ON THE ORIGIN FROM THE SPINAL CORD OF THE VASO-DILATOR FIBRES OF THE HIND-LIMB, AND ON THE NATURE OF THESE FIBRES[1]. By W. M. BAYLISS. (Seventeen Figures in Text.)

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CONTENTS.

I. Introductory and Historical.

Introductory. It has been known since the work of Goltz[(1)] (p. 184 *et seq.*)[2] that the sciatic nerve contains fibres, excitation of which produces dilatation of the blood vessels of the hind-limb. These are the fibres the origin and nature of which I propose to consider in the following paper. We call them vaso-dilator fibres, in contradistinction to vaso-constrictor fibres, which increase the state of contraction of the vessels.

Central inhibition of the tonic excitation of these vaso-constrictors may also produce vascular dilatation, as also may section, when in a state of tonic excitation; this form of vascular dilatation will only be referred to incidentally.

[1] Prelim. Account. This *Journal* (*Proc. Physiol. Soc.*) xxv. xiii. 1890; xxvi. ii. 1890.

[2] See Bibliography at the end of this article, p. 208.

The term vaso-motor is often used as synonymous with vaso-constrictor. This leads to confusion, the term vaso-motor should only be used when it is wished to include both vaso-constrictor and vaso-dilator actions under one name.

It is obvious that when vascular dilatation is produced by the excitation of the peripheral end of a divided nerve, it can only be brought about by the presence of vaso-dilator fibres; unless we are prepared to accept the doctrine of peripheral ganglia in connection with blood vessels, a theory of vaso-motor action which has little, if any, evidence in its favour. (See Langley[18], pp. 655 and 671.)

It is necessary to be thus precise in defining the terms used, since the facts to be brought forward in the following pages are of a rather revolutionary nature, and therefore it is of more than ordinary importance to be quite clear as to the meaning of the words used in describing them.

Historical. It is, I think, unnecessary to give a detailed account of work relating to excitation of the sciatic nerve as it will be found in the text-books (*e.g.* Tigerstedt[2], p. 497); where it especially concerns the present subject of research it will be discussed in the text.

The first definite statement as to the origin from the cord of the vaso-dilators of the hind-limb was made by Stricker in 1876[3]. He finds that in the dog electrical or mechanical excitation of the peripheral ends of the divided posterior roots of the 6th and 7th lumbar nerves[1] causes considerable vascular dilatation in the hind-limb of the same side, as evidenced by rise of temperature in the paw. These results were confirmed by Gärtner[4], Morat[5], and Werziloff[6]. Cossy[7] (2 experiments only), on the other hand, obtained no constant effect, while Vulpian[8] (4 experiments only) and Kühlwetter[9] failed to obtain dilatation. As regards the last-named observer, however, it appears from his descriptions that, in the only experiments that can be considered successful, the roots excited were upper lumbar, and as he speaks of muscular twitches occurring during excitation it is obvious that his failure to obtain dilatation does not count for much. Hasterlik and Biedl in 1893[16] confirm Stricker. The only remaining papers needing reference are those of Bonuzzi[10], a pupil of Stricker's, who also confirmed his results, Laffont[11] who

[1] He calls them 4th and 5th, but at that time it was usual to reckon 15 thoracic nerves in order to make the lumbar equal to 5 as in man; we now reckon 13 thoracic and 7 lumbar in the dog.

found vaso-dilators in anterior roots, viz. in those of the 2nd to 4th lumbar nerves, and Bornezzi[12] who states that vaso-dilator fibres run centrifugally in all the posterior roots.

Notwithstanding their confirmation by several observers, the results of Stricker have not been generally accepted. This is, no doubt, due in part to their violation of the Bell-Magendie law, but chiefly to the fact that the experimental methods used, both by himself and others, were not sufficiently free from objection to warrant the acceptance of results so contrary to previous experience. I criticise the experimental methods in the next section, and will here only mention that the numerous conditions stated by Stricker to be necessary for the production of the effect, viz. young animals, absence of anæsthesia, no curari and previous section of the cord, tend to throw doubt on the reality of its presence. On the other hand Morat finds only two conditions necessary, viz. young animals and strong stimulation[5] (p. 695). Unfortunately, Morat did not use mechanical excitation, a fact which makes his experiments less convincing than those of Stricker. It seems to me that, taking the work of both observers together, the fact of vascular dilatation taking place on excitation of fibres in posterior roots is fairly established.

The statements made by certain observers as to the occurrence of vaso-dilators to the hind-limb in the abdominal sympathetic chain, as well as that of Laffont, that they are present in lumbar anterior roots, will be dealt with later.

II. Methods of experiment.

The most serious failing in previous work is, to my mind, the absence of a blood-pressure tracing taken simultaneously with the observations on the limb-vessels. It is plain on a little consideration that, even supposing no active change takes place in the limb, a rise of blood-pressure, due, for example, to reflex constriction in the splanchnic area, will passively distend the limb-vessels, and there will appear to be a genuine dilatation. This fact it is especially necessary to bear in mind in experiments involving excitation of nerve-roots; the posterior columns of the cord are extremely excitable and the least escape of current from the electrodes to them will produce a considerable rise of blood-pressure. It is remarkable that the earlier investigators of vaso-motor action, with the exception of Nussbaum, paid so little attention to this fruitful source of error;

Nussbaum's remarks are, however, so much to the point that they are worth quotation. He says[13] (p. 380), "But what is of still more importance is the fact that if the whole arterial system constricts reflexly, and if in certain regions the constriction is more pronounced than in others, a condition of things extremely probable *à priori*, the consequence may be, that an artery, although it attempts to constrict to a slight degree, will be passively distended by the greatly increased blood-pressure. In such a case dilatation is seen, although the reflex may be a purely constrictor one." And, of course, the same applies to direct, as well as to reflex, excitation of vaso-motor nerves, and, *mutatis mutandis*, to vaso-dilators as well as to vaso-constrictors. I regard it, therefore, as of paramount importance to take a tracing of the arterial blood-pressure at the same time as the observations on the condition of the limb-vessels.

Next, as to the best method of detecting vascular dilatation. Stricker noted, from minute to minute, the readings of a thermometer placed between the toes of the animal; Morat brings forward the following objections to this method, and to my mind justifiably:

Firstly, the local temperature is an index of the circulation only so far as there is a notable difference of temperature between the part of the animal in question and the surroundings.

Secondly, the variations in general body temperature of the animal interfere with the local changes.

Thirdly, the thermometer is slow in its indications and the tissues also take an appreciable time to warm. On these grounds he prefers to note the appearance of the skin, *i.e.* its redness or paleness. For my part I find it very difficult to be certain of changes in the colour of the skin, especially if the change is not great; moreover, for obvious reasons, the method is not easy to use for purposes of demonstration to others. On the whole the plethysmographic method is the most convenient and, I venture to think, the best, although I am aware that a worker of such experience as Langley prefers the method of inspection. Other advantages of the plethysmographic method are:

(1) That it allows the temperature of the limb to be easily and quickly altered, keeping it at the same time constant.

(2) That it enables the experimenter to give his whole attention to the delicate operation of exciting the nerve-roots, since the curve is being traced continuously and can be inspected afterwards.

(3) That it gives permanent records which can be preserved and compared together at any subsequent time. It must not be understood,

however, that a more convincing nature is claimed for records of this kind than for data afforded by other methods; tracings on smoked paper may easily be made to give expected results, so that their value depends more on the reliability of the investigator than on the method used.

In this research glass plethysmographs were used, the junction with the limb being made tight by an india-rubber collar. Instruments of different size were used according to the size of the animal. To apply the instrument, the skin, with the hair uncut, is plentifully rubbed with vaseline where the collar is to lie, the india-rubber collar turned back over the glass tube, the limb inserted as far as possible, and the collar turned over in contact with the skin; as a rule no leakage will be found to occur. It was formerly the practice to cut off the hair where the india-rubber collar is situated; I find, however, that it is better not to do so, the hair, matted with vaseline, forms a soft pad, which fills up interstices between the collar and any depressions on the limb, and so makes it easier to get a tight joint. The cheap vaseline sold for veterinary purposes is better than the refined article, since it is thicker, more tenacious, and melts at a higher temperature. The space in the plethysmograph surrounding the limb is now filled with warm water (about 40° C.). It might be expected from the results of Lepine [14] and Bernstein [15] (p. 589) that cold water would favour the manifestation of vascular dilatation. This, however, has not been my experience. If the limb is cold the circulation is apparently more or less at a standstill, and the vessels seem to be in a rigid, inexcitable condition. Whatever may be the explanation, the fact remains that I have several times failed to obtain dilatation with cold water, whereas, on replacing this with warm water, the same strength of stimulus has given a considerable effect[1]. The use of air instead of water is not to be recommended; one does not get the pulse-beats shown by the recording lever, owing to the large volume of air, and the size of the pulse-beats is often a useful sign of vascular dilatation; it is not so easy to detect leakage; one has not the power of varying the temperature of the limb; and the air is more sensitive to changes of temperature in the atmosphere of the room than water is. The changes in the volume of the limb were recorded by a piston-recorder of Hürthle's pattern (made by Albrecht) con-

[1] Of course, when cold water is replaced by warmer, it is necessary, before proceeding to excite nerves, to wait until the direct dilatation produced by the warmth has attained its stationary condition.

nected with the tube on the top of the glass plethysmograph by an india-rubber tube containing air; the piston-recorder was made about as sensitive as a moderately delicate Marey's tambour, its advantage over the latter is that its excursions are proportional to the change of volume throughout its range.

The mode of excitation was usually by an ordinary Du Bois Reymond coil with Wagner hammer, interrupting about 40 per sec., the scale was graduated in arbitrary units, but of known relative strength, *e.g.* an excitation with secondary coil at 1000 was ½ the strength of one at 2000[1]; the strength of current just felt on the tongue was at 1350 of the scale and unpleasantly strong at 1800; other methods of excitation used for special purposes will be referred to when occasion arises.

The arterial blood-pressure was recorded in the usual way by a canula in the carotid artery in connection with a mercurial manometer, the connecting tube being filled with saturated solution of sodium sulphate.

Dogs were almost invariably used; cats and rabbits occasionally.

A hypodermic injection of morphia (30 to 130 mgrms. according to size of animal) was given about 4 hrs. before the experiment complete anæsthesia was produced for the operation by A.C.E. mixture. It was found that by section of both vagus nerves the blood-pressure was kept more constant. This of necessity involved the use of artificial respiration, which, however, had the advantage that the degree of anæsthesia was under complete control, since a portion of the air, of amount capable of adjustment by stop-cocks, was allowed to pass through A.C.E. mixture in a Woulff's bottle. The air was always warmed by passing through a spiral tube immersed in boiling water. A canula was inserted in the external jugular vein for injection of curari or other drug. If curari was necessary it was found advisable to give it as early as possible in the experiment, in order that the fall of blood-pressure produced at first might have time to pass off before the nerve-roots were excited. After the various operations mentioned above, the animal was turned over on its belly, an india-rubber hot-water bottle placed under it, and the exposure of the spinal cord in the lumbar region proceeded with. This was done in the usual way, the

[1] It is frequently lost sight of that by giving the strength of exciting current in degrees of Kronecker's scale, nothing is stated as to the actual strength of stimulus as compared with that used by another observer with secondary coil at same position of scale, the two would be equal only if the current in the primary coil was the same in the two cases.

muscular mass first separated from the spinous processes and laminæ of the vertebræ, and drawn well aside by weighted hooks. It is well, in order to obtain a clear field, to snip off the transverse processes, an operation which allows the muscles attached to them to be drawn well to the side. The spines were cut off by bone forceps, and the laminæ removed. Bleeding was usually stopped by pressure, sometimes, and especially when from venous sinuses in the bone, it was impossible to completely stop it, but, if mopped out immediately before exciting nerves, the wound remained clean long enough for a stimulus of considerable duration, and the oozing of blood had the advantage of keeping the cord and nerves moist. Having exposed the dura mater of the cord, and stopped bleeding as far as possible, the wound was covered with cotton-wool, the limb placed in the plethysmograph, and the arterial canula connected with the manometer. The dura mater was then slit up in the middle line by probe-pointed scissors, a small aneurism needle passed under the bundle of posterior roots belonging to each nerve in turn, a ligature tied around the bundle as near the cord as possible and then the nerve-root cut away from the cord; by means of the ligature it could then be held up, and excited close to the place tied. Sometimes the cord, together with the anterior roots, was cut out, sometimes merely cut across at the upper level of the wound. As a rule, however, I preferred to leave the cord intact, as by this means the least escape of exciting current was shown by a rise of blood-pressure, if the animal was curarized, or, by movements in addition, if curari had not been given. For a similar reason I only gave curari when anterior roots or sciatic nerves were excited, thus being able to detect escape to anterior root-fibres, which would obviously, in the uncurarized animal, give rise to muscular contractions. If it was wished to obtain as long a piece of nerve-root as possible, the dura mater was cut through where the posterior root pierces it, and the latter could then easily be separated down to its exit from the spinal canal. The cord and nerve-roots were at intervals flooded with warm physiological saline, in order to prevent loss of excitability by cooling, and, in the intervals between excitation, the wound was kept covered with cotton-wool.

Werziloff[6] makes a point of removing the laminæ from one side of the vertebral column only, this, to my mind, renders his results worthless, it would be impossible to excite the nerve-roots without considerable escape of current to neighbouring structures. Moreover by his method of complete curarization and neglect to take a tracing

of the general blood-pressure, he makes it impossible to detect any such escape. This error is all the more to be regretted since his experiments are, in other respects, very complete.

III. The vaso-dilator fibres of posterior roots.

When I commenced the present research, so little did I credit the results of Stricker, that I did not think it worth while to excite the anterior and posterior roots separately, and contented myself at first with exciting the mixed roots outside the dura mater; on one occasion, however, having a large dog under experiment and a long nerve-root, of the 7th lumbar, prepared for excitation, it seemed a favourable opportunity for testing the truth of the results of the above observer. The posterior root was therefore separated from the cord and excited. To my surprise, a large dilatation of the limb was produced, in fact quite as large as had been previously obtained from the mixed roots. Subsequently, therefore, anterior and posterior roots were excited separately. I may say at once that I have never obtained the least dilatation from any of the anterior roots from the 3rd lumbar down to the 2nd sacral inclusive, whereas such was always obtained, with the exception of one experiment to be referred to presently, from posterior roots from the 5th lumbar to the 1st sacral inclusive. The amount of effect was in proportion to the size of the nerve-root; the 6th and 7th lumbar and 1st sacral being the largest roots taking part in the lumbo-sacral plexus of the dog, the vascular dilatation was greatest from them, and usually that from the 7th lumbar was the maximum. In one experiment I obtained an effect from the 4th lumbar, but in all probability this was a case of Langley's anterior form of plexus, and the 4th lumbar was therefore equivalent to the 5th of the ordinary type of plexus. I have never obtained any effect from the 2nd sacral nor from any nerve-roots below it. Fig. 1 is an example of the effect from the 7th lumbar.

This tracing was obtained in an old bitch, curarized, cord cut at level of 3rd lumbar vertebra, anterior and posterior roots of 5th, 6th, 7th, l. and 1st s. prepared for excitation. The latent period is seen to be of considerable length, and the dilatation lasts very much longer than the excitation. The strength of stimulus was that obtained from secondary coil at 1700 of the scale. As regards the latent period, it was, as might be expected, of very different length, according to degree of cooling of nerve, anæsthesia or shock of the animal and so forth, and

varied from 2 to 8 secs.[1] I do not lay any stress on the apparent duration of the effect, in many cases it lasted considerably longer than that shown in Fig. 1, and in most of the subsequent figures in this

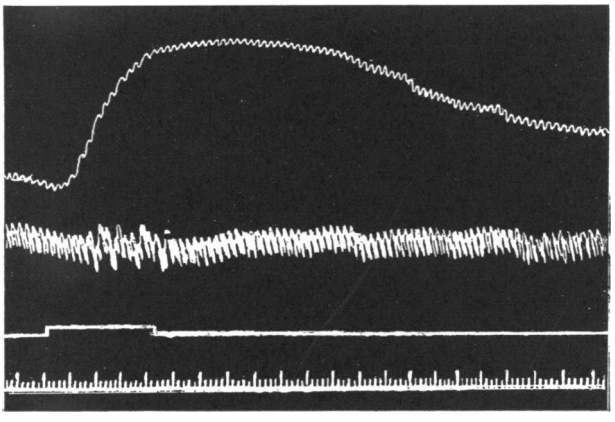

Fig. 1. Excitation of peripheral end of 7th l. posterior root. Uppermost curve—volume of limb; next below—blood-pressure, the 3rd line marks period of excitation, and the bottom line time in secs. Blood-pressure zero 25 mm. below time marker.

paper I do not give the whole length of the curve for sake of space. It is plain that the india-rubber collar at the upper end of the plethysmograph must necessarily compress the superficial veins to some extent, and this will vary according to whether the india-rubber is new or has become softened by vaseline. I have endeavoured to keep it as loose as possible consistent with prevention of leakage, but it was impossible to have at hand collars of the innumerable variety of sizes required for the different sizes of dogs used. Compression of the superficial veins will, while not appreciably affecting the onset of the arterial dilatation, no doubt tend to obstruct the outflow from the limb of the blood which has rushed in when the arteries expanded. It is well known that vaso-dilator effects do, as a rule, considerably outlast the excitation of the nerves causing them, but it seems to me that the long duration of the expansion seen in some of my curves needs a further explanation, and that given above is quite sufficient to account for it. Fig. 2 is given as an example of the difference between anterior and posterior roots; it is taken from the same experiment as Fig. 1, with weaker excitation.

[1] Not two to eight *months*, as by a slip of the pen Asher makes me to state (*Centralblatt f. Physiologie*; XIV. p. 354). 1900.

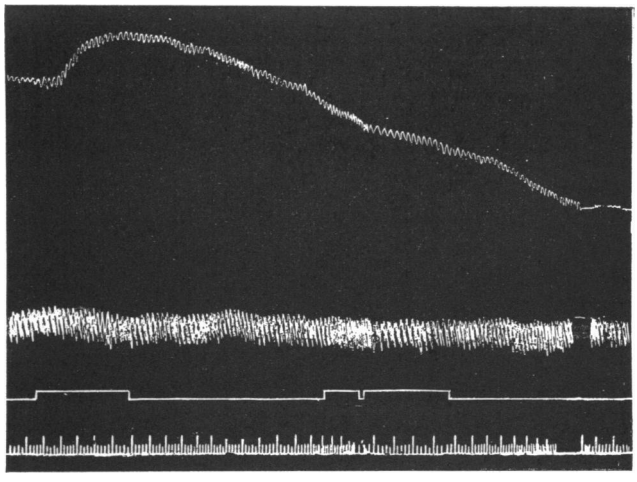

Fig. 2. Explanation as for Fig. 1. The first excitation is of 7th l. posterior root, coil 1600, the second that of the corresponding anterior root, same strength of excitation.

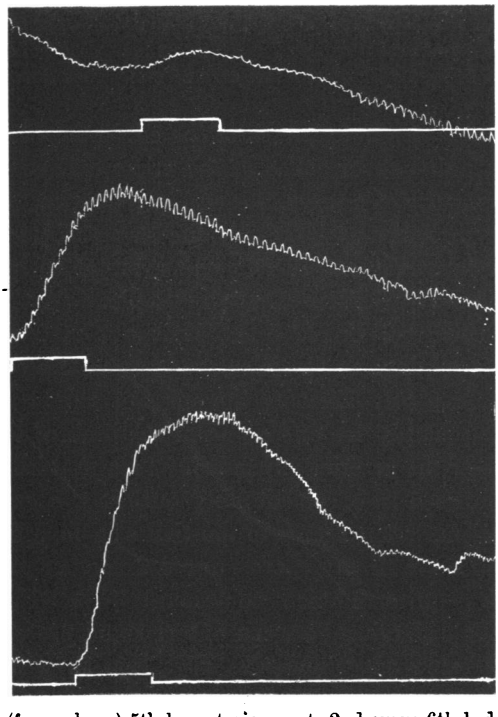

Fig. 3. 1st curve (from above) 5th l. posterior root, 2nd curve 6th l. do., 3rd curve 7th l. do.; all with excitation of equal duration, coil at 1700.

It is not a good tracing, the recording surface was moving irregularly, but I did not think it of any use to preserve many tracings of negative results; the apparent slight rise of the curve with anterior root excitation was due to the paper moving more quickly at that place as will be seen by referring to time traces, so that the continuous fall of the curve appears less steep. I have no doubt whatever of the absence of dilators from these lumbar and sacral anterior roots, having excited them many times without result; it will be necessary, however, to refer again to this point. Fig. 3 shows the increase of effect from 5th l. to

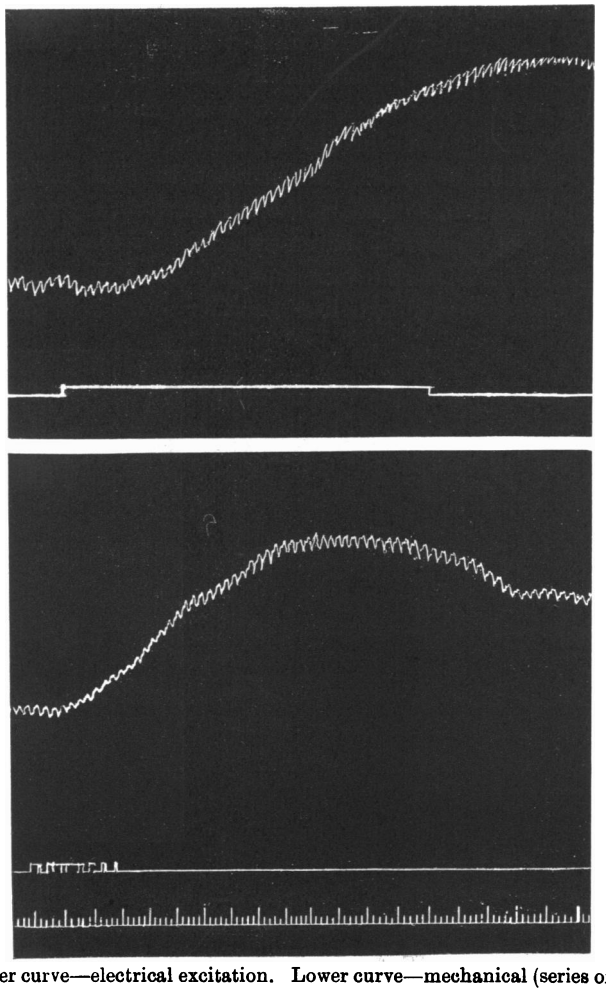

Fig. 4. Upper curve—electrical excitation. Lower curve—mechanical (series of 7 pinches). Time tracing at bottom marks secs. and applies to both curves.

7th l. These tracings were taken from a young animal, uncurarized, cord left *in situ*, but cut across at 9th thoracic vertebra.

I have found the vaso-dilator fibres in question extremely excitable to mechanical excitation. So much, in fact, is this the case as to be sometimes an inconvenience. The mere placing of the nerve-root on electrodes frequently causes a very considerable dilatation of the limb, and since one must wait until this has passed off, before proceeding to give a definitive excitation, the nerve-root becomes more or less cooled and dry. Fig. 4 will serve to show the effect of mechanical excitation, and also that it is as marked as that of maximal electrical excitation.

These tracings were obtained from a large bitch, no curari given, cord left *in situ* and uncut; there was no trace of muscular movement on excitation of posterior roots, although the anterior roots were very excitable. The strength of electrical excitation in the case of the curve reproduced was 1600 of scale. An increase to 1700 did not increase the degree of dilatation, so that, as the curves show, as great a dilatation can be produced by a series of seven pinches by forceps as by maximal electrical excitation. Of course in pinching one begins at cut end, and makes each successive pinch a little further away from cut end. The

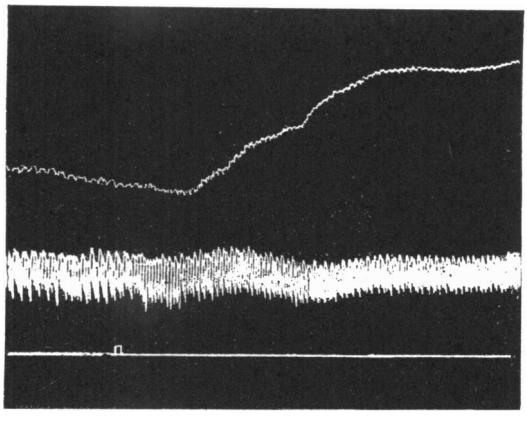

Fig. 5.

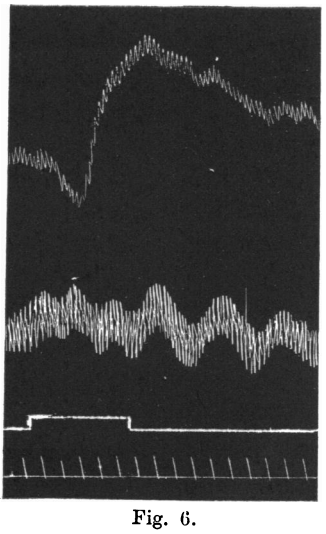

Fig. 6.

Fig. 5. Upper curve—volume of limb. Lower curve—blood-pressure. At mark on bottom line a crystal of sodium chloride was placed on the nerve (7th l.) which lay on a strip of celluloid film.

Fig. 6. Upper curve—volume of fore-limb. Lower curve—blood-pressure. Time trace in 10 secs. intervals.

effect can also be produced by thermal excitation, and by chemical (Fig. 5).

The fact that these fibres are so easily excited mechanically or chemically disposes of the possible objection that the effect may be produced by electrotonic escape to other nerve-fibres; but since electrical excitation is by far the most convenient, and was in fact nearly always employed (except as a final test), it is necessary to meet objections to it. I have already excluded escape to cord by simultaneous blood-pressure tracing, and it is incredible that vaso-dilator fibres in anterior roots should be excited by currents from an induction coil and ordinary motor fibres not be excited at the same time; moreover excitation of the anterior roots themselves does not produce dilatation. The only possibility, then, is that electrotonic currents may excite the grey rami passing from the abdominal sympathetic to join the nerves of the lumbo-sacral plexus. Langley and Anderson have shown that these rami pass up the nerves, after joining them, nearly as far as the spinal ganglia, and then turn downwards again to be distributed in the various branches of the nerves (17, p. 110). Now, in the case of the lower lumbar nerves the spinal ganglion is situated in the intervertebral foramen, the point excited is quite two inches away from it, and the currents necessary are not strong, that is, are not at all unpleasant to the tip of the tongue. Taking these facts into consideration, I do not think it probable that the grey rami are excited. Moreover, it is by these grey rami that the vaso-constrictors reach the hind-limb, and, even supposing that there were vaso-dilators with them, coming from some hitherto unknown source, experience with the sciatic nerve teaches us that ordinary tetanic excitation excites the constrictors only. In the case of the fore-limb it is quite easy to excite the grey rami, since the nerve-roots are much shorter than those of the lumbar region. Fig. 6 shows the effect of exciting the cut peripheral end of the 1st thoracic posterior root, coil at 2000.

It will be seen that there is a slight constriction, followed by considerable dilatation. Fig. 7, a similar experiment on same nerve-root, but with coil at 2500, shows a large constriction, followed by smaller dilatation.

Fig. 8 shows result of exciting same nerve-root with shocks at intervals of 1 sec., coil at 3000. No constriction is seen, dilatation alone is produced.

That the vaso-dilators in this case really run in the posterior root is shown by Fig. 9, which is the effect of pinching the nerve-root at

the tied end; this was done very carefully, so as not to pull upon the nerve, and so possibly excite the made up nerve beyond the spinal

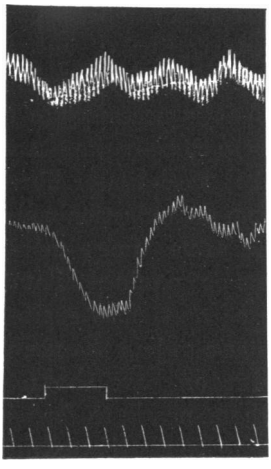

Fig. 7.

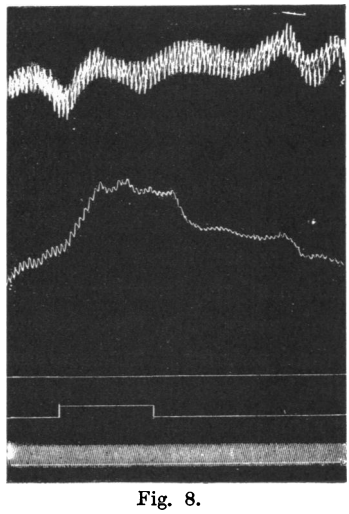

Fig. 8.

Fig. 7. Upper curve—blood-pressure. Lower curve—volume of fore-limb.

Fig. 8. Upper curve—blood-pressure. Lower curve—volume of fore-limb. Time trace, 1 sec. intervals.

ganglion. It is known that no vaso-constrictors to the fore-limb leave the cord by this nerve-root (Bayliss and Bradford[19]) and the constriction must therefore have been produced by electrotonic excitation of the grey ramus by the strong currents used. A similar result was obtained from the 8th cervical nerve, and as this nerve gives off no white ramus at all (see Langley[18], p. 638) it would perhaps have been more convincing to have given results from it; unfortunately, I had not so complete a series of curves. I think, therefore, that if we consider the case of Fig. 6, where the nerve-root was not more than $\frac{1}{2}$ an inch long, and yet, even with coil at 2000, the constriction was not great, we may rest satisfied that no electrotonic current would excite the grey rami of the lower lumbar nerve-roots in the case of an excitation with coil at 1400, and nerve-roots two inches or more in length[1]. In any case, however, the fact of the vascular dilatation being so readily produced by mechanical excitation puts at once out of court any question of escape to neighbouring fibres; all evidence points to the impossibility

[1] I have described this experiment at some length because it shows the circumspection necessary in interpreting results obtained from exciting short nerve-roots.

of the electrical currents of action in any particular fibre exciting a contiguous fibre. It may, indeed, be as well to point out that

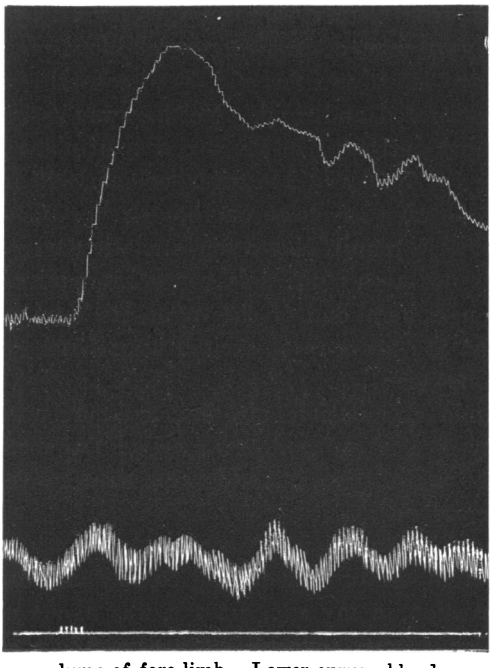

Fig. 9. Upper curve—volume of fore-limb. Lower curve—blood-pressure, its zero being 45 mm. below the line marking excitation. The rate of movement of paper was same as Figs. 6, 7 and 8.

Hering's experiments on "nerve-excitation by the nerve-current" [20] (p. 27 of reprint) were cases in which there was a common section of both sets of fibres, the exciting and excited, and that the effect was produced by the sudden abolition of the demarcation current in one set by the action current set up by excitation in the other set. This demarcation current had been previously compensating the similar current in the neighbouring fibres, and when it was abolished the demarcation current of the latter would suddenly manifest itself and cause their excitation. In the case before us no such conditions exist.

The figures I have chosen for reproduction were intentionally selected to show that I have not found necessary any of the conditions stated to be essential by Stricker or Morat. All my animals were anæsthetized with morphia and A.C.E., curari had no injurious effect, nor had the age of the animal in itself any influence. I have notes of

three or four experiments in which the animal was obviously of considerable age, but the dilatation was present. The only animal in which no effect could be obtained was one which did not seem aged, but the limb-vessels were plainly very rigid, as shown by their failure to respond passively to changes in the general blood-pressure. It seems therefore that age is only so far of influence as the vessels are more likely to be degenerated and rigid. Neither was it found necessary to use strong exciting currents; in the majority of cases a marked effect could be obtained at 1400 and a maximal one at 1600 or 1650, a current which could comfortably be borne on the tongue. Compared with the strength of excitation required by a frog's sciatic nerve, this is no doubt strong, but it is not so strong as is generally required to inhibit the heart from the peripheral end of the vagus in the dog, and it must be remembered that the nerve-roots excited were large, and therefore the current density not great.

Slow rhythmic stimulation, viz. induced currents at the rate of one shock every sec. or every 2 secs., as well as interrupted battery currents, have been also tried, but not found so effective as the ordinary tetanizing coil currents.

The degree of dilatation is as a rule very considerable, Stricker found a rise of temperature amounting to, in some cases, as much as 7° C. The expansion, in my experiments, was about equal in amount to the constriction obtained by exciting the peripheral end of the sciatic nerve with strong tetanizing currents.

The conclusion, then, to be drawn from the above experiments is, that there are nerve-fibres in the posterior roots of the 5th, 6th and 7th lumbar, and 1st sacral nerves, excitation of which, when cut away from the spinal cord, gives rise to vascular dilatation in the hind-limb of the same side.

IV. The fibres do not pass into abdominal sympathetic chain.

Stricker[3] found the effect still present after removal of the abdominal sympathetic; and it would seem *à priori* improbable that they should pass into this chain, since there are no white rami below the 4th lumbar, and there are no efferent fibres from the cord in the grey rami (see Langley[21], p. 60). I have performed one experiment to test the point. In a dog under morphia and A.C.E. no curari, the abdominal sympathetic on the left side was extirpated from behind the

kidney to the middle of sacrum, including the 1st sacral ganglion. The posterior roots of the 5th, 6th, 7th lumbar and 1st sacral were prepared in the usual way and on excitation, expansion of the limb obtained from all. Fig. 10 shows effect from 5th lumbar; the effect is not so

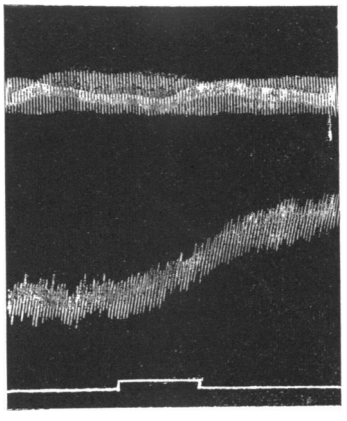

Fig. 10.

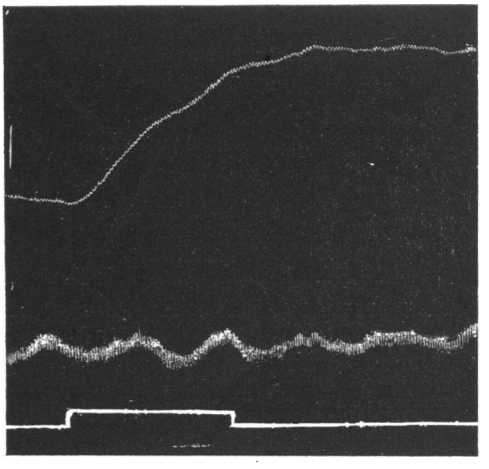

Fig. 11.

Fig. 10. Upper curve—blood-pressure. Lower curve—volume of limb. Bottom line marks excitation, coil 1800. Blood-pressure zero 28 mm. below excitation marker.

Fig. 11. Upper curve—volume of limb. Lower curve—blood-pressure. Bottom line marks excitation of 7th lumbar nerve-roots. Blood-pressure zero 50 mm. below excitation line.

great from this nerve as that from those below, but I give this one as being the highest and therefore cut off from passage through the sympathetic with most certainty.

V. Their "trophic centres" are in posterior root ganglia.

It is well known that Lenhossek[22] (p. 276) has described in the chick-embryo a number of fibres arising from cells in the anterior horn, which pass through the posterior root ganglion without being in connection with cells therein. No similar fibres have been described in the mammal, and it is most probable that the condition in the chick-embryo is a vestige of that remaining permanently in some fish (Petromyzon and Pristiurus), where some of the cells properly belonging

to the posterior root ganglion are situated in the spinal cord. However this may be, it is obvious that, if there were such fibres in the adult mammal, they would degenerate on section of the posterior root between the cord and ganglion. Experiments of this kind have been performed by Singer and Münzer[23], by Münzer and Wiener[24], by Kohnstamm[25], and by Sherrington[26], who found no degenerated fibres peripheral to the place of section; this result I can confirm with respect to lower lumbar roots of the dog, treated by the method of Marchi. The complementary experiment was performed by Sherrington[27] in the cat and monkey; after section of posterior roots no undegenerated fibres were present in the central stumps.

Although there is, therefore, no anatomical evidence of the presence of efferent fibres in posterior roots, I thought it advisable to test the question by excitation of degenerated nerve-roots. For this purpose I divided the lower lumbar and 1st sacral posterior roots in seven bitches as near as possible to the spinal cord. The operation was, of course, done under antiseptic precautions. After an interval of from eight to fourteen days the animals were anæsthetized and the nerve-roots excited in the way previously described. It was found impossible to prepare in a satisfactory manner the cut ends of the posterior roots inside the dura mater, owing to the new tissue in that situation; therefore curari was given and the mixed roots outside the dura mater excited. In the first two or three experiments, owing to an oversight, the anterior roots only were excited, and no effect on the limb produced; these experiments, accordingly, only confirm the previous statement as to the absence of dilators from the anterior roots. In the remaining cases dilatation was observed, and of an amount little, if at all, inferior to that in the normal animal. Fig. 11 (*supra*) is an example.

In this experiment the posterior roots of the 6th and 7th lumbar and 1st sacral nerves had been cut eight days previously. Both hind-limbs were in plethysmographs; dilatation was observed from all the nerves on both sides, except the 7th lumbar on the sound side, which had probably been injured in preparation; the dilatation was equal on both sides from corresponding nerves (except of course in the case of the 7th lumbar).

It may be of interest to mention that these animals, after recovery from the operation, showed the symptoms described by Baldi[28], viz. the affected limb not used for walking, often trailed with dorsal aspect of foot on ground, but used in association with vigorous movements of fellow (normal) limb, etc. (see also Sherrington[29], p. 802).

The spinal cord from the region of the lesion was examined by Marchi's method in two cases, and showed the usual ascending degeneration following section of posterior roots, viz. that of posterior root-zone and postero-median column on the same side.

In one experiment, in order to be more certain of the absence of escape of current to other parts, the whole lumbar cord down to the end was removed; nine days later the experiment was performed in the usual manner *without* curari; no muscular twitch was seen on excitation of the mixed roots, so that the muscular fibres had completely degenerated, there was nevertheless a considerable dilatation of the hind-limb, see Fig. 12, which is an excitation of the 1st sacral nerve-roots.

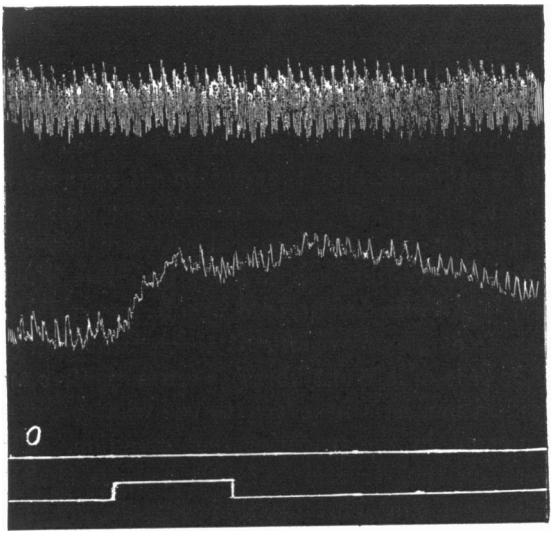

Fig. 12. Upper curve—blood-pressure. Lower curve—volume of limb. Bottom line, excitation marker.

The expansion of the limb is not so great as in most cases, partly no doubt owing to the greater severity of the operation, so that the animal was not in so good a condition as the others, and partly because the animal was a small one.

A doubt may arise as to whether a sufficient time was allowed for dilator fibres to degenerate; with respect to this, I may say that I took the longest time given by Dziedziul[30], viz. seven days (and this was exceptional) for the dilator fibres in the sciatic to lose their excitability,

and made my earliest observation on the 8th day. Dziedziul's results, moreover, are put in question by Langley[18] (p. 626), who, in conjunction with Anderson, found no effect whatever on excitation of the sacral nerves on the seventh day after section; Bowditch and Warren[31] (p. 443) found no effect from the sciatic of the cat after five days.

I conclude, therefore, that the vaso-dilator fibres of the posterior roots, whatever be their nature, do not degenerate on section between posterior root ganglion and cord, so that they are not spinal efferent fibres. It will be shown in a later section that they *do* degenerate when the posterior root ganglia are extirpated, hence their "trophic centres" are in these ganglia.

VI. They are identical with the afferent fibres of the posterior root.

From what has already been shown with regard to the course of these fibres, it is apparent that they are in all respects similar to the ordinary, afferent, sensory, posterior root-fibres; and the question at once suggests itself are they not identical with the latter? It has long been known that a nerve-fibre can conduct impulses in both directions, but whether an impulse in what would usually be considered the wrong direction is able to evoke any results at the termination (that is, at the periphery, in the case of afferent fibres) is quite another matter. Before coming to any decision, it is necessary to see what elements have been found to be present in the posterior root ganglion. The most comprehensive work on the structure of this body is that of Dogiel[32]; Fig. 13 is a diagram simplified from his figures, which will enable a short account of his results to be given.

There are, then, five elements (see explanation of Fig. 13) to be taken account of: 1. The neurons of the first type, *i.e.* the ordinary well-known sensory fibres with T junctions, these are of two kinds, viz., large cell-bodies with thick axons, and small cell-bodies with fine axons; 2. The neurons marked *d* in figure, which have their end-organs, instead of at the periphery in skin, muscle, etc., in the spinal ganglion itself; 3. The neurons of the second type, entirely included within the ganglion; 4. The "sympathetic" multipolar cells of unknown relations, except that they, also, appear to have the termination of their processes within the ganglion (why they should be called "sympathetic" is not

quite clear); and finally there are the fibres entering from the sympathetic chain along the grey ramus[1].

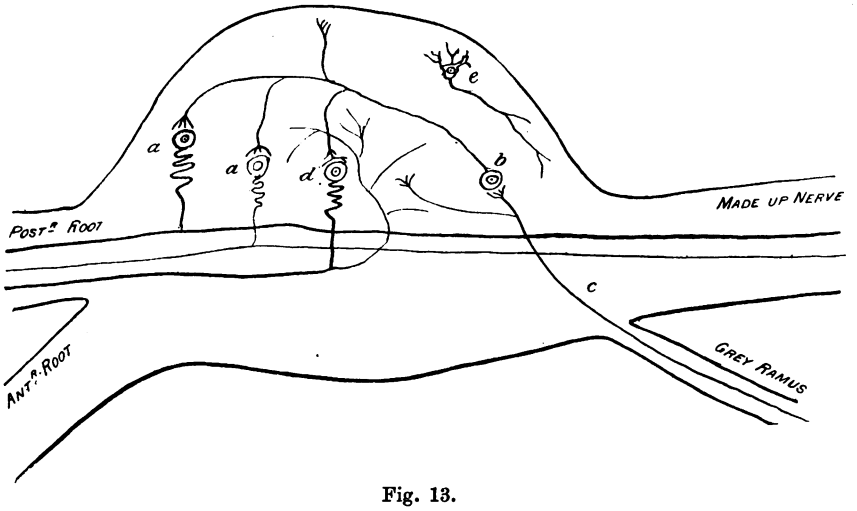

Fig. 13.

a. Neurons of Dogiel's first type.
b. A neuron of the second type, forming synapses with *a*.
c. Axon from sympathetic system, forming synapses with *b*.
d. A neuron similar to *a*, but its peripheral process, instead of passing down spinal nerve, breaks up into fine network around capsules of the other cell-bodies, and is, according to Dogiel, a sensory end-organ in the spinal ganglion.
e. Multipolar cell, connections uncertain, called by Dogiel "sympathetic."

Now the fact that mechanical excitation of the posterior root is as well able to produce the vascular dilatation as is electrical excitation, enables us to exclude from any share in the phenomenon the elements *b*, *c*, and *e*, since no part of them is situated within the posterior root itself. This conclusion is strengthened by the result of application of nicotin, as shown by the following experiment: A medium-sized bitch was anæsthetized and curarized, the 7th lumbar and 1st sacral posterior roots prepared as far as their spinal ganglia, so as to lay these bare, and the lumbar cord cut out. On excitation, these two roots gave a large dilatation of the limb; the cavity of the wound was then filled with a 1 % solution of nicotin tartrate in physiological saline, care of course being taken that it did not reach the cut end of the cord, the spinal ganglia were thus soaking in the solution; after waiting some minutes,

[1] Dr Mott informs me that it is quite easy, by Dogiel's methylene blue method, to confirm most of the facts described by him.

the nicotin solution was mopped up, and the nerve-roots again excited by the same current as before; the effect was undiminished. We may conclude from this that the course of the nerve-impulses is uninterrupted by synapses in the spinal ganglion. The only elements left are the cells of the first type, those marked *d* in the figure, and the sympathetic fibres *c*, the last can be excluded at once, since our dilator fibres do not pass into the sympathetic; the elements *d* can, I think, also be excluded by the following consideration. Let us suppose for the sake of argument that impulses pass along the fibre into the terminal ramifications, and there, by some obscure process, excite neighbouring structures. Now these structures can only be either the elements already described, and eliminated, or the neurons of Dogiel's first type (*a*), which comes to the same thing as if these latter were the neurons directly excited. We are, therefore, driven to the conclusion that the vaso-dilator action in question is conveyed along what are called afferent fibres, but in an efferent direction. This conduction of impulses in the contrary direction to that of the afferent impulses I shall speak of as an *antidromic* conduction.

It would be idle, in the present state of knowledge, to speculate on how this effect is produced, but a few words may be advisable with respect to some suggestions that have been made; hypotheses suggest experiments to confirm or refute them. Perhaps the simplest explanation is one suggested to me by Prof. Langley. The afferent fibres of muscle arise chiefly, or solely, in the muscle-spindles. Now, it is possible that, under certain circumstances, impulses in the sensory fibres, passing in what I call the antidromic direction, may set up changes, chemical or other, in the muscle-spindles, which may somehow affect the blood vessels. A certain support is given to this view by the experiments of Severini[34] (p. 96), who finds that carbon dioxide causes dilatation of capillaries, these experiments, however, so far as I can ascertain, have not been repeated. But, it seems to me, that the above interpretation is directly negatived by the following two experiments. In the first experiment, the skin of one leg of a dog was removed, and the foot cut off at the ankle-joint, so that only the muscle mass and bones were left. This was inserted into a plethysmograph in the usual manner, using necessarily physiological saline, instead of water, to fill the tube. The posterior roots having been prepared, they were excited, and the dilatation of the muscular vessels observed. Now, if the above explanation were correct, one would expect that the effect would be very nearly, if not quite, as great as that in the whole limb, since the

explanation implies that the effect is confined to the muscles. In this experiment we have removed extremely little muscular tissue; on the contrary, however, we see (Fig. 14) that the increase of volume is very small.

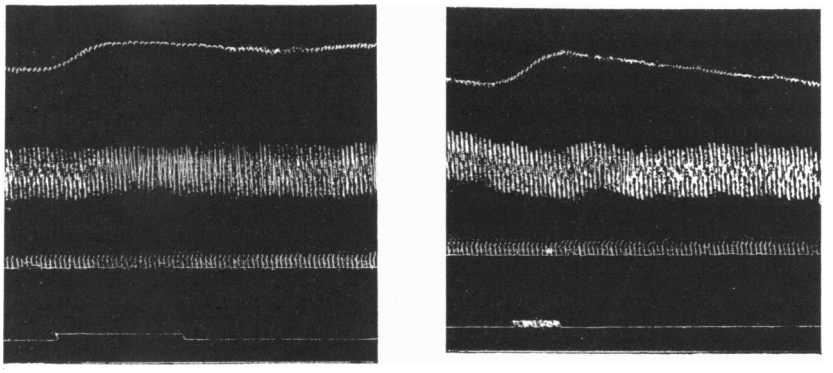

Fig. 14. In both tracings the upper curve is volume of limb, the lower curve—blood pressure. The time tracing marks seconds, and the bottom line duration of excitation. The upper tracing is with electrical excitation, the lower with mechanical. The blood-pressure zero in both is 45 mm. below the line of excitation marker.

The next experiment is the converse of this, and shows that there is a very large effect in the skin alone. The foot of a dog, as far as the

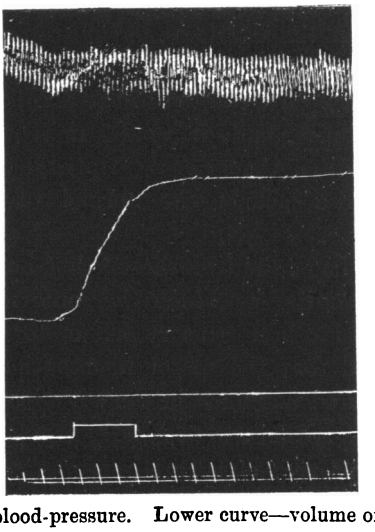

Fig. 15. Upper curve—blood-pressure. Lower curve—volume of foot. Top line is zero of blood-pressure. Middle line—excitation marker. Bottom line—time in 10 sec. intervals.

ankle-joint only, was put into the plethysmograph; the amount of muscle present here is infinitesimal, and yet, we see in the tracing (Fig. 15) that the dilatation is very considerable on excitation of the 7th lumbar posterior root.

If we take into consideration the relative volume of the tissues concerned in these two experiments, I think we must conclude that the chief seat of the vascular dilatation is in the skin. The long duration of the effect in some cases may appear to lend some support to the theory of chemical change, but the explanation of this fact given above (p. 181) seems to me quite sufficient.

Another suggestion is, that the posterior root fibres may divide on nearing their termination, one branch going to sensory end-organ in skin, muscle, etc., and the other going to blood vessels, and terminating there as a motor end-organ, the arrangement would then be somewhat similar to that concerned in the production of Langley's axon-reflexes[35]. The objection to this hypothesis is, that a vascular reflex from excitation of skin to vessels in itself would have practically no latent period, since the excitation would travel up one branch, and, at the fork, immediately pass down the other branch to the vascular muscle.

There is a certain amount of evidence that the blood vessels are supplied with sensory nerves (Heger[36]), it may be, therefore, that these are the fibres responsible for the vaso-dilator effect under discussion.

I think it scarcely possible that there should be a local nervous system in relation with the arterioles, having complex functions similar to that in the intestinal wall (see Bayliss and Starling[37], p. 114); to assume this would be unwarranted in the absence of any histological evidence of its existence, and, it would, moreover, be very like returning to the discredited theory of "peripheral ganglia"; whereas all evidence points to the fact of the normal vascular tone being of myogenic origin[1].

On the whole, perhaps, the hypothesis[2] that has the fewest inherent difficulties is that according to which the same nerve-terminations in the vascular muscle serve both sensory and motor functions. It seems fairly well established that the motor terminations in smooth muscle are of the nature of free filaments in contact with the muscle cells (see

[1] It is hardly sufficiently recognised that Bernstein (15 p. 602) so long ago as 1877, propounded the theory of the myogenic origin of vaso-motor actions, in opposition to the theory of peripheral ganglia then paramount.

[2] Yet another possibility may be worth mention. If the sensory motor fibres end in a common peri-arterial plexus, it may happen that antidromic impulses down afferent fibres may spread in the plexus, and so excite the motor fibres.

amongst others, Retzius[60], p. 50); the sensory terminations in many tissues are of the same character, and there is no apparent impossibility that the same termination may serve at one time to transfer efferent excitation from the cord to the muscle, and at another time to take up excitation from the blood vessel and convey it on to the nerve-fibre where it becomes an afferent impulse to the cord. A certain difficulty in this theory is, that in some reflexes the same fibres would convey both the afferent and efferent impulses.

A short article by Kohnstamm[38] bearing on this subject has recently appeared; in this an explanation is given of the effects obtained by Steirach on the frog's intestine, to which effects I shall have to refer later. So far as I can understand Kohnstamm's description, which is far from clear, his theory involves the assumption of a peripheral nervous system, but in other respects is similar to that suggested above.

VII. Is the hind-limb supplied with vaso-dilators from any other source?

The remark will probably be made, that, although these antidromic phenomena may be of interest in themselves, as a kind of physiological curiosity, there is no evidence that they play any part in the normal life of the organism. Now, I think, I can bring evidence that tends to show that they do play a part in normal conditions; but, before doing so, I should like to state that I do not regard the experiments related in this section as in themselves sufficient to demonstrate so extraordinary a phenomenon, and purpose to continue them; my object in bringing them forward here is that I wish for other observers to repeat them, and verify or refute my results.

There is no doubt that vascular dilatation is produced in the hind-limb under normal conditions, and that it may be produced in two different ways, either by excitation of vaso-dilator fibres, or by inhibition, from the central nervous system, of previously existing excitation of vaso-constrictors. It would be distinctly anomalous if the limb-vessels were only capable of dilatation from the central nervous system by the latter method, but of course the possibility must be considered. If we grant for the present that vaso-dilator fibres can be excited from the centre, it is of the utmost consequence whether the hind-limbs receive vaso-dilators from any other source than the posterior roots of which I have spoken. Various statements

to this effect have been made. In fact, it seems to have been almost taken for granted, up to the present time, that the dilators must run in the abdominal sympathetic, but the actual evidence for this is very unsatisfactory. Ostroumoff[39] obtained by excitation of the abdominal sympathetic with slow rhythmic shocks in one experiment only a slight rise of temperature in the paw of the same side, a number of similar experiments were without result, or gave fall of temperature; but the evidence on which he lays most stress is of a very indirect, and, as it seems to me, extremely questionable nature. He states that a rise of blood-pressure, produced by excitation of the peripheral end of the splanchnic, and therefore not brought about reflexly, is incapable of dilating the limb-vessels, but that a similar rise of blood-pressure produced by excitation of the central end of the vagus does do so, and finally that no dilatation is produced in the limb on exciting the central end of the vagus, if the abdominal sympathetic, on the side of the limb observed, has been previously divided, at the level of the bifurcation of the aorta. His interpretation of these results is as follows: passive dilatation is never produced because the peripheral nervous system of the vessels reacts against it, the dilatation observed on exciting the central end of the vagus is caused by reflex excitation of vaso-dilators, and its absence when the abdominal sympathetic is cut is due to the fact that these dilators run in that nerve chain. Now the first of the above statements is, to me, totally incomprehensible, and I can only ascribe it to the fallacious method employed, viz. measurements of temperature between the toes, on the contrary one of the greatest difficulties in working with vaso-motor nerves, and especially their reflexes, is to eliminate passive effects. As regards the second statement, I can only look upon it as particularly unfortunate that the central end of the vagus nerve was chosen for excitation, it is well known that from it both pressor and depressor reflexes are obtained, and which predominate depends on circumstances; in fact Ostroumoff himself sometimes obtained a fall of blood-pressure. As regards the last point, the experiments with intact and cut sympathetic were not performed on the same animal, and, moreover, division at the level of the aortic bifurcation would not cut off all the vaso-constrictor fibres from the limb. A converse experiment was performed by dividing all the roots of the lumbo-sacral plexus on one side, in this case, excitation of the central end of the vagus, as also asphyxia, caused a rise of temperature in both limbs, as would naturally be expected. According to Ostroumoff,

however, it shows that the vaso-dilators were equally intact on both sides. On the whole, after reading his paper carefully, I cannot admit that any satisfactory evidence is brought forward to prove his statement.

The experiments of Puelma and Luchsinger[40] are sometimes quoted as supporting Ostroumoff, but their statements are somewhat contradictory. The experiments consisted in dividing either the sciatic, or the abdominal sympathetic, in the cat, and observing the, presumably reflex, vascular dilatation of the paw produced on placing the animal in a warm atmosphere. The first statement made is that the dilatation is absent on the side of the lesion in both cases. In another series of experiments, the sciatic was cut on one side and the abdominal sympathetic on the other side; the dilatation on warming was now found to be less in both hind-paws than in the fore-paws, a fact in itself not of great moment, while it was obviously greater on the side on which the sympathetic only had been cut, showing, as they themselves admit, that dilators do pass into the sciatic from other sources than the abdominal sympathetic. Thus although they express themselves as believers in the passage of dilators down the sympathetic the evidence is not conclusive.

Dastre and Morat[41] (p. 247) are, so far as I can find out, the only remaining observers who have made experiments on this point. They find that excitation of the sympathetic just above the diaphragm, or above the 2nd and 3rd lumbar ganglia, causes dilatation in the hind-foot, whilst excitation below these ganglia causes constriction. They consider that the 2nd and 3rd lumbar ganglia send vaso-constrictor fibres to the vessels of the foot, and that the tonic action of these ganglia is inhibited by fibres running to them from the spinal cord. Langley[18] (p. 675) has not been able to detect any such difference between excitation above and below these ganglia, "except in so far that more care is required to avoid reflex dilatation when stimulating above than when stimulating below the ganglion. And the action of nicotin in the cat shows," he thinks, "that the 2nd and 3rd lumbar ganglia send no nerve-fibres of any kind to the foot."

Having shown, then, that there is no evidence of vaso-dilator fibres for the hind-paw in the abdominal sympathetic, we come to the statements of Laffont[11] who finds that the dilator fibres concerned in the production of Lovén's reflex on the saphenous artery leave the cord by the anterior roots and sympathetic rami of the 2nd, 3rd and 4th lumbar nerves. Now we know that vaso-constrictors are given

off as far down as the 4th lumbar, and, since Laffont did not take any blood-pressure tracing, there is no doubt that he produced a considerable rise of blood-pressure, which, in its turn caused a passive distension of the saphenous artery.

Schäfer[42] has shown that in the anterior roots of the cat there are cells probably belonging to the anterior horn; it is possible that there may be similar cells in the dog, and that these may be in connection with vaso-dilators. It has been shown above that excitation of anterior roots has no effect on the limb. But, it may be said, constrictors may be simultaneously excited and counteract the dilator effect. In answer to this, I may point out that when dilators and constrictors are together present in a nerve-trunk, as for instance the sciatic, excitation by tetanizing currents always produces a constriction, which may or may not be followed by a dilatation. Nothing of this kind, however, can be seen in the case of the lower lumbar anterior roots, and I do not think that there is any reason to suppose that the cells in question, even if present in the dog, have anything to do with the production of vascular dilatation in the hind-limb. Of course, in the case of the experiment described earlier in this paper (p. 191) in which the lower part of the cord was removed, the fibres arising from Schäfer's cells would not be degenerated, since, however, no muscular contraction was obtained on exciting the roots, the neurons in question, if present, must belong to the autonomic system.

Prof. Schäfer has also suggested to me that these cells might send dendrites up the posterior roots and that their excitation might account for the posterior root effect, without necessitating the assumption of antidromic impulses in afferent fibres. Apart from the fact that we have, so far as I am aware, no histological evidence of the existence of such structures, I think the result of the experiments described below, in which excision of the lower lumbar and upper sacral spinal ganglia caused degeneration of all the vaso-dilators of the lower limb, although the anterior roots were uninjured, as shown by the absence of motor paralysis, sufficient to show the non-existence of such dendrites.

The experiments in question, three of which have been performed up to the present, were as follows:

The spinal ganglia on one side were extirpated from the 4th lumbar down to the 2nd sacral inclusive, and the cut peripheral ends of the two sciatic nerves excited on the ninth day after the operation, curari being given. On the side of the lesion vascular constriction only could be obtained, either on excitation with rhythmic induction shocks

every 1 or 2 secs. of various strengths, or on pinching the end of the nerve; on the sound side vascular dilatation was obtained in most cases of excitation by rhythmic shocks and always by pinching the nerve. Fig. 16 shows the different effect on the two sides.

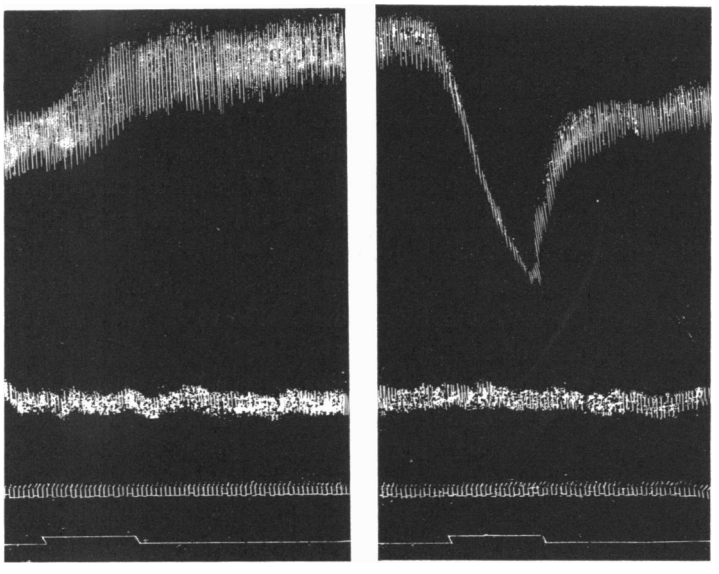

Fig. 16. Upper curves—volume of limb. Lower curves—blood-pressure. Time trace 1 sec. Bottom line marks excitation, shocks 1 per sec. of same strength in both cases, and the second tracing was taken immediately after the first. Blood-pressure zero 77 mm. below excitation marker.

It will be seen that there is no trace of dilatation on the side of the lesion, not even after the constriction has passed off. I conclude, therefore, that all the vaso-dilators were degenerated.

These results, if true, and it is necessary that more experiments be done to decide the question finally, mean that, if vascular dilatation in the hind-limb is produced at all by excitation of vaso-dilator fibres, the impulses must be of the kind called by me antidromic, and must pass down posterior root fibres.

An unexpected difficulty was met with in some experiments made for the purpose of finding some method of excitation that could be depended upon to excite any vaso-dilator fibres in the sciatic, if such were present. Rhythmic shocks of 1 per sec., or every two seconds, do not invariably produce dilatation in the normal animal, but I hope

to find some form of electrical excitation, either by condenser discharges or currents from an alternator, that will approximate more closely in time-course to the optimal stimulus for these fibres, the "characteristic" as Waller[43] calls it, which is evidently very different from that for the vaso-constrictor fibres. Fortunately, we have in mechanical excitation, by pinching or crimping, a means which, as far as my experience goes, never fails to reveal the presence of dilators in nerves where they are present. It is obvious, however, that this form of excitation can only be practised once or twice on the same nerve, so that it can only be used as a final crucial test.

Since, then, all the vaso-dilator fibres of the hind-limb appear to be afferent posterior root fibres, it must be that there is in normal life an antidromic excitation of these fibres, unless we are prepared to deny excitation of vaso-dilators and to postulate that the only vascular dilatation taking place normally in this case is that produced by inhibition of vaso-constrictor tone.

Now, in some experiments in which I have had occasion to cut the abdominal sympathetic I have been struck by the fact that no dilatation of the limb was produced; once or twice there was a slight expansion, but it was so small as to be within the limits of experimental error. Moreover, in two experiments made for the purpose, freezing the sciatic nerve produced a slight constriction in the limb. These results have led me to doubt whether there is any notable amount of tonic vaso-constriction in the case of the hind-limb, and to think that Goltz is probably correct in his statement that the effect of section of the sciatic is due to traumatic excitation of vaso-dilators[1] (p. 190). The question, however, needs further investigation.

An old observation by Luchsinger[44] seems to show that vaso-dilators are actually excited in normal vascular reflexes. The experiment was as follows:—In a kitten the sciatic nerve on one side was cut. By this means the maximal dilatation possible by inhibition of constrictor tone was produced, and indeed exceeded, since section of the sciatic excites the vaso-dilator fibres (as shown by Goltz). The toe-pads on the side of the lesion were now redder than on the sound side. If, however, the animal was placed in an incubator heated to 60° or 70° C. the sound paw become very much redder than that in which the sciatic was cut, showing plainly that reflex excitation of dilators had taken place, since the effect was greater than that produced by removal of tonic constriction. Another form of the experiment is also of interest; the kitten was first exposed to the warm atmosphere; both

paws became red, but on section of one sciatic the paw on that side immediately became paler.

In some experiments that I have made for the purpose I have obtained some evidence of reflex excitation of posterior root vaso-dilator fibres, but as the work is still incomplete I will at present merely indicate the nature of the experiments in a few words. In the rabbit I find the dilatation of the hind-limbs obtained by excitation of the central end of the depressor nerve (Bayliss[51]) still present after extirpation of the abdominal sympathetic on both sides from the 4th to the 7th lumbar ganglia inclusive, by which means all vaso-constrictors are cut off from the limbs. I have not yet been able to apply the crucial test of dividing the lumbar posterior roots on one side and thus abolishing the effect on that side while leaving it present on the other side; the rabbits would not stand the severe double operation. In the dog the central end of the vagus sometimes, with weak exciting currents, gives a fall of blood-pressure and dilatation of the hind-limb, this effect is not prevented by extirpation of both abdominal sympathetics but is abolished by section of cord at the third lumbar nerve-root. I have not yet succeeded in exciting the depressor in the dog, though Cyon states that this can be done[45].

I may point out here that the experiments of Gotch and Horsley on the mammalian spinal cord[46] (p. 489) and those of Mislawsky on that of the frog[47] show that there is no block to the passage of impulses from the cord backwards down the posterior roots, nor from one posterior root to another; whereas there is such a block to a passage up the anterior roots, an impulse cannot pass from any anterior root into the columns of the cord, much less into a posterior root or another anterior root.

As to the bearing of the experiments related in this section on the mode of action of the depressor nerve, and the cognate question of the existence of a vaso-dilator centre, I must be content for the present with referring those interested to Cyon's article in Richet's *Dictionnaire de Physiologie*[45] (p. 784 *et seq.*).

VIII. The vaso-dilators of the fore-limb, and other 'antidromic' effects from posterior roots.

It would be a very anomalous state of things if the vaso-dilators of the hind-limb of the dog were the only nerve-fibres capable of the antidromic excitation treated of in the preceding pages.

On the fore-limb of the dog I have performed four experiments, and obtained vascular dilatation from the posterior roots of the 6th, 7th and 8th cervical and 1st thoracic nerves, these are, as will be recognized, the nerves forming the brachial plexus. No effect was obtained from the nerves lower down, except constriction on using strong currents, which was no doubt due to electrotonic escape to anterior root-fibres or rami. I have already (p. 27) discussed one of these experiments, and given tracings (Figs. 6, 7, 8 and 9) of the effects produced. In one experiment a slight effect was obtained from the 5th cervical.

As regards the cat, I have found it more difficult to obtain positive results, the nerve-roots, both anterior and posterior, seemed to lose their excitability very quickly. Whether this was due to anæsthetic vapour in the air of the room (see Gotch and Horsley[46], p. 281) I am unable to say. Two experiments, however, were successful; by making the observations as soon as possible after preparation of the nerve-roots, I obtained dilatation in the hind-limb from the posterior roots of the 6th and 7th lumbar nerves. Fig. 17 shows the effect.

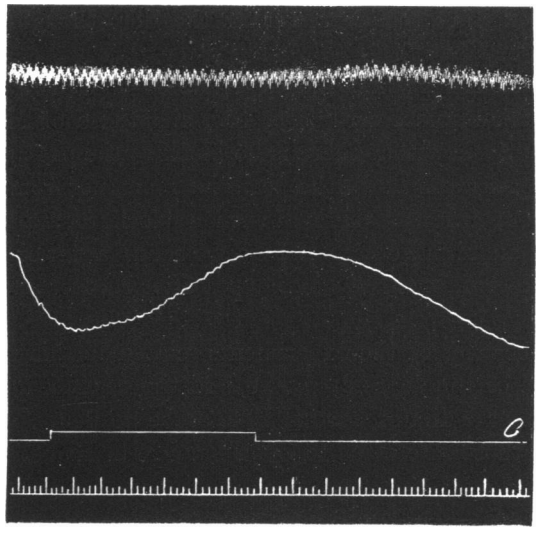

Fig. 17. Upper curve—blood-pressure. Lower curve—volume of limb. Upper of the two bottom lines—excitation marker, lower one—time in 1 sec.

The fall at the beginning of the limb tracing, before excitation, may, perhaps, be looked upon with suspicion, the cause of it, however, has nothing to do with the vascular mechanism, as is shown by the

entire absence of any change in the blood-pressure curve, it was simply due, in fact, to the experiment having been performed immediately after filling the plethysmograph with warm water, and, being done on a cold day in March, the water was cooling rapidly and so diminishing in volume. The nerve excited in the tracing was the 7th lumbar, coil at 1700. A slight effect was obtained from the 6th lumbar. Ten minutes later no effect was to be got from either nerve and the anterior roots also were inexcitable.

Bradford[50] (p. 387) has shown the presence of vaso-dilators from the kidney vessels in the mixed roots of the 11th, 12th and 13th thoracic nerves, I thought it worth while, therefore, to excite the posterior roots of these nerves; I have only done one experiment as yet and obtained a very slight effect from the posterior root of the 12th thoracic. On consideration, I think the kidney an unfortunate choice for the investigation of vaso-dilators to the viscera, since it appears to have a very scanty supply of these nerves; this is shown by the fact, amongst others, that no actual increase of volume of the kidney can be obtained on depressor excitation, although all other organs investigated show such. (See my paper on the depressor nerve[51] [1].) It appears, indeed, that the large dilatation produced in the kidney by diuretics is due to a direct action on the blood vessels, analogous to what seems to be the case in voluntary muscle. In future experiments, accordingly, I propose to take either the intestine, or spleen, for observations on posterior root dilators.

Another kind of antidromic action of posterior root-fibres is that described by Steinach and Wiener[52], who state that movements of the intestines in the frog can be obtained by excitation of peripheral ends of posterior roots; Horton-Smith[53] was unable to confirm their results, but obtained effects on skeletal muscle; Steinach[54] reaffirmed his previous statements in 1898, while Horton-Smith's results were confirmed by Wana[55]. The question must be looked upon as undecided up to the present.

I may also hazard the suggestion that Heidenhain's "pseudo-motor" contractions in the tongue obtained by exciting the lingual nerve after degenerative section of the hypoglossal[59] may come under the head of antidromic actions.

[1] I may perhaps be allowed to take this opportunity of adding to the list of organs in which actual expansion takes place the following, viz. the spleen of the cat, and the ear of the rabbit; on both of which experiments were made since the publication of the paper referred to.

It appears certain that some vaso-dilators pass out from the spinal cord in anterior roots; Gaskell[56] has shown this in the case of the nervi erigentes, and Dastre and Morat[41] (p. 100) in that of the vaso-dilators of the bucco-facial region.

IX. Notes on some related points.

Vaso-dilators of voluntary muscle. A subject only incidental to the present work, but of some interest in itself, is that of the vaso-dilator nerves of voluntary muscle. The tracings already given in Fig. 14 and also the fact that no greater effect was obtained by pinching the sciatic nerve, seem to lend considerable support to Langley's contention[18] (p. 640) that the results of Gaskell[48] are not due to excitation of vaso-dilator nerves properly so called, but to some effect of the contraction of the muscular fibres, perhaps products of metabolism. Severini's experiments on the action of carbon dioxide[54], if correct, are of interest in this connection. Lactic acid, according to Osborne and Vincent, has no effect on the blood vessels of the mammal[49] (p. 293); according to Gaskell[58], however, it dilates the arteries of the muscle of the frog; and, moreover, he himself[58] (p. 67) suggests an explanation of vascular dilatation in active muscle similar to that of Langley mentioned above.

The impression one gets from the small amount of vascular dilatation obtainable by excitation of vaso-dilator nerves to muscle is that the blood vessels of this tissue take part in general vascular reflexes to aid in the production of a large fall of general blood-pressure, but that the effect is not large enough to be of importance in the functional activity of the tissue.

Relation to certain pathological facts. I do not feel competent to discuss the bearing of the facts brought forward in the preceding pages on pathological phenomena, and will therefore merely refer to the well-known vascular lesions associated with tabes, which is an affection of the sensory side of the central nervous system; and also to the interesting work of Head[57] on changes in the posterior root ganglia in cases of Herpes Zoster, which seems to show the existence of antidromic impulses in the posterior root-fibres of another kind than that treated of in the present paper.

In conclusion I should like to express my thanks for valuable suggestions and criticism to Dr Anderson, Prof. Langley, Prof. Morat, Dr Mott, Prof. Schäfer, and Prof. Starling.

X. Summary of conclusions.

1. There are nerve-fibres in the posterior roots of the 5th, 6th, and 7th lumbar and 1st sacral nerves, excitation of which, when cut away from the spinal cord, gives rise to vascular dilatation in the hind-limb of the same side. The excitation may be either electrical, mechanical, chemical, or thermal, and of these, mechanical excitation is most effective.

2. These fibres do not pass into the abdominal sympathetic chain, and therefore must proceed directly into the lumbo-sacral plexus.

3. They do not degenerate when cut between spinal cord and posterior root ganglion, hence they are not spinal efferent fibres. They do degenerate when posterior root ganglia are extirpated, hence their "trophic centres" are in these ganglia.

4. They are, in fact, identical with the ordinary sensory afferent posterior root-fibres; the name "antidromic" is suggested for the process by which nerve-fibres convey impulses in a direction contrary to that assumed by the Bell-Majendie law, when such impulses produce effects in the organs at the origin of such fibres, *e.g.* when afferent fibres excited at their ends in the central nervous system produce vascular dilatation at their peripheral ends in the tissues of the body.

5. There is no evidence that the hind-limbs receive vaso-dilator fibres from any sources other than the above-named posterior roots.

6. There is a certain amount of evidence tending to show that these fibres are excited, antidromically, in reflex vascular dilatation of the hind-limb, but further work is necessary.

7. It is doubtful whether there is normally any considerable amount of tonic excitation of vaso-constrictors of the hind-limb, and, this being so, reflex vascular dilatation must be produced chiefly by excitation of vaso-dilators, and only to a small degree, if at all, by inhibition of vaso-constrictor tone.

8. Voluntary muscle is too scantily supplied with vaso-dilator nerves for these to have any importance in the functional activity of the tissue.

9. The vaso-dilators of the fore-limb of the dog are situated in the posterior roots of the 6th, 7th, and 8th cervical, and 1st thoracic nerves, perhaps to a small amount also in that of the 5th cervical.

10. Vascular dilatation has also been obtained in the hind-limb of the cat by exciting the posterior roots of the 6th and 7th lumbar nerves.

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