An inquiry into the parts of the nervous system which regulate the contractions of the arteries / By Joseph Lister.

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XXIX. *An Inquiry regarding the parts of the Nervous System which regulate the contractions of the Arteries.*

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Great light has been thrown in recent times upon the nature of the influence exercised over the blood-vessels by the nervous system. In 1852 it was shown by M. Bernard that division of the sympathetic nerve in the neck of a cat, or other mammalian, was followed by turgescence of the blood-vessels of the ear, and increased heat of that part and of the whole side of the face, together with contraction of the pupil. Early in the following year Mr. Augustus Waller performed the converse experiment of galvanizing the sympathetic above the point where it had been cut or tied, with the very striking result of rapid subsidence of the turgescence of the vessels, and fall of the temperature of the face; while the pupil became so extremely large, as to imply that the dilating fibres of the iris were thrown into a state of energetic contraction†.

From these experiments it appeared to follow pretty clearly that the sympathetic nerve in the neck presides over the contraction of the vessels of the face, which, becoming relaxed and dilated when the influence of the nerve was removed by its division, allowed the blood to flow through them in larger mass than before; but on the other hand, when excited to extreme constriction by the galvanic stimulus applied to the nerve, permitted but little blood to pass. This conclusion appears to be confirmed by the observation since made by Brown-Séquard, that the elevation of temperature which occurs in Bernard's experiment is never greater than is to be accounted for by the increased mass of warm blood which must be sent through the part, on the hypothesis that the turgescence of the vessels is simply the result of their dilatation. It was further shown by Messrs. Waller and Budge, that the same region of the spinal cord which they had previously ascertained to preside over dilatation of the pupil, namely, the part included between the last cervical and third dorsal vertebræ, also regulated the vessels of the face. When that part of the cord was removed, turgescence of those vessels occurred; but galvanizing the anterior roots of the spinal nerves proceeding from

* This paper, and that on the Pigmentary System of the Frog, were read as supplements to the Essay on the Early Stages of Inflammation which succeeds them. The author has since extended his investigations into the subject of the present memoir, in accordance with a recommendation from the Council, and the results have been incorporated into the text, all new matter thus introduced being indicated as such either by date or by note at the foot of the page.

† Comptes Rendus, vol. xxxvi. p. 378.

that part produced the same effect as irritation of the sympathetic, namely, pallor with diminished temperature*. M. SCHIFF afterwards ascertained, that after destruction of the lower part of the cervical and upper part of the dorsal region of the cord in Bats, there is an immediate dilatation of the small vessels of the wings†, and BROWN-SÉQUARD had previously shown that after transverse section of the spinal cord in the lumbar region in Birds and Mammals, an increase of 1°, 2°, or 3° FAHR. took place in the temperature of the paralysed parts‡. All these facts tend to the same conclusion, namely, that the spinal cord is the part of the nervous centres which presides over the blood-vessels, and that one important action at least which it induces in them is constriction of the circular coat of the arteries. But there still remains, I believe, some difference of opinion with regard to the interpretation of BERNARD'S experiment; and there might be some colour for the idea that the red and turgid state of the vessels seen after division of the sympathetic in the neck was due to a change in the blood, such as occurs in inflammation, and that the pallor ensuing upon galvanizing the nerve was the result of a return of the vital fluid to its normal condition after restoration of nervous influence. But all ambiguity of this kind seems to me to be removed by some observations made several years ago by Mr. WHARTON JONES upon the Frog. This animal is peculiarly adapted for investigations on this subject, because both the calibre of the vessels and the state of the blood as it flows through them can be observed with the utmost facility in the web; and Mr. JONES found that division of the sciatic nerve was followed by dilatation of the arteries, but that this increase of calibre, so far from being caused by an obstruction in the progress of the blood, was accompanied with unusually free and rapid flow through the capillaries§. But with regard to the part of the nervous system which regulates the contractions of the arteries, some more recent observations by the same author are at variance with the conclusion above drawn from experiments by others upon Mammalia. For he states that the division of the roots of the sciatic nerve within the spinal canal failed to produce dilatation of the vessels; whence it was inferred that the sympathetic fibres of the sciatic trunk, as distinguished from those derived from the cord, are the channels through which the stimulus is transmitted to the arterial coats‖. WALLER and BUDGE'S experiments, on the other hand, appear to show that it is from the cord that the sympathetic derives its controlling power over the arteries. This discrepancy upon a matter of such great importance in physiology appeared to me to demand further inquiry¶, and I propose in the present paper to communicate the results to which this investigation has led.

* Comptes Rendus, vol. xxxi. pp. 377, 575.

† Gazette Hebdomadaire de Med. et de Chir. 1854, pp. 421, 424.

‡ Experimental Researches, New York, 1853, p. 8.

§ Essay on the State of the Blood and the Blood-vesselsin Inflammation, by T. WHARTON JONES, Esq., F.R.S. Guy's Hospital Reports, vol. viii. p. 12.

‖ Observations on the State of the Blood and the Blood-vessels in Inflammation, Med. and Chir. Trans. vol. xxxvi.

¶ Since this paper was read, my attention has been called by Professor GOODSIR to experiments recently

The first experiment which I performed with reference to this subject (October 27, 1856), namely, division of the sciatic nerve on one side, gave somewhat puzzling results. Knowing how difficult it is to judge correctly of differences of calibre in the vessels by mere inspection, I tied out both feet of a frog (under chloroform), so that a slight movement of the stage of the microscope would bring either into view, and thus, after performance of the operation in one limb, the other foot might serve as a standard of comparison. I then selected a particular artery of the left foot for measurement with the eyepiece micrometer, and, having noted the limits between which its calibre varied during half an hour, isolated the nerve from surrounding parts by dissection, without any material change taking place in the diameter of the vessel. I next tied a piece of thread tightly round the nerve, with the effect of causing within the first few seconds distinct constriction of the artery, which then gradually expanded, and within two minutes had a larger measurement than I had previously observed. In other words, the effect of the ligature had been constriction speedily followed by dilatation. But on examining the web half an hour later, I found the artery had contracted again to about its usual proportions; after a few minutes the amount of constriction was very considerably greater, and continued so after division of the nerve above the ligature, and on looking at the other foot I found the arteries there similarly contracted. During the next twenty-four hours I made frequent careful comparisons of the conditions of the arteries in the two feet, and found that they presented exactly the same variations in calibre; being sometimes closely constricted, at other times fully dilated in both. The constrictions generally commenced a very short time before a struggle of the animal, and gradually subsided when it had become quiet. It was thus evident that the arteries had experienced no permanent dilatation whatever from the division of the sciatic nerve, a result quite at variance with the experience of previous observers.

The explanation of this will shortly appear. On the 8th of April, 1857, I laid open the spinal canal of a frog in its entire length, and divided, as I supposed, all the roots of the nerves coming off from the left side of the cord from the occiput to the sacrum, and immediately examined the webs of both feet, the frog being under the influence of chloroform. In the right limb the circulation was almost entirely arrested, while in the left it was going on freely. My attention was then diverted for half an hour, when the arteries of the right foot were found of medium size; but in all the three webs of the left foot they were extremely dilated, appearing to have two or three times the diameter of those of the right limb*. This observation was of itself sufficient to prove that the

performed by PFLÜGER. Operating upon the large edible frog of the continent (*Rana esculenta*), he succeeded in applying the galvanic stimulus to the anterior roots of the sciatic nerve within the spinal canal, with the effect of causing complete constriction of the arteries of the webs. Division of the same roots on the other hand was followed by full dilatation of the vessels (see HENLE and MEISSNER's Bericht, 1857). Clear proof had thus been given, before my investigation of the subject commenced, that the spinal system does influence the arteries of the frog's foot.

* In this and other cases of division of roots of the spinal nerves, I observed that the skin of the limbs supplied by the nerves cut became perfectly smooth, instead of being, as usual, rough with minute papillæ. This appears to show that the unstriped muscular tissue of the skin is under the control of the spinal system.

spinal system, as distinguished from the sympathetic, does influence the contractions of the arteries of the frog's foot. Here, however, as in the case of the divided sciatic nerve, the effects were not permanent. Six hours later the arteries on the left side appeared smaller than they had been, though still bearing marks of the operation by remaining constant in calibre, whereas those of the right foot exhibited very frequent variations, from pretty full dilatation to almost absolute closure. Next day the same state of things continued, the vessels of the left foot being constant in size for four minutes together, while in the right foot an artery exhibited about eight distinct variations of calibre per minute as observed by micrometer; but after three days more they had become both small and variable in the left foot, and seemed to have quite recovered. On the application of galvanism to the cord, however, both legs were thrown into violent spasm, showing that communications still existed between the left limb and the nervous centre; and it appeared probable that the branches which remained undivided had come after a while to supply more or less perfectly the place of those which had been cut. A similar explanation seemed applicable to the speedy recovery of contractility in the vessels after cutting the sciatic, other nerves in the limb supplying the place of the divided trunk.

In another experiment, performed on the 11th of April, the roots of the nerves on the right side were divided within the spinal canal, beginning at the head and proceeding gradually backwards. No enlargement of the vessels of the webs occurred until the roots of the sciatic plexus were cut, when full dilatation of the arteries of the right foot took place, one which had a few minutes previously varied from 1 to 2 degrees of the eyepiece micrometer being now $3\frac{1}{2}°$ in diameter, and remaining so for ten minutes together. Half an hour later, however, I was astonished to find the artery again contracted to 2°, and not quite constant in calibre. But next day, on dissecting the animal, I found that some branches of considerable size between the cord and the sciatic plexus remained entire.

This experiment, while confirming the proof of the influence exerted by the cord over the arteries of the feet, convinced me how difficult it is to make sure of dividing all the roots of the nerves for the hind legs within the spinal canal; the operation being a very delicate one, while the parts are obscured by the bleeding which occurs in the living animal. At the same time the speedy recovery of function after partial division of the roots, pointed out a ready source of fallacy in such experiments. Had I deferred the examination of the web for half an hour in this case, there would have been no evidence of any effect produced on the vessels by the operation, and yet, had it not been for dissecting the frog, I should not have doubted that all the roots had been severed.

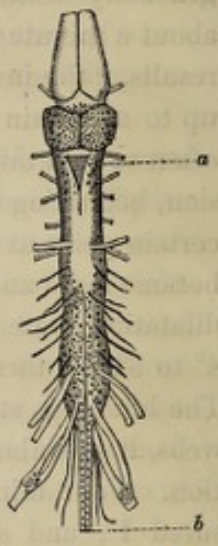
Dilatation of the vessels of the webs having been found to follow division of the roots of the spinal nerves, it appeared important, in order to complete the evidence on the point at issue, to observe the occurrence of contraction in the arteries on irritation of the cerebro-spinal centre. For this purpose, on the 14th I laid open the cranium of a frog under chloroform and thrust a very fine needle into the cerebral hemispheres, while one of the feet was stretched under the microscope: no effect was, however, pro-

duced upon the arteries; one selected for micrometrical observation, the largest of the web, measuring, as it had done before, nearly 4°, which was a state of full dilatation. I then treated in a similar manner the posterior dark-coloured portion of the brain, including the optic lobes, cerebellum and medulla oblongata, which were not distinguished from one another in the experiment. As I continued this treatment for a few seconds, keeping my eye over the microscope, the artery became contracted to 1°, which was the length of a red corpuscle. The leg then became spasmodically extended, and the artery was carried out of the field; but when I next looked at the web after removal of the needle, the vessels had dilated again to pretty full size. Having selected a main artery of another web more conveniently placed, I repeated the experiment of thrusting the needle into the posterior portion of the brain. This vessel, which just before, though by no means at its largest size, measured $2\frac{1}{2}°$, became contracted to almost absolute closure, and remained so till the needle was removed, after which it gradually dilated, and in three minutes measured 2°; forty seconds later $2\frac{1}{2}°$; and about a minute afterwards 3°. The experiment was repeated several times with similar results, "the invariable rule" (to quote from my notes) "being contraction of the artery up to a certain point, and maintenance in the contracted state during the *whole* time, often several minutes, that the needle was stirred about in the brain; and then expansion, beginning almost immediately after withdrawal of the needle, and advancing to a certain point at which it remained till the needle was again introduced." As the brain became more and more broken up, the contractions grew less and less energetic, and the dilatations were increased, till the needle failed to produce greater contraction than from 4° to 3°. I then thrust the needle into the spinal canal and withdrew it immediately. The hind legs started, and, after a few seconds, when I first caught sight of one of the webs, it was almost bloodless, and the arteries were invisible through extreme constriction. Four minutes later the artery before observed had begun to dilate and measured 1°, and after five minutes more it was 3°. A repetition of this experiment produced similar effects*.

* The constriction of the arteries of the webs on irritation of the cord may be readily demonstrated in the following simple manner. The head of the frog being depressed so as to stretch the ligament between the occiput and first vertebra, a sharp knife is carried across the spinal canal immediately behind the head, so as to divide the cord from the brain. The toes may now be tied out and any observation made upon the web without the inconvenience generally produced by voluntary struggles on the part of the animal, while at the same time the use of chloroform is avoided; which is very desirable, on account of the irritating effect of its vapour on the web and the constant care required for its administration. If the webs be examined immediately after the operation, they will be found exsanguine from extreme constriction of the arteries; but in a few minutes this state will give place to dilatation with free flow of blood. If now a fine needle, curved at the end, be introduced through the wound into the spinal canal, so that its point may penetrate a short distance into the cord, while the eye of the observer is kept over the microscope, the arteries will be seen to become constricted to absolute closure, and dilate again after withdrawal of the needle. The experiment may be repeated as often as may be desired till the cord becomes disorganized.

I have lately found the above-mentioned mode of preparing the frog the best adapted also for experiments

Abundantly sufficient proof had now been obtained that the cerebro-spinal axis does contain a nervous centre for regulating the contractions of the arteries of the feet. But it was uncertain whether that centre were confined to any one part of the cord, or diffused extensively through it and the brain; or even whether a similar office might not also be discharged by some of the sympathetic ganglia. With a view to determining these points, which are of great physiological interest, several experiments were performed, some of which it will be necessary to relate; but in order to make their description intelligible, it will be well to say a few words regarding the arrangement of the spinal cord in the frog. It does not occupy the entire length of the spinal canal, but extends backwards only seven-tenths of the distance from the occiput to the sacrum, while the posterior three-tenths of the canal contain merely the cauda equina, including a slender filiform prolongation of the cord, which, though apparently composed in part of nervous matter, seems to give off no nerves.



In the accompanying sketch of the superior aspect of the brain and cord of a frog, magnified two diameters, the distance from *a* to *b* represents the length of the spinal canal. The principal nerves for the hind legs spring from the cord near its extremity, but other smaller branches with the same destination arise nearly as far forward as the middle of its length. There are also connecting filaments between these and some nerves for the abdominal parietes, taking origin slightly further forward than the middle of the cord. Thus the nerves for the posterior extremities are furnished chiefly, but not quite exclusively, from the posterior half of the cord. To expose the cord in its entire length without injury to it or any of its slender branches is troublesome, and also involves much loss of blood. It is therefore very desirable to be able to come at once on any part of the cord you may desire, without laying open the whole canal. This can be readily done from the data above given. The articulation between the occiput and first vertebra can be felt through the skin, as also can the commencement of the sacrum; and the distance between these points is the length of the spinal canal. This, multiplied by 0·7, is the length of the cord: the requisite fraction of this length is then measured from the occiput and gives the place required.

Assistance may also be derived from the circumstance that the posterior edges of the scapulæ correspond very nearly with the mid-length of the cord, overlapping the posterior half by only about $\frac{1}{20}$th of the whole.

To proceed with the experiments. On the 16th of April, a large frog being put under chloroform, the entire brain was removed about 3 o'clock P.M. without injury to the cord. After this operation, the arteries, which had previously been of pretty full size

elucidating the nature of inflammation. Little if any reflex action of the limb occurs when irritants are applied to the web; and if no great amount of blood have been lost in the operation, the creature will survive it a long while, *e. g.* eight days in one case.

and transmitting rapid streams of blood, were found completely contracted, so that the webs appeared bloodless except in the veins, and continued so for some minutes. At $3^h\,10^m$ an artery selected for special observation was dilating, having already attained to a diameter of $1\frac{1}{2}°$, and the circulation was returning in the web. At $3^h\,15^m$ the vessel measured 3°, but two minutes later was $2\frac{1}{2}°$, and half an hour afterwards exhibited the spontaneous changes in calibre commonly seen in arteries in health, the limits observed being $1\frac{1}{3}°$ and 2°. It thus appeared that the removal of the brain had had no further effect upon the arteries than the temporary constriction induced by the irritation of the anterior part of the cord in the operation, followed by a brief period of dilatation. At 4^h, a small part of the spinal canal having been laid open, the anterior sixth of the cord was removed, corresponding to the anterior third of the scapulæ. At $4^h\,3^m$, when the web was first looked at, the artery was contracted to absolute closure, and the web exsanguine; and this state of things continued till $4^h\,7^m$, when the vessel began to dilate. At $4^h\,8^m$ it measured $2\frac{1}{2}°$, and at $4^h\,13^m$, 3°. Four minutes later it was short of 3°, and after five minutes more it was observed to be undergoing spontaneous variations of calibre from $2\frac{1}{2}°$ to $2\frac{2}{3}°$. Finally, at $5^h\,30^m$ its condition was just as it was before the experiment was performed, varying from $1\frac{1}{2}°$ to 2°, without any struggle on the part of the creature, the blood at the same time flowing rapidly through it*. At 6^h, another vertebral arch having been taken away, the subjacent portion of cord was removed, the canal being thus cleared as far back as the level of the mid-scapulæ, corresponding to rather more than a quarter of the cord. The operation caused contraction of the artery to 1°; but this passed off in half a minute, and was followed by no further dilatation than to $1\frac{1}{3}°$, and a few minutes later the artery was again spontaneously varying from 1° to $1\frac{1}{3}°$; at the same time the heart's action was somewhat enfeebled. At $6^h\,15^m$ the portion of cord corresponding to another vertebral arch was cut away. The operation induced contraction from $1\frac{1}{3}°$ to $\frac{1}{2}°$, followed by gradual dilatation (in fifteen seconds) up to $1\frac{2}{3}°$, and this, in a few seconds, gave place to spontaneous contraction to $1\frac{1}{2}°$. By this last operation the vertebral canal had been cleared as far back as the posterior third of the scapulæ, corresponding to between one-third and one-half of the length of the cord.

At $6^h\,30^m$, having removed another vertebral arch, I divided the cord imperfectly, as far back as it was exposed, namely, at the level of the posterior edges of the scapulæ, which is in the commencement of the posterior half of the cord; and on looking at the web twenty seconds later, found the artery undergoing oscillations in calibre, such as had never before been seen in it, contracting and dilating distinctly five times in a minute, from 1° to $1\frac{1}{3}°$ or $1\frac{1}{2}°$. At $6^h\,32^m\,20^s$ the cord was cut fairly through at the point indicated, without removal of the segment from the canal, and at $6^h\,34^m$ the

* The transient character of the effects produced upon the arterial calibre by these operations, led me at first to conclude that the anterior parts of the cerebro-spinal axis did not contain any nervous centre for the arteries, and this view was expressed in the original manuscript. My opinions on this point have, however, been altered by the results of subsequent experiments, as will appear at the conclusion of the paper.

artery was found quite constricted and the web exsanguine. At $6^h\ 36^m\ 10^s$ the artery had somewhat dilated, and measured $1\frac{1}{3}°$, but the blood was moving very slowly through the vessels, the heart being evidently exceedingly enfeebled. At $6^h\ 40^m$ the portion of the cord was detached from the roots of the nerves which sprung from it and removed from the canal, immediately after which the artery was found dilated to $1\frac{2}{3}°$, but the blood had ceased to move in consequence of the feebleness of the heart.

The experiments upon this animal show that if the brain and anterior third of the cord act at all as nervous centres for the arteries of the feet, they are certainly not the only parts which possess that function; and also, that irritation of any part of the anterior half of the cord gives rise to contraction of the arteries of the webs, followed by dilatation, varying much in extent and duration, but generally proportioned in both respects to the previous constriction. It is probable that the dilatation would have been greater after the last operations, had the heart been working more powerfully; for it will hereafter appear that a certain amount of distending force on the part of the blood is necessary for the vessels becoming fully expanded.

On the 18th of April, having put a large frog under the influence of chloroform, I removed a vertebral arch opposite the junction of the middle and posterior thirds of the scapulæ, and then cut across the cord in that situation, *i. e.* rather more than a line anterior to its middle; a slight retraction of the two segments proved that the division had been thoroughly effected. This was at 10 o'clock A.M. A few minutes later the arteries had recovered from the effects of the irritation; one selected for special observation, having measured $1\frac{2}{3}°$ just before the operation, now varied occasionally between $1\frac{1}{3}°$ and $1\frac{2}{3}°$, and the circulation was rapid through the vessel. The next vertebral arch posteriorly having been removed, the cord was divided as far back as it was exposed, at $10^h\ 23^m\ 50^s$; immediately after which the web was found exsanguine in consequence of complete closure of all the arteries, which continued almost in the same condition for ten minutes, at the end of which time the artery selected was still so small as to transmit single corpuscles with difficulty. At $10^h\ 35^m$ the portion of cord included between the points of section was detached from the roots of the nerves connected with it and removed from the canal. It measured nearly a line in length, and the posterior segment thus shortened proved afterwards to be only a very small fraction more than half the length of the cord. The vessels afterwards relaxed slowly, so that at $10^h\ 37^m$ the corpuscles were passing a little more freely through the artery. At $11^h\ 15^m$ the artery measured $1\frac{1}{2}°$, but transmitted the blood in a very languid stream; and at noon the evidences of circulation were so equivocal, that I suspected the creature, which was weak to begin with, to be dead, though this afterwards proved to be a mistake. At $0^h\ 45^m$ P.M. the same state of things continued, and the artery still measured $1\frac{1}{2}°$, having remained unaltered in calibre for the last hour and a half; but I determined to try the effect of irritating the posterior segment of the cord, and introduced the point of a needle a short distance into its anterior extremity and withdrew it immediately, keeping my eye over the microscope. The effect upon the artery was immediate constriction, causing a retro-

grade stream of the blood in it for about a second, and then absolute obliteration of calibre. At $0^h\ 49^m$ the artery allowed single corpuscles to pass through it with considerable difficulty. At 1 o'clock the arteries of the web were still small, but I noticed that they were undergoing very remarkable oscillations in calibre, just as occurred on one occasion in the frog last operated on, but in the present case they were more striking. I noted the variations for some time, and give in the following Table a specimen of those which occurred during one minute:—

	h	m	s		
At	1	2	57	the diameter of the artery was	$1\frac{1}{4}^\circ$
At	1	3	9	the diameter of the artery was	1
At	1	3	20	the diameter of the artery was	$\frac{1}{2}$
At	1	3	25	the diameter of the artery was	0
At	1	3	38	the diameter of the artery was	$\frac{1}{2}$
At	1	3	45	the diameter of the artery was	0
At	1	3	50	the diameter of the artery was	$\frac{1}{2}$

These oscillations continued for upwards of half an hour, but during the latter part of that time the extreme degrees of constriction were not observed.

At $1^h\ 43^m$ P.M. I raised the vertebral arches from the end of the spinal canal, and removed the posterior half of the cord together with the cauda equina; immediately after which, the artery, which for the last hour had not exceeded $1\frac{1}{4}^\circ$, became expanded to $2\frac{1}{4}^\circ$, a dimension which it had never before been observed to attain, except during the secondary dilatation that ensued after the first division of the cord when the heart was in powerful action. All the other arteries of the web became dilated at the same time, and remained of perfectly constant diameter during the hour that I continued to observe them. Finally, at $2^h\ 40^m$ I introduced a needle into the anterior part of the spinal canal which had hitherto been undisturbed, and irritated both the anterior portion of the cord and the brain, but no effect whatever was produced upon the vessels.

The constriction of the arteries, which resulted in this case from irritation of the posterior half of the cord isolated from the rest, and the permanent dilatation which ensued on removal of the same part, prove that this portion of the cerebro-spinal axis certainly contains a nervous centre for regulating the contractions of the arteries of the feet. The frequently alternating contractions and dilatations which occurred in this animal, as well as in the last, after irritation of the posterior half of the cord, are curious, and may perhaps be considered analogous to rapid action of the heart under the influence of stimulus. The fact that the arterial contractions so constantly observed to result from irritation of the anterior part of the cord, while it retains its connexion through the rest of the cord with the roots of the nerves of the hind legs, fail to occur after removal of the posterior two-thirds of the cord, has been confirmed by subsequent experiments upon other frogs. It appears to imply that if the brain and anterior part of the cord discharge the functions of a nervous centre for the arteries of the feet, they do not exert

that influence through the branches which connect them with the sympathetic, but only through the roots of the nerves given off from the more posterior parts of the cord.

On the 2nd of June, a large frog having been put under the influence of chloroform, the vertebral arches were removed, from the sacrum to the posterior edges of the scapulæ, and at $0^h\ 30^m$ P.M. the cord was divided immediately behind the latter situation, *i. e.* a little behind its middle. The left foot being examined shortly after, the arteries were seen to be considerably constricted; one of them, which appeared to be a principal trunk, permitting single corpuscles to pass with difficulty, and the contraction became extreme after irritation of the posterior segment of the cord with a needle. The whole of the exposed part of the cord and the cauda equina, including the chief branches of nerves for the hind legs, were then removed (at $0^h\ 56^m$), and when the foot was again looked at, at $1^h\ 10^m$, the circulation, which had been previously entirely arrested by the contraction of the vessels, was going on rapidly through dilated arteries, the one before mentioned now measuring 3°. This, however, proved not to be the extreme degree of dilatation of which the vessel was capable; for a stream of water at about 120° FAHR., thrown for perhaps a second upon the foot, induced, after brief imperfect contraction, an expansion to nearly 4°, which again was followed after a few minutes by a return to 3°. This experiment was several times repeated. In the right foot, which had not been subjected to the hot water, though necessarily equally affected with the other by the removal of the portion of cord, the arteries were found of moderate size at $3^h\ 45^m$, having evidently recovered, to a considerable extent at least, their contractile power during the $2\frac{3}{4}$ hours which had elapsed since the operation. One which at this time measured $1\frac{2}{3}°$, became dilated on the application of hot water to 3°, and afterwards contracted spontaneously to 2°.

At $4^h\ 15^m$ an additional portion of the cord was removed, so as to clear the spinal canal as far forward as the anterior third of the scapulæ. The arteries became at once dilated to some extent, notwithstanding that the heart's action was greatly enfeebled by this operation; and at $6^h\ 45^m$ they had attained nearly the full diameters that the hot water had before induced, while the circulation had somewhat recovered. Next morning the arteries of the two feet, the dimensions of which were before given, measured 4° and 3° respectively, and they continued without the slightest variation until $5^h\ 25^m$ P.M.; the circulation meanwhile had continued to improve, and was healthy, though still languid. I then removed the remainder of the cord and the entire brain without producing any effect whatever on the size of the arteries, and they still measured precisely the same at $10^h\ 45^m$ P.M. The following morning the frog was dead, and the tissues of the web had become opaque by the imbibition of water.

In this case the arteries recovered their contractile power after the removal of the greater part of the posterior half of the cord, together with the chief roots of the nerves for the hind legs; but when the part which furnishes branches to the posterior extremities had been completely removed, the arteries became permanently dilated; and, though

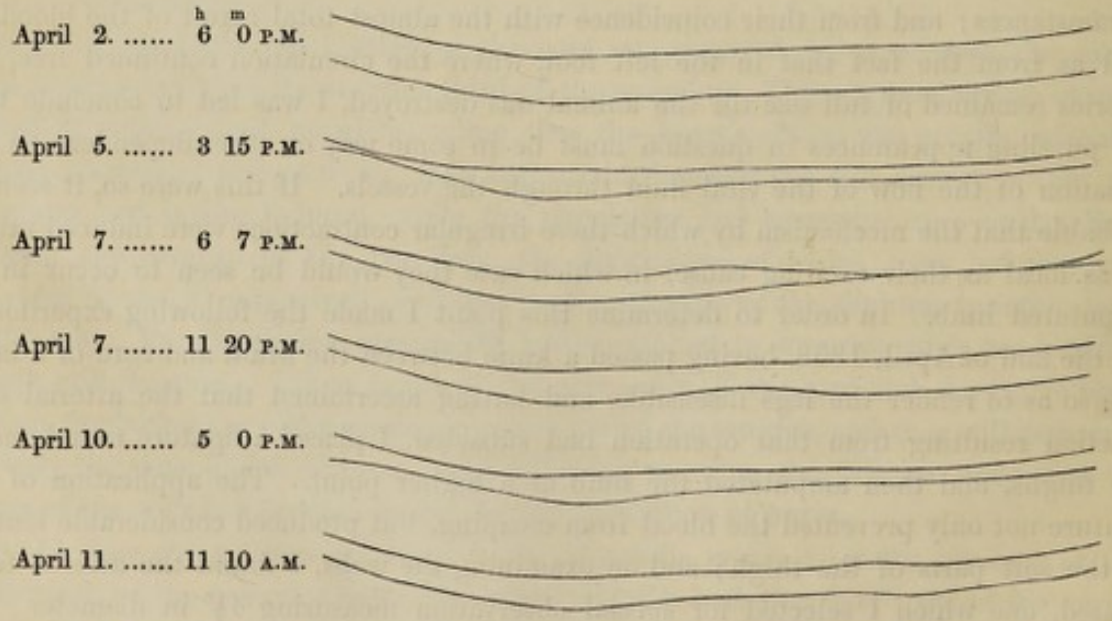
the circulation was then feeble, soon attained the full calibre which hot water had induced at a time when the heart was in powerful action.

The perfect constancy with which the vessels observed maintained these dimensions for more than thirty hours after the operation, implied that they were not then at all acted on by the nervous system; and hence I was led at first to infer that there existed no other ganglionic apparatus for the arteries of the feet than that contained in the cerebro-spinal axis*.

I have since witnessed in other frogs the permanence of the dilatation of the arteries after removal of the brain and cord. The following case, however, appeared at first inconsistent with these observations. On the 23rd of October the brain and cord of a large frog were completely removed, and an operation was performed upon the right thigh, which, as it turned out, tended to interfere with the freedom of the circulation in the webs; so that after twelve hours, the blood, though not presenting the appearances of inflammation, was almost motionless in that foot. At the same time, two arteries in one of the webs, which had till then remained perfectly constant in calibre, as determined by micrometer, began to exhibit variations, and during the next twenty-four hours continued to change their diameter occasionally. There were, however, certain peculiarities about these changes such as I had never before seen. Generally speaking, all the arteries of a web are found in the same degree of contraction at any one time; but here, one of the vessels under observation was sometimes small, when the other, though in the same web, was large; and not only was there no proportion between the degrees of contraction in the two vessels, but in one and the same artery the amount of constriction was very different at different parts. The unusual character of these contractions implied that they were caused by some unwonted circumstances; and from their coincidence with the almost total arrest of the blood, as well as from the fact that in the left foot, where the circulation continued free, the arteries remained of full size till the animal was destroyed, I was led to conclude that the puzzling appearances in question must be in some way or other dependent on the cessation of the flow of the vital fluid through the vessels. If this were so, it seemed probable that the mechanism by which these irregular contractions were induced might be as local as their exciting cause, in which case they would be seen to occur in an amputated limb. In order to determine this point I made the following experiment. On the 2nd of April, 1858, having passed a knife between the brain and cord of a large frog so as to render the legs insensible, and having ascertained that the arterial constriction resulting from that operation had subsided, I placed a ligature round one of the thighs, and then amputated the limb at a higher point. The application of the ligature not only prevented the blood from escaping, but produced considerable tension in the soft parts of the thigh; and on examining the webs, I found the arteries fully dilated, one which I selected for special observation measuring $4\frac{1}{2}^{\circ}$ in diameter. At

* This was the view expressed in the original manuscript, but it has been since modified by further experiments mentioned in the text, made, as their dates imply, subsequently to the reading of the paper.

6^h P.M., an hour and a half after the amputation, the vessel still maintained the same calibre, but at 7^h 35^m it was slightly less, viz. 4°, which was still its measurement at 11 o'clock. Hitherto no change distinctly referable to vital contractility had taken place, but on the following morning the vessel was reduced to 3° in diameter, and on the 4th of April it was of different sizes in different parts, viz. from 1½° to 3°, and varied somewhat during the course of the day. Still more striking changes in the diameter of the artery appeared on subsequent days; thus the vessel was sometimes constricted to absolute closure in one part of its course, and dilated to a very considerable degree, *e. g.* 3½°, in another part. More commonly, however, the artery, though never uniform in size as in health, had a general tendency either to moderate constriction or dilatation. The variations occurred frequently during the twenty-four hours, and on one occasion I saw the artery in the act of slow contraction at one part driving the blood into a dilated portion at a little distance. So late as the evening of the 10th of April, *i. e.* during the ninth day after amputation, far later than vital contractility is generally believed to last in a limb so circumstanced, variations of calibre continued to show themselves; but on the 11th of April the vessel had an almost uniform width of nearly 3°, and exhibited no variations, while, at the same time, other evidences of loss of vitality in the tissues began to show themselves. The accompanying outlines of the calibre of a limited portion of the artery, which was the subject of special observation, have been made from micrometrical measurements selected from among a large number daily registered. They will serve to convey an idea of the more striking varieties of appearance presented at different times. It may be mentioned, that the diameter of the vessel, when most dilated, was about 4½ times the length of a red corpuscle of the frog's blood.



It must be added, that the limb was kept wrapped in clean wet lint in a cool place in the intervals of the observations, and that during the periods of examination care was

taken to guard against warmth or dryness, or any other agency calculated to injure the delicate tissues of the webs.

Thus irregular contractions, precisely similar to those which accompanied local arrest of the circulation in the experiment of October 23rd, took place in consequence of amputation of the limb; and as there could be no doubt that in both cases they were produced in the same manner, there was no longer any reason to suspect that sympathetic ganglia in the trunk might have had any share in their development in the former instance. Yet the circumstance above mentioned, that in the amputated limb the tendency to constriction usually affected a considerable tract of the vessel, and sometimes its entire length, to nearly the same degree, or in other words, that the muscular fibre-cells of the circular coat of the artery still contracted in concert with each other, seemed to imply the operation of a coordinating nervous apparatus contained in the limb. It appears probable that the means by which these concerted movements are induced are nerve-cells disseminated through the limb, in the same manner as MEISSNER has lately shown to be the case in the mammalian intestine*. The intestines also present a parallel to the arteries, in the fact that contractions of their unstriped muscular fibres result from arrest of the circulation in them; and I have lately shown† that these movements are not due to any influence exerted directly upon the contractile tissue, but that the intestinal nerves are essential to their production. Thus we have support from analogy for the view that the muscular contractions which occur under similar circumstances in the arteries are induced by nervous agency.

The fact that the contraction produced in an artery of the frog's web by pressure upon a particular point affects a considerable extent of the vessel, instead of being limited to the spot irritated, is also an argument for the existence of a local coordinating apparatus; for I find that this occurrence continues to take place in an amputated limb. The observation was made on the 4th of August, 1858. One of the hind legs of a frog having been removed after a ligature had been passed round the thigh so as to prevent escape of the blood, pressure was made with a fine but blunt instrument over a particular point in the course of a large artery, whose calibre had previously been accurately determined by micrometer. The contractions which resulted affected the immediately adjacent parts of the vessel to an extreme degree; the effect, however, was not limited to these, but gradually shaded off in both directions; and even at a considerable distance, where by ordinary observation no change might have been detected, the micrometer showed a diminution from 6° to 5°‡, occurring immediately upon the irritation and subsiding soon after. Similar results were obtained on repetition of the experiment.

* HENLE and PFEUFER's 'Zeitschrift,' 2nd series, vol. viii. 1857.

† Vide "Preliminary Account of an Inquiry into the Functions of the Visceral Nerves, &c.," Proceedings of the Royal Society, vol. ix. No. 32. p. 370.

‡ These degrees have a different value from those mentioned in other parts of this paper, a different micrometer having been employed.

From the analogy of the intestinal and cardiac movements*, it is probable that the local coordinating apparatus for the arteries comes into play in all cases of arterial contraction in the living animal, and is the medium through which the nerves which arise from the cord act upon the vessels. But it is very important to bear in mind that it is, under ordinary circumstances, in entire subjection to the spinal system, and only acts independently under special conditions of local irritation.

It remained as yet undecided whether the nervous centre for the arteries contained in the cerebro-spinal axis were extensively diffused or limited to some particular region of it. The experiments hitherto related had revealed nothing absolutely irreconcileable with the hypothesis of a spot about the middle of the cord being the special regulator of the contractions of the vessels; a view indicated, though by no means proved, as regards the arteries of the face and fore-limbs in Mammalia, by the observations of WALLER and BUDGE and of SCHIFF, alluded to at the commencement of this paper. It appeared probable that this point might be readily determined by removing the middle third of the cord, and ascertaining whether or not the arteries still retained their contractility†. Accordingly, on the 26th of August, 1857, having selected for measurement an artery in one of the webs of a frog, I divided the cord transversely at the distance of a quarter of its length from the posterior end, at $11^h\ 7^m$ A.M. During the next half-hour the diameter of the vessel was observed varying frequently from $\frac{1}{2}°$ to $1\frac{1}{2}°$. At $11^h\ 34^m$ the cord was again cut across opposite the middle of the scapulæ, *i. e.* at a distance of a little more than a quarter of its length from the occiput. After this operation the artery was observed for about a quarter of an hour varying occasionally in calibre between 1° and 2°. At $11^h\ 53^m$ the portion of cord intervening between the two transverse incisions, and measuring very nearly half its entire length, was removed, immediately after which the artery measured $1\frac{1}{2}°$. At $11^h\ 55^m$ its diameter was 1°, the heart meanwhile continuing in good action, and twelve minutes later the vessel was again seen to change in calibre from 1° to $1\frac{1}{2}°$ and back again to 1°. The heart's action afterwards became very feeble, and the parts of the nervous centres concerned in regulating the arterial calibre appeared also to be failing in their functions, the vessel varying very slightly, and gradually increasing in diameter, till towards 1^h P.M. its measurements were from 2° to $2\frac{1}{4}°$. At $1^h\ 1^m$ the posterior end of the cord was removed, immediately after which the diameter of the artery was above $2\frac{1}{4}°$, or larger than ever seen before; at $1^h\ 4^m$ it was near $2\frac{1}{3}°$, and continued so at $1^h\ 10^m$. Soon after this the circulation ceased entirely.

In this case, notwithstanding the removal of the two middle quarters of the cord, the arteries were observed moderate in size and varying in calibre at a time when the heart was acting well. Hence it was evident that the middle portions of the cord are not

* See "Preliminary Account, &c.," before referred to.

† In the original manuscript I was obliged to express my regret that time had not yet permitted me to carry out this idea. The dates in the text indicate that it has been done since the paper was read.

essential to the regulation of the arterial contractions in the feet. The following experiment confirmed this important conclusion, and also furnished additional information.

On the 20th of October, a large frog having been placed under chloroform, the cord was divided transversely at the distance of about one-fifth of its length from the posterior extremity. At 4^h 20^m P.M., just after the operation, an artery in the right foot measured $2\frac{1}{2}°$, the vessels appearing generally of pretty full size, and the flow of blood rapid through the web. At 4^h 25^m the cord was again cut across a little behind the mid-scapulæ, at a distance from the occiput of somewhat more than a quarter of the length of the cord. At 4^h 33^m the diameter of the vessel was $1\frac{1}{3}°$. At 4^h 40^m the portion of cord included between the incisions was removed, without any interference with either the anterior or posterior segment. It was observed that a large branch for the hind legs, furnished by the middle segment, had to be divided during its removal, and immediately after the operation the artery measured $2\frac{1}{3}°$, and the flow of blood in the web was much more rapid than before. At 4^h 45^m the artery had contracted to 2°, at 5^h 7^m it measured short of 2°, and a minute later was again 2°. At 5^h 11^m I introduced a fine needle into the anterior segment of the cord with the effect of causing convulsive movements of the fore legs, but no change whatever in the calibre of the artery in the hind leg. I afterwards repeated this experiment twice, and the last time carried the needle on into the brain, and stirred it up thoroughly, but no effect was produced upon the vessel. At 5^h 23^m the whole brain was removed, together with the anterior segment of the cord; the artery, however, still continued to measure 2°. At this time the circulation, though somewhat enfeebled, was still pretty good. At 5^h 53^m a complicated operation was performed upon the left thigh, to which I need not allude further than to mention, that it no doubt involved exposure of the other foot to a higher temperature than before, in consequence of the vicinity of my hands, and this was probably the cause of the dilatation of the arteries observed immediately afterwards, that which had been previously measured being now $2\frac{2}{3}°$. Five hours later the artery was again 2°, but the heart's action was excessively languid. Next morning the circulation was going on steadily, though somewhat slowly, the heart having obviously recovered to some extent during the night. The arteries were larger than ever seen before; the calibre of that above noted being $3\frac{1}{4}$, and there were a good many blood-corpuscles adhering to the walls of the vessels. It is probable that the small posterior segment of the cord had become impaired in its powers, but that it was still acting to some extent was evident from the circumstance that after its removal at 10^h 56^m A.M., the vessel was found increased to 4°, and in consequence of the arterial dilatation, the stagnation of the red corpuscles, which existed in several parts of the webs, was almost entirely dispelled, although the action of the heart did not appear to have been changed. During the next half-hour the artery was measured four times, and was in every instance found to be still 4° in diameter. I may mention that I measured the posterior segment of the cord immediately after its removal, and found its length to be one-sixth of that of the whole cord; it was in fact little more

than the tip of it; but allowing for a certain amount of contraction, it may be reckoned as one-fifth.

This case shows that the extremity of the cord acts as a nervous centre for the arteries. But the experiment of the 2nd of June proved that after the removal of the greater part of the posterior half of the cord, the vessels still remained under the control of the nervous system*. Hence it is clear that the nervous centre for the arteries is not confined to any limited region of the cord.

This experiment also indicates, in a very striking manner, how small a piece of the cord will suffice to regulate the calibre of the arteries, and how little effect may be produced, even in the first instance, by the removal of a large portion which also possesses that function. For it was shown, by the absence of contraction in the vessels when the anterior segment was irritated, and still more conclusively by the absence of dilatation when the anterior segment and the brain were removed, that the posterior segment was the only part capable of acting on the arteries after the removal of the middle segment; or, in other words, that this operation deprived the arteries of the influence of the whole cerebro-spinal axis, except the posterior fifth of the cord. Yet, although the heart was acting powerfully at the time, the dilatation produced by this procedure was only moderate in amount, and very transient. Hence it follows that the mere fact of the speedy return of the arteries to their former state of contraction, after removal of an anterior portion of the cerebro-spinal axis, as seen in the experiment of April 16th, 1857†, is no ground whatever for believing that such a portion does not act as a nervous centre for the arteries. This being clearly understood, the invariable occurrence of contraction, when the posterior part of the brain or the anterior half of the cord was irritated, in the experiments of April 14th and 16th, 1857‡, must be regarded as strong presumptive evidence, if not absolute proof, that they as well as the posterior half of the cord preside over the arterial contractions in the feet, although, as shown at page 615, they appear to exert their influence only through those roots of nerves which take origin from the posterior regions of the cord. On the other hand, the cerebral hemispheres seem to take no part in this function, so far at least as it is safe to draw any inference from the negative evidence derived from a single experiment performed upon them, viz. that mentioned at page 610.

The fact that the removal of a large portion of the cord is followed by only temporary dilatation of the arteries, provided that a part remains which furnishes roots of nerves for the posterior extremities, is in harmony with the transient effects which were seen to be produced upon the vessels by partial division of the roots of the nerves within the spinal canal in the experiments of April 8th and 11th, 1857§. In both these cases the arteries of the webs appeared to recover their contractile power completely, although the leg remained nearly, if not entirely, paralysed; which seems to indicate that a few fibres of the nerves for the blood-vessels of a part can supply the place of the rest more perfectly than is the case with the ordinary nerves of sensation and motion. This peculiarity of

* Vide page 616. † Vide page 613. ‡ Vide pp. 611, 613. § Vide pp. 609, 610.

the "vaso-motor" nerves is more strikingly illustrated by the first experiment mentioned in this paper*, in which it may be remembered that the arteries of the webs completely recovered their usual powers of varying their calibre within half an hour after division of the sciatic, although this is an operation which abolishes for days at least all sensation and voluntary motion in the leg. I have since seen yet more remarkable instances of the same thing. On the 10th of October, 1857, with the view of investigating the nature of the control exercised by the nervous system over the actions of the pigment-cells†, I divided all the soft parts in the middle of the thigh of a frog, except the main artery and vein. The first effect upon the arteries was full dilatation; but about twenty-four hours later they were again of moderate size, while the circulation was still active. After the death of the animal, I examined with the microscope the coats of the artery and vein, and also the periosteum, together with a very slight amount of muscular tissue adhering to it, but could detect no nerves in any of them, although from the method of examination I could hardly have missed branches containing more than very few nerve-tubes. Comparing the result in this case with the permanent dilatation which always occurred after removal of the spinal cord, so long as the circulation continued active, it was evident that the slender filaments contained in the coats of the vessels, or possibly in the bone, had served as an efficient means of communication between the cerebro-spinal axis and the arteries of the foot.

On the 13th of the same month I repeated the experiment upon another frog, operating in this case upon both thighs. In the first place, I divided thoroughly all the soft parts except the artery, vein and nerve, the circulation remaining unaffected. The nerves were then successively cut, full dilatation of the arteries and rapid flow through the capillaries being the immediate result. An hour and a half later, however, the flow was observed to be less rapid, no doubt in consequence of slight contraction of the arteries, one of which, in the left foot, measured 3° by micrometer, and after sixteen hours more they were both moderate and variable in calibre in both feet; that in the left limb before noted now changing between $1\frac{1}{2}°$ and 2°, and a principal artery in the right foot between 1° and $1\frac{1}{2}°$. The circulation meanwhile continued active, and remained so more than twelve hours longer; from which circumstance, as well as from the normal appearance of the contractions, it was evident that the arteries were still under the control of the cord; and I may add, that in another animal in which the same operation was performed upon the thigh after removal of the brain and cord, the arteries remained of full size and without variation for thirty-four hours, after which circulation ceased.

From these facts it appears that there exists a very remarkable provision for ensuring the proper regulation of the arterial calibre in a part in spite of almost complete divi-

* Vide page 609.

† Further information regarding this experiment, as respects the pigmentary system, will be found in the next paper in these Transactions.

sion of the nerves connecting the vessels with the nervous centre which presides over their contractions. It has been shown by recent discovery that sensation and voluntary motion are abolished in parts whose nerves have been divided, until repair has been effected by a process of fresh formation of the nerve-fibres. But the control of the flow of the nutrient fluid is not allowed to be interrupted in this manner, but continues to be exercised more or less perfectly, notwithstanding nearly absolute severance of nervous connexion.

Allusion has been more than once made to the circumstance that arteries do not dilate so fully when the heart is very feeble as when it is in powerful action. This was strikingly illustrated in the case of the frog which was the subject of operation on April 16, 1857. Immediately after the experiments recorded at page 614, the heart having ceased to cause movement of blood in the web, I induced complete constriction of the arteries by irritating with a needle the posterior part of the cord, and then thoroughly cleared the spinal canal of its contents. The artery under special observation did not, however, become dilated to a greater diameter than $1\frac{1}{2}°$, although during the earlier experiments, when the heart was acting vigorously, it had been observed to attain sometimes a calibre of 3°. The heart never recovered its power, and the vessel maintained this medium width as long as I continued to examine the animal, namely, three hours.

From this and other similar observations, I infer that full dilatation of the arteries is a merely passive phenomenon as respects the parietes of the vessels. Contraction is effected by the muscular fibre-cells of their circular coat, on the relaxation of which the elasticity of the arteries tends to make them expand to a certain degree, beyond which they do not dilate, except in so far as they are distended by the blood.

It was observed by Wharton Jones*, that section of the sciatic nerve in the thigh of a frog was followed after a time by œdema of the limb and exfoliation of the epidermis. If this were dependent on the dilatation of the arteries produced by the division of the nerve, the fact would have a very important bearing upon the cause of inflammatory effusion. I find, however, that neither œdema nor exfoliation results from permanent full dilatation produced by operations upon the cord or the roots of the spinal nerves; while, on the contrary, both took place in the case of division of the sciatic, given in the early part of this paper, in which it will be remembered that the arteries recovered their contractility completely within half an hour, and presented, during the next twenty-four hours, precisely similar appearances with those in the other foot. Hence it is evident that the phenomena in question are not due to vascular relaxation, but to some other circumstances attending the operation performed upon the thigh.

It remains to be added, that, in a healthy state of the web, no change in the properties of the blood was ever observed to accompany the constriction of the arteries on irritation of the cord, or the dilatation which followed the destruction of the nervous

* Medico-Chir. Trans. *loc. cit.*

centre. The exsanguine condition of the web in the former case, and the turgid state of the vessels in the latter, were simply the effects of the variations of calibre in the arteries, the blood flowing more freely in proportion to their width *.

To sum up the principal results of this inquiry, it appears—

1st. That, of the nervous centres usually recognised, the cerebro-spinal axis is the only part which regulates the contractions of the arteries of the webs; this function being apparently exercised by the whole length of the cord and the posterior part of the brain, operating through fibres which arise from the same region of the cord as do those through which sensation and motion are effected in the hind legs.

2nd. That there exists within the limb some means, probably ganglionic, by virtue of which the fibre-cells of the circular coat of the arteries may contract in concert with each other, independently of any ganglia contained in the trunk.

And 3rd, that the local coordinating apparatus, though capable of independent action in special conditions of direct irritation, is, under ordinary circumstances, in strict subordination to the spinal system; while a remarkable provision exists for the maintenance of this control, notwithstanding almost complete severance of nervous connexion between the cord and the limb.

* The subject of the effect of variations in the calibre of the arteries upon the flow through the capillaries, will be found fully discussed in the paper "On the Early Stages of Inflammation," published in this volume.