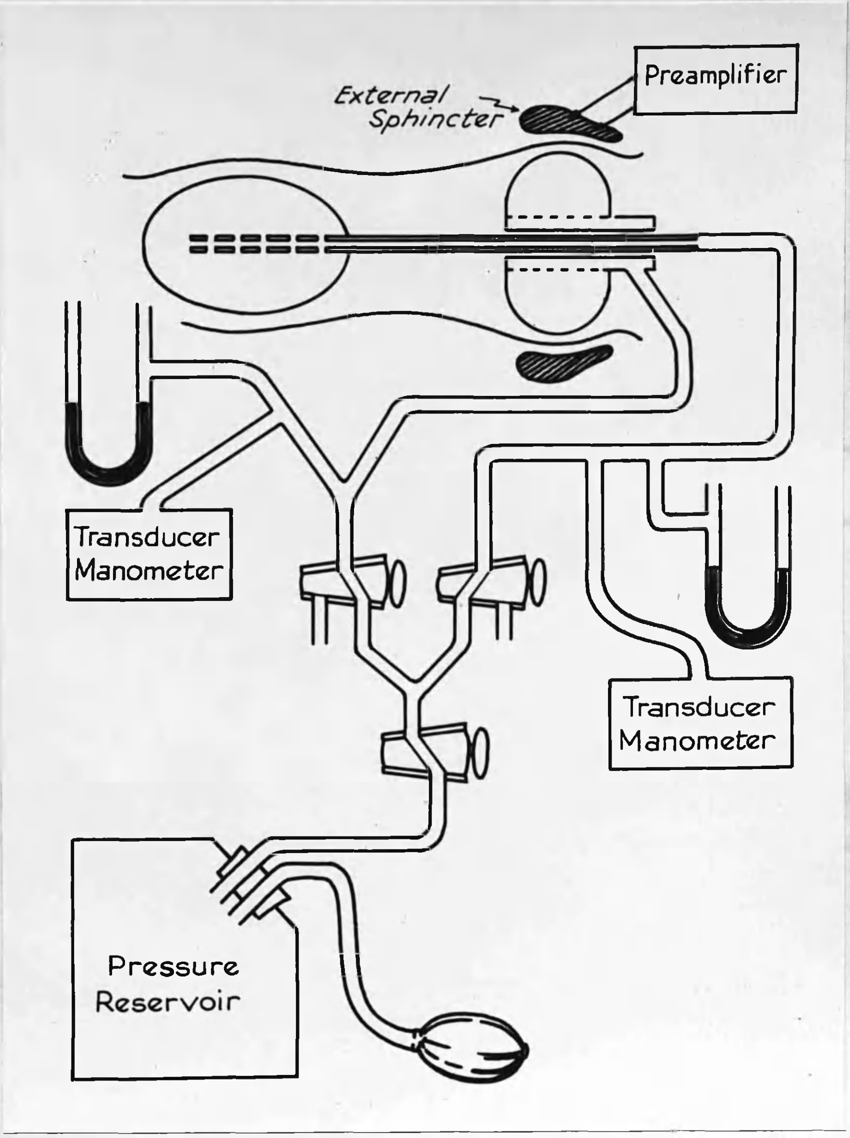

Fig. 24. A diagram of the experimental set-up used to investigate the reflex behaviour of the external anal sphincter and the sensory innervation of the anal canal.

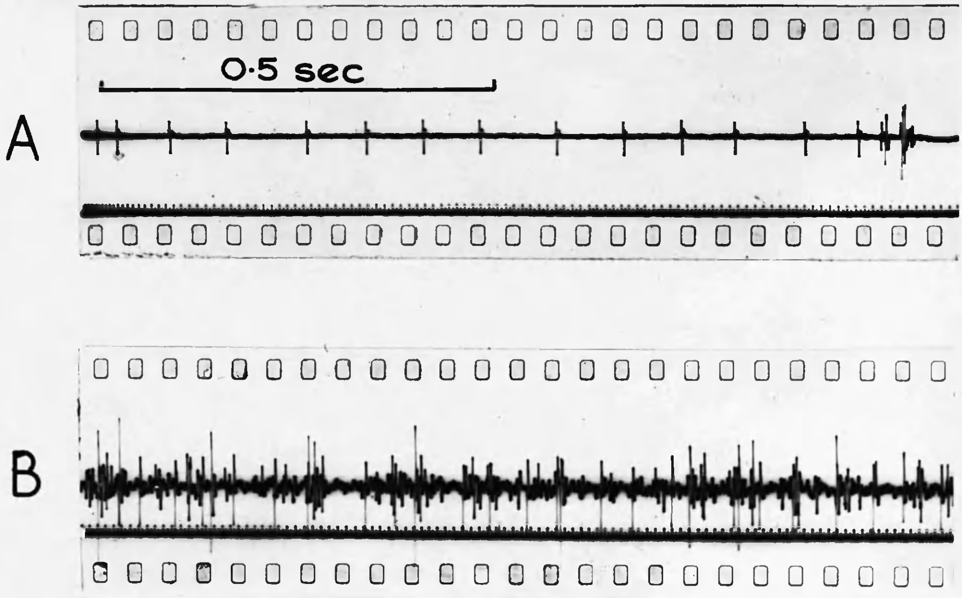

Fig. 25. Decerebrate male cat; oscillograph records of resting tone recorded from the external anal sphincter; (A) a record showing the activity of a single motor unit discharging at 12 impulses/sec. (B) a record showing several active motor units. A discharge of the second type was used in most of the records made with the pen-recorder. Records read from left to right.

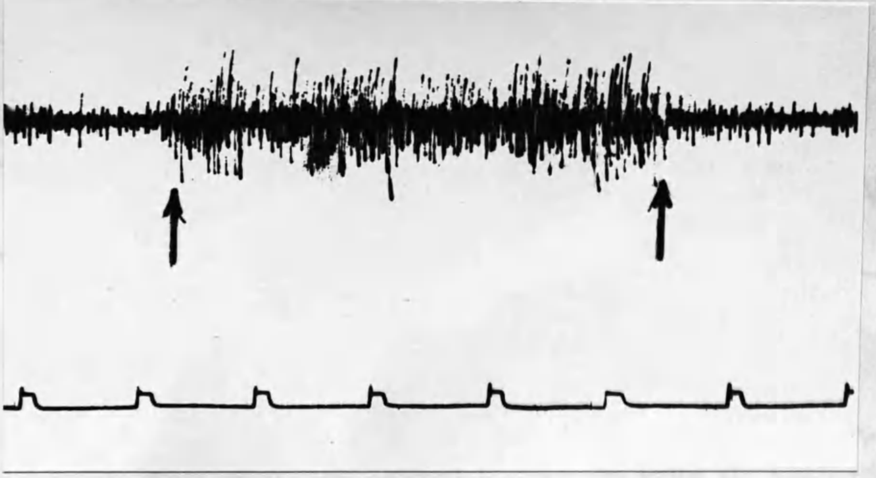

Fig. 26. Decerebrate female cat; pen-oscillograph record from the external anal sphincter. Between the arrows the circum-anal skin was stimulated with the point of a sharp needle. Note the increase in the discharge (the anal reflex). Record reads from left to right. Time = 1 sec.

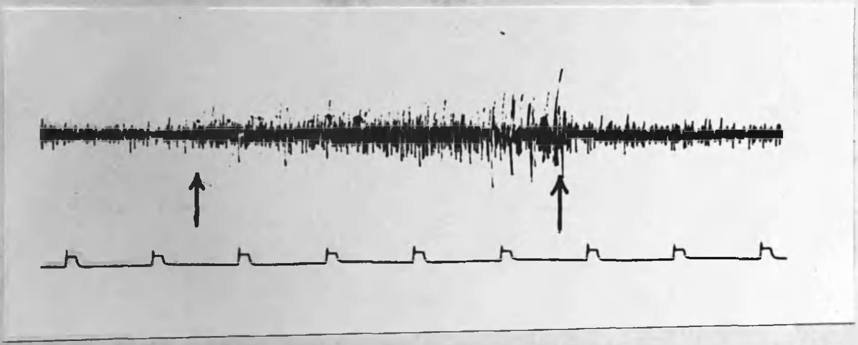

Fig. 27. Decerebrate female cat; pen-oscillograph record from the external anal sphincter. Between the arrows pressure was applied over the lower anterior abdominal wall. Note the increase in the discharge. Record reads from left to right. Time = 1 sec.

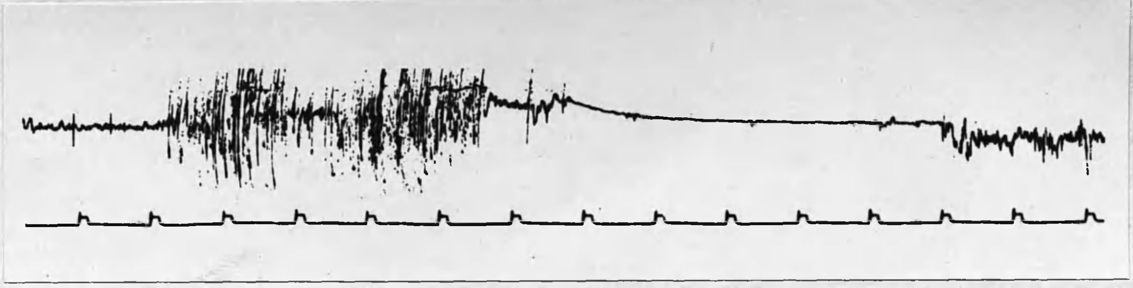

Fig. 28. Decerebrate male cat; pen-oscillograph record taken from the external anal sphincter while a foreign body (a thermometer lubricated with vaseline) was introduced into the anal canal from without. Note the initial burst of activity which is followed by a period of reduced discharge before the tonic activity reappears. Record reads from left to right. Time = 1 sec.

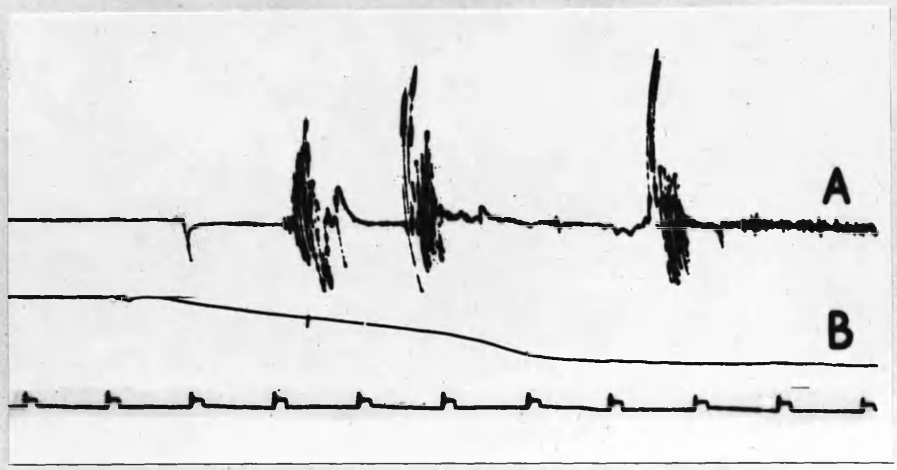

Fig. 29. Decerebrate male cat; (A) pen-oscillograph record from the external anal sphincter; (B) pressure in colonic balloon (an upward deflection indicates an increase in pressure). The balloon had been inflated to 60 mm Hg two minutes before the record was taken and the pressure was maintained. Eventually a 'defaecation' response set in and the balloon was expelled through the anal canal at the time indicated by the fall in pressure shown in this record. Note the bursts of sphincter activity which accompany the passage of the balloon through the anal canal. Record reads from left to right. Time = 1 sec.

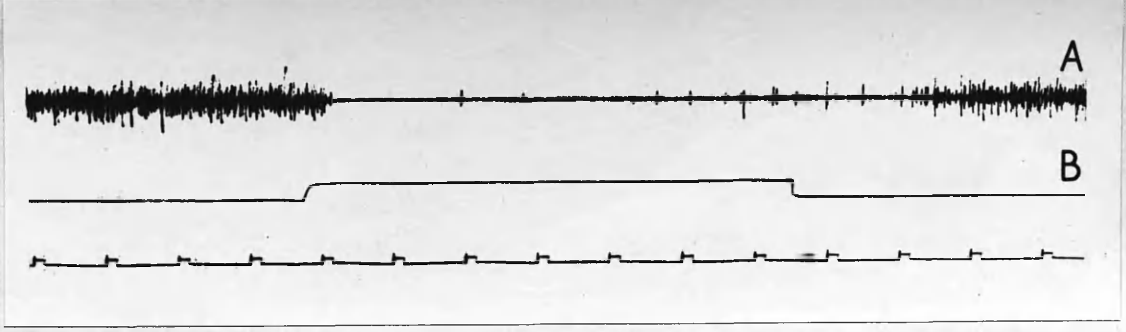

Fig. 30. Decerebrate female cat; (A) pen-oscillograph record from the external anal sphincter; (B) pressure in a balloon lying in the colon 5 cm from the anus (an upward deflection indicates an increase in pressure). The balloon was inflated to a pressure of 20 mm Hg from a reservoir of air. Note the inhibition of the discharge from the sphincter when the pressure is raised. Record reads from left to right. Time = 1 sec.

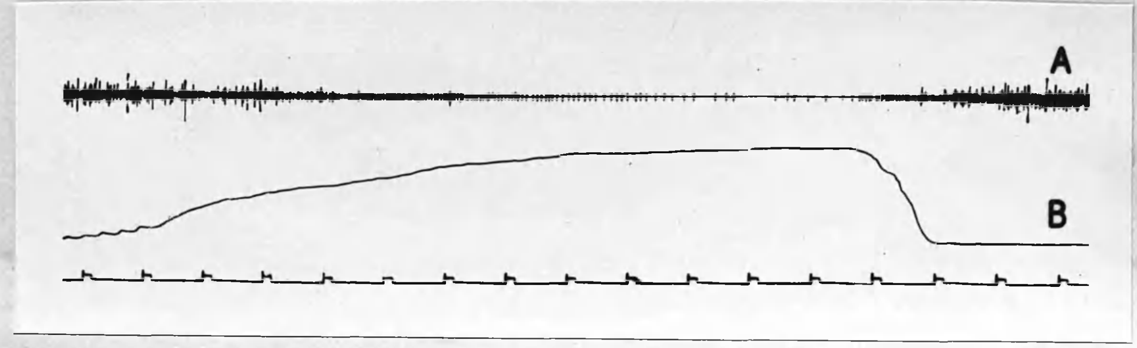

Fig. 31. Decerebrate female cat; (A) pen-oscillograph record from the external anal sphincter; (B) pressure in a balloon lying in the colon (an upward deflection indicates an increase in pressure). The balloon was gradually inflated to a pressure of 60 mm-Hg using hand bellows. Note the reduction in the number of motor units firing and the reduction in firing frequency of the individual units. Record reads from left to right. Time = 1 sec.

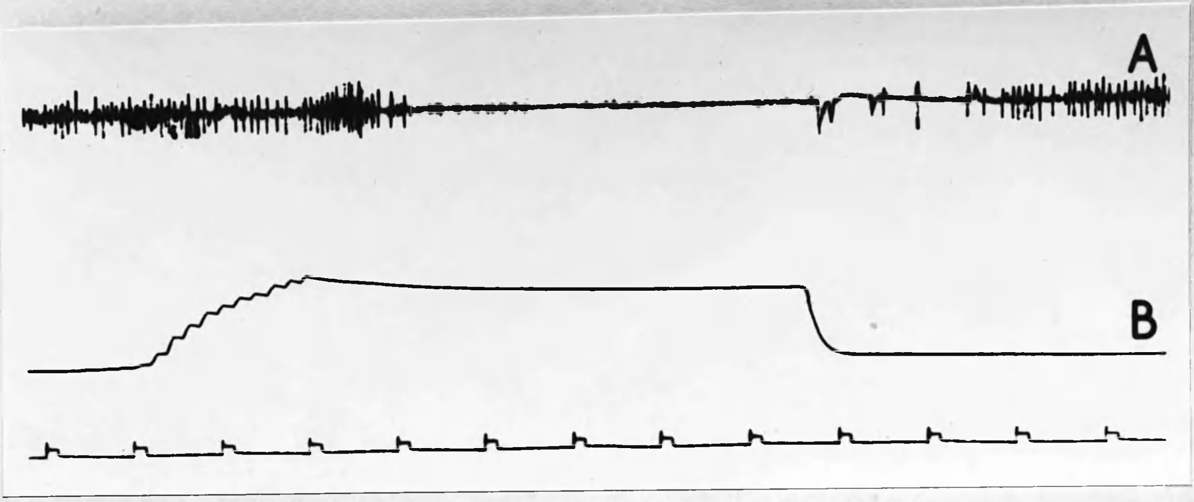

Fig. 32. Decerebrate male cat; (A) pen-oscillograph record from the external anal sphincter; (B) pressure in a balloon lying in the colon (an upward deflection indicates an increase in pressure). The balloon was inflated using hand bellows to a pressure of 30 mm Hg. Note the increase in sphincter activity which accompanies the distension of the colon and precedes the inhibition of sphincter activity. Record reads from left to right. Time = 1 sec.

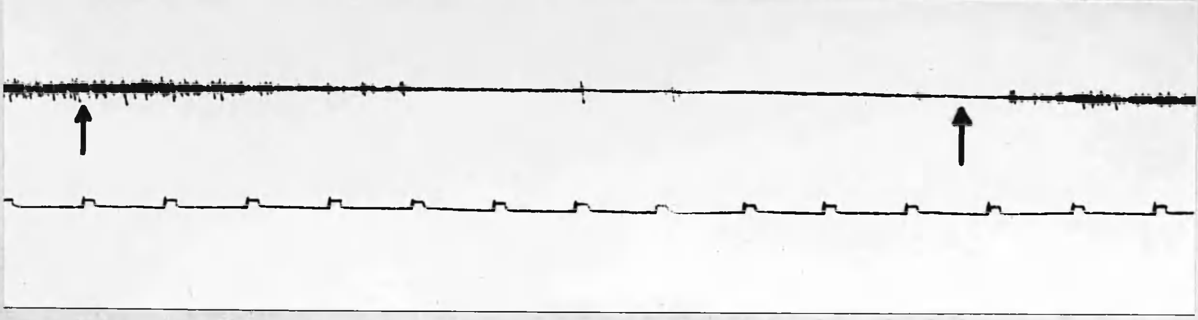

Fig. 33. Decerebrate male cat; pen-oscillograph record from the external anal sphincter. Between the arrows a deflated balloon on a metal balloon holder was moved to and fro within the colon. Note that movement within the colon, without distension, is an effective stimulus to sphincter inhibition. Record reads from left to right. Time = 1 sec.

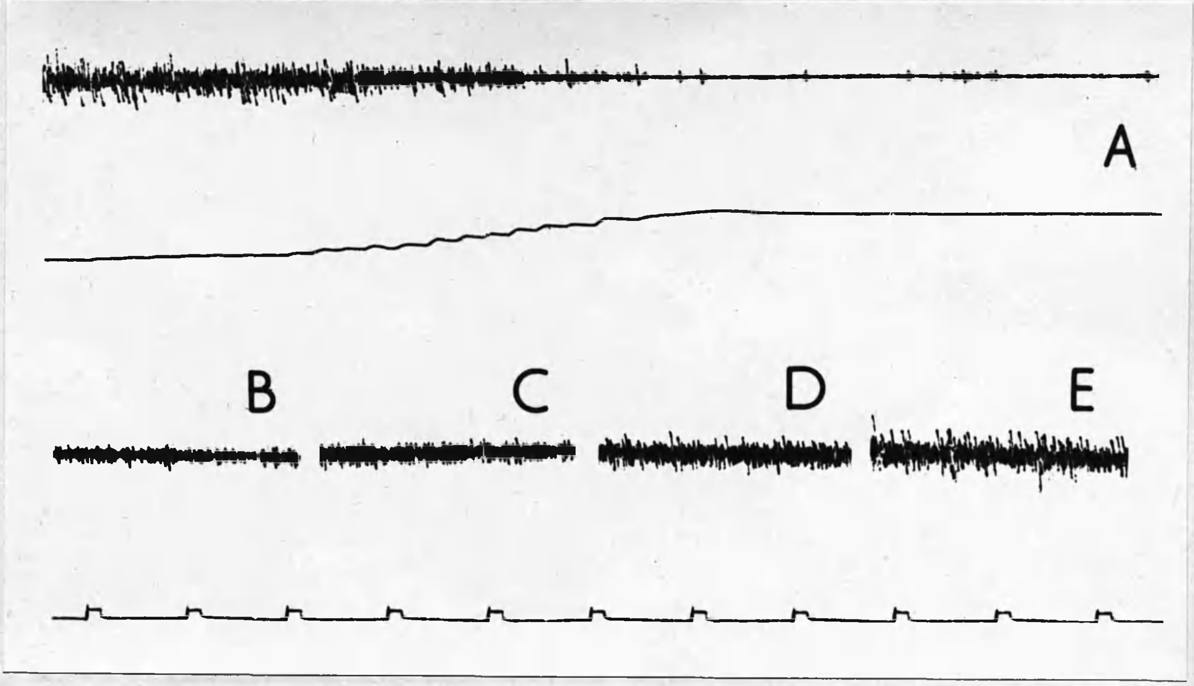

Fig. 34. Decerebrate female cat; the response of the external anal sphincter to prolonged distension of the colon. A balloon lying in the colon was inflated to 20 mm Hg and maintained at this pressure. (A) inflation of the balloon; the upper record is a pen-oscillograph record from the external anal sphincter, the lower line is the pressure in the balloon lying in the colon (an upward deflection indicates an increase in pressure); (B) pen-oscillograph record of the discharge after 30 seconds; (C) pen-oscillograph record of the discharge after 1 minute; (D) pen-oscillograph record of the discharge after 1 minute 30 seconds; (E) pen-oscillograph record of the discharge after 2 minutes. Note that the discharge from the sphincter gradually returns to its normal level, although the distension of the colon is being maintained. Records read from left to right. Time = 1 sec.

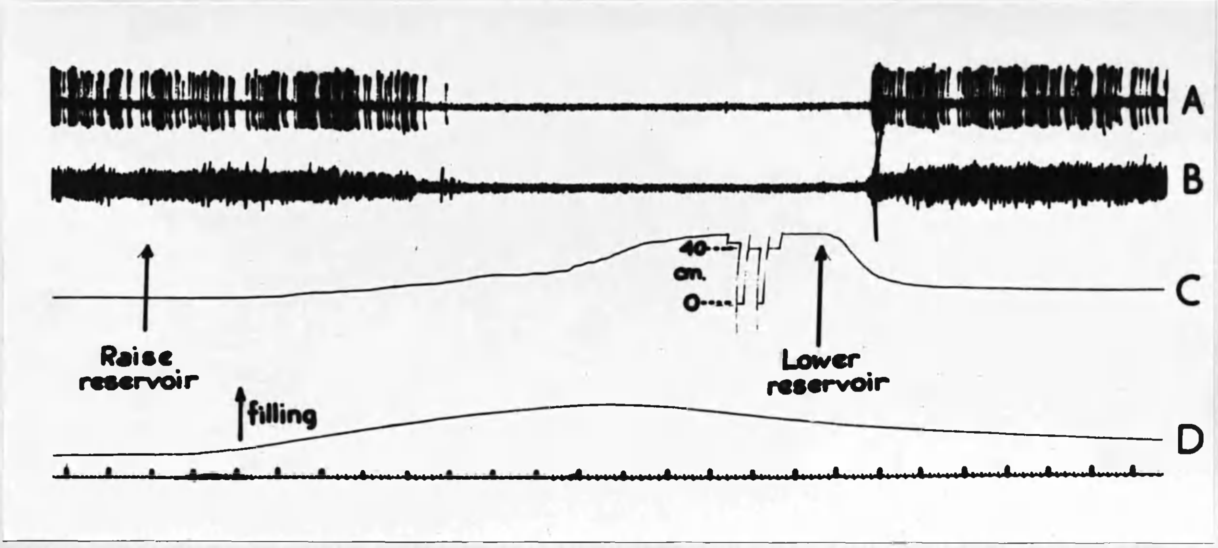

Fig. 35. *Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) pen-oscillograph record from the external anal sphincter; (C) intra-vesical pressure with calibration in cm H_2O; (D) change in bladder volume. Raising the reservoir fills the bladder until reflex bladder contraction sets in as shown by the sharp rise in intra-vesical pressure. Note that disappearance and reappearance of activity occur in both sphincters simultaneously. Record reads from left to right. Time = 10 secs.*

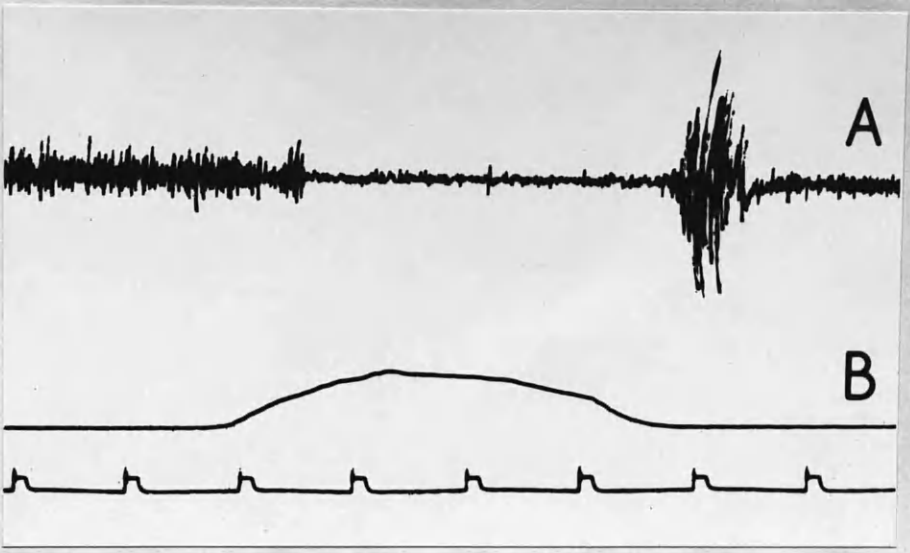

Fig. 36. Decerebrate female cat after the spinal cord has been tied at the lower thoracic level; (A) pen-oscillograph record from the external anal sphincter; (B) pressure in colonic balloon (an upward deflection indicates an increase in pressure). The pressure was raised to 30 mm Hg. Note the post-inhibitory burst of activity which is characteristic of the spinal preparation. Record reads from left to right. Time = 1 sec.

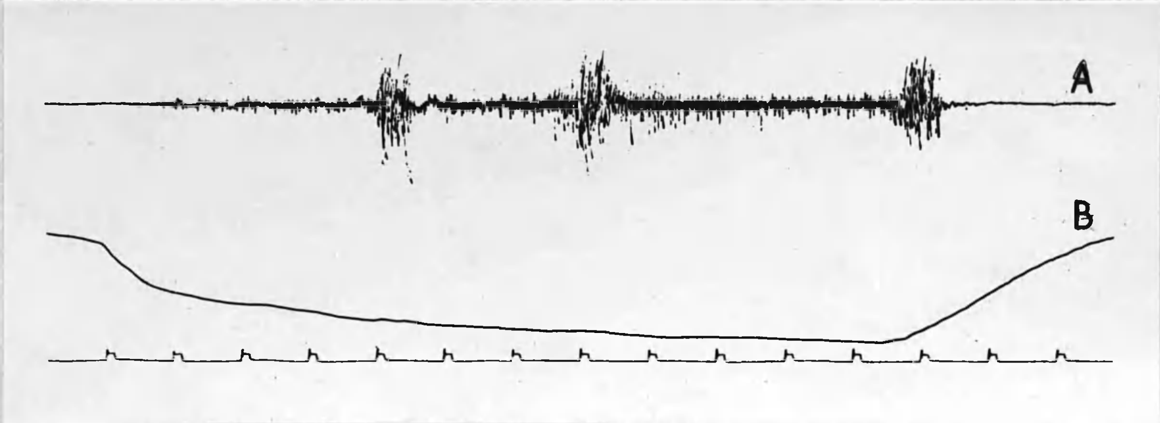

Fig. 37. Decerebrate female cat after the spinal cord has been tied at the lower thoracic level; (A) pen-oscillograph record from the external anal sphincter; (B) pressure in colonic balloon (an upward deflection indicates an increase in pressure). Note the rhythmic contractions of the external sphincter which occur in some spinal preparations and the fact that these are inhibited by colonic distension. Record reads from left to right. Time = 1 sec.

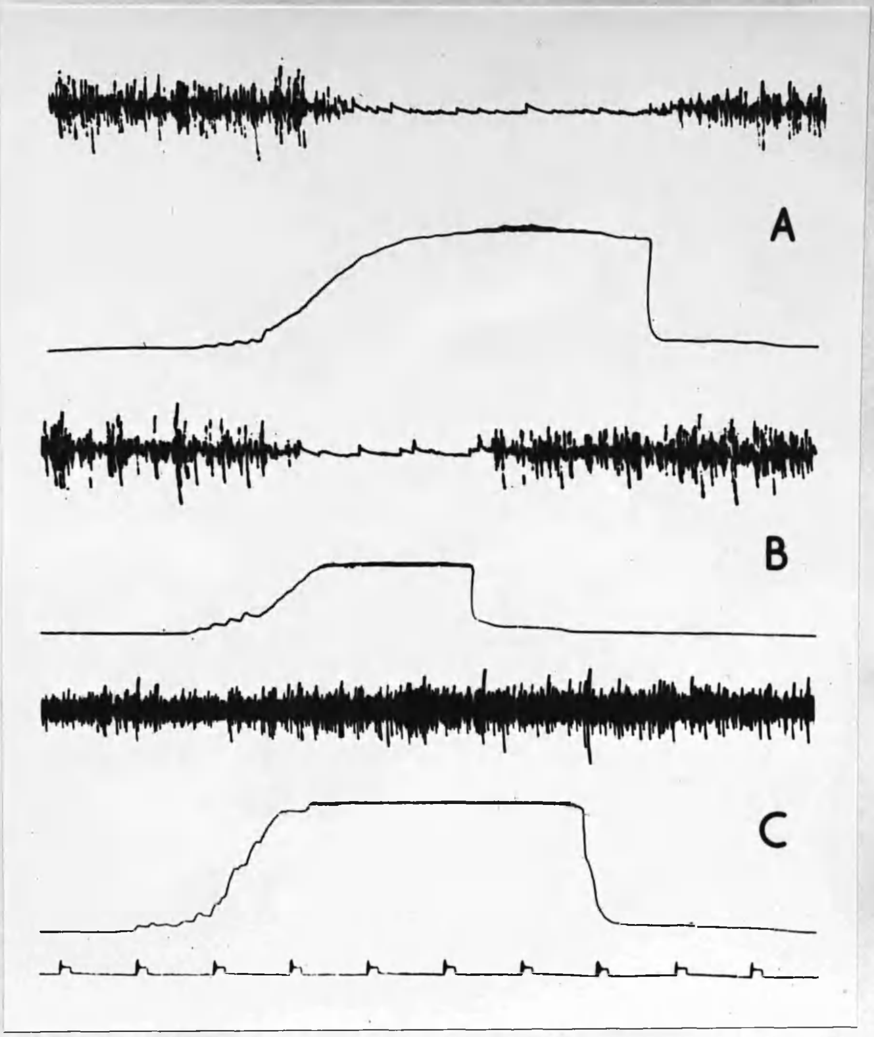

Fig. 38. Decerebrate male cat; the effect of nerve section on the response of the external anal sphincter to distension of the colon. In each case the upper record is the pen-oscillograph record from the external anal sphincter, while the lower record shows the pressure in a balloon lying in the colon (an upward deflection indicates an increase in pressure). (A) normal response (pressure 40 mm Hg); (B) after destruction of the lumbar sympathetic outflow (pressure 20 mm Hg); (C) after section of the pelvic nerves (pressure 100 mm Hg). Note that the pressure required to produce inhibition of the external anal sphincter is reduced after destruction of the sympathetic outflow, while after the pelvic nerves have been cut distension of the colon no longer leads to inhibition of the external anal sphincter. Records read from left to right. Time = 1 sec.

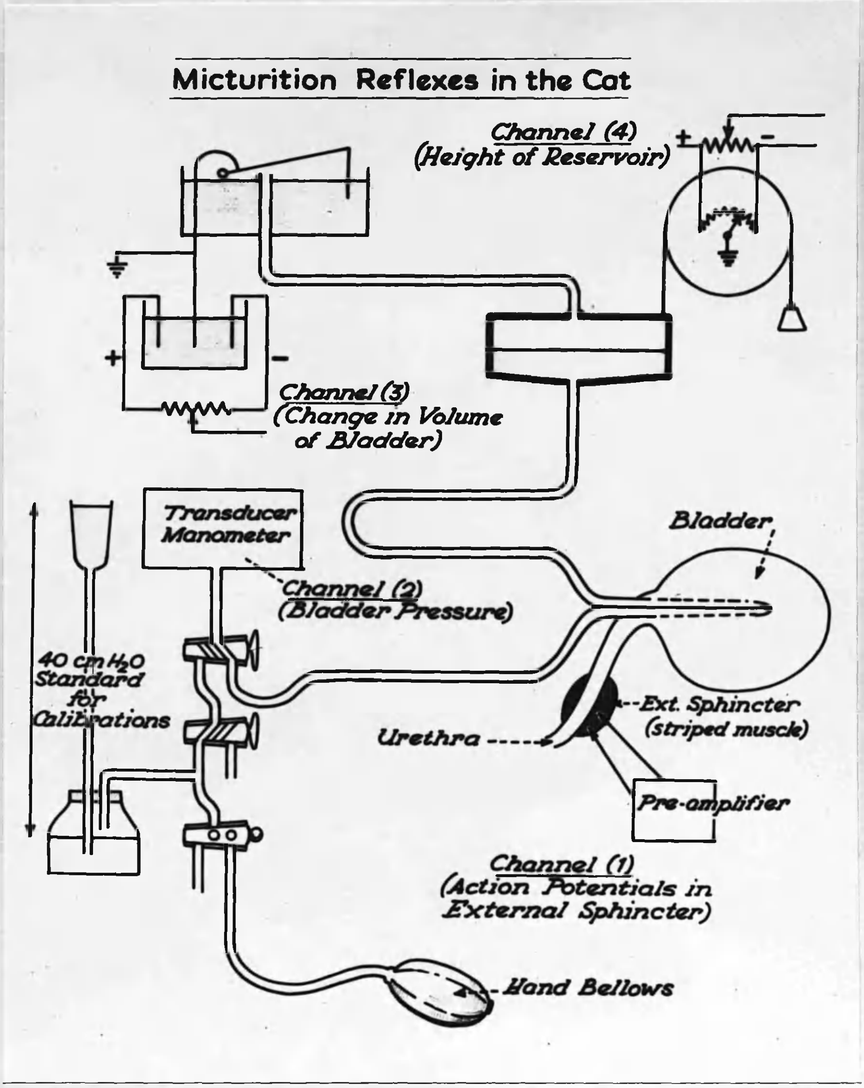

Fig. 39. A diagram of the experimental set-up used to investigate the reflexes from the bladder to the external sphincter of the urethra.

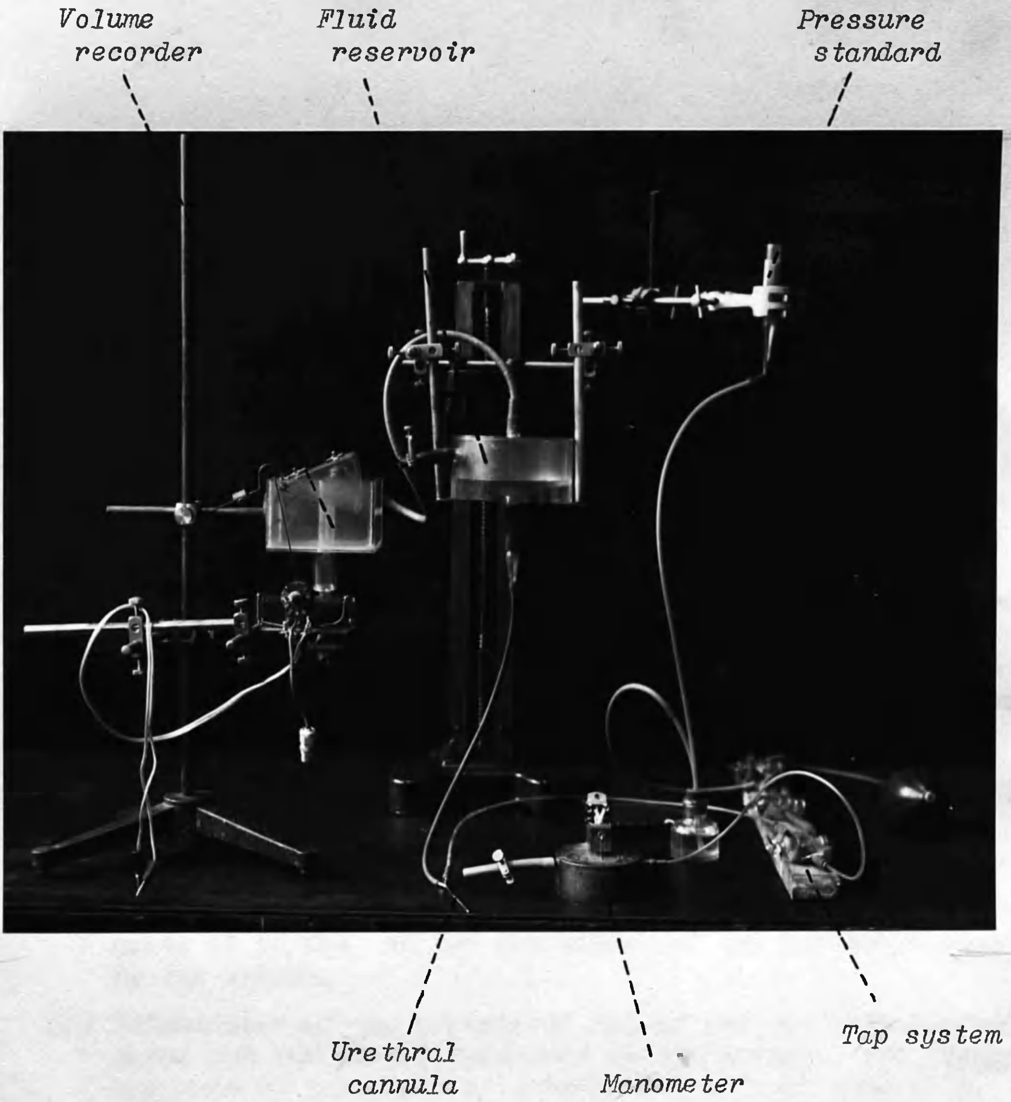

Fig. 40. The apparatus used for the simultaneous recording of changes in bladder pressure and in bladder volume, showing the reservoir mounted on an adjustable stand, the volume recorder, the manometer, the pressure standard for calibration which is connected to the manometer through a system of taps and the cannula for insertion into the bladder from the proximal urethra. Note that the pulley system for recording reservoir height is not shown.

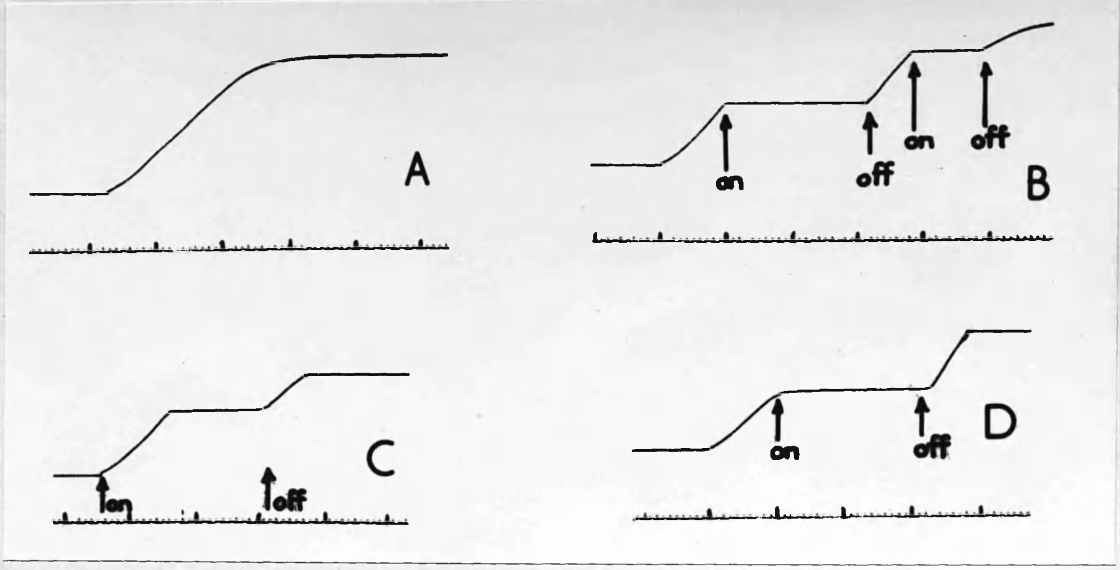

Fig. 41. *The effect of the urethral closing mechanisms on the flow of fluid along the urethra. The record is produced by a volume recorder connected to the air-inlet of the reservoir and indicates the total volume which has passed along the urethra plotted against time. The reservoir is in each case 60 cm above the bladder. Both pudendal nerves have been cut. In each case stimulation of the nerve is carried out with 1 msec pulses, with the voltage adjusted to be just above that necessary to produce the maximum mechanical response. All records read from left to right. Time = 10 secs.*

(A) Flow along the urethra on opening the tap.

(B) Stimulation of the peripheral end of the cut left pudendal nerve at 20/sec. on two occasions for the periods indicated by the arrows.

(C) Stimulation of the peripheral end of the cut left pudendal nerve for the period indicated by the arrows. The frequency was zero at the start of stimulation and was gradually increased to 20/sec. Note the sudden arrest of the flow which accompanied the onset of tetanic contraction of the external sphincter.

(D) Stimulation of the peripheral end of the cut hypogastric nerves at 50/sec. Note that the arresting of flow and resumption of flow is less abrupt than with stimulation of the pudendal nerve.

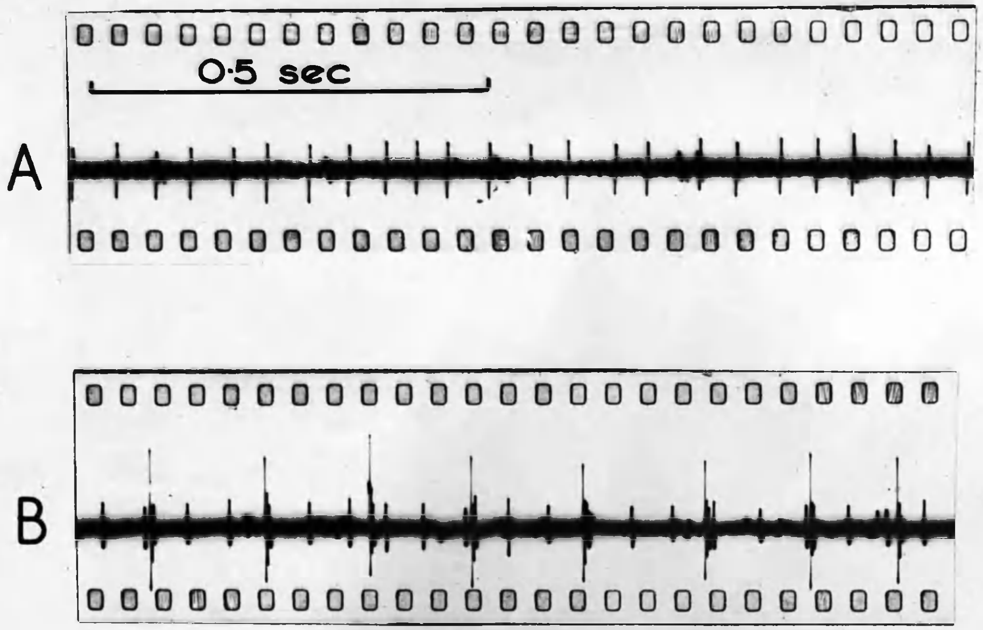

Fig. 42. Decerebrate male cat; oscillograph records of resting tone recorded from the external urethral sphincter; (A) a record showing the activity of a single motor unit discharging at 20 impulses/sec; (B) a record showing the activity of two motor units, one discharging at 18 impulses/sec. and the other discharging at 8 impulses/sec. Records read from left to right. A discharge of the second type was used in most of the records made with the pen-recorder.

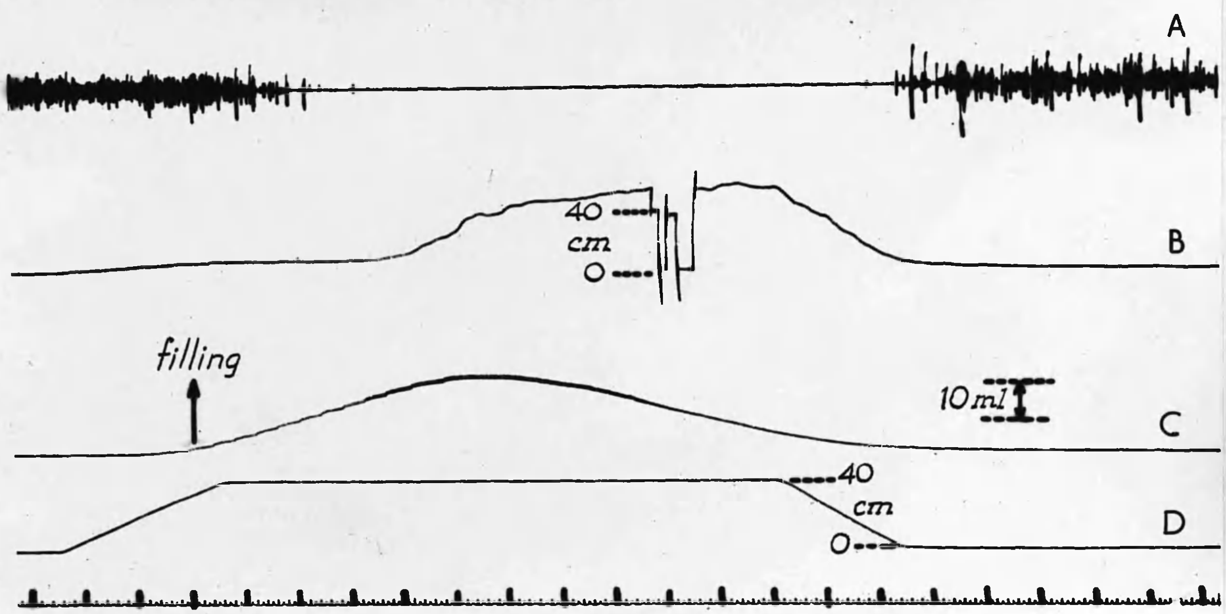

Fig. 43. *Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure with calibration in cm* H_2O*; (C) change in bladder volume with calibration in ml; (D) height of reservoir above the bladder. Note that reduction in sphincter activity precedes the rise in bladder pressure by approximately 25 seconds. Record reads from left to right. Time = 10 secs.*

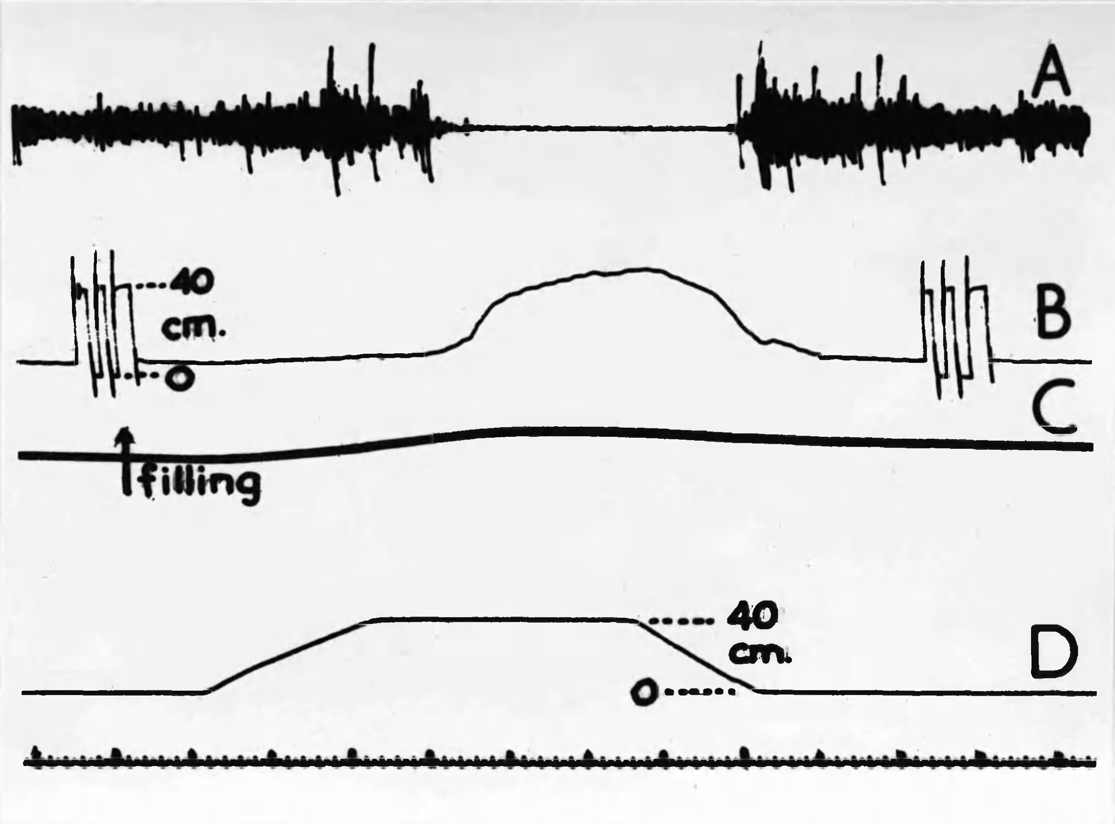

Fig. 44. Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure with calibration in cm H_2O; (C) change in bladder volume; (D) height of reservoir above the bladder. Note the increase in sphincter activity which accompanies the early stages of bladder filling and precedes the inhibition of sphincter activity. Record reads from left to right. Time = 10 secs.

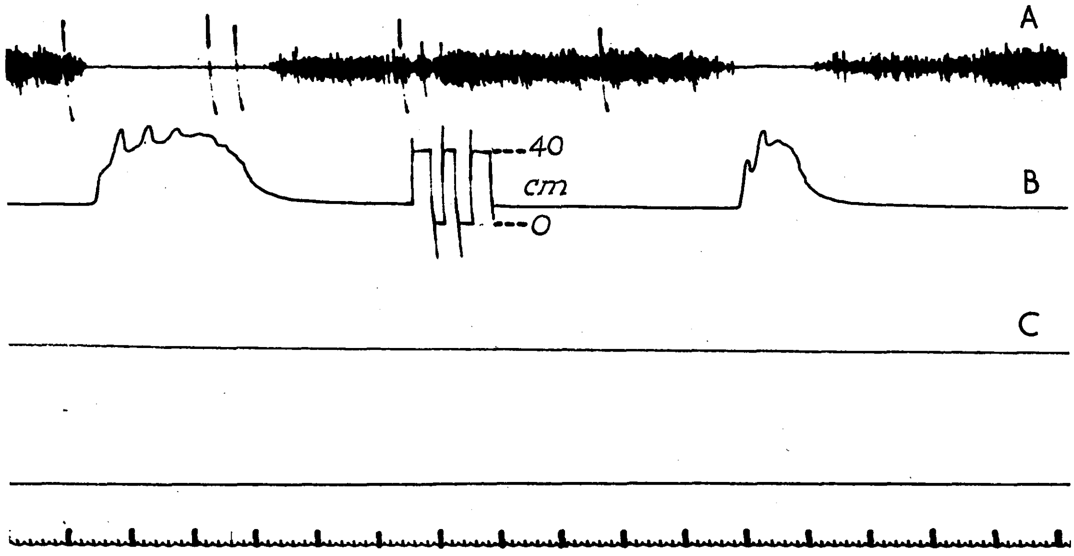

Fig. 45. Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure with calibration in cm H_2O; (C) change in bladder volume. Note that bladder contraction is isometric since the outflow from the bladder is closed and that reduction in sphincter activity occurs without any change in the volume of the bladder. Record reads from left to right. Time = 10 secs.

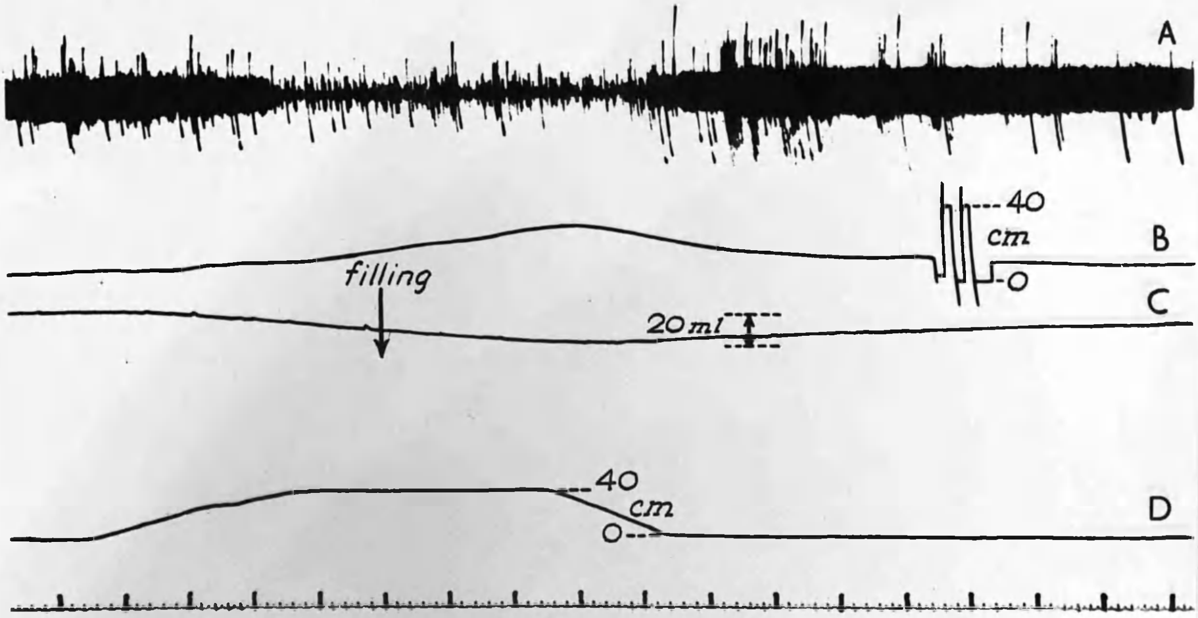

Fig. 46. Decerebrate male cat after the spinal cord has been cut at the lower thoracic level; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure with calibration in cm H_2O; (C)-change in bladder volume with calibration in ml; (D) height of reservoir above the bladder. Note that reflex contraction of the bladder is absent but reduction in sphincter activity accompanies passive distension of the bladder. Record reads from left to right. Time = 10 secs.

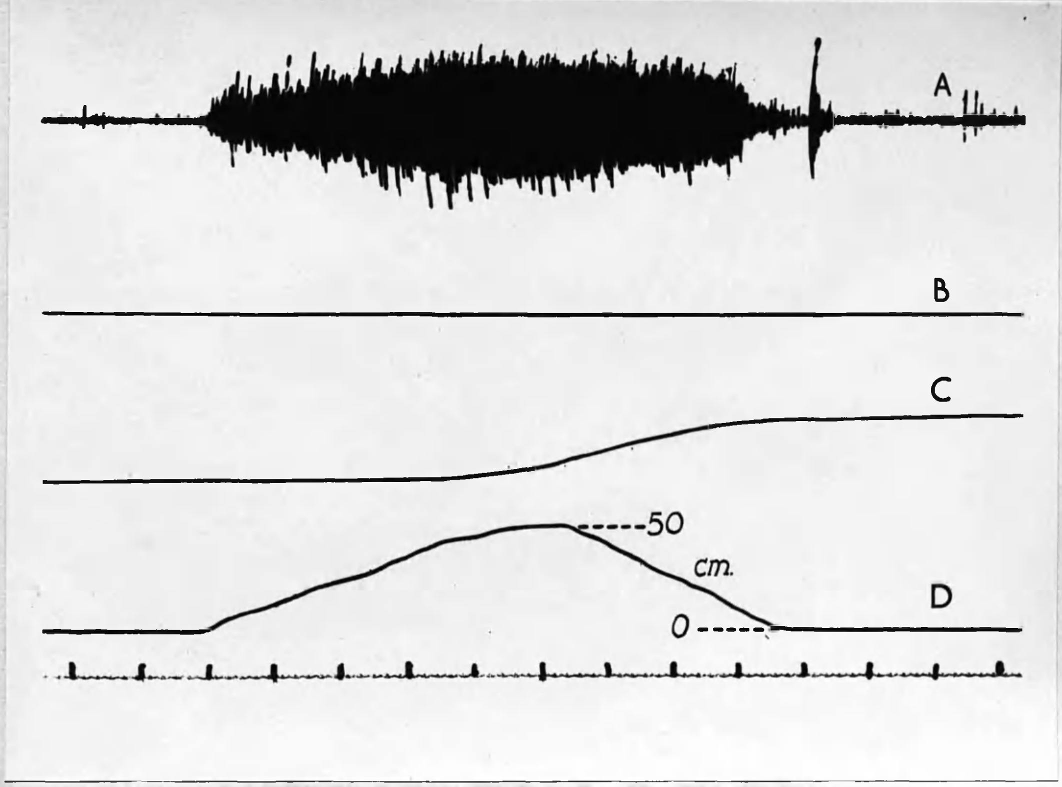

Fig. 47. Decerebrate female cat with bladder empty; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure; (C) volume of fluid which has flowed along the urethra (the slope of the line at any point indicates the rate of flow at that point); (D) pressure applied to distal urethra. Note that increasing pressure applied to the distal urethra induces activity in the external urethral sphincter corresponding to the increase in pressure. Flow along the urethra starts when the pressure reaches 50 cm H_2O but continues as the pressure is reduced and while the external sphincter is still active. Record reads from left to right. Time = 10 secs.

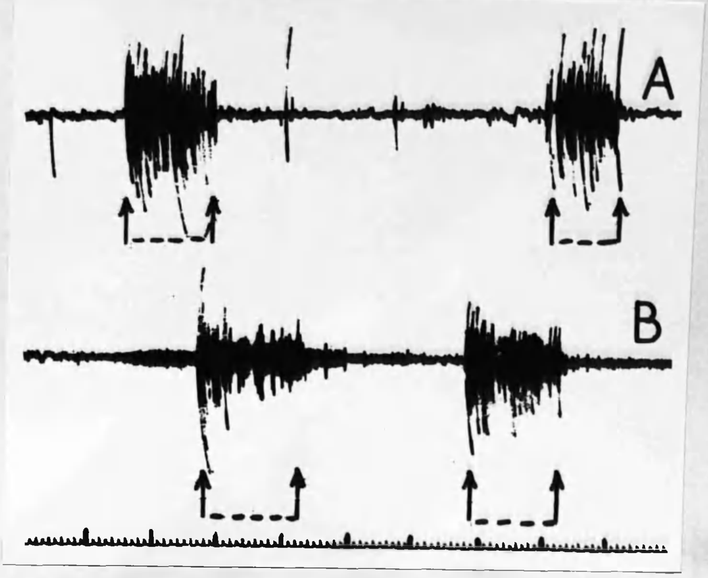

Fig. 48. Decerebrate male cat; pen-oscillograph records from the external urethral sphincter; (A) movement of a piece of smooth polythene tubing in the urethra for the periods indicated by the arrows; (B) distension of a small balloon lying in the urethra within the external sphincter for the periods indicated by the arrows. Records read from left to right. Time = 10 secs.

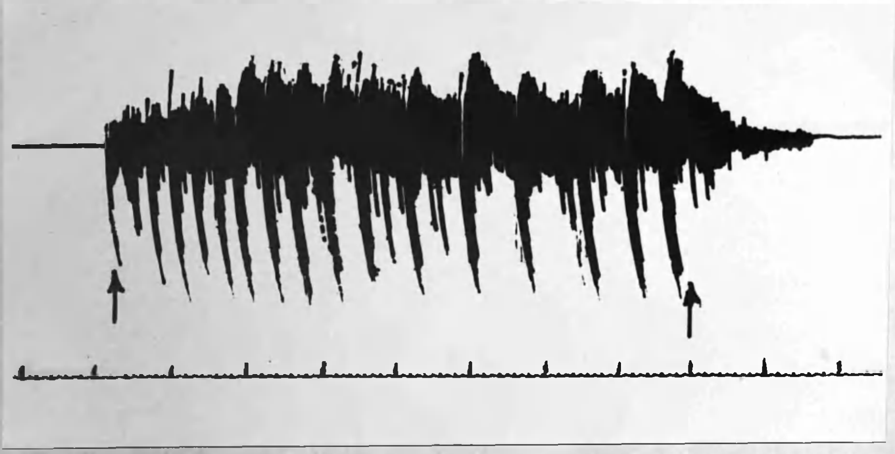

Fig. 49. Decerebrate male cat after the pelvic nerves have been cut; pen-oscillograph record from the external urethral sphincter. Between the arrows water was forced at a pressure of 60 cm H_2O, distally along the urethra. Note the rhythmic contractions of the external urethral sphincter. Fluid escaped in spurts. Record reads from left to right. Time = 10 secs.

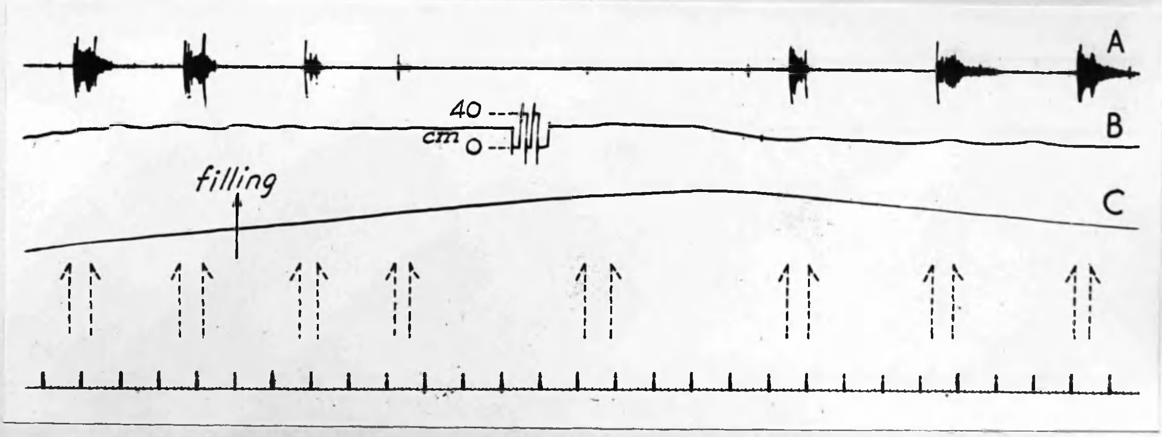

Fig. 50. Decerebrate female cat; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure with calibration in cm H_2O*; (C) change in bladder volume. The urethra was tied distally; at the times and for the durations indicated by the vertical dotted lines the pressure in the distal urethra was raised abruptly to 60 cm* H_2O *by opening a tap. Note that the response of the external urethral sphincter to distension of the urethra dies out as the bladder fills and reappears as the bladder empties. Record reads from left to right. Time = 10 secs.*

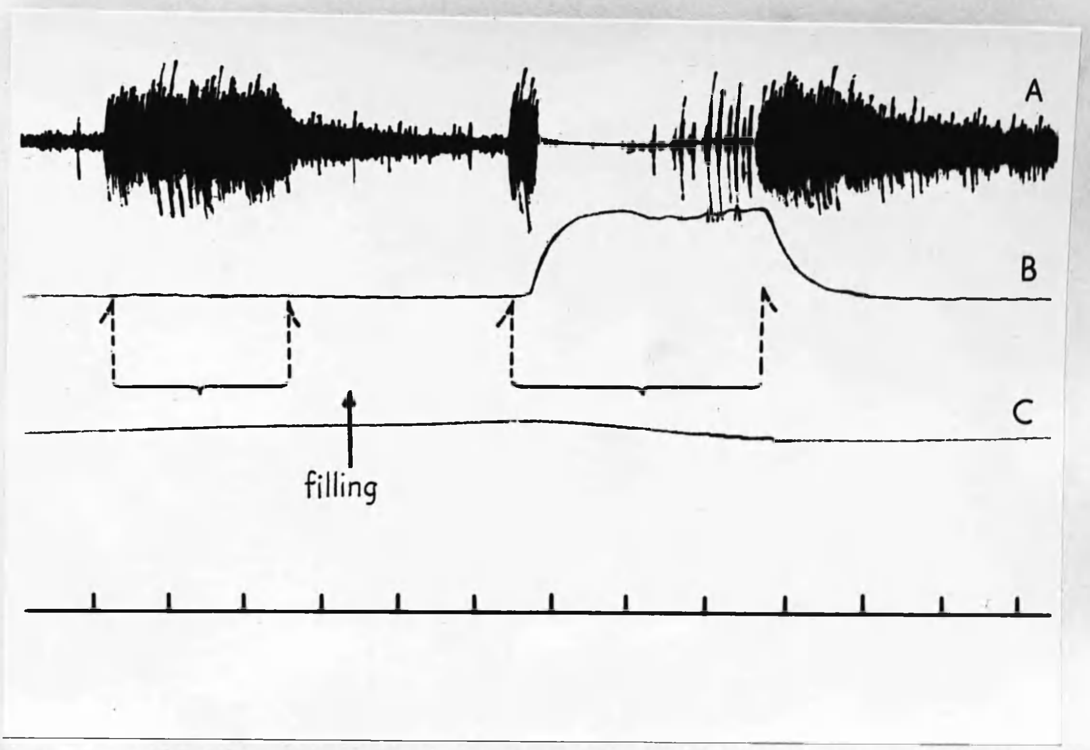

Fig. 51. Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) intra-vesical pressure (an upward deflection indicates an increase in pressure); (C) change in bladder volume. Fluid is running slowly into the bladder; at the times and for the periods shown by the vertical dotted lines, the distal urethra was suddenly distended by a pressure of 40 cm H_2O. In the first instance there was no contraction of the bladder and the activity of the external sphincter was greatly augmented. In the second instance, when the bladder was somewhat fuller, distension of the urethra initially augmented the activity of the external sphincter but when the bladder responded by contracting, the activity of the external sphincter ceased. Record reads from left to right. Time = 10 secs.

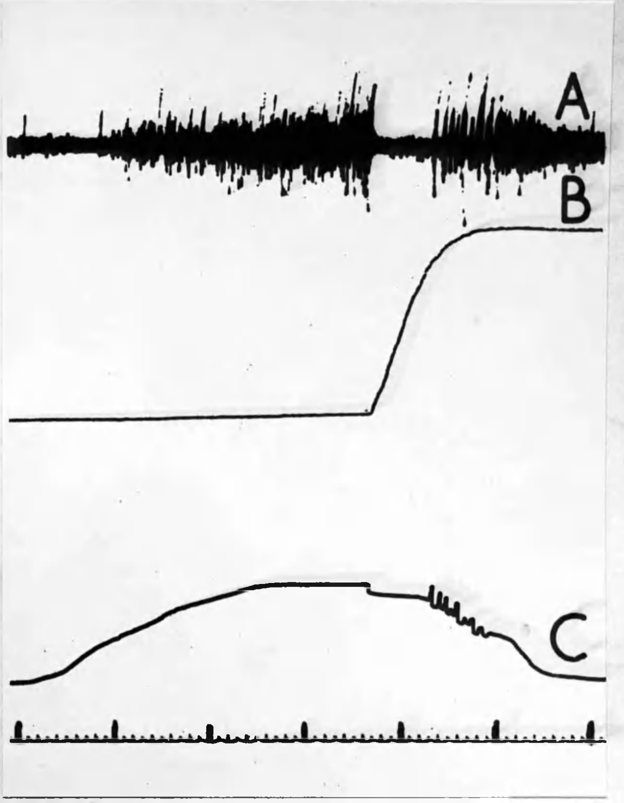

Fig. 52. Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) volume of fluid which has flowed along the urethra (the slope of the line at any point indicates the rate of flow at that point); (C) intra-urethral pressure (an upward deflection indicates an increase in pressure). The reservoir connected to the distal urethra was gradually raised. Reflex bladder contraction developed (not shown in this record) and lead to inhibition of the external urethral sphincter. Note the sudden onset of flow along the urethra when the external urethral sphincter is inhibited and the sharp drop in intra-urethral pressure which occurs at the same time. Note also that when activity returns to the external sphincter, it is at first rhythmic and leads to fluctuations in intra-urethral pressure. Record reads from left to right. Time = 10 secs.

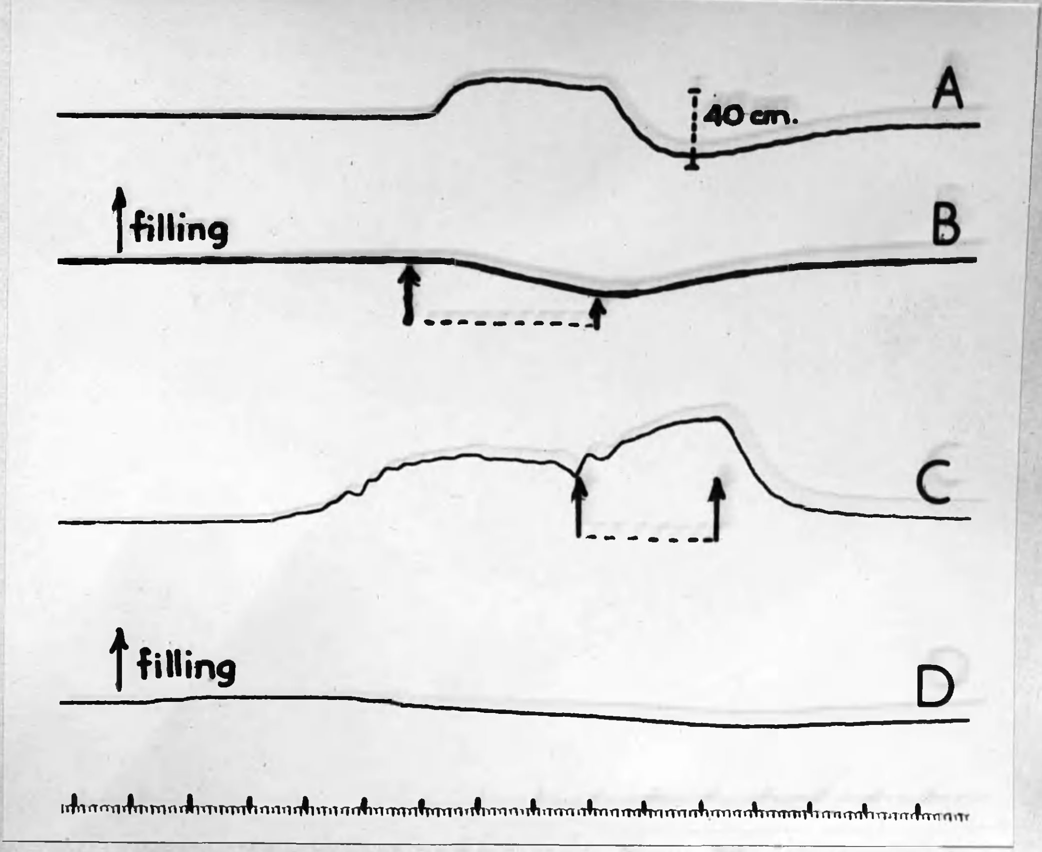

Fig. 53. *Decerebrate female cat; effect of contraction of the external urethral sphincter on the bladder. (A) and (C) intra-vesical pressure with calibration in cm* H_2O *(an upward deflection indicates an increase in pressure); (B) and (D), change in bladder volume. In each case, for the period indicated by the arrows, the peripheral end of the cut left pudendal nerve was stimulated with 1 msec pulses of supra-maximal voltage at 20/sec causing contraction of the external urethral sphincter; the other pudendal nerve was intact. Note that contraction of the bladder accompanies contraction of the sphincter and that the pressure developed in this way may be greater than that developed in response to filling the bladder and may be produced at a time when the contraction of the bladder in response to filling is passing off. Records read from left to right. Time = 10 secs.*

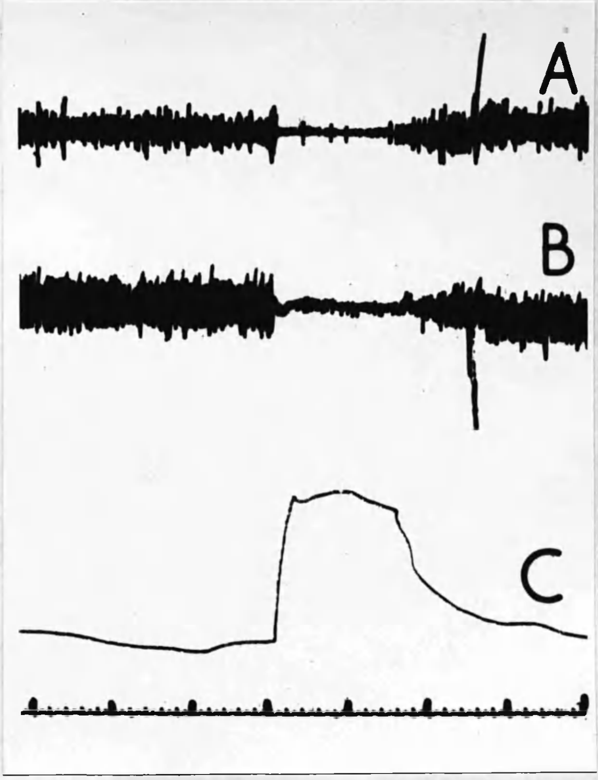

Fig. 54. Decerebrate male cat; (A) pen-oscillograph record from the external urethral sphincter; (B) pen-oscillograph record from the external anal sphincter; (C) pressure in colonic balloon (an upward deflection indicates an increase in pressure). The pressure was raised to 60 mm Hg. Note that changes in activity occur in both sphincters simultaneously. Record reads from left to right. Time = 10 secs.

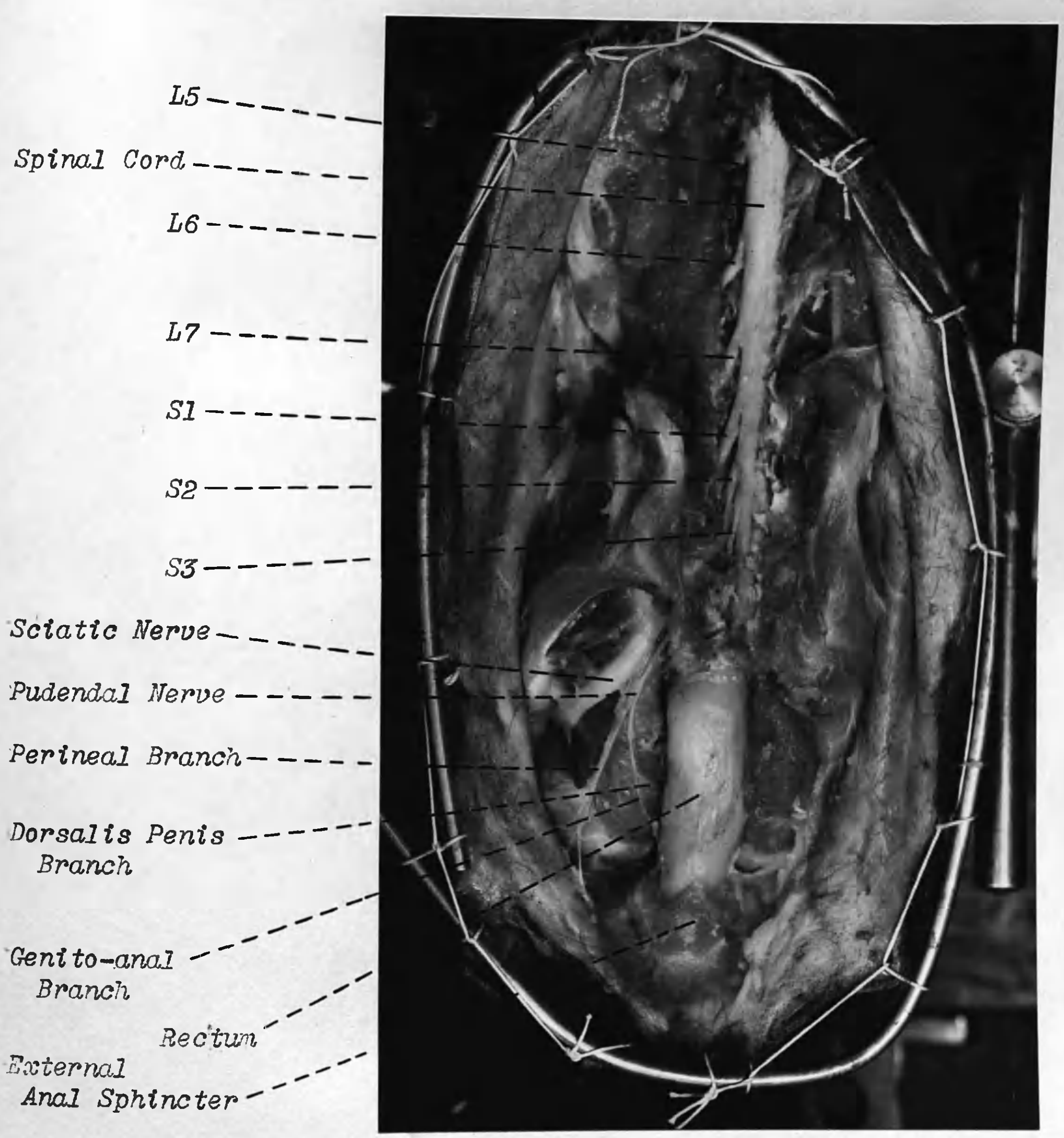

Fig. 55. View of the preparation during the dissection for recording from dorsal root fibres. The tail has been dis-articulated at the sacro-caudal junction and the skin edges stitched to a brass ring. Bilateral laminectomy has been carried out over L6, L7 and the sacrum, and the extra-dural fat removed. The dura has not yet been opened. The dorsal aspect of the distal rectum and anal canal has been exposed and the branches of the sacral plexus on the left side dissected. Note the relations of the various lumbar and sacral spinal roots to one another, and the wide access given to the anal region by the dorsal approach.

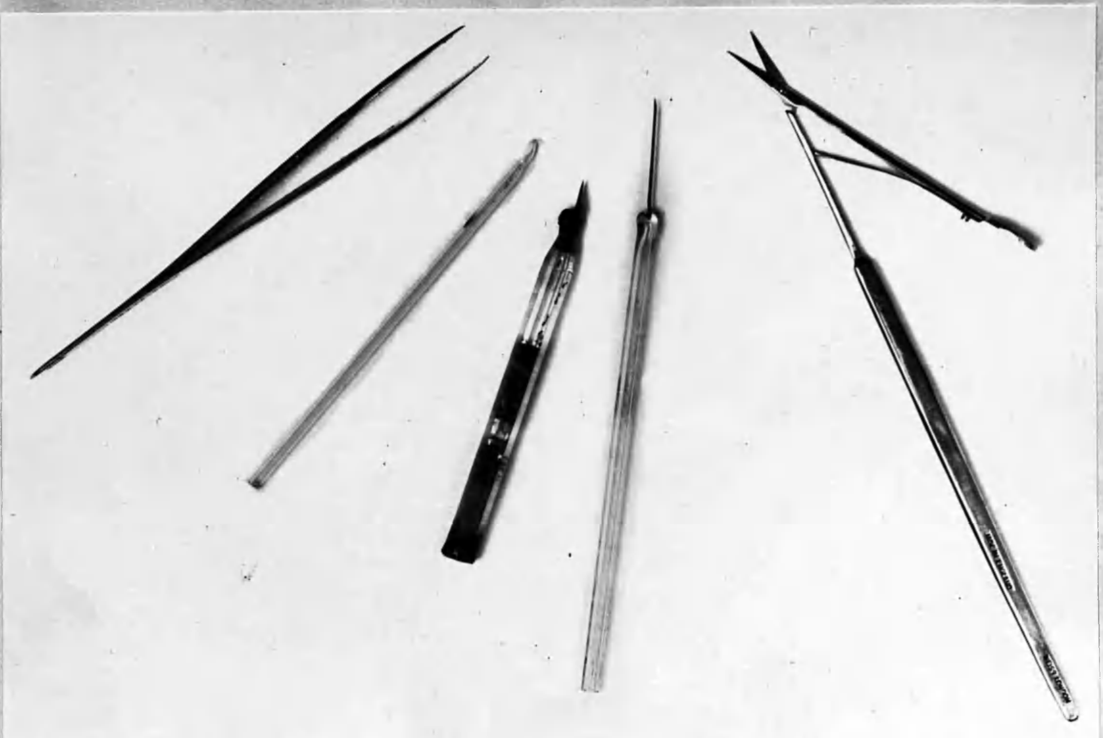

Fig. 56. Examples of some of the instruments used in division of the dorsal root into fine strands. From left to right: Watch-makers' forceps, glass hook, fine mounted knife, mounted needle and dural scissors.

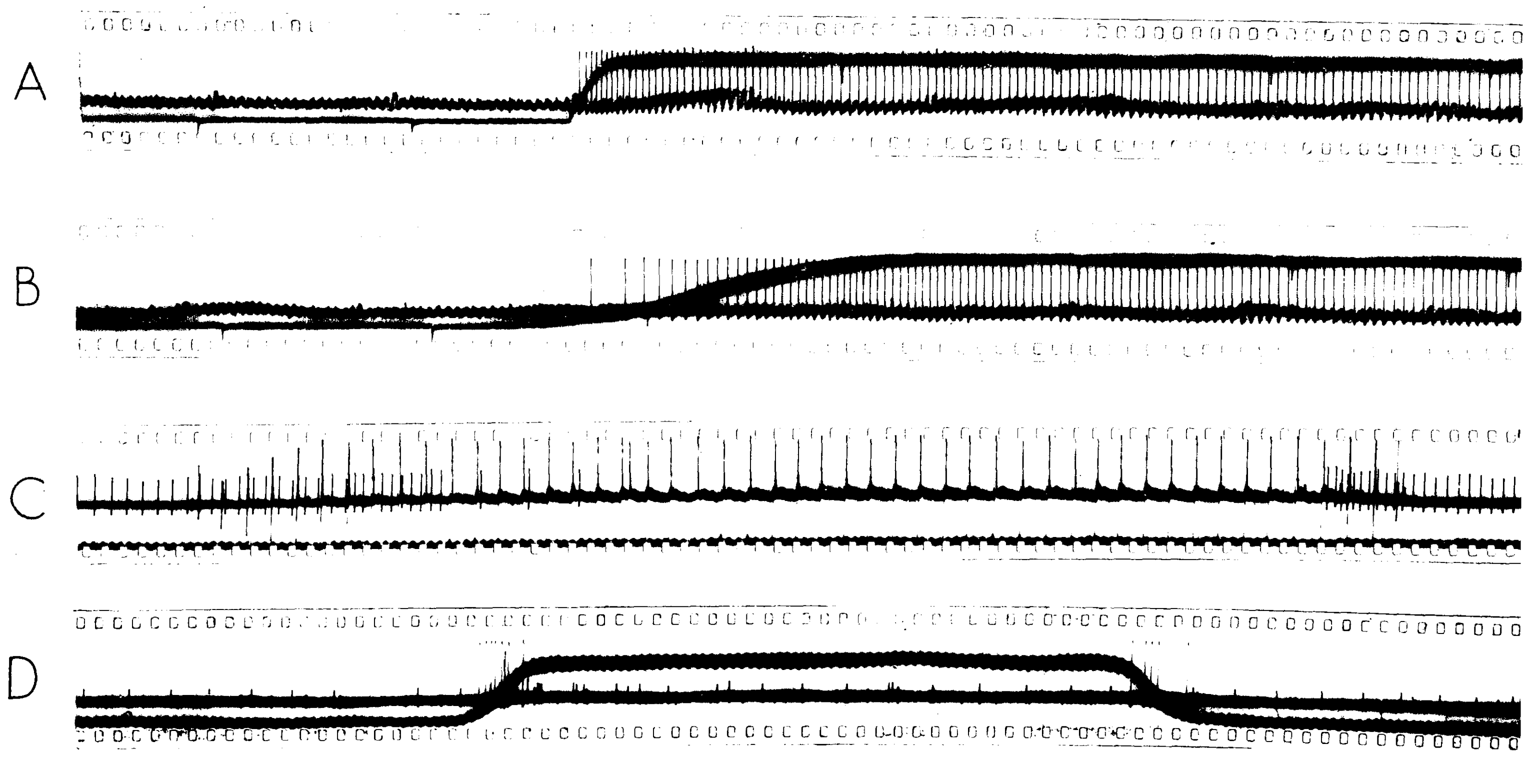

Fig.57. Oscillograph records of discharges in the sacral dorsal roots after section of all branches of the sacral plexus except the pudendal nerves. In each case the second beam (the lower of the two at the left side of the record) signals pressure and in the first two records it carries a half second time marker. All four records were taken at the same paper speed.

(A) A record from the first sacral dorsal root showing the response of a slowly-adapting stretch receptor in the external anal sphincter during rapid inflation of a balloon in the anal canal to 30 mm Hg.

(B) A record from the first sacral dorsal root showing the response of a slowly-adapting stretch receptor in the external anal sphincter during the gradual inflation of a balloon in the anal canal to 30 mm Hg.

(C) A record from the first sacral dorsal root showing the response of a slowly-adapting stretch receptor in the external anal sphincter to stimulation of the corresponding ventral root with 1 msec pulses at 16/sec with a balloon inflated to 30 mm Hg in the anal canal. The voltage of the stimulating pulses was gradually increased from zero to one which gave a maximal mechanical response. Note that the first effect is an increase in discharge frequency, which is later followed by abolition of the discharge when tetanic contraction of the muscle develops.

(D) A record from the second sacral dorsal root showing the response of a rapidly-adapting receptor in the anal region during inflation of a balloon in the anal canal to 30 mm Hg.

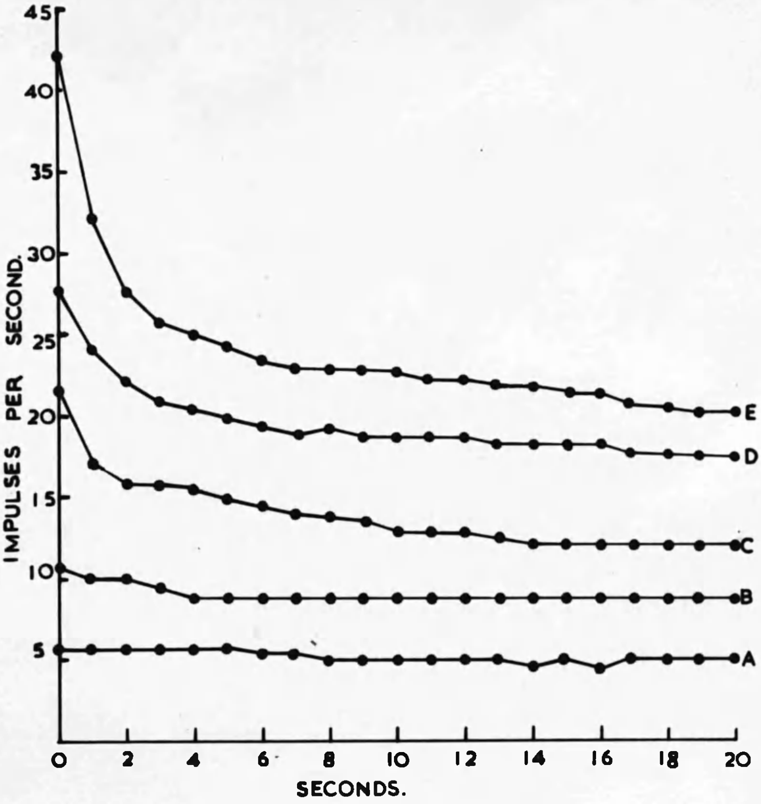

Fig. 58. Graph of the alteration in discharge frequency of a single slowly adapting receptor in the anal region during the period of 20 seconds following the inflation of a balloon in the anal canal to various pressures:- (A) resting discharge; (B) pressure 10 mm Hg; (C)-pressure 20 mm Hg; (D)-pressure 30 mm Hg; (E) pressure 40 mm Hg. The full-pressure was reached at zero time in each case and was maintained constant during the subsequent 20 seconds. Note the similar form of the adaption curve in each case.

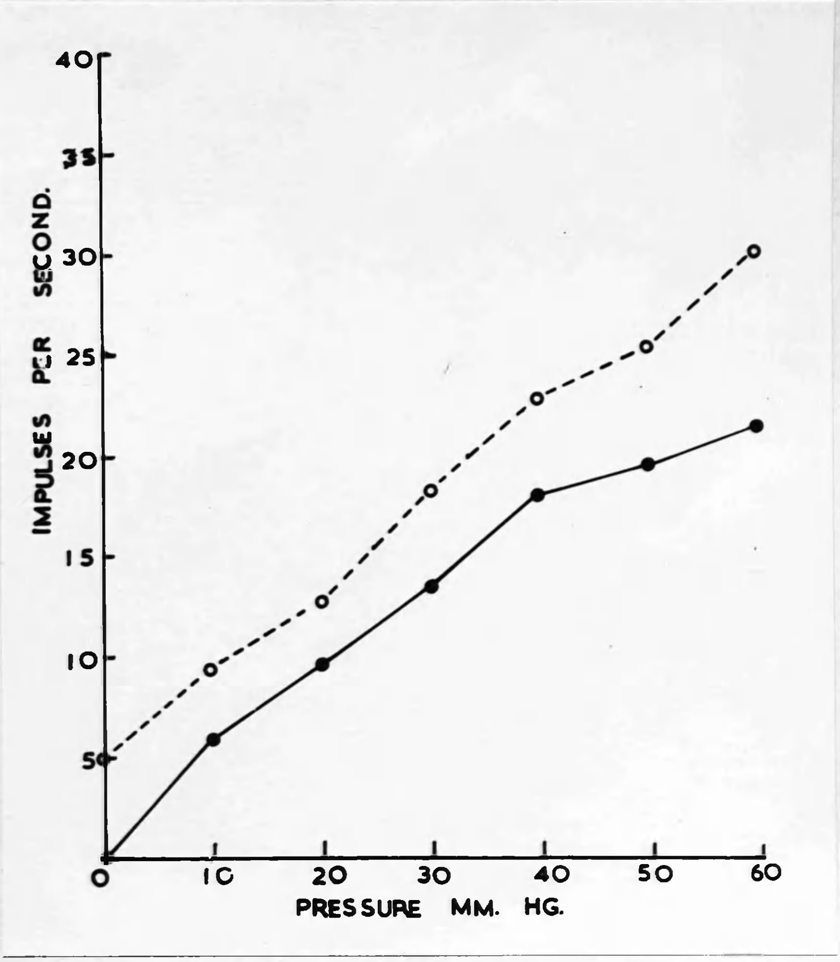

Fig. 59. Graph of the relation between the pressure in a balloon lying within the anal canal and the adapted discharge frequencies recorded, 20 seconds after the application of the pressure, from two slowly adapting receptors in the anal region.

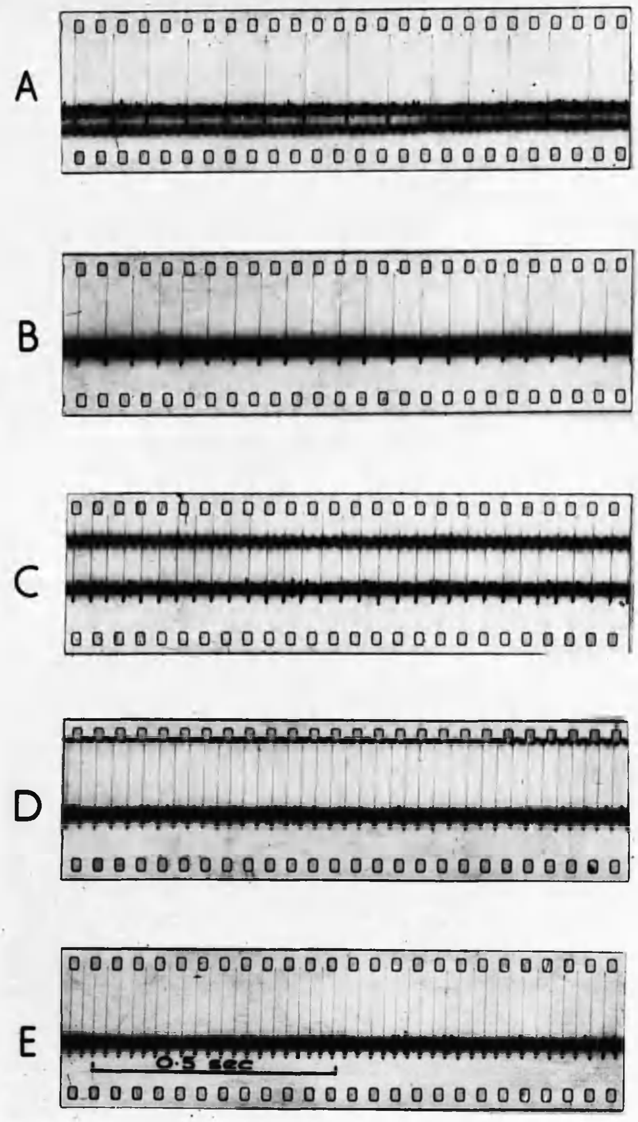

Fig. 60. Oscillograph records of discharges in the sacral dorsal roots after section of all the branches of the sacral plexus except the pudendal nerves. All records were taken at the same paper speed. A balloon lying within the anal canal was inflated to the pressures indicated 20 seconds before each record was taken.
(A) pressure 10 mm Hg; (B) pressure 20 mm Hg;
(C) pressure 30 mm Hg; (D) pressure 40 mm Hg;
(E) pressure 50 mm Hg.
All records read from left to right.

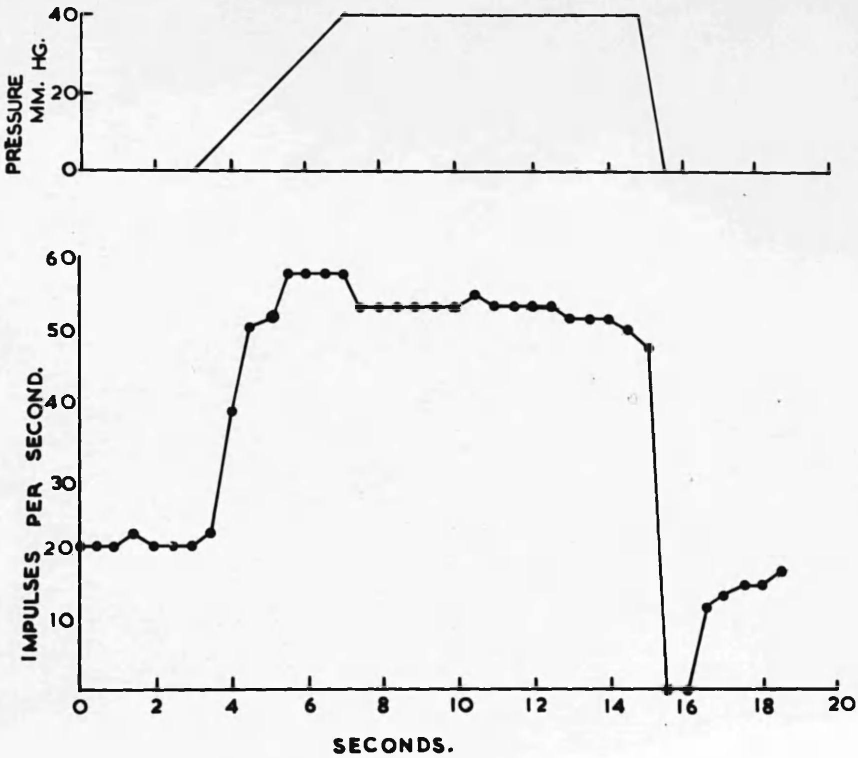

Fig. 61. Graph of the alteration in the discharge frequency of a single slowly-adapting receptor in the anal region during the inflation of a balloon lying in the anal canal to a pressure of 40 mm Hg. The upper record shows the changes in pressure within the balloon, the lower record shows the frequency of discharge. Note the resting discharge and its gradual reappearance after the pressure has dropped to zero.

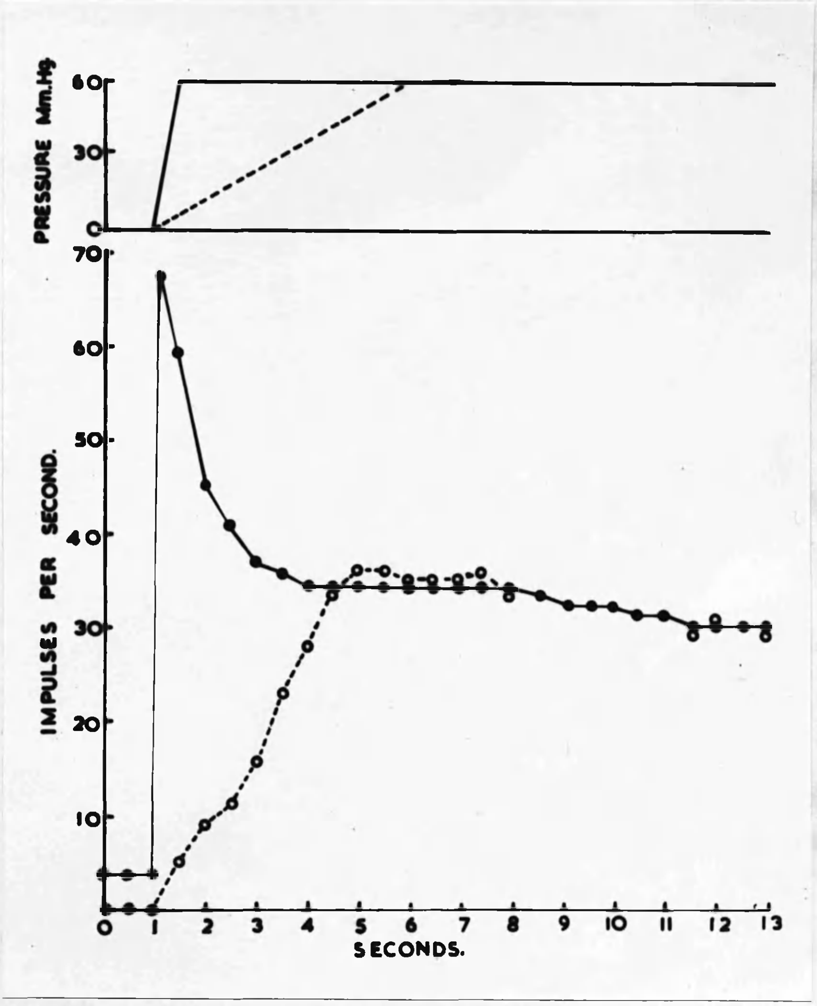

Fig. 62. Graph of the alteration in discharge frequency of a single slowly adapting receptor in the anal region during the inflation of a balloon lying in the anal canal to a pressure of 60 mm Hg. The upper record shows the rate of development of pressure within the balloon at two different rates: continuous line rapid development, dotted line slow development. The lower record shows the frequency of the response: continuous line to rapid development of pressure, dotted line to slow development of pressure. Note that the final adapted discharge frequency is the same in each case, while the peak discharge frequency is largely a function of the rate of application of the stimulus.

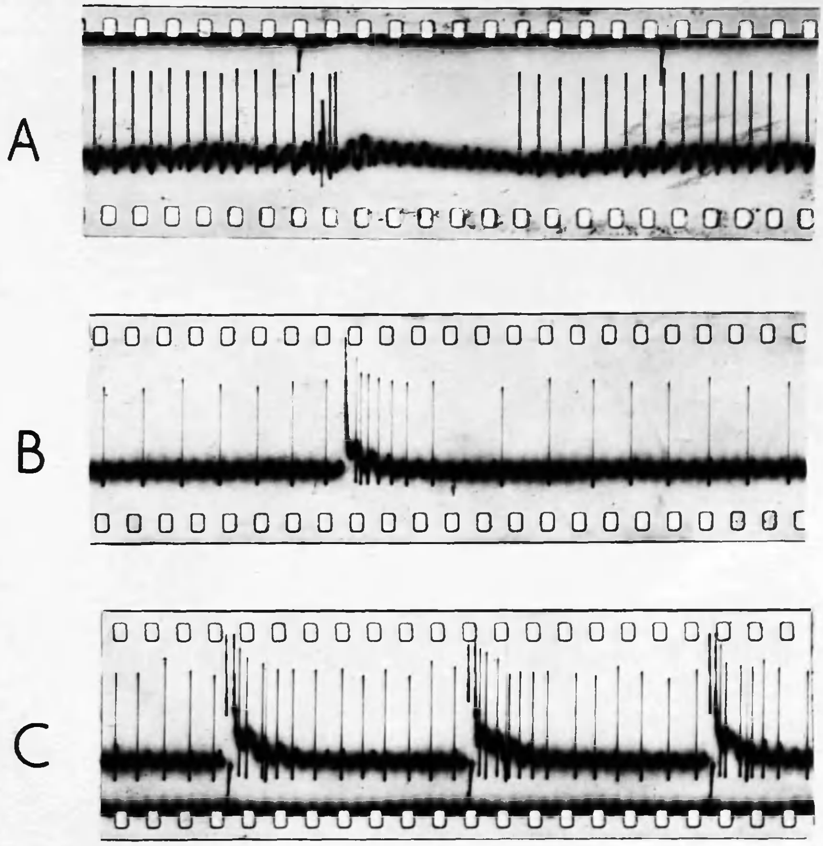

Fig. 63. Oscillograph records of discharges in the sacral dorsal roots after section of all the branches of the sacral plexus except the pudendal nerves. In each case a balloon inflated to 30 mm Hg lies within the anal canal. The corresponding ventral root was stimulated with 1 msec pulses. Note that the response to stimulation of the ventral root can be either a pause in the discharge, a burst of impulses followed by a pause, or a burst of impulses without a pause. It was possible to obtain any of these responses from most of the units studied by altering the experimental conditions. Records read from left to right. Time = half seconds.

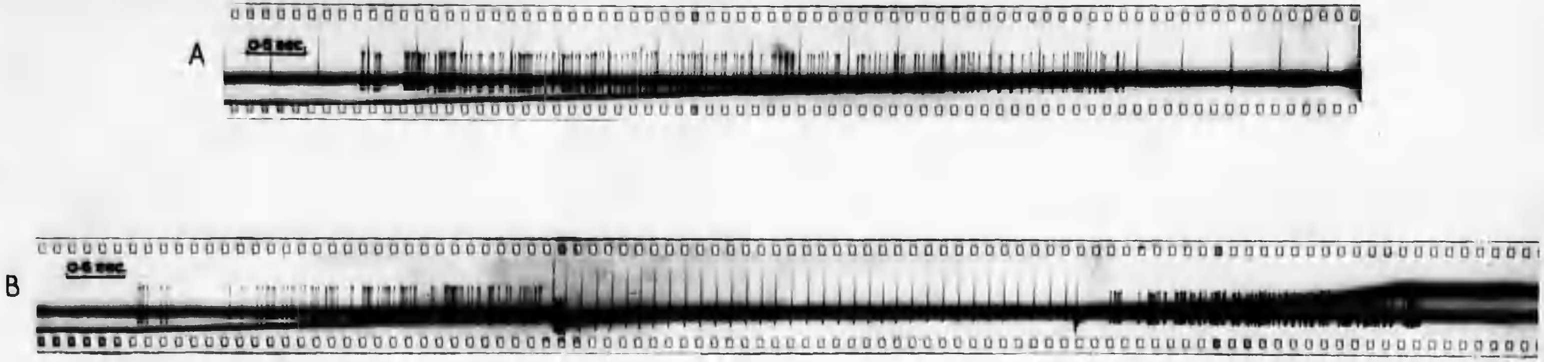

Fig. 64. Oscillograph records of dicharges in twigs of the sacral dorsal roots after section of all the branches of the sacral plexus except the pudendal nerves. The second beam in each record (the lower of the two at the left side of the record) is operated by a volume recorder attached to the air-inlet of the reservoir and gives a record of the total volume which has flowed along the urethra. The slope of this line at any time indicates the rate of flow at that time. Fluid flows distally along the urethra from a reservoir of fluid 60 cm above the bladder. Flow is started and stopped by opening and closing a tap.

(A) Activity recorded from a twig of the second sacral dorsal root while fluid was flowing along the urethra. The corresponding ventral root was stimulated with 1 msec pulses of supra-maximal voltage at a frequency of 2/sec. Note the relation between the discharge and the period of flow. Stimulation with single pulses has little effect on discharge.

(B) Activity recorded from a twig of the second sacral dorsal root while fluid was flowing along the urethra. The corresponding ventral root was stimulated with 1 msec pulses at a frequency of 16/sec. Note that the tetanic contraction of the external urethral sphincter stopped the flow. The discharge corresponds closely with the period of flow.

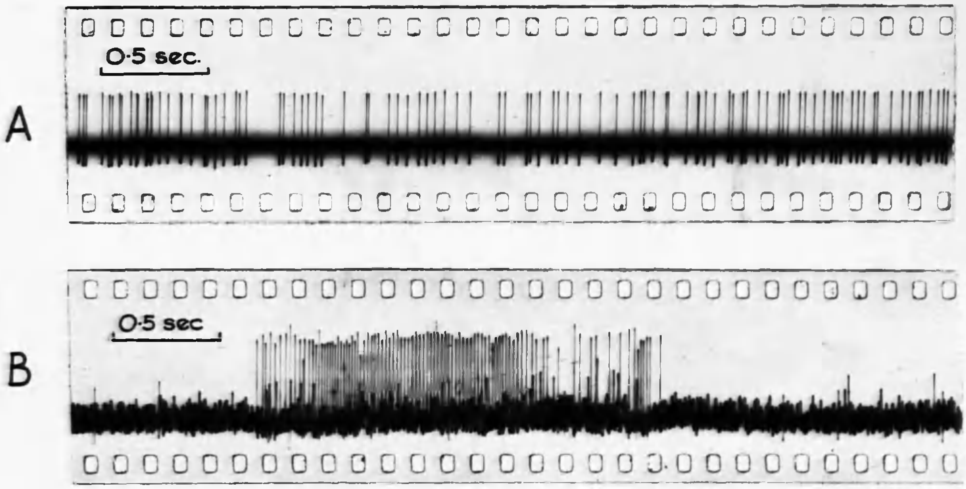

Fig. 65. *Oscillograph records of discharges in twigs of the sacral dorsal roots after section of all branches of the sacral plexus except the pudendal nerves.*

(A) Activity recorded from a twig of the second sacral dorsal root while fluid was flowing through the urethra from a reservoir 60 cm above the bladder. Note the totally irregular nature of the discharge.

(B) Activity recorded from a twig of the second sacral dorsal root while air was blown along the urethra from a syringe. Note the much higher frequency of the discharge in this case.

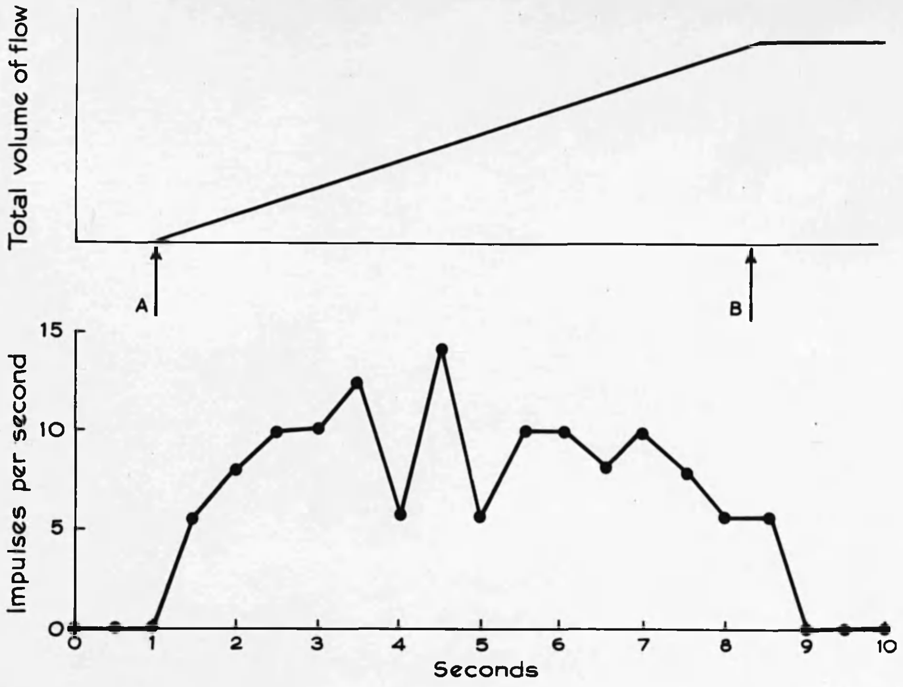

Fig. 66. *Graph of the response of a single urethral receptor during the flow of fluid distally along the urethra from a reservoir 60 cm above the bladder. The tap connecting the reservoir and the cannula was opened at A and was closed at B. The upper record shows the total volume of fluid which has passed along the urethra plotted against time, the lower record shows the response of the receptor. Note the correspondence between the flow and the discharge and the irregularity of the discharge frequency.*

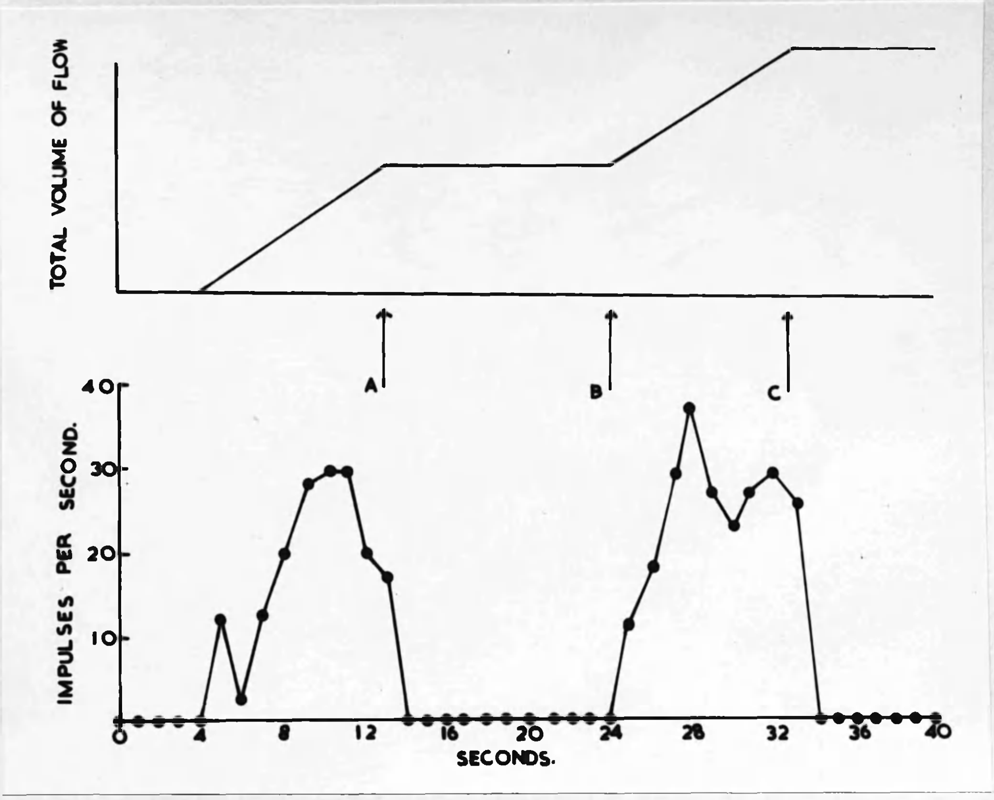

Fig. 67. *Graph of the response of a single urethral receptor during the flow of fluid distally along the urethra from a reservoir 60 cm above the bladder. The upper record shows the total volume of fluid which has passed along the urethra plotted against time, the lower record shows the response of the receptor. From A to B the second sacral ventral root of the same side was stimulated with 1 msec pulses of supramaximal voltage at a frequency of 16/sec., thus producing a tetanic contraction of the external sphincter muscle and so stopping the flow. At C the tap connecting the reservoir to the cannula was closed. Note the correspondence between the flow and the discharge.*

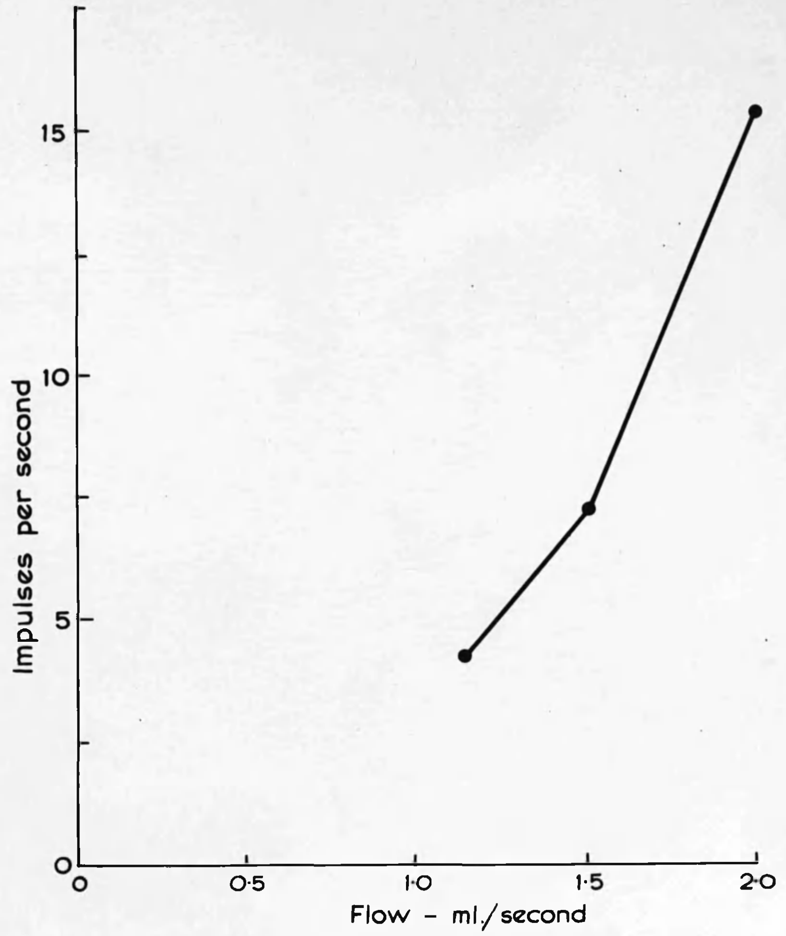

Fig. 68. Graph of the relation between the discharge frequency of a single urethral receptor and the rate of flow of fluid along the urethra from a reservoir. Both discharge frequency and rate of flow were calculated as the average over the same ten second period. The reservoir was set at three different heights above the bladder to produce three different rates of flow.

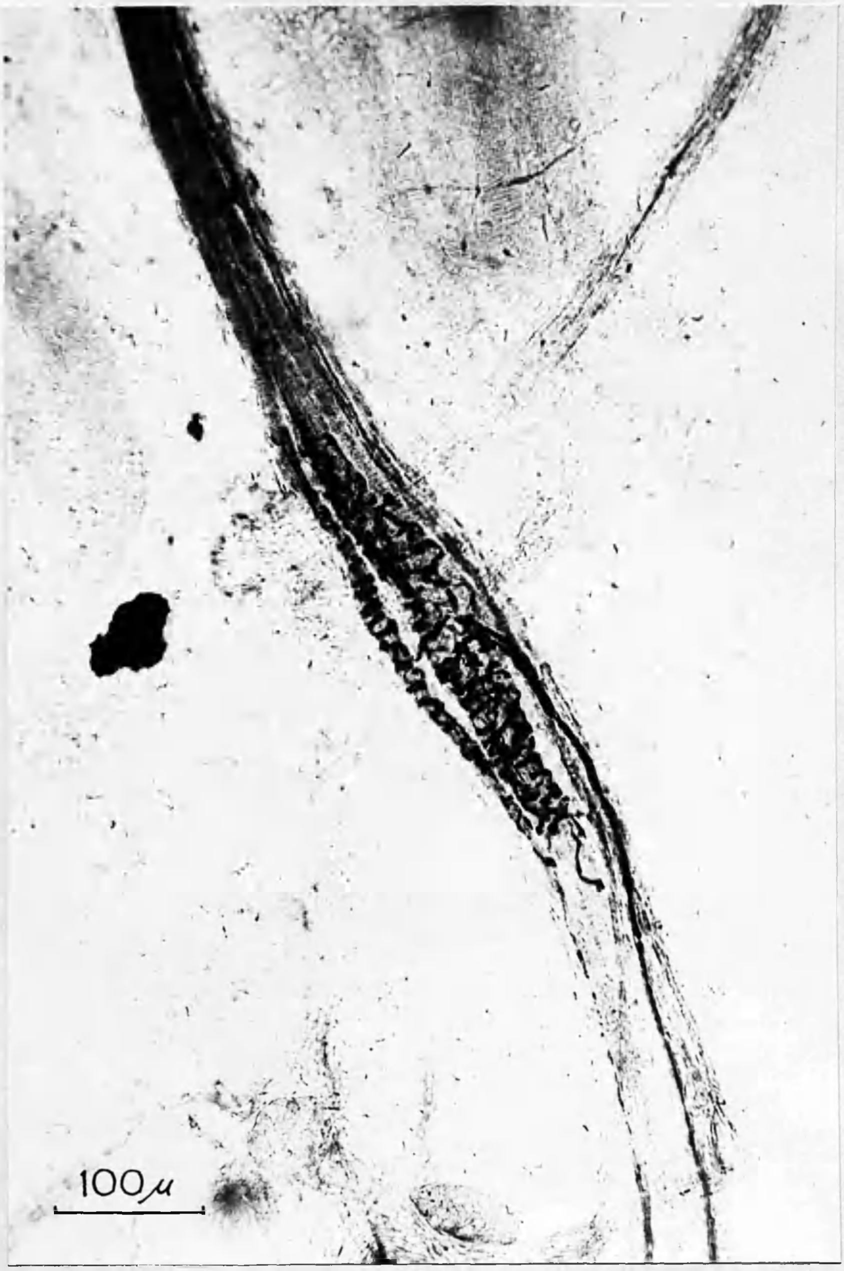

Fig. 69. A simple muscle spindle seen in a teased preparation of the external anal sphincter of the cat, stained with gold chloride. Note that the only sensory ending present is an annulo-spiral ending.

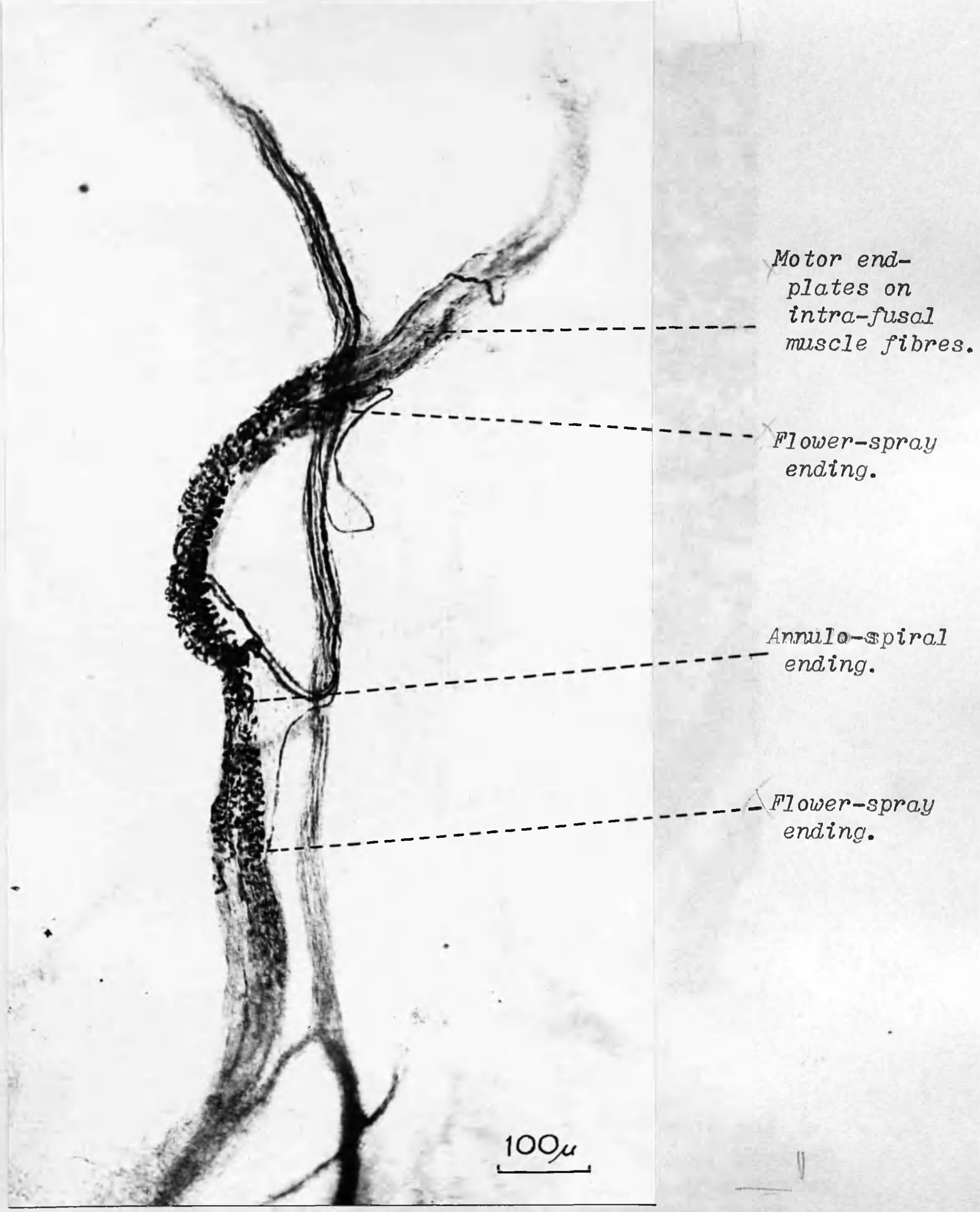

Fig. 70. A complex muscle spindle seen in a teased preparation of the external anal sphincter of the cat stained with gold chloride. Note that one annulo-spiral ending and two flower-spray endings can be seen as well as motor end-plates on the intra-fusal muscle fibres.

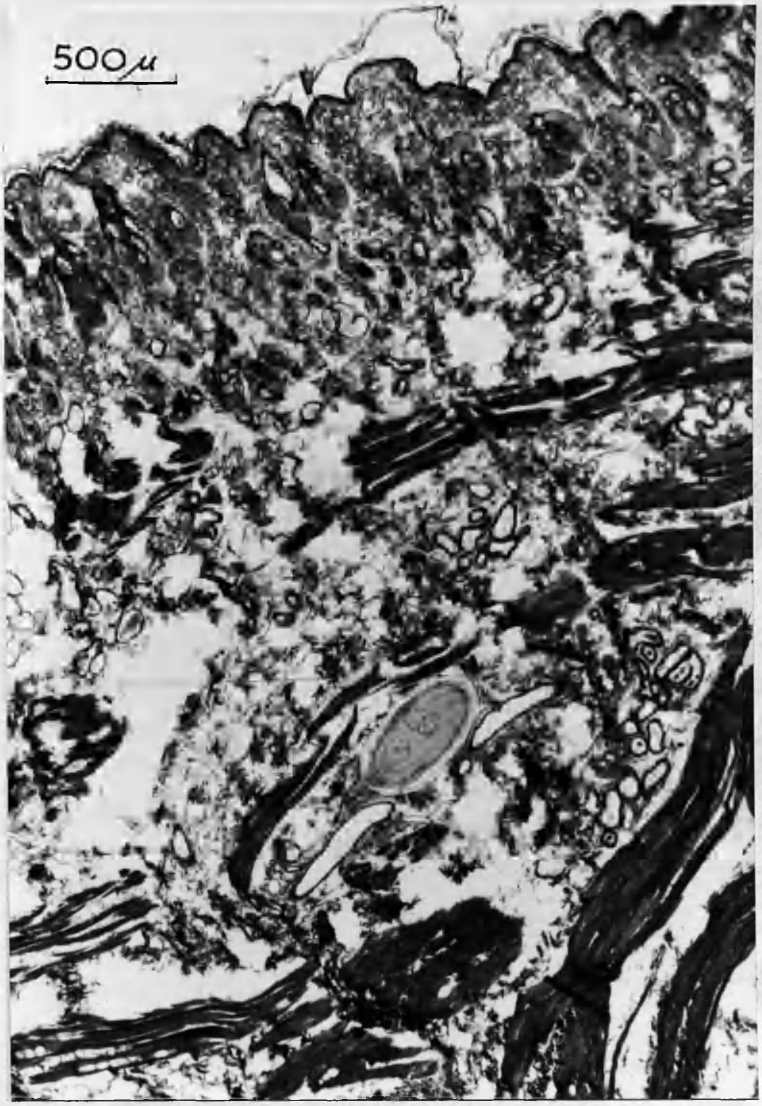

Fig. 71. A transverse section through the peri-anal skin and subcutaneous connective tissue of a female cat, stained with haemalum and eosin. Note the bundles of striated muscle fibres lying in the subcutaneous tissue which form the superficial part of the external anal sphincter and the lamellated end-organ lying in the outer part of this muscle.

Fig. 72. Part of a transverse section of the urethra of a male cat taken at the level of the external urethral sphincter, stained by the Masson method. It shows a large lamellated receptor of the Pacinian corpuscle type lying in the periurethral connective tissue.

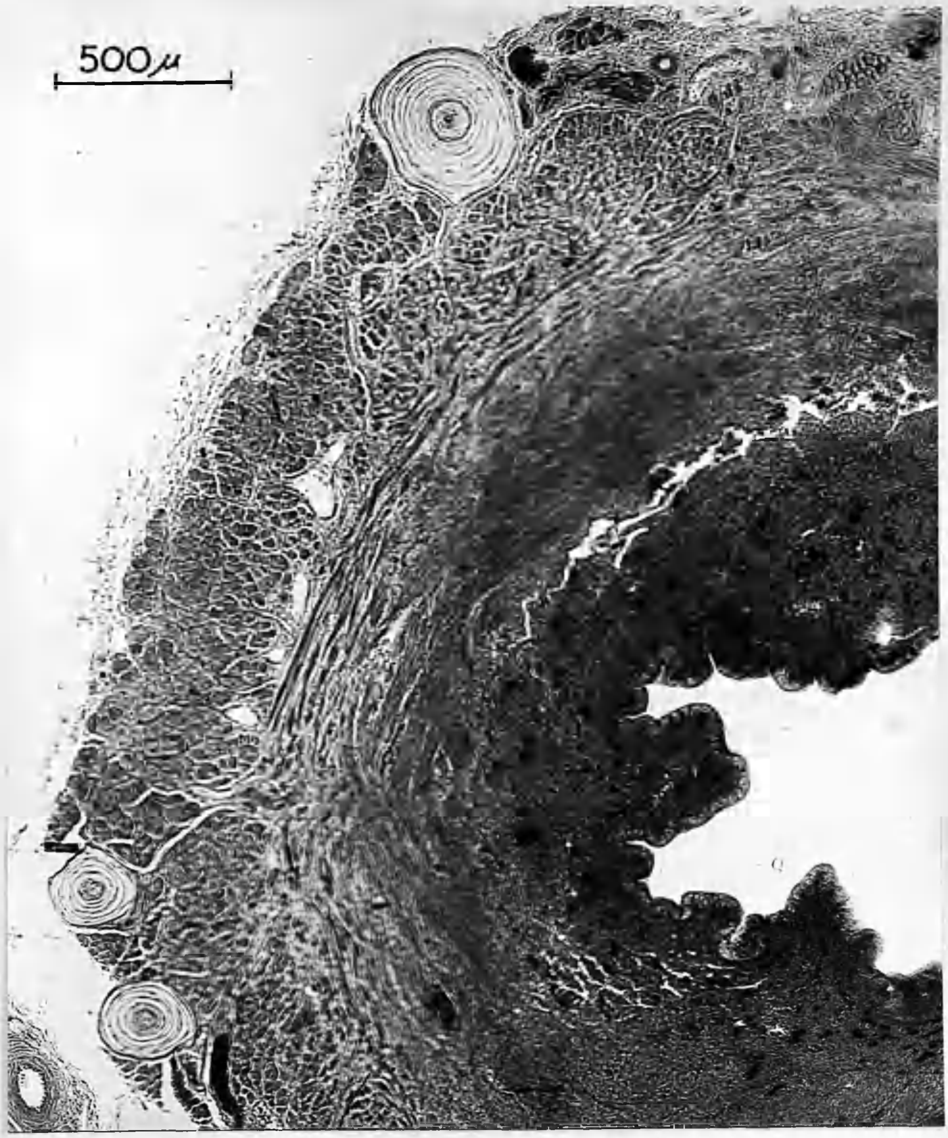

Fig. 73. Part of a transverse section of the urethra of a male cat taken at the level of the external urethral sphincter near the entrance of the ejaculatory ducts, and stained with the Bielschowsky-Gros silver method. Note the three lamellated end-organs embedded in the outer part of the muscle coat.

Fig. 74. *Part of a transverse section of the urethra of a male cat at the level of the external sphincter stained by the Bielschowsky-Gros silver method, counterstained with haemalum. It shows a group of lamellated end-organs lying beneath the surface epithelium at the tip of a mucosal fold.*

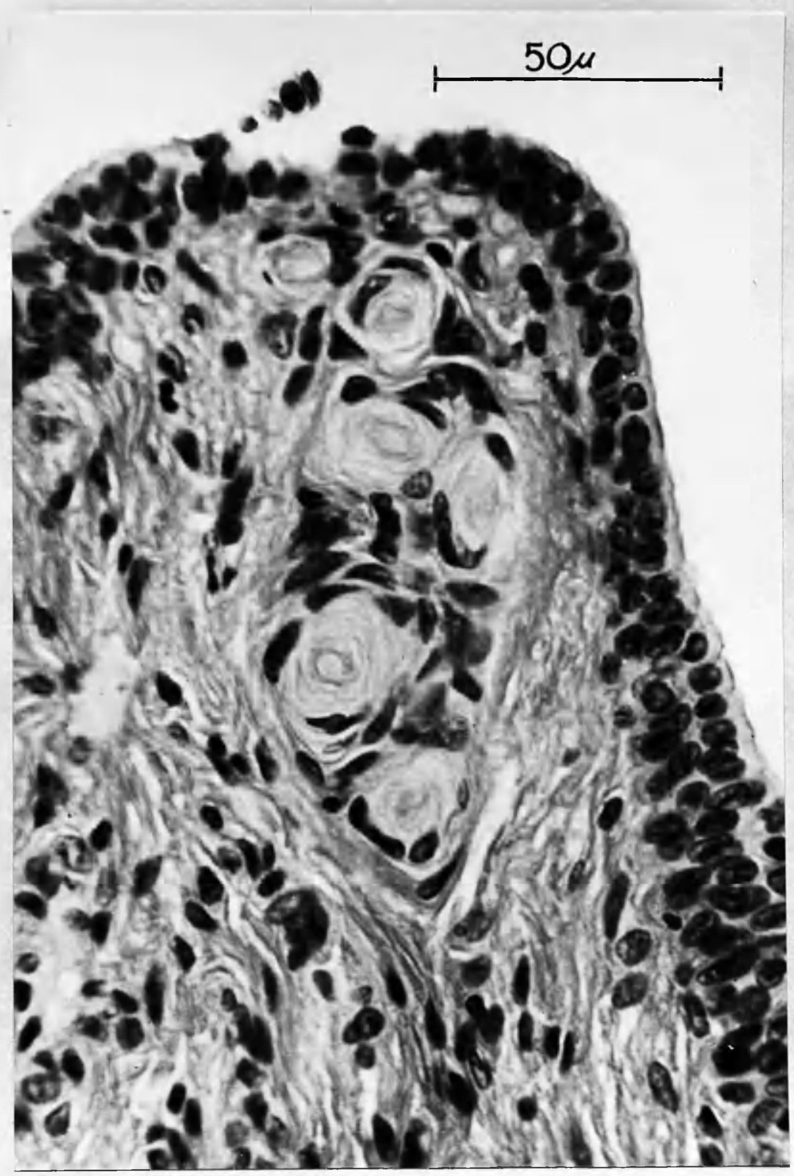

Fig. 75. Part of a transverse section of the urethra of a male cat stained with haemalum and eosin, showing a group of small lamellated end-organs lying at the tip of a mucosal fold.

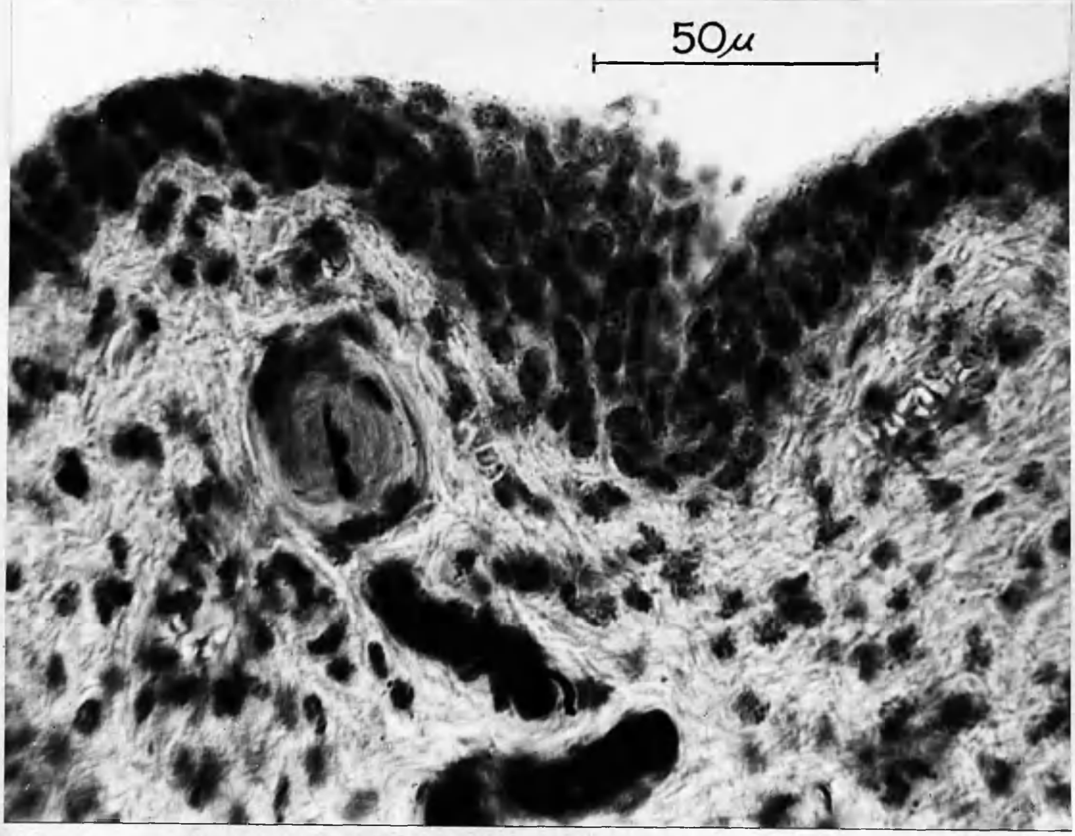

Fig. 76. Part of a transverse section of the urethra of a male cat at the level of the external sphincter stained by the Bielschowsky-Gros silver method, counterstained with haemalum, showing one of the small lamellated end organs in cross section and part of the nerve fibre supplying it.

Fig. 77. *A teased preparation of the urethral mucosa of a male cat stained with gold chloride, showing a small lamellated end organ.*