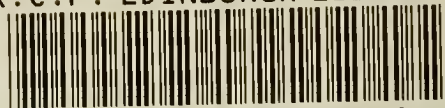


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ON

ANIMAL ELECTRICITY.

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ON
ANIMAL ELECTRICITY:

BEING

AN ABSTRACT OF THE DISCOVERIES OF

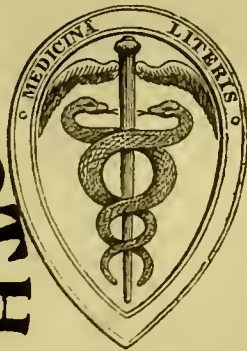
EMIL DU BOIS-REYMOND,

MEMBER OF THE ACADEMY OF SCIENCES OF BERLIN, ETC. ETC.

EDITED BY

H. BENICE JONES, M.D., A.M. CANTAB. F.R.S., &c.

PHYSICIAN TO ST. GEORGE'S HOSPITAL.



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MICHAEL FARADAY, D.C.L., F.R.S.,

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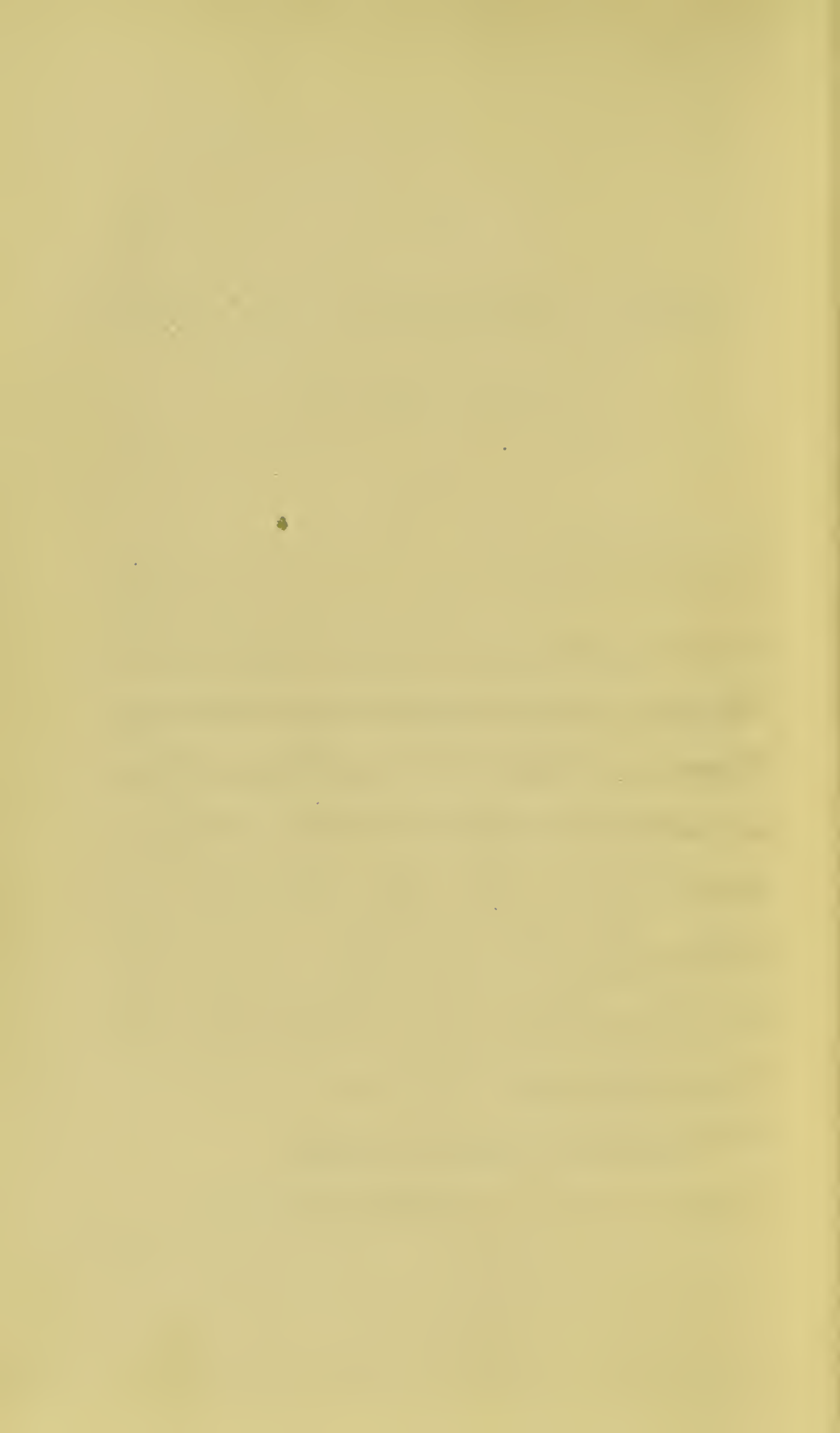
DEAR MR. FARADAY,

It was owing to your kindness that Dr. du Bois-Reymond had the opportunity of making at the Royal Institution the experiments which you watched with so much care. Allow me therefore to dedicate to you this Abstract of the discoveries which these experiments illustrate; being well assured that the discoverer himself desires above all things to follow the example which you have set before him in his search after truth.

Believe me, dear Mr. Faraday,

Your faithful friend,

H. BENICE JONES.



PREFACE

BY THE EDITOR.

THE abstract of Dr. du Bois-Reymond's German work, of which the following pages chiefly consist, was made by Dr. John Müller, Professor of Physics in Freiburg. It must be considered as an introductory statement of the discoveries which Dr. du Bois-Reymond has published. Unfortunately, the size of his original work, and the uncertainty as to the time when the last volume will be finished, has hitherto prevented, and I fear will long prevent the appearance of an English translation.

However, from this abstract, a better knowledge of the new facts will be obtained than from the report of the French Academy, published in the *Comptes Rendus*, 1850, or from any other source except the original work ; and as those who have witnessed Dr. du Bois-Reymond's experiments during his stay in England generally asked where they could find an account of what they had seen, I have the more readily used the opportunity which I possessed for obtaining the best information from him on all the points mentioned in the abstract.

Many other and most interesting questions have been discussed, and hence some experiments and statements have been added to the German abstract.

Conclusions and practical deductions Dr. du

Bois-Reymond is as yet most unwilling to draw. Whilst his work is unfinished ; whilst the experimental investigation on electric fishes is not commenced ; whilst new experiments in the course of a few months may modify or extend his anticipations, he can hardly be blamed for exercising the utmost caution.

Perhaps the following summary will be the best preface to the facts which this little volume contains. The great object of these experiments is, first, to obtain clear ideas regarding the existence of electric currents in muscles and in nerves. Secondly, to determine whether during motion and sensation any changes in the intensity or direction of the electric currents occur. Thirdly, if possible, to trace the connexion between the electric

changes and the contraction or sensation which ultimately takes place.

The practical application of these results to pathology and the treatment of disease cannot as yet even be foreshadowed; but this at least may be said, direct experiments on the action of electric currents upon the nerves and muscles themselves must precede any clearness and certainty in the employment of electricity as a remedial agent.

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ANIMAL ELECTRICITY.

CHAPTER I.

HISTORICAL INTRODUCTION.

OUR knowledge in the department of Animal Electricity has of late been much increased by the very important and well established discoveries which have been made by Dr. du Bois-Reymond, who has devoted himself more to this department of knowledge than any one who has preceded him.

Not only has he discovered many new truths, but he has also traced out the connexion of the phenomena with critical acuteness, and he has thereby succeeded in deducing definite laws where previously the greatest disorder prevailed.

Du Bois-Reymond has described the results of his numerous experiments, which have occupied him for years, in a work which appeared in Berlin in the years 1848-49, entitled

“*Researches in Animal Electricity*,” (“*Untersuchungen über thierische Elektrizität*.”)

This work makes us fully acquainted with the recent progress of electro-physiology, for besides the experiments of the author, it contains a complete account of the labours of other philosophers in the same field.

Du Bois-Reymond prefaces his own researches with an historical introduction, in which he goes back to Galvani’s experiments.

This is very necessary, because hitherto the history of that important epoch in the science of electricity has always been regarded from a single point of view, that is, only in its relation to voltaic electricity; and also, because many documents previously unknown, have been lately brought to light, by a new publication of the Institute of Bologna, entitled “*Opere edite ed inedite del Professore Luigi Galvani*,” &c.

Whoever reads this introduction, will scarcely lay down the book unsatisfied. Du Bois-Reymond has gone to the original sources of information, and has written with praiseworthy truthfulness, and he places before the reader a picture of that remarkable period in physical science,

which he has coloured vividly and drawn most accurately. The following passage may be taken as an example in which the relation of Galvani and of Volta to the new discoveries in electricity is beautifully shown.

“No one, who has read Galvani’s writings, can, without reverence, turn away from the simple picture of that man, whose restless yet blind labours and naïve desire for knowledge were destined to bear such fruits. Every one will easily excuse his having wandered in that way which we shall soon see him take. The problem presented to him was an equation with two unknown quantities, one of which was the galvanism which Volta discovered, the other animal electricity, which latter, after half a century, now again appears claiming its proper place.

“Galvani really discovered not only the fundamental physiological experiment of galvanism properly so called (the contraction of the frog when touched with dissimilar metals), but also that of the electricity inherent in the nerves and muscles. Both of these discoveries were, however, hidden in such a confusion of circum-

stances, that the result in both cases appeared equally to depend upon the limbs or tissues of the animals employed.

“Galvani was by profession an anatomist and physiologist. He was possessed with the idea, which then was popular, of an animal electricity; which he demonstrated to his class in the anatomical theatre. It is not, therefore, to be wondered at that he should endeavour to solve the problem in that manner which appeared to open the way to the explanation of a multitude of facts. Volta, indeed, held the same opinion, though at first he was sceptical, in consequence of the many deceptions which had already occurred in this branch of knowledge. He passed, as he himself tells us, from unbelief to fanaticism, as soon as he had handled the wonderful facts. Nevertheless, he was ready to reject those bright prospects which Galvani’s discoveries appeared to unfold for the physiology of the muscles and nerves, as soon as he considered that he had proved that they were not tenable in the existing state of science.

“No one who wishes to judge impartially of the scientific history of those times and of its

leaders, will consider Galvani and Volta as equals, or deny the vast superiority of the latter over all his opponents or fellow-workers, more especially over those of the Bologna school. We shall scarcely again find in one man gifts so rich and so calculated for research as were combined in Volta. He possessed that 'incomprehensible talent,' as Dove has called it, for separating the essential from the immaterial in complicated phenomena; that boldness of invention which must precede experiment, controlled by the most strict and cautious mode of manipulation; that unremitting attention which allows no circumstance to pass unnoticed: lastly, with so much acuteness, so much simplicity, so much grandeur of conception, combined with such depth of thought, he had a hand which was the hand of a workman. It is strange, indeed, that a German voice should call an Italian philosopher to order for depreciating the great Volta."

The philosopher here alluded to is Gherardi, who chiefly undertook the arrangement of the previously mentioned collection of Galvani's works. He endeavours in a prefatory "Rapporto" to

exalt as far as possible Galvani's fame as a philosopher, even by detraction from that of Volta.

After Galvani had examined the shock produced by a spark from the electric machine on a frog prepared for that purpose, he tried the same experiment with lightning. These experiments occupied him during the summer of 1786. In the autumn of the same year he endeavoured to discover the action of atmospheric electricity on the prepared legs of a frog when the sky was stormless. It was on the 20th September that Galvani made that eventful observation upon muscular contractions in animals, which forms the starting point for the new science of electricity.

Galvani first published these experiments with his deductions, in 1791, in his celebrated work, "*De viribus Electricitatis in motu musculari Commentarius.*" In this Commentary, the experiment is represented as having been made with copper hooks (*aereus*), while among Galvani's papers a sketch of an experiment was found, dated 30th October, 1786, in which he speaks only of iron hooks. Without doubt this arose from the fact that he became acquainted

during his experiments with the properties of combinations of different metals, and that he wished to give the utmost certainty to future repetitions of his first experiment in its original form.

Upon the cover of a journal, which contains his first experiments in September, 1786, there is this inscription in Galvani's handwriting—*“Esperimenti circa l'Elettricità de' metalli.”* He had at first, therefore, a true idea of the source of electricity, which was presented to his notice when he discovered the contractions in animals, but this did not last long, for the treatise of October 30th is entitled, *“De Animali Electricitate.”*

According to Galvani's theory, the muscles chiefly contain the animal electricity. They represent a Leyden jar, their outer surface being charged with negative, their inner with positive electricity. The nerve is the conductor of this jar, and, together with the blood vessels, it supplies the muscles with electricity.

“The storm,” says du Bois-Reymond, “which was produced by the appearance of the above-named Commentary among philosophers, phy-

siologists, and physicians, can only be compared to that which disturbed at that time (1791) the political horizon of Europe. It may be said that wherever frogs were to be found, and where two different kinds of metal could be procured, everybody was anxious to see the mangled limbs of frogs brought to life in this wonderful way. The physiologists believed that at length they should realize their visions of a vital power. The physicians, whom Galvani had somewhat thoughtlessly led on with attempts to explain all kinds of nervous diseases, as sciatica, tetanus, and epilepsy, began to believe that no cure was impossible; and it was considered certain that no one in a trance could in future be buried alive, provided only that he were galvanized.

This commotion was, of course, greatest in Italy, and chiefly in Volta's neighbourhood. In many ways he seems to have been particularly adapted to undertake these researches, because he had already instituted some most accurate experiments regarding the electrophorus and condenser.

When Volta had convinced himself of the

truth of the new facts, he at first explained them as Galvani did, but his researches at once took a more physical character. Thus Volta showed that the limbs of the frog were acted upon by a charge of a Leyden jar, which moved Bennet's gold leaf electrometer only 0·1 of a degree, and which could only be observed by means of the condenser. Regarding the limb of the frog as a Leyden jar, according to Galvani's view, he endeavoured to estimate the tension of its charge, and compared it to 0·05 of a degree, or, at most, to 0·1 of a degree of his straw electrometer. To determine whether the positive electricity existed in the nerve or in the muscle, he discharged through the frog a very slightly-charged jar, at first from the spine to the muscles, then in the contrary direction, and finding that contractions resulted in the former case and not in the latter, he concluded that the current from the slightly-charged jar and that in the frog's limb passed in the same direction in the first case, and in the opposite direction in the second, and hence, contrary to Galvani's opinion, that the nerve is endued with negative, and the outer surface of the muscle with

positive electricity. In this instance, Volta hit the real truth by accident, for, as we shall see, the phenomena must be explained in a very different way.

But soon Volta began to doubt Galvani's theory. He found that except in favourable circumstances, the contractions could only be produced by combinations of heterogeneous metals. By the same arrangement he endeavoured to produce muscular contractions in the living human body. He touched the upper and under surface of the tongue with tin and silver respectively, and found when the two metals came in contact, that instead of the anticipated contraction, a peculiar taste was generated. Thus Volta, for the first time, put Sulzer's old experiment in its proper place. In this case, there could be no question of any discharge of electricity, but of some mysterious action caused by a combination of heterogeneous metals, which continued constantly as long as the circuit was closed.

Volta accordingly pronounced it as his opinion that most of the galvanic phenomena had nothing whatever to do with animal elec-

tricity, but that the contractions were caused by a very feeble artificial electricity, which was produced by the application of heterogeneous metals to the limbs of the animals. He then went still further, for he contended that even when the metals were believed to be homogeneous, some slight difference on their surfaces which had escaped observation had produced the electricity. To show what slight differences were sufficient, he made the experiment with a rod of really homogeneous metal, that is, one which produced no contraction in the limbs of a frog. He then dipped one end of this rod in boiling water for half a minute, and repeated the experiment before it had become cool, and the muscular contractions immediately occurred. The same result happened when one end was softened, while the other remained hard. He therefore rejected altogether the existence of an animal electricity, and wherever contractions occurred, he alleged that they were caused by a heterogeneous metallic combination.

To support Galvani's theory, it now became necessary to show that contractions could be

obtained with absolutely homogeneous metals, or without any metal at all. Aided by his nephew, Aldini, Galvani endeavoured to obtain the proof of these points. Their defence cannot in any respect be considered fortunate, for they often show that they did not rightly comprehend the import of Volta's objections. Yet Galvani succeeded so far as to produce contractions without the intervention of any metal whatever, which undoubtedly ought to have been considered as the effect of animal electricity. Had he and his followers been content to claim these contractions and those produced by absolutely homogeneous metals, as belonging to animal electricity, and had they fairly confessed that those much stronger contractions caused by heterogeneous metals ought to be explained by Volta's theory, the controversy would have subsided, and each side would have been near the truth. But they endeavoured to extend Galvani's theory to all the phenomena of muscular contractions, and they explained the greater power of heterogeneous metals by the supposition that such a combination offered a greater resistance to the passage of animal elec-

tricity, and that it was therefore collected in larger quantities in the limb, whereby a more powerful discharge was procured.

Galvani varied the experiment in which contractions were obtained without metals, and he published the results in an anonymous paper, which probably appeared about the year 1794, entitled, "Dell' uso e dell' attività dell' arco conduttore nei contrazioni de' muscoli." This had but a small circulation. Some forms of Galvani's experiments are not unobjectionable; but the following may be looked upon as the fundamental experiment on the electricity of muscles and nerves. The limb of a frog, prepared according to Galvani's ordinary method, is taken, and the nerves are cut off close to their exit from the spine. Then, without dipping them into any fluid, and without exposing them to any agent that could effect any change in them, they are brought in contact with the outer surface of one thigh. This may be done either by lifting them with a non-conductor and letting them fall again, or by pressing them gently on the surface, so that, if possible, they touch only a single point of the

muscle. On so doing the limb will immediately be convulsed.

Galvani even caused the limb to contract by simply bringing the nerve in contact with the muscle of another animal, insulated from the limb. Without taking the skin off the limb, he allowed its nerve to fall upon a piece of abdominal muscle, which was lying on a plate of glass and had no connexion with the frog; the limb was convulsed. The true signification of these phenomena will shortly be explained.

Volta met these experiments by declaring that these contractions were extremely weak in comparison with those caused by heterogeneous metals, that they only arose in rare cases of extreme irritability in the frog's limbs, and he tried to explain them by the supposition of a mechanical stimulation of the nerves. But afterwards, when he had so modified his theory as to include the explanation of these facts, he acknowledged that he had gone too far. He then said that these experiments, if requisite, might admit of a return to the same position which he had taken in 1792—namely, that of ascribing one portion of the phenomena to the action of heterogeneous

metals, whilst the other portion, consisting of the contractions caused by circuits of homogeneous metals, and those brought about without any metal at all, might be ascribed to a true animal electricity. "But why," he asked, "should the same effect be considered to proceed from two different causes, when the theory included both results, different as they appeared to be?" Volta's explanation was simply this, that two heterogeneous tissues, as the nerve and muscle, were, by the interposition of a moist conductor, made into an electric circuit. To the success of the experiment, it was essential, as even his adversaries allowed, that the muscle with which the nerve was in contact, should be moistened with blood or some thick fluid, and if by any accident the limb remained motionless, it was only necessary, in order to induce the muscular contractions, that the parts to be brought in contact should be moistened with saliva, brine, mucus, &c., or still better, with soapy water, and best of all, with a strongly acid or alkaline fluid.

At this period, when animal electricity was almost defeated, Humboldt stepped into the

lists, and described in his celebrated work, called, "Experiments on stimulated Nervous and Muscular Fibres," &c., ("Versuche über die gereizte Muskel-und Nervenfasern, u. s. w.,") a series of experiments in which all suspicion of mechanical irritation and of the interposition of blood, mucus, &c., was entirely avoided, for the circuit consisted only of nerve and muscle. Humboldt gives the following summary of his experiments:—

"Thus I excited vivid muscular contractions—

"1st. By bending the thigh of an animal upon its ischiatic nerve when these parts were in organic connexion.

"2nd. By touching simultaneously the crural nerve and the muscles of the thigh with a portion of the crural nerve which had been cut off.

"3rd. By establishing a circuit between one point of the nerve and some other point of the same nerve by means of some animal tissue.

"In the first case, contact was made between parts organically connected; in the two last, it was made by separated parts, which shortly before had belonged to the stimulated organ, and were homogeneous with the sensitive or irritable fibres."

Humboldt, moreover, proved the possibility of contractions arising from the contact of perfectly homogeneous metals. In opposition to the contrary statement of Volta, he says: "It is indisputably true, and is proved by the observations of the great Ticinian natural philosopher, *that when an animal is not convulsed when touched by homogeneous metals, it may be so affected, when the metals are made heterogeneous by the slightest alteration in mixture, polish, hardness, form, or temperature.* It appears to me," he continues, "that this is the result of Volta's experiments, and not that contractions can only occur when there is some difference in the metallic substances employed.

Thus Humboldt, in the midst of a bitter controversy, clearly perceived and at once took up the right ground.

Galvani also, in several letters to Spallanzani, endeavoured to weaken the attacks which Volta had made on the contractions without metals. Shortly afterwards, however, he quitted the field, dying on December 4, 1798, happily perhaps for him, before the discovery of the battery which caused the total destruction of his theory.

During this period Volta had made gigantic strides in his own course. Hitherto he had left it undetermined whether the cause of the current was to be ascribed to the contact of the metals themselves, or to that of the metals with the fluid; he leaned, indeed, towards the opinion that the points of contact between the metals and the fluid were the seat of the action which produced the current. Afterwards he convinced himself that in the ordinary galvanic arrangement, where the metals are moistened with water or some other wet conductor, much more is to be ascribed to actual contact of the metals than to their contact with the fluid. Hence followed that remarkable series of experiments which is known under the name of Volta's fundamental experiments, by which the production of electricity by the contact of heterogeneous metals was experimentally proved.

Towards the end of 1799 he discovered the voltaic battery; a step which he himself declares to have been a great one.

By this discovery Volta's opinions gained a complete victory. Aldini alone exerted himself for the lost cause of animal electricity. In

1804 he published a work in French called "Essai théorique et expérimental sur le Galvanisme." In this book, among many worthless experiments, he claims many as new which had been previously described by others; indeed he goes so far as to attempt a plagiarism on his uncle, Galvani, for he claims the discovery of muscular contractions without metals as his own. Animal electricity disappeared with Aldini's work for a space of twenty-three years; until 1827, when Nobili demonstrated the electro-magnetic action of the current of the frog. Meanwhile, there appeared only a few scattered facts in support of the fundamental experiment of muscular contraction excited without the intervention of any metal.

CHAPTER II.

ON THE ELECTRO-MAGNETIC ACTION OF THE
CURRENT OF THE FROG.

OERSTED had, in the year 1820, discovered the deflection of the needle by the galvanic current ; this soon led to the construction of the galvanometer. By this instrument, as du Bois-Reymond happily says, metallic electricity was enabled to atone for the wrong she had done to her more tender twin sister in their earlier years.

By the judicious application of Ampère's astatic double needle, Nobili had given to the galvanometer a delicacy beyond expectation. The first use he made thereof was to seek for electric currents in the nerves ; in this he failed. He then compared the sensitiveness of the frog's limb with that of his galvanometer. It is an old experiment that when the spinal column and the feet of a frog are dipped in two vessels containing water or brine, the limbs contract as soon as the vessels are connected by some conductor, as a strip of moist asbestos or of

cotton. His galvanometer being included in the same circuit as the frog, the needle remained motionless, whilst the frog was convulsed. The weak current, which had power to make the prepared frog contract, had no effect on the galvanometer.

Nobili now endeavoured to make a new and more perfect instrument, and he obtained one, which, with a solution of salt in the conducting vessels, showed a deflection of 10° , 20° , and even 30° . When the vessels contained pure water the deflections amounted to only a few degrees, and even these vanished when the length of the column of water between the electrodes was increased; while, in the same circumstances, a strong frog continued to show its extreme sensitiveness by slight contractions. The deflections of the needle when present always indicated that a positive current was passing from the muscle to the nerve, or from the feet to the head in the frog. This current (which was the same by which Galvani produced the contraction without metals), Nobili calls "*la corrente propria della rana*;" it may be called the frog-current (Froschstrom).

The most important facts which Nobili discovered with regard to the frog-current are these.

It is not only present at the moment of closing the circuit, but it is permanent. In a single experiment he obtained 5° of permanent deflection. The action is increased by inclosing in the circuit several frogs arranged as a battery. For a second frog gave 8° , a third 11° of permanent deflection. The frog-current itself is quite independent of the property which the leg of the frog possesses of contracting by the action of that current. For the frog-current can be shown by the galvanometer for several hours after death, while the leg, when subjected to the action of its own current, will contract at most for a quarter of an hour. Generally, freshly prepared frogs show contractions only when the circuit is closed, but some very strong frogs also contract when the circuit is broken.

It is a remarkable fact in the theory of the frog-current, that Nobili should have believed its origin to be thermo-electric, and that he should have ascribed it to the more rapid cooling which the smaller mass of nerves underwent

by evaporation in comparison with the slower cooling of the larger mass of muscles.

It is no doubt owing to this opinion of so great an authority, that the discovery of the frog-current did not attract greater attention and had so small an influence on the direction in which the researches on animal electricity were pursued.

It was reserved for Matteucci to recall the attention of experimenters to these capital phenomena; unfortunately, his papers, though calculated to attract attention, were most difficult to understand, and he shows not only a want of clearness, but sometimes of fairness, which is greatly to be regretted.

Becquerel, in the year 1836, proposed a theory of the electric fishes. He considered that at the moment of the shock the electricity was developed in the brain, and was thence conveyed to the electric organ, to charge the little cylinders of which it is composed.

Matteucci seized upon this idea, and, without naming its author, published it in various journals. In his "*Traité des Phénomènes électro-physiologiques des Animaux*, 1844," he makes

no mention of this theory, because he had in the mean time found it untenable ; yet he nowhere plainly confesses that he has changed his opinion.

This theory then induced him to study the electric current in the frog. Assuming that electricity originated in the brain by the contact of the nervous and sanguineous elements in that organ, he perceived that the same constituents were concerned in the electric action in the leg of the frog ; and he then desired to remove from the frog-current all suspicion of a simple chemico- or thermo-electrical origin.

Matteucci published his first experiments on the frog-current, together with those on the torpedo, in the year 1837. In the year 1838 he published another paper on the frog-current alone. He used for these experiments a galvanometer, with 2500 coils of wire, with platinum poles dipping into two porcelain vessels, *a* and *b*, containing a weak solution of salt ; *a* was connected by a piece of thick cotton with a third vessel *c*, and *b* with a fourth *d*, also containing a weak solution of salt. The closure of the circuit was effected by connecting *c* and *d* by means of the prepared frog.

The following are the most important results, which he then published:—

As powerful a current as that produced by Galvani's mode of preparing the frog is obtained by using the whole frog, unamutilated but skinned, by dipping its feet into one vessel, and its head or back into the other. A current of undiminished power, and in the same direction, is obtained if, after having entirely removed the nerves, the upper part of the thigh be dipped into one vessel, and the lower part into the other. As for the action of the galvanometer, when the two intervening vessels were removed, Matteucci obtained an immediate deflection of 25° to 30° , and a permanent one of 3° ; but this last, in consequence of the increasing polarization in the platinum, sank, within a quarter of an hour, to 2° . If the frog were then taken away, and in its stead the circuit closed with a piece of cotton, the needle varied from 15° to 20° on the other side, in consequence of the reaction of the polarization of the electrodes. Matteucci then strangely concluded that because the frog-current traversed a tolerably long column of salt water, therefore it must be capable of an electro-che-

mical action; and he endeavoured to prove it with iodide of potassium, without using metallic electrodes. He also states that the current is absent in frogs, when under the influence of tetanus, as well as when cooled by ice for *some minutes*, &c.

In this communication he does not again mention the “*courant propre des nerfs et du sang*;” although he originally started with that hypothesis, but he here says that the origin of the frog-current is altogether unknown.

Matteucci's merit in this paper is that he showed that the electromotive action in the frog, upon which the frog-current depends, is independent of the contact of the muscle and nerve, external to the limb, so that by connecting any two parts of the frog, the back and the leg for instance, a current is obtained. This discovery entirely overthrew the old Voltaic doctrine and Nobili's theory of thermo-electricity, as well as the idea of any electro-chemical action; moreover, the method of observation here described by Matteucci, but afterwards abandoned, contains the germ, the further development of which gave the means of search-

ing deeper into the laws of the electric current in muscles. This paper, which was reprinted in Paris in 1840, unchanged and without any addition, in Matteucci's "Essai sur les Phénomènes électriques des Animaux," as the sixth chapter of the second part of that book, forms the starting point for the researches which du Bois-Reymond has made in animal electricity.

He obtained his first results in the spring of 1842. In the January number of Poggendorff's *Annalen*, for 1843, a paper by du Bois-Reymond appeared, under the title of "A Preliminary Abstract of Experiments on the Frog-current and on Electric Fish." (*Vorläufiger Abriss einer Untersuchung über den Froschstrom und über die elektromotorischen Fische*), which contains the result of his first investigations. This paper will not be more particularly noted, because its contents are embodied in the larger work which is now under consideration

CHAPTER III.

ON DU BOIS-REYMOND'S IMPROVED GALVANOMETER.

THE substance of du Bois-Reymond's most important remarks upon the construction and use of a galvanometer fit for experiments on animal electricity, may be shortly stated thus.

First the copper wire of the galvanometer may be a very long and thin one, without impairing the intensity of the currents, because the resistance to conduction in all parts of animal bodies is very considerable. Du Bois-Reymond has, therefore, in making his galvanometer, far exceeded the number of coils generally employed up to his time by Gourjòn, Ruhmkorff, and others, and he has succeeded accordingly in giving to his instruments a sensitiveness far beyond what had previously appeared attainable.

In du Bois-Reymond's work, two galvanometers are described, of different sizes and

degrees of sensitiveness. The smaller, which was first made, he calls the galvanometer for the muscular current, because with it all the phenomena of the muscular current can be exhibited. The nervous current, also, and most of its phenomena were discovered with the same instrument. Its wire is about 3280 feet long, and $\cdot 0067$ inch in diameter, and is coiled 4650 times round the frame.

In order, however, to observe certain most delicate variations of the nervous current, the presence of which he had anticipated theoretically, without being able to detect them by the galvanometer for the muscular current, du Bois-Reymond afterwards constructed a new and more powerful apparatus, which he called the galvanometer for the nervous current. This latter instrument is much more elaborate than the former one. Moreover, it is easy, by diverting a part of the current, to adapt its sensitiveness to the greater intensity of the muscular current. It will, therefore, only be necessary to give a minute description of du Bois-Reymond's galvanometer for the nervous current.

The general arrangement of the instrument is very nearly the same as in Poggendorff's sinus-galvanometer.

The frame, the support of the needles, and the four screws which terminate the double wire are fixed on a circular plate which can be rotated on a central axis. The amount of rotation may be determined by a graduation on the limb of the circular plate.

The frame within is 1·7 inch long and 1·6 inch broad. The height of the space in which the lower needle is suspended, which is identical with the thickness of the cross beams on which the wire is wound, is only 0·1 inch. The sides of the frame are 4·6 inches long, and they are 3·1 inches high. The cross beams are 0·3 inch broad; they are convex externally, so that their internal outline corresponds to a circle of 2·6 inches in diameter. The ivory pillars by which the slit in the upper half of the coil is kept open are ·08 inch broad.

The wire wound upon this frame is a copper wire 5584 yards, or 3·17 English miles long, and about ·0055 inch in diameter. The wire forms around the frame 24,160 coils.

The needles are cylindrical, and each end of them is sharpened into a long point. They are 1·5 inches long, and ·03 inch in diameter ; they are connected by a thin piece of tortoiseshell, nearly 1·6 inch long. The two needles weigh together 4 grains. The connecting piece weighs only 0·9 grain. When out of the galvanometer coil the astatic system makes a single vibration in thirty-three seconds.*

The galvanometer ought to be placed upon a solid ledge, from which it ought never to be removed as long as it is in use. Its adjusting screws should stand on three insulating pieces of glass. After having levelled the instrument, the coil should be placed nearly east and west, and it will then be ready to receive the needles.

A perfectly astatic system of needles, indeed, does not come to rest on the magnetic meridian ; but in proportion as its time of oscillation increases with the astatic state, it is seen to leave the meridian and to take a position of equilibrium, which is the more remote from the meridian the more astatic the needles are. This

* It will hereafter be seen how the galvanometer coil acts in modifying the time of oscillation of the astatic system.

phenomenon is called by du Bois-Reymond the *spontaneous deflection* of an astatic system. Nobili first observed it, and immediately succeeded in pointing out its real cause—namely, that the horizontal projections of the two needles never quite coincide, but form with one another a greater or less angle. This will be easily understood by reference to fig. 1. Let $n s$ and

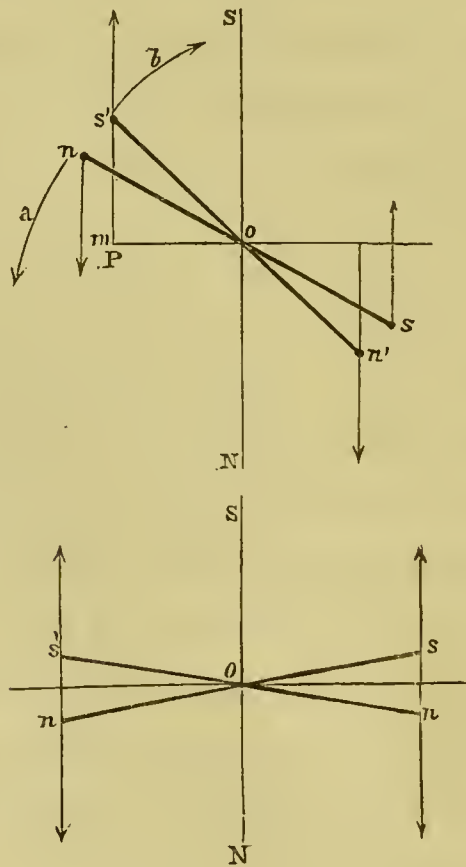


Fig. 1.

$n' s'$ be the horizontal projections of perfectly similar and equally magnetic needles. $N S$ the magnetic meridian, passing through the point of intersection o . Let it be supposed that the forces which act to turn the needles are applied at their extremities. The direction of these forces must be parallel to $N S$, as shown in the figure by the arrows. If we call k the force applied to n , in a direction parallel to $N S$, then $k l$ will be the statical momentum with which this force acts to turn one of the needles in the direction of the arrow a ; l being the leverage $o m$. The total force which acts in that direction on the needle s is $2 k l$, because there is at the other end of the needle an equal force with an equal leverage acting in the same direction. The force by which the other needle, $n' s'$, is driven in the opposite direction, viz., in that of the arrow b , may be taken as $2 k l'$; if the leverage $o p$ be called l' . Between the statical momenta, $2 k l$ and $2 k l'$, which tend to turn the system in opposite directions, equilibrium can only exist when l equals l' , and this only happens when the needles have the position shown in fig. 1, viz., when the straight line which bisects the angle

between the similar poles of the needles makes a right angle with the magnetic meridian.

The more unequal the magnetic intensity of the needles, the nearer to the magnetic meridian will they come to rest. Practically the spontaneous deflection is no disadvantage in the use of the galvanometer ; on the contrary, it affords a convenient means of determining the degree in which the system is astatic, without having recourse to the observation of its time of oscillation.

When the system within the coil is more astatic, another cause of deflection occurs, which seriously impairs the usefulness of the instrument. It is very difficult to get copper wire for the coil, quite free from all paramagnetic action. Perfectly pure copper, indeed, may be procured by a galvanic process ; but this galvanic copper cannot be drawn out to a wire fine enough for the galvanometer. Besides the very wire-drawing causes some iron to adhere to the surface of the copper ; in fact, the wire coil has always some, though but a slight paramagnetic influence on the needles, instead of the

diamagnetic action which it ought to exercise if it were thoroughly free from iron.

Generally this influence manifests itself thus. In a less astatic condition of the system no disturbance is perceived ; the needles return to the zero line. But when the system is more astatic it may first be observed, that its position in the galvanometer does not quite agree with that observed when it is not suspended within the coil. If the needles be followed by the coil, they recede up to a certain position at the side of the zero line, whilst the angle between them and that line can be diminished to a certain extent ; but when that limit is passed, the needles suddenly return through the zero point, and come to rest on the other side.

If the system be made still more astatic, the phenomena become more and more complicated. The disturbance produced by the wire coil on a perfectly astatic system, that is, upon one which is quite free from the influence of terrestrial magnetism, may be first considered. Such needles may take up in the wire coil two positions of stable equilibrium, in either of the

diagonals of the wire coil, as shown in fig. 2, where $abcd$ represent the horizontal projection of the coil.

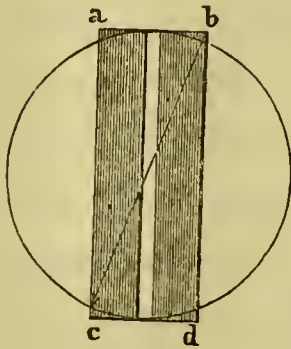


Fig. 2.

If the perfectly astatic needles are moved from their position at bc to either side, they will be drawn back by the magnetic attraction of the coil into their former place. The position in which the system would be parallel to the coil, would be one of unstable equilibrium. If it be moved ever so little to the left it will assume the position bc , while the slightest movement to the right will cause it to take that of ad . At the zero of the scale the forces which draw the system to either side are equal to zero, that is, the system is drawn with equal power either way; on the right of the middle or zero point, to the right side; on the left, to the left side. The amount of the force by which the astatic needles are affected in different parts of the scale is represented in fig. 3, a , by the curve $kqpors h$, which du Bois-Reymond calls the *disturbance curve*. In the

figure the abscissæ represent the degrees into which the circle is divided. The ordinates are proportioned to the forces which act on the

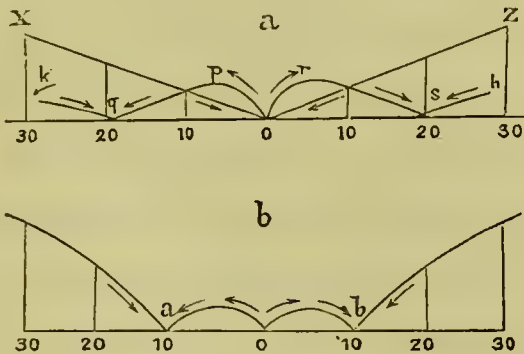


Fig. 3.

needles. The direction of these forces is indicated by the arrows: 0 marks the zero point of the division. The point 0 is therefore the position of unstable equilibrium, for the system is drawn away from it to either side. The points q and s , are the points of stable equilibrium, for when the system is placed on either side of these points, it is driven back towards them. Somewhere about the points p and r the power which drives the needle to the position of stable equilibrium is at its maximum. As to the manner of finding, by experiment, the form of the disturbance curve which belongs to each instrument, du Bois-Reymond's work must be consulted.

Besides the influence of the wire upon the needles, there is the action of terrestrial magnetism, which alone would keep it upon the zero point of the division, and would drive it back with greater force, the further it was distant from that point. In general, the more astatic the system is made, the less is it influenced by terrestrial magnetism. In fig. 3, a, the ordinates of the curves XO and ZO , represent the amount of the force of the earth, which tends at any point of the abscissæ to drive back the system to the zero point. These curves, which refer to a tolerably astatic system, intersect the disturbance curve in two places. The simultaneous action of the force of the earth and that of the coil upon the needles is represented in fig. 3, b, which is formed by a combination of the two curves in fig. 3, a, in the following way. In those points of the graduation where the forces act on the needles in the same direction the sum of the ordinates is taken, but where the actions are contrary, the difference. In this case also, O is a point of unstable equilibrium, and on either side of the zero there are points of stable equilibrium, namely a and b . If the needles are less astatic

the lines $x o$ and $z o$ become less inclined. Then the points of intersection with the disturbance curve, that is, the points a and b of stable equilibrium, approach nearer and nearer to the zero point; and, when the needles are so far from being astatic that $x o$ and $z o$ do no longer anywhere intersect the disturbance curve, fig. 4 then results; the zero point itself becomes a point of stable equilibrium as in fig. 4, d .

If, in consequence of the disturbing influence of the coil, the needle cannot be brought upon the zero point in a position of stable equilibrium, the

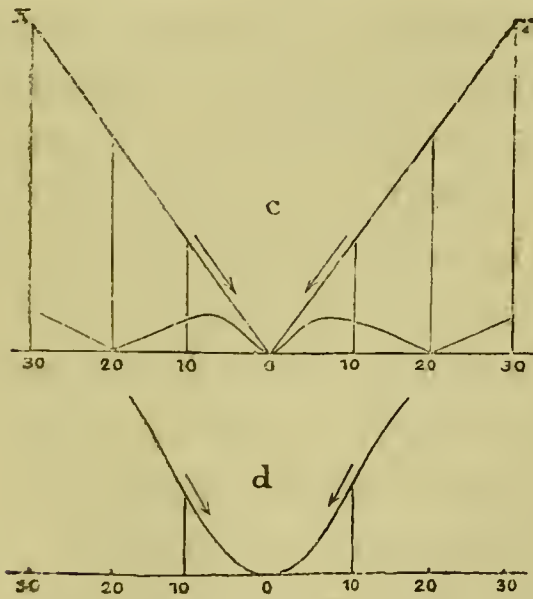


Fig. 4.

instrument, of course, is in a useless condition; and the question arises, what can be done to avoid or to neutralize the disturbing influence of the coil on the astatic system?

This question has been answered in different ways by different philosophers. Some have attempted to obtain copper wire free from iron. Others have tried to give the coil such a shape as would avoid the position of unstable equilibrium falling on the zero line. Others have not attempted wholly to suppress the disturbing action of the coil, but they have contented themselves with inquiring how the astatic condition of the system might be diminished just so far and no further than is necessary for keeping the needle on the zero line. This would, of course, be exceedingly difficult, by merely modifying the magnetic intensity of the needles themselves. But Nobili perceived that it might easily be attained by placing some axis of magnetic power in the vertical plane of the zero line, whereby the force exerted on the system by the earth might be diminished or increased. By varying the position of that axis of power in different ways, the directing force, dependent on the

astatic state of the system, could be conveniently modified, so that it would only slightly exceed the amount required in consequence of the magnetic action of the coil. As to the best position for such an axis of magnetic power, several opinions have prevailed. Nobili himself, and afterwards Melloni, Ruhmkorff, and others, have proposed that a magnetic bar should be placed at a considerable distance from the system, with one of its poles near to one of the poles of the system. For some time du Bois-Reymond also used this method, but he soon became aware that it is by no means an unexceptionable one. Beyond the position of stable equilibrium on either side of the zero line, the astatic system is indeed no longer drawn by the forces of the coil from the zero point, but, on the contrary, towards it, as is shown by the arrows in fig. 3, a. Beyond the points of the division corresponding to these positions, it is therefore not only unnecessary, but even prejudicial to the sensitiveness of the instrument, to add anything to the directing force of the earth. This, however, is the case when the magnet is placed at any considerable distance from the astatic system, because then

the distance between the magnet and the system remains nearly the same when the latter is deflected.

A method of compensating the magnetic action of the coil must therefore be devised, in which no perceptible action is produced by the correcting magnet, beyond the points of stable equilibrium on either side of the zero line. The way in which this may be obtained is obvious, from what has previously been stated. The correcting magnet ought to be very small, and it ought to be placed very near to the end of one of the needles. Du Bois-Reymond, therefore, uses the broken point of a very fine bead needle, which is placed very close to one of the ends of the upper needle on a brass rod. By means of micrometrical screws very delicate changes can be made in its position, either forwards or backwards, to the right or to the left side. In this way, with any coil whatever, the system can be kept on the zero point with the least possible acceleration of its time of oscillation, in other words, with the least possible loss of sensitiveness.

Little pins are generally fixed at the 90°

points, against which the upper needle strikes when its deflection tends to exceed a right angle.

Du Bois-Reymond has observed that these pins are objectionable, because when the needle strikes violently against them, it may injure its magnetism. He therefore puts in the place of these pins two very thin and therefore flexible plates of mica, by which the needle is checked in the gentlest manner.

For further particulars regarding the construction and management of the galvanometer, reference must be made to du Bois-Reymond's work.

CHAPTER IV.

ON THE MODE OF USING THE GALVANOMETER FOR
DETECTING ELECTRIC CURRENTS IN PARTS OF
ANIMALS.

Now that a description has been given of the chief points of importance in a galvanometer which can be used in experiments on animal electricity, the next point is to inquire how the limbs or other parts of animals should be placed between the ends of the wire in order to determine (without the danger of interference from extrinsic electric actions) whether they have the power of producing a current.

The ends of the galvanometer should be provided with platinum plates, through which the current should pass from the fluid part of the circuit to the coil. It is absolutely essential that these platinum plates should be as far as possible homogeneous; for the smallest difference between them will of itself cause a current

when the circuit is closed. A current, for instance, will arise if the heterogeneous plates are dipped into the same vessel of water. Now, if a portion of an animal were placed between two of these heterogeneous plates, it would be manifestly doubtful whether the deflection observed were caused by the animal electromotor, or by the heterogeneity of the plates.

Du Bois-Reymond cleans the plates first with a mixture of alcohol and sulphuric ether. He then washes them clean with nitro-muriatic acid. Then he uses distilled water, and, lastly, he heats them to incandescence for half a minute by means of a Berzelius lamp.

Even when the plates of platinum are quite homogeneous, a current will arise when they are not simultaneously immersed into any fluid. Fechner, in his excellent treatise on Galvanism and Electro-chemistry, (*Lehrbuch des Galvanismus und der Elektrochemie*) which forms the third volume of his translation of Biot's *Traité de Physique*, collected all the statements made up to that time, on the currents produced by unsimultaneous immersion of homogeneous metals. Afterwards Schröder published, in

Poggendorff's *Annalen*, vol. 54, p. 57, minute researches on this subject. It is not improbable that this phenomenon results from a layer of some gas, which adheres to the metal in the air, but which disappears when immersed into the liquid. However that may be, the heterogeneous state produced by the unsimultaneous immersion of homogeneous plates of platinum soon disappears. In order to be certain that the plates continue homogeneous when they have once become so, they ought never to be removed out of the liquid in which they became homogeneous; and at the times when the apparatus is not in use, the plates should be connected by a metallic wire as well as by the liquid so as to form a perfect circuit. This du Bois-Reymond obtains thus:—

Two platinum plates* are made to communicate with each end of the galvanometer, and they are plunged into a cylindrical glass vessel of three inches in diameter. These plates, as

* Du Bois-Reymond found, for several reasons, that he could much more easily overcome the differences of the platinum electrodes, when he used two at each end of the galvanometer wire instead of one only.

is shown by fig. 5, are held in a clamp fixed

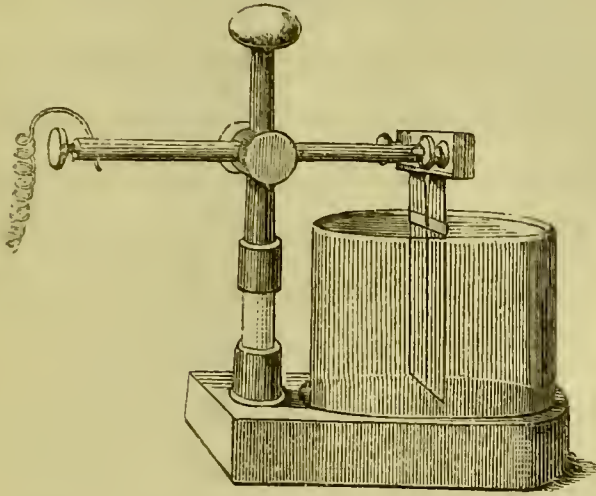


Fig. 5.

on a horizontal brass rod, which can be moved parallel to itself, up and down, backwards and forwards upon a vertical brass rod, insulated by a glass foot. The rod can be fixed by screws in every suitable position. The conducting wire of the galvanometer is connected with the other end of the horizontal rod.

The other end of the galvanometer wire is connected in an exactly similar manner, with a similar vessel, into which two similar plates are plunged. Each platinum plate is 2.5 inches long, and 1 inch broad. The vessels are filled with a saturated solution of common salt. The circuit is completed by connecting the two

vessels, by means of a large syphon-like tube, also filled with a saturated solution of salt, the ends of which are closed with bladder. If the plates thus immersed in the liquid are found to be homogeneous, it only remains to remove the *connecting tube* and to place between the vessels that part of the animal whose electromotive action is to be examined. This may be done in two ways, either by taking the plates out of the liquid, and putting them on the animal parts, or by putting the latter between the two vessels, after removing the connecting tube, so as to complete the circuit by means of those parts.

Now, it is plain, that in the first method, that of placing the plates on the parts, inequalities both in the manner and time of making contact can hardly be avoided, and that the second method is, therefore, much more certain.

To secure the plates against any accident, by which their homogeneity could be endangered, du Bois-Reymond wraps them in closely folded blotting-paper up to the line of immersion, and above this he applies varnish, leaving the upper rim, which is fastened into the clamp, untouched.

It is only in coarse experiments that the

animal parts can be dipped directly into the salt solution, because this solution, by attacking the animal substances, has an injurious action, which would render fine observations impossible, and also because it would not be easy to complete the circuit between two points of a nerve or a muscle by means of the vessels alone.

Hence, du Bois-Reymond uses cushions of blotting-paper for more delicate experiments. These cushions are made of many layers of fine blotting-paper, swelled with the saturated solution of salt; they rest against the edge of the vessel, as shown in the figure 6. They also

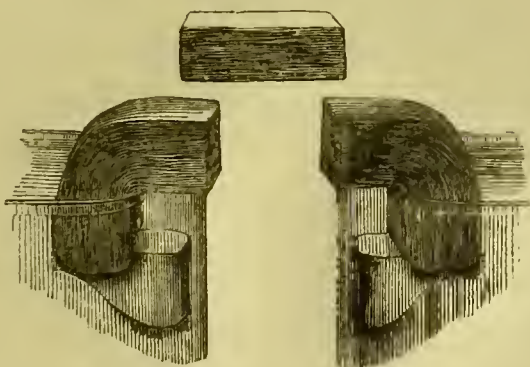


Fig. 6.

rest, not only on the edge of the glass, but inside, upon little blocks of wood which are

fixed to the side of the glass.* These paper cushions may be called the *conducting cushions*. When these cushions are used, the circuit, instead of being closed by the connecting tube, is closed by means of a *connecting cushion*, which is also wet with the saturated solution. To bring the animal part into the electric circuit the connecting cushion must be removed. Still the animal part must not be laid directly on the conducting cushions, lest such a corroding action should take place as would cause contraction of the muscles, and most rapidly destroy the vital properties of the nerves. To avoid this immediate contact, du Bois-Reymond places a guard of pig's bladder perfectly moistened with white of egg, on that part of the conducting cushion on which the animal part is to be laid. The piece of bladder should be about 0·8 inch long and 0·6 inch broad. Thus, on the cushion the guard is laid, and on the guard the animal part.

* At present du Bois-Reymond, instead of glass vessels, uses for the saturated salt solution, square porcelain vessels, which are made with a little porcelain ledge projecting from one side.

For many experiments an *intermediate cushion* is necessary, which should be placed between the conducting cushions in the manner shown in fig. 7.

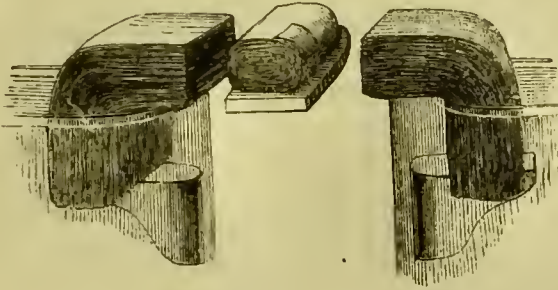


Fig. 7.

On the intermediate cushion, in the figure, there is also an albuminous guard.

CHAPTER V.

ON THE GENERAL FORM OF AN EXPERIMENT ON ANIMAL
ELECTRICITY BY MEANS OF THE GALVANOMETER.

THE general form of an experiment on animal electricity with the galvanometer is this. The needle of the galvanometer is kept by means of the adjusting rod at zero. The conducting vessels with their platinum plates are formed into a circuit without the galvanometer, and when this instrument is included, there should be no, or very slight, deflection of the needle. The connecting cushion must now be removed, and the conducting cushions should be covered with the albuminous guards; the connecting cushion must then be replaced, to ascertain that the homogeneous state of the platinum plates still exists. When the connecting cushion has been once more removed, the space between the conducting cushions must be closed by the animal electromotor. The first sudden deflection

of the needle should then be observed as regards its extent and direction. Sometimes it may be desirable to allow the needle to come to rest, in order to observe the permanent deflection. This will happen much nearer to the zero point than might be expected, from the extent of the first deflection, in consequence of the polarization of the platinum electrodes. When the observation is completed, or when a permanent deflection is not required, the animal electromotor must be quickly removed and the connecting cushion put in its place; then a deflection will be observed in an opposite direction to that which first occurred. This is caused by the electro-chemical reaction of the substances, which the current of animal electricity evolved on the platinum plates by means of its electrolytic action. The intensity of the secondary current is proportional to that of the original current; but the former may far exceed the latter, because the resistance of the connecting cushion may be almost infinitely smaller than that of the electromotor. These circumstances are not particularly disadvantageous; they may even often be of considerable service, chiefly because

they are corroboratory evidence that the phenomena arose really from the electromotor ; thus a secondary current, strong or weak out of proportion to the primary current, indicates some error in the experiment. A common method of making sure of the genuineness of the action observed, when the electromotor is placed in the circuit, is to reverse its position, when the action should of course take place in the contrary direction. This change in the position of the animal part may be combined with the action of the secondary current, in order to make very weak currents more evident. This may be effected by turning round the electromotor without first replacing the connecting cushion, and without giving the polarization time to decrease, in consequence of the circuit being too long open. Then the reverse primary and the secondary current will unite to produce a stronger action on the needle.

CHAPTER VI.

ON THE LIMB OF THE FROG AS A TEST FOR WEAK
ELECTRIC CURRENTS.

IT has already been mentioned, that Nobili considered that the prepared limb of a frog was a more delicate test of electricity than the galvanometer. But as the galvanometer is now very much improved, the prepared frog is no longer the most sensitive. Nevertheless, its peculiar properties sometimes render it indispensable. Hence it must be more particularly examined.

The prepared limb of the frog becomes extremely sensitive only when the electric current, in some portion of its course, is confined to the nerve alone. In order to use the frog as a test of electric currents, it is usual to direct that it should be prepared according to Galvani's method. To this method, however, du Bois-Reymond assigns only an historical interest. For many purposes it is exceedingly convenient to have the nerve as long as possible: and the preparation

should consist of the leg and foot only, while the whole length of the sciatic nerve, from the knee to the loin, should be left attached. This preparation (fig. 8) will be hereafter called the *rheoscopic Limb*.



Fig. 8.

As a precautionary measure, it is important to keep the rheoscopic limb as insulated as possible, so that neither the proper current of the limb nor any other current may pass through the nerve.

The rheoscopic limb, in its application to animal electricity, has the advantage of being the only test for electric currents which can be used without the intervention of any metal in the circuit. Thus the great difficulties arising in the preparation of homogeneous metals are avoided. But, on the other hand, its use is hampered with many objections. It does not admit of any comparison in the results regarding the degree of action, for the irritability is not only different

in different frogs, but varies with the season, and decreases rapidly after death. The rheoscopic limb contracts only when the circuit is made or broken, so that it cannot be decided whether there is a permanent current or a momentary discharge. Lastly, although, as we shall presently see, some conclusion as to the direction of the current may be obtained, yet, upon these indications, implicit reliance cannot be placed.

CHAPTER VII.

ON THE GENERAL LAW OF THE EXCITATION OF
NERVES BY AN ELECTRIC CURRENT.

IT has been already observed that the prepared frog is only affected when a current is made or broken, or, to speak more generally, only when variations occur in its strength; so that, during a current of uniform strength, no effect is produced. Du Bois-Reymond announced this as the chief law of electric excitation in these words:—“*The motor nerve is not excited by the absolute amount of the density of the current,* but by the variations of this amount from one instant to another, and the excitation caused by these changes is the greater the more rapidly the changes take place, or the greater they are in any given time.*”

This very important law may be illustrated by

* By density of the current in any section of the circuit, du Bois-Reymond expresses the quotient of the intensity of the current divided by the size of the surface of the section of the conductor.

the following diagrams, in which the abscissæ represent the time. Each of the figures consists of two parts.

The ordinates of the lower curve represent the density of the current in the nerve. Fig. 9, for instance, shows the manner in which it may be supposed that a current begins, increases

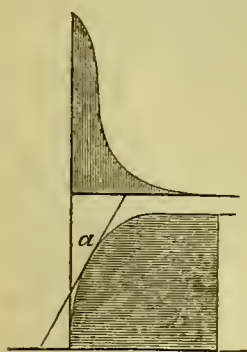


Fig. 9.

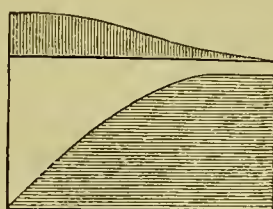


Fig. 10.

rapidly to a certain degree, and then remains constant, as may be seen by observing that the lower curve, after rising rapidly, runs horizontally. In fig. 10, the density of the currents increases from zero to the same height as in fig. 9, but rather more slowly.

The ordinates of the upper curves, on the contrary, represent the amount of irritation which is produced in a nerve at any moment. This amount depends on the steepness of the

curve. We are still ignorant of the exact law which this dependence follows. Some supposition must be made so as to allow the curve which represents the irritation to be traced. It may, therefore, be assumed that the irritation bears a direct proportion to the steepness of the curve, which represents the variations of the current in the nerve. Let a tangent be drawn to any point a in this lower curve, and it will form an angle with the abscissæ; then the ordinate of the upper curve corresponding to the point a is made always proportional to the trigonometrical tangent of that angle, and all the upper curves are traced on this principle.

If fig. 9 be compared with fig. 10, it will be seen that the greater ordinate of the upper curve corresponds to the greater degree of steepness of the lower curve, that is, to a more rapid variation of the density of the current in the nerve. From the very moment in which the density remains constant, the irritation (the amount of which is represented by the ordinates of the upper curve,) becomes equal to zero.

In fig. 11 the density of the current is seen to increase from zero to a certain amount, when it remains for a time constant, and then sinks again

to zero on the breaking of the circuit. The upper curve shows why a contraction takes place



Fig. 11.

when the current is made and broken, whilst no contraction occurs as long as the density of the current in the nerve remains constant.

In fig. 12 the lower curve represents a strong current, which for a time continues without any

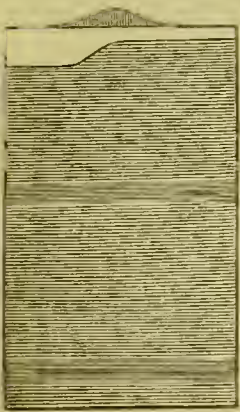


Fig. 12.

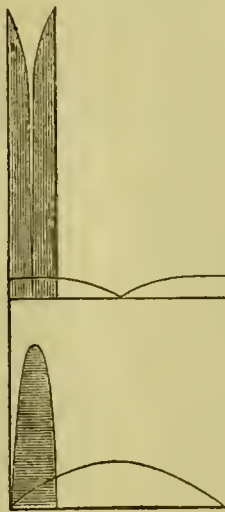


Fig. 13.

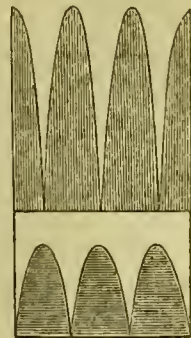


Fig. 14.

variation, and then slightly increases; at the same time a slight irritation of the motor nerve occurs during the increase of the density of the current in it.

Fig. 13 represents two curves of the density of the current, and of corresponding irritation in the nerve. The under curves show the discharge of a given quantity of electricity at two different times; as, for example, would be produced by a Leyden jar successively discharged through two conductors having unequal resistances. It is obvious that the more rapid discharge implies the greatest amount of irritation.

Lastly, fig. 14 shows the curve of irritation which would be produced by a series of successive discharges rapidly following one another, as, for example, a series produced by any machine by which the electric current is rapidly made and broken. The effect of such a series of discharges, when they follow one another rapidly enough, is a tetanic contraction of the muscles, as was first observed by Volta, and afterwards pointed out again by Nobili. This method of causing a muscle to be attacked by tetanus will be often employed hereafter.

In many and most important experiments in animal electricity it is essential to have some means for observing exceedingly quick and very slight variations of very slight currents. The mobility of the magnetic needle is not sufficient for this purpose. The rheoscopic limb, on the contrary, in consequence of the properties which have been previously mentioned, answers excellently. Of this, special instances will be hereafter mentioned.

After these statements, no doubt can be entertained as to the opinion which must be pronounced upon Matteucci's researches, which were published in his paper, "*Mesure de la force nerveuse développée par le courant électrique*," in which he endeavours to find a constant relation between the consumption of zinc in the production of an electric current, and the mechanical effect produced in the contraction of the limb of a frog, through the nerve of which the current passes. The principle on which his experiments are based is so fundamentally incorrect, that it is unnecessary to enter into the consideration of the results which he obtained.

Regarding the above-mentioned law, it must

further be stated that it applies strictly to the motor nerves only. The nerves of sensation, as far as they can be submitted to experiment, not only suffer the same irritation as the motor nerves, when variations of the density of the current occur, but they are also affected by a constant current. Long since Volta observed a remarkable and continuous sensation, which lasted whilst a zinc and silver battery of a hundred elements was closed ; and any one can feel the sharp pain which the current produced by a single element causes on a sore place. The electric taste is also continuous. As for the sense of sight, Volta himself seems only to have observed the flash which occurred when the circuit was made and broken ; but Ritter, long since, with a single element, obtained a continuous sensation of light. If the current of a battery, consisting of thirty or forty pairs of plates, is passed into the ears by means of wires, a continual humming noise is heard. But though, according to these observations, the presence of a constant current is perceived in the nerves of sensation, yet even in these nerves the action, when the current is made and broken, is much more evident.

Thus it appears that a great analogy exists between the excitation of nerves by the electric current and the induction of currents. This analogy Marianini first pointed out

CHAPTER VIII.

ON THE INFLUENCE OF THE DIRECTION OF THE
CURRENT IN THE NERVES UPON THE CONTRACTION.

IN the fresh prepared limb of a frog, which still possesses a considerable degree of excitability, an evident contraction on opening and closing the galvanic circle is observed, whether the direction of the current be up or down the nerve. When the excitability decreases, differences arise between the intensity of the contractions when the current is made and broken; and these differences depend on the direction of the current in the nerves. The law of this dependence is thus stated by du Bois Reymond

“ It is found in most cases when a moderate degree of irritability exists, that according to the direction of the current in the nerve, sometimes the contraction on making, sometimes that on breaking the circuit is the stronger; and that sometimes even the one or the other contraction

is entirely absent. The more violent contraction on making contact takes place when the current passes from the origin to the expansion of the nerves. On breaking contact the contraction is greatest when the current is in the opposite direction."

The following is the simplest method of showing this phenomenon, fig. 15 :—the pelvis of a

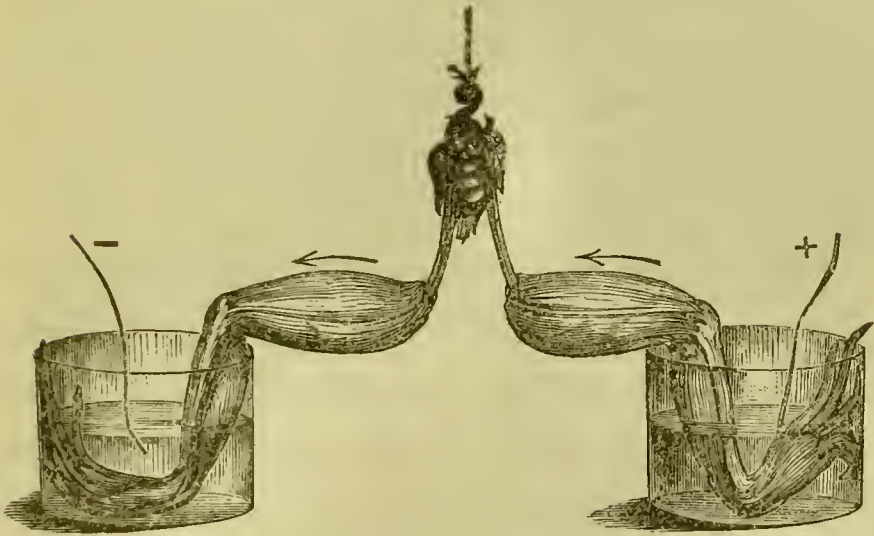


Fig. 15.

frog, prepared according to Galvani's method, should be divided in the middle, so that the two thighs communicate together only by means of the sciatic plexuses which still adhere to a piece of the vertebral column. Each foot of this preparation must be put into a vessel

containing water, and in these vessels the electrodes of a voltaic battery, the current of which will thus of course be up one limb and down the other, so that by taking one of them out, and putting it in again, the current can be broken or made at pleasure.

If the excitability of the nerves has sufficiently diminished, one limb will contract on breaking, the other on making the circuit; that current which passes from the origin to the expansion of the nerve may be called the *downward*; that which passes from the expansion to the origin of the nerve the *upward* current.

We can by this law determine the direction of a current. If the limb contract on making, and not on breaking the circuit, the current is probably downward. If the nerve be brought into the circuit in a contrary direction, the limb should remain motionless on making, and should contract on breaking the circuit.

But this test of the direction of the current is by no means as certain as that furnished by the galvanometer, since, in the former, irregularities in the contractions frequently occur.

The first observation which bore at all on this

law was made by Volta, at a time, too, when he held Galvani's opinions on the cause of these contractions in frogs. But as we have seen in page 9 and 10, he did not then know the real import of his observations, but drew from them a false conclusion.

Pfaff was the true discoverer of this group of phenomena, since as early as 1793-95 he published minute and profound papers upon the subject. Ritter, Marianini, Nobili, Matteucci, and others made further researches into this matter. Du Bois-Reymond refers particularly to their labours, he himself having as yet made no experimental researches in this direction.

CHAPTER IX.

ON CONTRACTIONS CAUSED BY INDUCTION IN OPEN
CIRCUITS.

ALTHOUGH the following facts are not immediately connected with the subject of animal electricity; still, whoever pursues these researches must not disregard them, and had better be well acquainted with them. They relate to a disturbance of electric equilibrium in an open circuit when it is in the same condition in which a current would have been induced, supposing the circuit had been closed; that is, by approaching or removing a magnet, or by closing or breaking a voltaic circuit in the proximity of the open circuit. This disturbance of the electric equilibrium, which, if the circuit had been closed, would have given rise to a current, is easily made apparent in the following way by means of the rheoscopic limb.

The circuit being open, and the nerves of two rheoscopic limbs being applied one to each end,

on making or breaking a current close to the open circuit, or by causing a magnet to approach or recede from it, no contraction will be obtained, provided the open circuit has been most carefully insulated. But if one of the two rheoscopic limbs is at the same time touched with the finger, or put in connexion with the ground in any other way, on making or breaking the primary current a contraction will take place. If the two rheoscopic limbs are both highly sensitive, both will be seen to contract, that is, not only the one which is touched with the finger, but also that which is not directly in communication with the ground. If, however, the two limbs possess a lower degree of excitability, only one will be convulsed, namely, that one in which the induced current would have been directed downwards, had the circuit been completed by making contact by means of the feet of the two frogs. The contraction, however, in this case often fails in the limb which is not in direct communication with the ground. As these contractions occur at one of the poles as it were of an induced circuit, they may be called *unipolar contractions by induced currents*.

There is another rather complicated form of the same experiment which is of still greater practical importance. Let the induced circuit, instead of being open as before, be completed by a bad conductor of some length, for example, by a wet thread; let then the nerve of a rheoscopic limb be tied so that a current can be passed through the portion of the nerve above the ligature without causing contraction. If this portion of the nerve is placed on any point of the wet thread, whilst the limb is carefully insulated, no contraction will take place on making or breaking the primary current. Nor will any contraction occur when the limb is not insulated, provided the portion of the nerve above the ligature exactly touches the middle of the wet thread. But, the limb being still not insulated, as soon as the same part of the nerve is placed on the thread nearer to one of the ends of it, contractions will take place on making or breaking the primary current.

If the sensitiveness of the limb is low, contractions will, however, only occur when the end of the induced current which is nearest to the

nerve on the thread is the positive electrode, and not when it is the negative one.

A nerve may be substituted for the thread in this experiment. Hence, contractions of the rheoscopic limb may also be obtained simply by passing an induced current through the portion of the nerve above the ligature, when the limb is not most carefully insulated. Thus in experiments on animal electricity, in which induced currents are used to excite contractions, great precautions must be observed, but these cannot be more particularly referred to here.

CHAPTER X.

THE FROG CURRENT SHOWN TO DEPEND ON A MUSCULAR CURRENT WHICH BELONGS GENERALLY TO THE MUSCLES OF ALL ANIMALS.

THE mode in which the electric current in the entire frog is shown by du Bois-Reymond's apparatus is this: the conducting vessels are used without the paper cushions, and the circuit is completed by the connecting tube. The platinum plates are placed as far back in the vessels as possible. The frog, the skin being removed, is dipped up to the middle of the two tarsi in one vessel, with the back towards the other vessel. The animal is then bent backwards, and its face and nose dipped carefully into the other vessel.

The needle immediately leaves the zero point, and indicates a current in the frog from the feet to the head, in the galvanometer wire from the head to the feet, that is, an upward one. Soon the needle comes to rest at some distance from

the zero point; but this deflection slowly decreases, becoming very small, though it does not disappear altogether for a considerable time.

If the frog be removed, and the connecting tube substituted for it, then from the polarity of the platinum plates, there will be a deflection in the opposite direction. Nobili's observation of the current in the limb of the frog, prepared according to Galvani's method, is the first step in the analysis of this experiment. It may be made thus. The connecting vessels are to be put closer, the feet are again dipped in one vessel, and the spinal column carefully made to touch the solution in the other. At the moment when this occurs the needle is deflected in the same direction as it was deflected by the entire frog, and simultaneously the limbs are convulsed. The same effect on the needle of the galvanometer is obtained when the lower extremities only are used, after having removed the nerves with the adhering piece of the vertebral column. The motion of the needle is somewhat greater, because the not inconsiderable resistance to conduction offered

by the nervous trunks is avoided, but the contractions are lost. Matteucci also used the lower limbs in the formation of his frog battery; but he always preserved the nervous trunks and a piece of the spinal column, which is not only useless but actually injurious, because it increases the resistance to conduction. This he did, although he was in consequence prevented from using a better conducting fluid in his conducting vessels, because such a fluid generally disturbs the experiment by a corroding action on the nerves, in consequence of which contractions will arise.

The trunk of the frog alone appears also to give a much weaker current in the same direction. A preparation of the foreleg, corresponding to Galvani's one of the lower limb, caused a deflection, the current being directed in the animal from the foot to the chest and shoulder.

One leg and one fore-leg cause a current, weaker than the two arms or two legs, but in the same direction.

Du Bois-Reymond then proceeded to make researches on other animals, thinking that Mat-

teucci's opinion was incredible, that the frog alone was gifted with the power of causing these currents.

The above experiments were all tried on the *Rana esculenta*, which is generally used for physiological experiments. Other species of frogs have the same, though a weaker action; toads give still more feeble actions. Humboldt long since observed, how remarkably slow they were in answering to Galvanic stimulation. The *Salamandra maculata* and the *Lacerta agilis* also gave currents. The thigh of a pigeon produced a downward current, the leg alone an upward one; it had, indeed, a stronger action than the whole limb. The whole leg of a rabbit gave a weak upward current.

The same current which in these experiments produced deflections of the needle, also gave rise to contractions, which were long since observed by Galvani. Du Bois-Reymond's apparatus is well adapted for making observations with accuracy, and without the interference of disturbing causes, upon those contractions, which are produced by the whole animal or by separate parts of it.

If a whole frog is introduced into the circuit, the current produced by it cannot convulse the same frog, because it is nowhere confined to the nerves alone, and it therefore nowhere in the nerves attains sufficient density* to cause contractions. To produce contractions by the current of the whole frog, it is necessary to use the limb of a frog prepared as a rheoscope, as in fig. 8.

The arrangement of the experiment is this: one of the conducting vessels is furnished with its conducting cushion; close to it an intermediate cushion is placed (the two cushions must be covered with their albuminous guards); the interval between the two cushions is bridged over with a portion of the nerve of the rheoscopic limb. The feet of the electromotive frog are now dipped into the other vessel, which is without a cushion; and it is then bent back till its nose touches the intermediate cushion: thus the current pervades the nerve of the rheoscopic limb, and contraction is often obtained, and simultaneously a deflection of the needle of the galvanometer occurs.

* Intensity divided by cross section. See above, page 58.

In using Galvani's preparation with its nerves and piece of spinal column, the intermediate cushion and the rheoscopic limb are not necessary, because it serves as its own rheoscope. The experiments may be conveniently performed by dipping the feet into one vessel while the pelvis is supported in any convenient way ; the piece of spinal column is placed on the conducting cushion of the other vessel at such a distance that the nerves hang loosely down.

In this experiment the galvanometer is, of course, unnecessary, but it is useful, because it can show that the circuit itself is homogeneous. There must in the metallic portion of the circuit be an interruption, where by means of a cup of mercury the circuit may be either made or broken at pleasure, in order to cause the contractions. This arrangement appears to be the best form of Galvani's experiment with homogeneous metals.

To produce contractions without metals by means of the current in the whole frog, three vessels and two frogs must be used. These vessels are so arranged as to form a triangle ; those vessels which form the short side of the

triangle may be called *a* and *b*. These are provided with conducting cushions, so that the space between them may be bridged over by the nerve of the rheoscopic limb. One frog forms the connexion between *a* and *c*; the other between *b* and *c*, in such a manner that the head of the one and the feet of the other are dipped into the same vessel. At the instant of closing the circuit by the second frog the limb is contracted. In this case it is the current of both frogs that causes the contraction of the limb.

The best manner of procuring the contractions without metals, in the frog prepared in Galvani's method, is that used long since by Nobili. The two preparations should be laid upon an insulating surface, so that they form a circuit, in which the united current of both is active. The nerve of each frog must be laid upon the muscles of the other frog.

To cause contractions in the rheoscopic limb, by means of the current which, as will soon be seen, is produced by the gastrocnemius of a frog, the following method may be employed: between two cushions, *a* and *b*, in fig. 16, an intermediate cushion is placed as in the figure. The

interval between *a* and *c* is bridged over by the nerve of the rheoscopic limb; that between *b* and *c* by the gastrocnemius, and the circuit is alternately closed and broken by means of a connecting cushion through the point. As soon as this is done, the limb contracts.

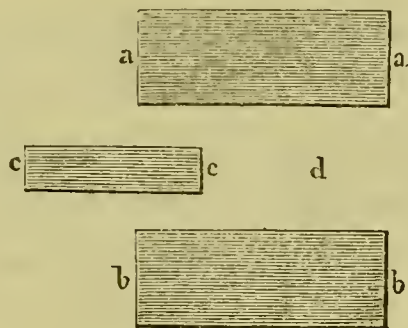


Fig. 16.

As to the origin of these currents, it is easy to show that they do not proceed from the contact of different tissues, for, as will be soon seen, this contact does not produce any electromotive action whatever. But if the gastrocnemius be cut from the frog at the ends of the tendons, without injuring the flesh of the muscle, and be laid on the conducting cushions, as shown in fig. 17, the needle directly leaves the zero point, and indicates a current in the

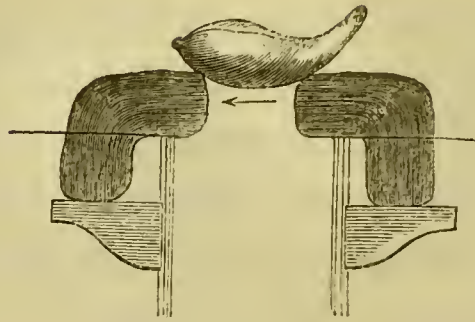


Fig. 17.

muscle from the tendo Achillis to the head of the muscle, that is, in the same direction as in all parts of the frog which have thus far been examined. The extensor cruris muscle, from the anterior surface of the thigh, shows the same effect.

In placing indiscriminately the different muscles of the thigh upon the cushions, phenomena which appear to follow no law are observed.

Some muscles, indeed, show no action at all, some give evidence of an upward, some of a downward current. Even one and the same muscle, according to the position in which it is placed, gives rise to all these different effects. This is also the case with the muscles of other animals, whether cold or warm-blooded.

It is highly probable that all the muscles pro-

duce their electric current according to the same law ; and differences hitherto observed in the electric action of the different muscles, most probably depend upon some change in the way in which the current is derived from the muscles, and not on any essential difference in the muscles themselves.

At all events, the frog current, and the similar currents observed in other animals, are reduced to a general *muscular current*. These currents, for the present, may be looked upon as the resultant of the partial currents, differing in intensity and direction, which are engendered by each muscle in the limbs of the animal. The apparent constancy of the upward current in the frog is thus seen to be accidental, and not essential.

CHAPTER XI.

ON THE MUSCULAR CURRENT.

IN order to find the law of these muscular currents, du Bois-Reymond examined the action of one and the same muscle, when placed in different ways on the cushions. He chose for this purpose such muscles as, when they are placed with their tendinous extremities, as in fig. 18, against the cushions, give rise to no



Fig. 18.

current. A muscle to be thus placed between the cushions may be conveniently supported by a triangular glass plate, as in fig. 19. This

plate, which is fixed on a proper stand, by its different widths gives the means of experimenting with muscles of different lengths. The

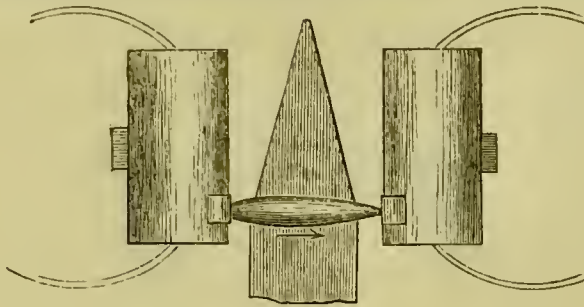


Fig. 19.

adductor magnus muscle is most fitted for these experiments, because it is most symmetrical in its form. In the position just named this muscle causes no, or but very slight, deflection; but if one end of it be bent up, and the vessels pushed closer together, so that the red flesh of the muscle touches one cushion, while its tendinous end (*a*) is in contact with the other, as in fig. 20,

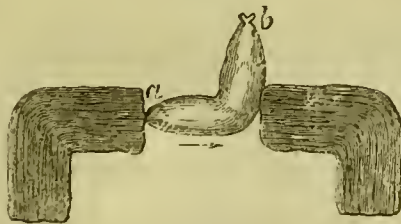


Fig. 20.

a considerable deflection ensues, which shows a current in the muscle from the tendinous end to the place of contact of the muscle with the other cushion. If the muscle is returned to the

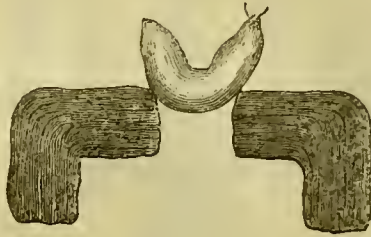


Fig. 21.

position shown in the fig. 21, the discharge of the secondary polarity takes place; if, then, the muscle is placed on the cushions, as in fig. 22,

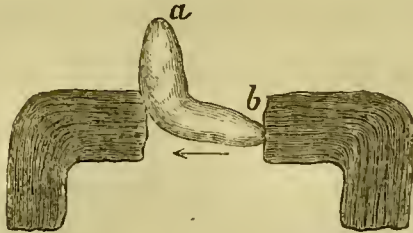


Fig. 22.

there will again be a considerable deflection of the needle, indicating a current from the tendon to the red flesh in the muscle. If *a* be the upper end of the muscle, and it be placed as in fig. 20, there would be a downward current, and

if placed as in fig. 22, there would be an upward one. Thus it will be perceived that the distinction of upward and downward currents is not dependent on any important difference, since it is easy at pleasure to obtain both directions by different positions of the same muscle.

In the position shown in fig. 21, where, on either side, the red portion of the muscle touches the cushions, the equilibrium of the needle remains undisturbed.

At the first glance it appears as though we might hence draw a conclusion as to the heterogeneity of the tendon and fibre of the muscle. It will soon be seen that this is not the case, but that the tendon rather plays the inactive part of a mere conductor.

When a gastrocnemius muscle is torn asunder in the direction parallel to its axis, it will be seen that the membranous prolongation of the tendo Achillis on the back of the muscle serves for the attachment of the lower end of the muscular fibres. This is also easy to be seen in the extensor cruris, more especially when the muscles have been previously hardened in lukewarm water or diluted alcohol. A glance at



Fig. 23.

fig. 23 shows that the tendon *a, b*, may be regarded as a coating of the natural transverse section of the muscle, if we understand thereby *a surface formed by the basis of the fibres of the muscles considered as prisms*.

It will also be seen, that what has hitherto been called the red flesh of the muscle, *b, c*, of fig. 23, may be regarded as the natural longitudinal section, if we understand thereby *a surface formed only by the sides of the fibres of the muscle again considered as prisms*. The supposition that these two surfaces of the muscle, its natural longitudinal and lateral transverse section, are heterogeneous, will explain the above phenomena; the tendon being considered as an indifferent conducting coating of the natural transverse section of the muscle.

But the following experiments make the attempt to explain the phenomena in any other way quite superfluous:—

If a muscle be divided in a direction more or less perpendicular to its fibres, an artificial transverse section will be made, and this artificial

section will behave in the same manner as the natural one covered by its aponeurosis, in the cases shown in fig. 20 to fig. 22. A piece of muscle terminated at both ends by transverse sections, when placed between the conducting cushions, as shown in the figure 24, produces



Fig. 24.

no deflection, or perhaps a very weak one, sometimes in one, sometimes in the other direction, partly because it is difficult to prevent some portion of the natural longitudinal section at either end from coming in contact with the cushions, and partly for other reasons.

But these effects are slight compared with those that take place when one end is bent up as in fig. 25, so that the transverse section lies

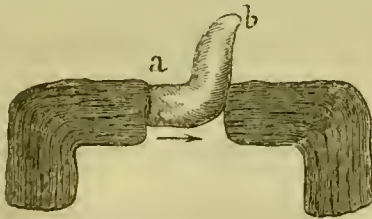


Fig. 25.

against one cushion, and the natural longitudinal section against the other. In this case, at least with larger muscles, the needle remains fixed at the checks of the galvanometer for the nervous current (see page 29); it always shows a current in the muscle from the transverse to the longitudinal section.

As the natural transverse section can be replaced by an artificial one, so it was to be expected that the artificial longitudinal section might be substituted for the natural section. The artificial longitudinal section is obtained by tearing the muscle asunder in the direction of its fibres. Experiment shows that the artificial longitudinal section acts in the same way as the natural section.

Hence it may be concluded, that *every point in the natural or artificial longitudinal section of a muscle is positive in relation to the transverse section whether natural or artificial.*

It was next to be determined whether different points in the same transverse section, as also whether different points in the same longitudinal section are quite homogeneous. Different points

of the natural longitudinal section, indeed, have already been tested regarding their homogeneous state; but these points, as is easily perceived, had a peculiar symmetrical arrangement.

The muscles of the frog are too small to admit of examination regarding the

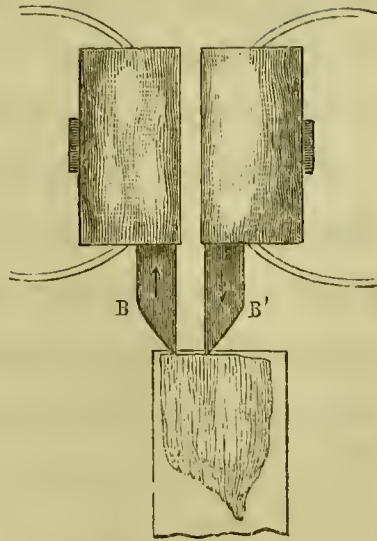


Fig. 26.

electromotive properties of different points in the same transverse section. Du Bois-Reymond chose for this purpose the muscles of a rabbit; the triceps femoris answered best. The section must be made with as sharp an instrument as possible, and all sawing action avoided, that the division of the fibres may be clean and present no ragged points.

The mode of arranging the apparatus is seen in fig. 26. The auxiliary cushions B and B', which consist only of a few layers of blotting paper, and which are soaked in the solution of salt, are to be fastened by their broadest ends between the layers of the usual cushions, or

merely laid upon them. Their points are then, as shown in the figure, to be placed against different points of the artificial transverse section.

The result of this experiment shows a certain heterogeneity between different points of the transverse section ; thus, those points that lie nearer the centre of the section are in a negative state in regard to those lying at a greater distance. The current obtained from two different points in the transverse section is however incomparably weaker than that obtained between one point in the transverse, and another in the longitudinal section. In the latter case the needle may strike against the checks, whilst in the former the deflection amounts only to 10 or 15 degrees.

Du Bois-Reymond thinks he has succeeded in showing, by experiments on the tendinous surface of the muscles in rabbits, that the natural transverse section acts exactly in the same manner as the artificial section.

The different points of the natural or artificial longitudinal section, are also not homogeneous when submitted to a careful investigation.

If the two points of the longitudinal section of the muscle which are put on the conducting cushions, are equally distant from the middle of the length of the muscle, there is no action, or at least a very slight one, as already shown. See fig. 22. But if they be so placed that one point of contact be further from the middle than the other, as in fig. 27, a current will be obtained which passes in the muscle from the point of contact, which is nearest to the end of the muscle, to the point which is farthest from it:—all

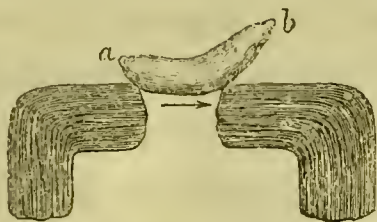


Fig. 27.

points on the longitudinal section of the muscle which lie nearest to the middle of it, are positive in regard to those lying nearest to the end of the same section. The intensity of the current between any two points of the longitudinal section, is also always incomparably less than the intensity of those currents which are obtained between the longitudinal and the transverse section.

These are the fundamental outlines of the law of the muscular current, by the determination of which du Bois-Reymond has placed electro-physiology on an entirely new basis.

This law of the muscular current is not confined to particular species of animals, but du Bois-Reymond states that it extends over the whole animal creation. He observed the current between the natural longitudinal section and the artificial transverse section in the muscles of man (muscles of an amputated leg), of the rabbit, guinea-pig, mouse ; pigeon, sparrow ; tortoise, lizard, adder, slowworm, different species of frogs and toads, tadpoles, land and water salamanders ; tench ; fresh-water crabs, and earth-worms. In the latter case, the whole cylindrical body of the animal was placed in the circuit, and treated as one muscle.

CHAPTER XII.

ON THE DISCOVERY OF THE LAW OF THE MUSCULAR
CURRENT.

THE discovery of the law of the muscular current was made by du Bois-Reymond, for he first obtained a current from one muscle alone, and he pointed out the electric antagonism between the natural or artificial transverse, and the natural or artificial longitudinal section. This he published in 1843, in his "Vorläufiger Abriss," (see page 27.) The difference between different points of the same transverse and of the same longitudinal section he had not then made out. What Matteucci has done on this subject may now be examined.

In September, 1841, he published in the "Comptes rendus" this observation, that when the interior of a muscle of a living or recently killed animal, is connected by means of the wire of a galvanometer, or by means of the nerve of a rheoscopic limb of a frog, with any other part of

the same animal, as for instance the surface of the muscle, including the part covered by the tendinous expansion, or by the skin, &c., a current arises which is directed in the animal from the interior to the exterior.

On the 21st February, 1842, and on the 17th October of the same year, Dumas communicated to the French Academy new papers of Matteucci, upon the negative state of the interior of muscles. In the first of these, it is stated that the current is directed in the animal from the interior of the muscle, or from its nerve to the surface of the muscle or to its tendon.

It may be seen from this, how far Matteucci was from a right knowledge of the law of the muscular current, as he had no idea of the electric antagonism between the cylindrical surface and the transverse section, either natural or artificial, of the muscular fasciculi. He drew from these observations an erroneous conclusion, and could not proceed further, till the discovery of the real connexion of the phenomena.

In the second paper, read by Dumas before the Academy, Matteucci speaks only of the contractions in the rheoscopic limb of a frog,

which may be obtained when its nerve is introduced into the wound of the transversely divided pectoral or femoral muscles of a pigeon.

In November of the same year, Matteucci published a paper in which he speaks of a battery formed of the half thighs of frogs. The thighs were cut across, and a battery formed in such a manner that the inner surface of the muscle in each thigh came in contact with the outer surface in the next thigh. The current was then always directed in the battery from the inner to the outer surface of the muscle. In this paper, among other statements, Matteucci again attributes the same electrical state to the nerve and to the interior of the muscle, compared with the surface of the muscle and with its tendon. If these researches be compared with those of du Bois-Reymond, no doubt can be entertained as to the independence of the discoveries of the latter.

Passing on to those researches which Matteucci published on this subject, after the appearance of du Bois-Reymond's "Vorläufiger Abriss, u. s. w.," the results up to 1844 are contained in his "Traité" &c., (see page 23.) He there states

more particularly the amount of action produced by his battery of thighs on his galvanometer. A battery of three elements caused a deflection of 15° when water was the conducting fluid employed, and of 35° when a solution of salt was used.

When it is remembered that in du Bois-Reymond's experiments, an almost microscopical piece of muscle causes a deflection of the needle to the checks, and therefore produces a much greater effect than a whole battery of thighs in Matteucci's experiment, it must be confessed that there is a great superiority in du Bois-Reymond's method over Matteucci's rougher and more complex manner of experimenting; since the latter, to say the least, has no advantage over the former, in respect to the demonstration of the origin of the current in the muscles.

Matteucci, for a long time, caused great confusion by making a fundamental difference between the frog current and the muscular current. He speaks of this difference in his "Traité," even as late as the year 1844. He there states that every animal possesses a muscular current, but that the frog, besides, possesses in its leg a

current in an upward direction, for which no ostensible reason can be assigned.

In March, 1845, he at last perceived the identity of the frog current and the muscular current, and he admitted the negative state of the tendons. He published these facts in 1846, in three different places, as the most important results of his own researches, although in the month of September, 1845, he admitted that he knew du Bois-Reymond's paper, published 1843.

CHAPTER XIII.

CONSIDERATIONS REGARDING THE LAW WHICH
GOVERNS THE MUSCULAR CURRENT.

A MUSCLE possesses electromotive action, whether it be bounded only by natural longitudinal and transverse sections ; or by natural and artificial ; or even by artificial sections alone. It is now to be determined what the position is of the heterogeneous elements in the muscle, from which its electromotive action proceeds.

Du Bois-Reymond in his "Vorläufiger Abriss," relates experiments which he made on little strips of muscle, which often consisted of only ten or fifteen primary fasciculi, and which in their most active position caused strong deflections of the needle. Afterwards he succeeded in repeating the same experiment even with a single primary fasciculus. This is the boundary which can be attained by direct observation. Hence it may be concluded, that the current is engendered in the primary fasciculi.

It must next be inquired what arrangement of heterogeneous elements in the primary fasciculus could produce the above-mentioned phenomena.

The question is whether an arrangement can be made whereby the electric phenomena of muscles can be imitated.

The following disposition appears at the first glance to fulfil the conditions.

A solid copper cylinder is taken, the base of which remains uncovered whilst the cylindrical surface is coated with zinc. If a moist conductor be placed with one end on the cylindrical surface and the other on the base of this cylinder, a current will pass along the conductor from the cylindrical surface to the base.

If the cylinder be cut through perpendicular to its axis, each section will show the same phenomena.

Thus far, this arrangement succeeds. But there are two conditions which it does not satisfy. First, if the conductor touch two points on the cylindrical surface alone, there will be no current, nor will there be any if it touch two points of the transverse section alone; while in the

muscle a weak current arises between two unsymmetrical points in the longitudinal or transverse section.

In order to imitate these currents of the muscle with the cylinder, it must be surrounded by a wet conductor, which forms at every point an equally thick layer.

On the surface of the cylinder thus surrounded a system of currents will be formed. The currents will constantly pass from different points in the cylindrical zinc surface through the fluid to the copper base. If a conductor be applied to two different points of the surrounding liquid, through this conductor a current will also pass; and if the cylinder, with its coating of liquid, really can imitate the effects of the muscle, these currents should correspond with those obtained by putting the muscle on the terminal cushions of the galvanometer wire.

Fig. 28 represents the longitudinal section through the axis of the above mentioned cylinder, surrounded by a layer of fluid. Those lines (marked with arrows) which run from the zinc (Z) to the copper (K) surface represent the curves in which the currents may

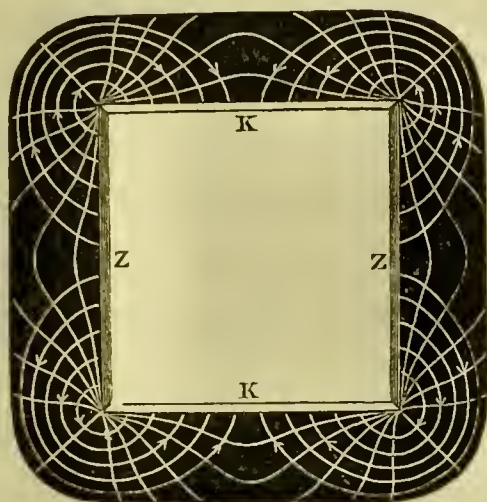


Fig. 28. .

be supposed to move from the zinc surface through the surrounding fluid to corresponding points on the copper surface. By aid of these curves a system of lines of equal electric tension in the fluid may be traced. These du Bois-Reymond calls *isoelectrical curves*.

Between each point of the zinc and copper surfaces there will always be a definite electric antagonism. In any of the lines representing the current which passes from a point of the zinc surface to a point of the copper surface, it is evident that in the middle of that line the electrical tension is equal to zero. From this neutral point in the same line the positive tension increases on approaching the zinc surface, while

the negative tension increases on drawing nearer to the copper one.

If now a new system of curves be so arranged that they cut the curves of the currents at right angles (as is really done in the figure 28) these are the isoelectric curves, that is, those that connect the points of equal electric tension in the fluid.

In figure 29, the isoelectric curves alone are

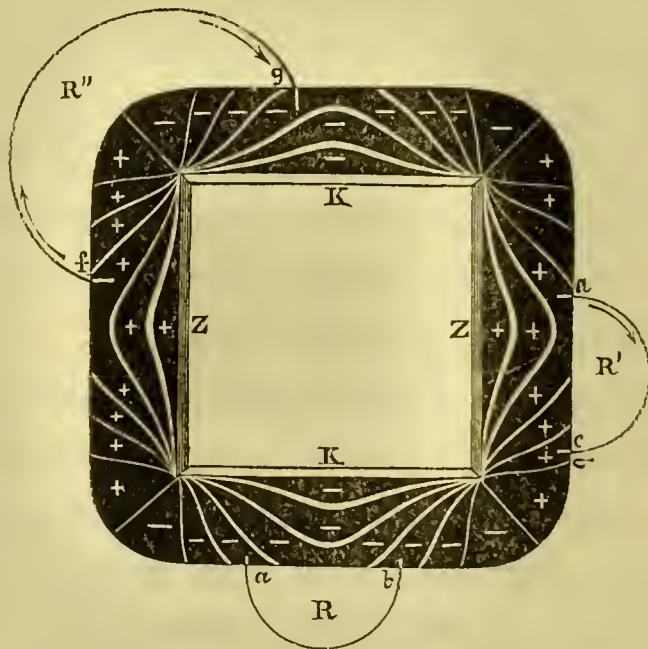


Fig. 29.

given, without the curves of the currents, and they are drawn broader at those points where the electric tension becomes greater. Whether

the electricity be positive or negative is indicated by + and —.

By means of this figure, the effects of placing a conductor on any part of the surrounding fluid will at once be seen.

If the conductor be placed as at *R*, so that its ends *a* and *b* are equidistant from the middle of the side with which it is in contact, no current will ensue, because there is the same negative electric tension at *a* and at *b*.

If the conductor be moved from the middle, as at *R'*, the tension of the electricity at each of its ends will no longer be equal. It is true that the electricity at *d* and *c* is the same in kind, being positive; but as there is more tension at *d*, a current will pass from *d* to *c*. This current of course becomes stronger when one end of the conductor is placed on the copper and the other on the zinc, as in *R''*, for *f* touches a point where the electrical tension is positive, *g* one where it is negative.

Du Bois-Reymond tried to establish these deductions experimentally. After various forms of experiment, he arrived at this, which faithfully represents the phenomena of the muscular

current. A cylinder of copper, 6·1 inches high and 2·1 inches in diameter, was covered with zinc on its cylindrical surface, while its base was left bare. The zinc was amalgamated on its surface. The cylinder hung from a well varnished hook, by a string, into a cylindrical glass vessel 3·5 inches in diameter, which contained water. (Fig. 30.) The stand which held up the cylinder carried a clamp in which there was a cork with two holes. In either hole there was a glass tube, in which was a copper wire covered with silk; the copper wire was hermetically sealed into the lower end of the tube. The tubes could be pushed up and down in each of the holes. At the lower end of the wire was soldered a square piece of platinum, 0·6 inch square. That portion of the wire and the soldered piece which projected beyond the tube, was, of course, so covered with mastic as to prevent any contact between the copper and the fluid. The platinum plates, which were to be opposed to the cylindrical zinc surface, had a horizontal position, while those which were intended to be opposed to the copper surface were vertical. The ends of the wires, which projected from the upper openings in the tubes,

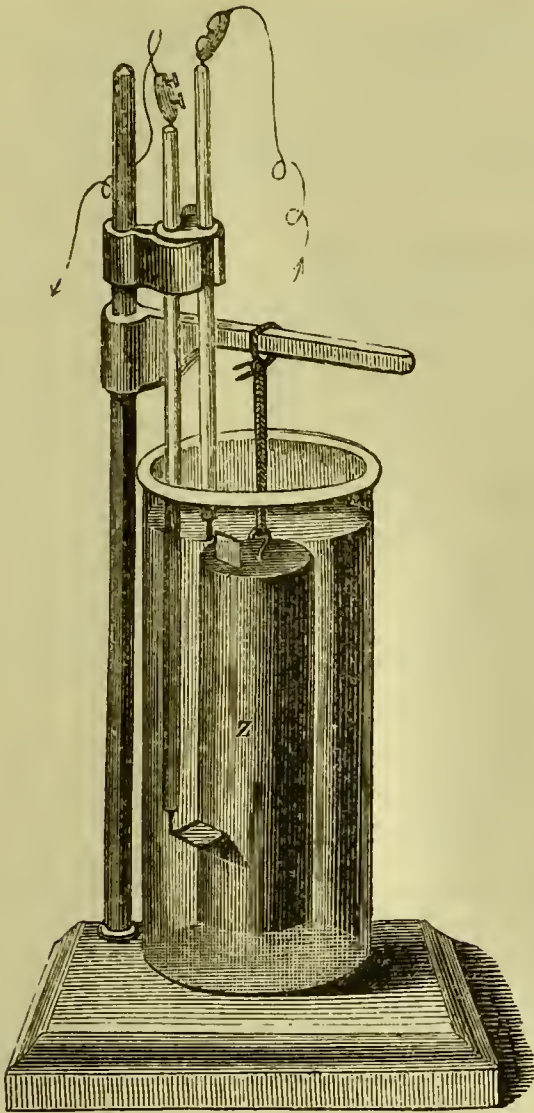


Fig. 30.

were connected with the wires of the galvanometer for the muscular current.

The arrangement depicted in the figure gave rise to a current in the direction shown by the

arrows, causing a deflection of the needle of 15° to 20° . If both the horizontal platinum plates were so placed opposite to the cylindrical surface, that one was as much above the middle of it as the other was below it, no current was obtained : if both plates were drawn up without changing their distance, a current causing a deflection of 5° or 10° was the result. An equally weak current arose when the two vertical platinum plates were placed over the upper copper base at unequal distances from its centre, so that one approached the circumference more nearly than the other.

All the effects of an entire muscle can thus be imitated on the cylindrical model when it is surrounded by a layer of an electrolytic liquid. But the longitudinal section of the model in that state would not fulfil the required condition of being positive in relation to the transverse section ; and neither the longitudinal nor the transverse section would have their different points heterogeneous, as they ought to be if the model in every respect truly represented the muscle in regard to its electric action. Each particle of the muscle, indeed, causes currents

which always follow the same law as the currents caused by the muscle as a whole. The model must therefore be changed so as also to satisfy this essential condition.

In order that every transverse and every longitudinal section should always show the same electrical arrangement, it must be imagined that in the interior of the muscle there are an infinite number of centres of electromotive action; each of which may be in itself represented by the diagram fig. 29, which was previously taken to represent an entire muscle. These centres may be called *electromotive molecules*, without however in the least anticipating the mode in which they produce their currents.

It is indifferent what form is assigned to these electromotive molecules in the muscles, but they must have two negative polar zones, and a positive equatorial zone. On account of this main feature in the constitution of these molecules, namely, that they have a circular positive zone around them, endowed with opposite electric properties as regards the polar zones, du Bois-Reymond proposes to call these molecules *peripolar molecules*. Moreover, the axes of each

and of all these molecules must be parallel to the axis of the fasciculi. If we suppose these molecules to be globular, fig. 31 will be a plan of

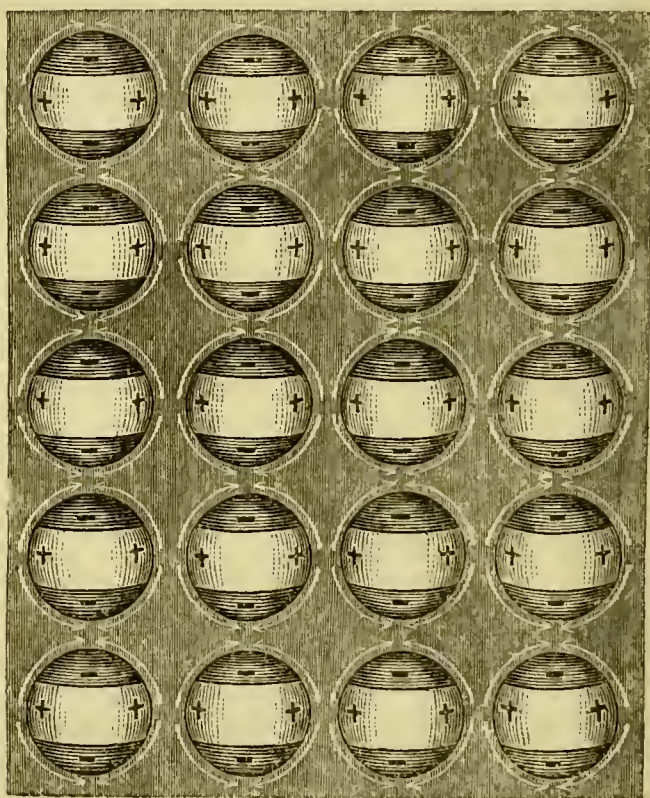


Fig. 31.

the longitudinal section of a muscle. The negative polar zones are shaded, whilst the positive equatorial zone is unshaded. The vertical boundary represents the longitudinal, the horizontal boundary the transverse section, the shaded background is the wet conductor.

Du Bois-Reymond tested this hypothesis by means of a zinc and copper model. He had tubes 0·4 inch in diameter made of copper, and along their cylindrical surface were soldered two strips of zinc, of such breadth that the circumference of the tubes was divided into four equal strips of alternate zinc and copper. The tubes were cut at right angles to their axes in lengths of 0·5 inch. The zinc was amalgamated; the copper inside was varnished, and these elements, 72 in number, were fastened with mastic by their circular extremities on a board 5·7 inches long and 3·3 inches broad. On this board they formed six rows, each containing twelve elements. The elements were 0·04 inch distant from each other in every direction. All the zinc sides were turned towards the long end, and all the copper sides to the short end of the board. Fig. 32 represents a part of the ground-plan of this model seen from below. The board which contained these 72 pieces was varnished, and at its upper surface it had a handle by which it could be sunk into a trough which was 7·1 inches long, 4·7 broad, and filled with water 0·2 inch high. On the inside

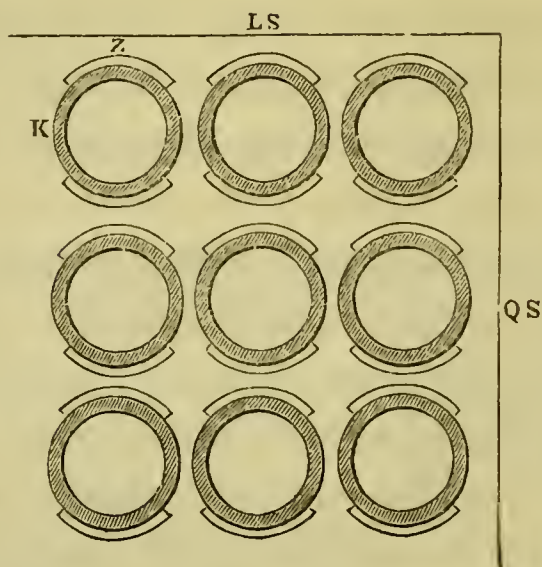


Fig. 32.

of the model in the trough, platinum plates were placed, these were connected with the galvanometer.

If the plates were put opposite to the longitudinal and transverse section of the model, on sinking it suddenly 20° of deflection were obtained in the same direction as from a muscle. When the plates were placed opposite to the longitudinal or transverse section alone, one in the middle, the other at one of the ends of the section, the deflection was only from 8° to 10° .

These experiments would justify the assumption, that in the muscles an electrical arrangement obtains similar to that which

has just been described. But in the following researches facts will be brought forward which will make some such hypothesis absolutely requisite. The currents in the muscles and nerves indeed show, in some circumstances, variations both of intensity and of direction, so sudden and so extensive, that it appears impossible to account for them by any change of larger heterogeneous elements, or in any other way than by assuming corresponding changes of position in almost infinitely small centres of action.

Du Bois-Reymond has also endeavoured to give a theoretical explanation of the weak currents obtained between two points of the longitudinal or of the transverse section alone of the last described model; but as he himself appears not to have been fully satisfied with the results, his considerations do not require to be mentioned here.

At all events it may be safely concluded from the considerations stated above—

1st. That the electric action of the muscular current not only produces a state of tension, but that the electric state of the muscles may always be compared to that of a closed circuit.

2nd. That every current, however it may be obtained from a muscle, is to be regarded as a derived current.

3rd. That the intensity of the derived current may be infinitely smaller than that which exists in the muscle itself, and from which the current in the galvanometer wire is derived; as is proved by experiments on the model, which acts much weaker than a muscle, although it consists of 144 elements of zinc and copper.

CHAPTER XIV.

INFLUENCE OF THE SIZE OF MUSCLES ON THEIR
ELECTROMOTIVE ACTION.

DU BOIS-REYMOND has inquired whether the electromotive action of the muscles may depend upon their size. He has arrived to the following results:—

1. Of two muscles of equal thickness, the longer one generally gives the more intense current; the certainty of this result, however, is not very great.

2. If two muscles are opposed one to the other in the same circuit, the longer one is always the stronger of the two.

3. Of two muscles of equal length, the thicker one always gives the more intense current.

4. If two muscles are opposed one to the other in the same circuit, the current of the thicker one will also still be paramount.

Hence it must be concluded that the electromotive force of muscles increases both with their length and thickness.

CHAPTER XV.

ON THE DIFFERENCE BETWEEN THE NATURAL AND
THE ARTIFICIAL TRANSVERSE SECTION OF THE
MUSCLE.

THE electrical properties of the natural and transverse section of the muscle have thus far been always represented as quite identical, and no distinction has been made in the volumes of du Bois-Reymond's work which are already published.

But in a paper read before the Academy of Sciences of Berlin (June 1851), he has recently pointed out some very striking differences between these two kinds of transverse section. The following are his principal statements on this subject.

The current obtained from the longitudinal section and the natural transverse section is seldom if ever so strong as the current obtained from the longitudinal section and the artificial transverse section. Very often, indeed, the former current appears incomparably weaker; and

by keeping the frogs for twenty-four hours at least, at a temperature of 32° F. (0° C) it is possible wholly to deprive the natural transverse section of its negative power when it is included in a circuit with the longitudinal section. But even the direction of the current between the longitudinal and the natural transverse section can be reversed by means of cold. If frogs have been frozen, their gastrocnemii are often found to give a current directed downwards, instead of the usual upward one which is produced by the natural transverse section at the lower end of the muscle, situated below the expansion of the tendo Achillis. Whichever of these various modifications of the electric power of the natural transverse section may prevail, the usual current, from the longitudinal section to the natural transverse section through the galvanometer (indicating a negative state of the latter section), immediately appears when this section is superficially injured in any way, so as to deprive an extremely thin layer of its vital properties and thereby of its electromotive action.

To demonstrate this truth a gastrocnemius is placed between the cushions, so as to touch them

only with its two tendinous extremities. It gives a weak upward current ; or if it belongs to a cooled or frozen frog, no current at all ; or even it may give a downward current. If, then, a drop of any liquid capable of corroding the muscular tissue is brought on the aponeurosis of the tendo Achillis, the muscle directly becomes strongly active in the usual direction ; that is to say, the evolution of an upward current takes place in the muscle.

It is quite immaterial what the nature of the corroding liquid may be, whether physical or chemical, whether it be acid, alkaline or saline ; whether it be a conductor of electricity or a non-conductor, as alcohol, ether, acetone, pyroxylic spirit, creosote, &c.

No action takes place if the muscle is in a state of decomposition ; or if the liquid is applied to the longitudinal section of the muscle instead of to the transverse one. The evolution of the upward current cannot therefore be ascribed in any way to a chemical action of the liquids upon the animal tissue. Moreover, if this were the cause of these phenomena, the current evolved could not have the same direction with acids and

with alkalis; whilst with insulating liquids it should be altogether absent.

The current may also be elicited by applying a gentle heat to the natural transverse section of the gastrocnemius; that is, by coagulating the albuminous and fibrinous liquids contained in a thin layer of the muscle below the expansion of the tendo Achillis.

The current, lastly, may also be evolved by completely removing a thin layer of muscular substance at the natural transverse section, instead of depriving it of its vital properties. This of course cannot be done without at the same time removing the expansion of the tendo Achillis. The natural transverse section is thus converted into the artificial one by mechanical means; but it is now obvious that this change must be considered merely as a particular case of the general rule, given above, for making the muscle properly active; that is, namely, by depriving a layer of muscular substance at the natural transverse section of its electromotive action.

These results cannot be accounted for in any other way than by the assumption that at the

natural transverse section there exists a layer of muscular substance, which consists of the ends of all the muscular fibres, and which is endowed with an electromotive action contrary to that of the rest of the muscle : that is, tending to make the natural transverse section appear positive instead of negative in regard to the longitudinal section. If the electromotive action of the rest of the muscle be called positive, then the action which belongs to the layer at the natural transverse section must, of course, be termed negative. According to circumstances yet undetermined, this negative electromotive action should be susceptible of different degrees of intensity. In its lower degrees it should only weaken the intensity of the current produced by the rest of the muscle. In a somewhat higher degree, corresponding to the state of the animal produced by keeping it twenty-four hours at a temperature of 32° F. (0° C.), the two contrary forces, viz., that of the muscle itself and that of the layer at its natural transverse section, should become equal, in consequence of which the muscle would appear inactive. But if the negative force of the layer be assumed to be further

increased, the muscle would become active again, but in the opposite direction : the natural transverse section being positive in regard to the longitudinal section. This may be taken to be the representation of the state of the muscle, as it is occasionally observed in frogs after they have been frozen.

If the layer of the natural transverse section is removed, or is deprived of its electromotive action by any other means, the positive force of the transverse section alone remains, and whatever may have been its state of action previously, the muscle becomes strongly active, according to the law of the muscular current.

Since the layer of muscular substance on the natural transverse section tends to reverse the law of the muscular current, du Bois-Reymond proposes to call it the *parelectronomic layer* (from *παράνομος* contrary to law), and he likewise calls that the *parelectronomic state* of the muscle, in which the muscle, in consequence of the *parelectronomic layer* having the intensity of its action increased, either appears inactive, or even becomes active in the negative direction.

The hypothesis of an extremely thin layer

existing at the natural transverse section of the muscle, the electromotive action of which is able to counterbalance and even to overcome the action of the whole remaining muscle, must, at first glance, appear most extraordinary ; nevertheless, du Bois-Reymond has succeeded in justifying this assumption in a very simple manner.

It has already been said that any form may be ascribed to the peripolar electromotive molecules. Provided they have two negative polar zones, and a positive equatorial zone (as is shown in fig. 31), they will be able to produce, in an electrical point of view, all the effects of the muscle in a state of rest. The form assumed in fig. 33, in which the peripolar molecules are represented as groups of two *dipolar* molecules touching one another with their positive poles, would therefore do as well as any other assumed form, and there are several reasons for preferring it to any other. It remains only to be stated that any mechanical agent, for instance the keenest razor, never can separate the two dipolar molecules, which form together a peripolar group, but it always passes between two such groups, in consequence of which any artificial transverse sec-

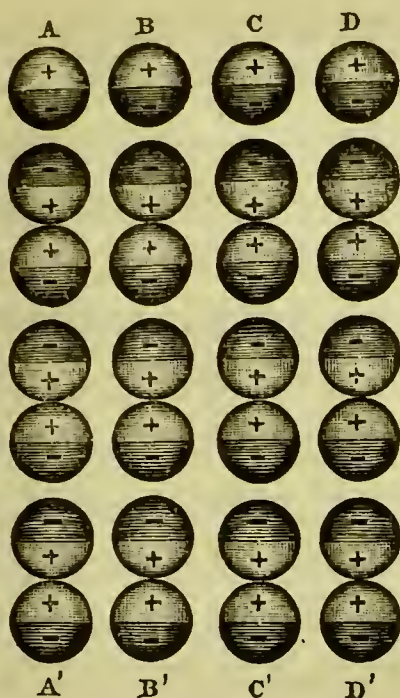


Fig. 33.

tion will always be negative to the neutral longitudinal section.

By adopting this mode of viewing the molecular arrangement of the muscles, it becomes easy to explain the phenomena of the parelectronic state. It may be supposed indeed, as is seen at A, B, C, D, fig. 33, that a single dipolar molecule is added to the end of each longitudinal series of molecules A A', B B', C C', D D', and that this molecule has its positive pole turned outward. Then the natural transverse section represented by the ends of the series

A, B, C, D, will no longer be negative, but positive to the neutral longitudinal section.

If only half of the longitudinal series AA', BB', &c., be terminated by a dipolar molecule turning its positive pole outward, then the natural transverse section will be as neutral as the longitudinal one, and the system will appear to be inactive. Hence it is easy to deduce the intermediate stages of weak, positive, and negative action of the muscle. All these different phenomena will be caused simply by the presence of a single layer of dipolar molecules upon the transverse section. This layer on the muscle may be supposed to be almost infinitely thin; and merely by removing it, or by depriving it of its electromotive power, the system will always be restored to the mode of action which is expressed in the law of the muscular current.

The correctness of these views du Bois-Rey-
mond has illustrated by means of experiments
with an apparatus similar to that described at
page 112, and shown in fig. 32.

CHAPTER XVI.

ON THE CURRENT OF THE LIVE UNDISSECTED
FROG.

MATTEUCCI long since obtained currents from the dissected muscles of frogs, whilst they were still in connexion with the living body of the animal. But these experiments do not prove, even in Matteucci's own opinion, that the current existed in the animal previous to any dissection or experimental arrangement. Du Bois-Reymond, in his last-mentioned paper, has succeeded in demonstrating the current in the live frog without any dissection.

In these experiments he first met with considerable difficulties, in consequence of the electromotive action of the skin interfering with the action of the muscles. After a careful investigation into the electromotive properties of the skin, he at last got rid of this disturbance by wetting the points of the skin from which the current was to be derived with a saturated solution of

common salt. By this management the skin is changed into a perfectly inactive moist conductor, and the current of the frog, as discovered by Nobili, may be observed on the live and unhurt animal.

The current, however, appears considerably weaker than it does after the skin has been removed, because the circuit is partially closed by means of the skin.

CHAPTER XVII.

ON THE INFLUENCE OF CONTRACTION ON THE
MUSCULAR CURRENT.

MATTEUCCI stated, as has been said, that when frogs are in a tetanic state they give no current. Afterwards he said that tetanus only weakened the current. From this it might be concluded that he had rightly observed the influence of contraction on the muscular current; but some years later he made an extensive series of experiments with batteries of frogs, in order to show that *during contraction the muscular current is increased*. Still more lately he says, at page 277 of his "Leçons sur les Phénomènes physiques des Corps vivants," which appeared in 1847, that during contraction the needle of the galvanometer shows no deflection whatever, provided no break or other change in the circuit occurs. The small positive or negative deflections of the needle which he sometimes succeeded in observing, he ascribed to chance dis-

turbances. He also admitted, regarding the supposed effect of the tetanic state in diminishing the current, that he did not intend his observations to apply to the state of the current during the contraction itself: but to the injurious effect of long continued contractions on the life of the muscle, and through this, upon its electric action.

Matteucci made no better use of his discovery of what he calls the induced contraction, or the *secondary contraction* as du Bois-Reymond prefers to call it. He first announced this discovery in February 1842 to the French Academy in a sealed packet, opened in October 1842. The experiment there described is this:—if the nerve of the rheoscopic limb of a frog be laid on a commonly prepared limb, the first limb will contract when the second in any way is made to contract.

Becquerel concluded that in the primary contracting limb, something like an electric discharge must take place at the moment of contraction, and that part of the discharge took its course through the rheoscopic nerve, and caused its limb to contract. At first Matteucci inclined

to this view, which, as will be seen, was near the truth ; and to prove it, he instituted the experiments mentioned above, by which he endeavoured to show that there was an increase in the intensity of the muscular current at the moment of contraction ; but he soon left this to involve himself in more extraordinary views.

In the year 1845 he published in the "Philosophical Transactions," a paper on this subject, entitled "On Induced Contractions." Here he endeavoured to prove that the secondary contraction is not of electric origin. He regards this phenomenon as "a first fact of induction of that force which circulates in the nerves, and which arouses muscular contraction."

Thus we owe to du Bois-Reymond the most important results which have been attained in this branch of science. A more particular statement of these may thus be made.

He first remarks, that in order to observe the electric action produced on the needle of the galvanometer by a muscle whilst in contraction, it is not sufficient to try the experiment with a single contraction, but on account of the inertia of the needle, the muscle must be *tetanised*, that

is, made to contract powerfully and uninterruptedly as long as possible. This may be effected in different ways, as by destroying the motor nerve at the proper rate, from the upper end down to the muscles, or by heat, or by a chemical agent, or merely by some mechanical means; or by poisoning the animal with strychnia; or, which is more convenient, by passing through the nerve a current the intensity of which is kept constantly varying, or by submitting the nerve to a continued series of shocks, such as is represented in fig. 14. Then, as Volta, and afterwards Nobili, observed long before, the contractions produced by the single variations of the current, or by shocks, coalesce, and thus produce a perfect continuous tetanus. (See page 62.)

Du Bois-Reymond had already stated, in his "Vorläufiger Abriss," that he had convinced himself by galvanometric experiment, that the current during a powerful and lasting act of contraction is sensibly diminished.

Fig. 34 shows the apparatus which du Bois-Reymond used for making the fundamental experiment on this subject. The gastrocnemius is placed on the cushions, and its nerve connects the platinum ends of the brass rods.

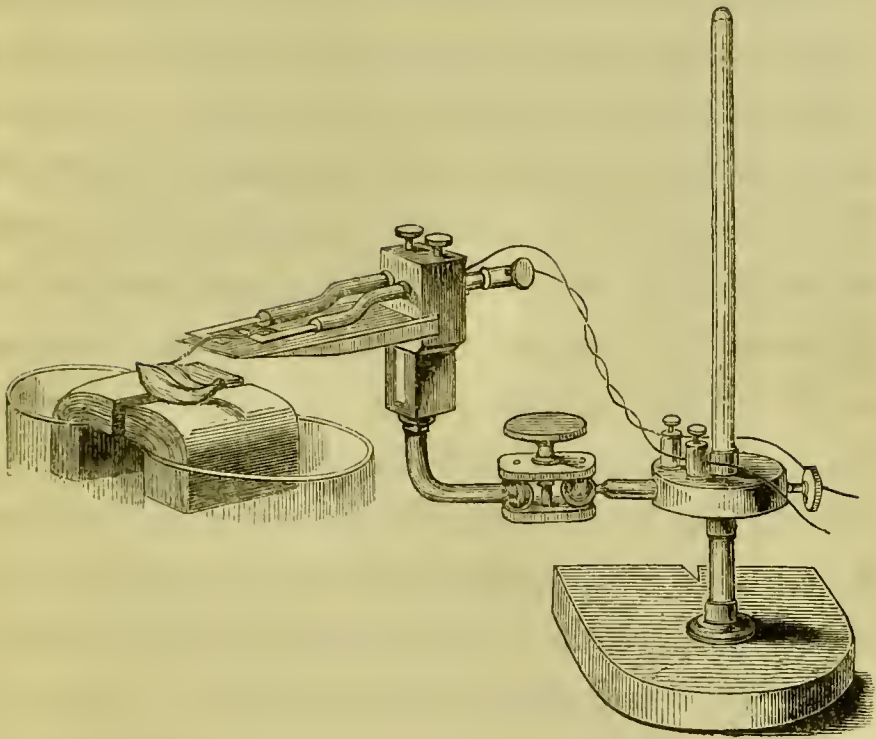


Fig. 34.

These rods, which pass through an ivory block, may be pushed backwards and forwards, and fixed in any desirable position. At their opposite ends there are two screws, by which wires can be fixed; these wires proceed to any galvanic apparatus which can give a continued series of alternating shocks of proper intensity, as, for example, an induction coil, in the primary circuit of which a wheel for making and breaking the circuit is interposed.

As soon as the muscle is laid on the cushions the needle is deflected, and at last comes to rest at some distance from the zero point. If, then, the wheel is turned, the muscle is convulsed by means of the induced currents which run through the portion of the nerve comprised between the two platinum ends. At the moment in which the muscle begins to be convulsed, the needle is deflected through the zero point, and is seen to oscillate on the negative side of the zero, until the contracting power of the muscle is exhausted, which always happens before the needle has had time to come to rest.

It might be suspected that these actions result in consequence of the current from the induction-apparatus invading the circuit of the galvanometer. This, however, from theoretical grounds, is seen to be impossible, provided both circuits, viz., that of the galvanometer and that of the coil, are carefully insulated so as to communicate only by the portion of nerve. Du Bois-Reymond, moreover, proves the impossibility by experiments.

Amongst others, these are the most striking :— let the nerve be cut somewhere between the plati-

num ends and the muscle, and its two ends put again in contact, or let it be tied or even totally removed and replaced, by a moist piece of thread, a strip of wet blotting paper or the skin of the frog—this substitute must lie with one end on the muscle, whilst the other must form a bridge between the two platinum ends. The connexion between the circuit of the galvanometer and that of the coil is now just the same as it was in the original experiment; but if the interrupting wheel be turned, there will neither be tetanus of the muscle, nor any action on the needle of the galvanometer.

Further, if the tetanus of the muscle be induced by some mechanical irritation, as by heat or chemical action, the same result as with electrical tetanus will follow, but in a weaker degree. The experiment can also be made with the gastrocnemius dissected in a living frog, and still in organic connexion with its spinal cord by the ischiatic nerve. The frog then is poisoned with strychnia; if the tetanic state sets in at the right moment, that is, after the needle has become stationary, and before the nerve dries, a strong deflection of the needle in the

negative direction will be seen to accompany the tetanus of the gastrocnemius.

After these experiments there can no longer be any question of the suspicion mentioned above, and the following attempt may now be made to analyse the phenomenon of the sudden passage of the needle to the negative side, which occurs as soon as the tetanus commences. At first it might be supposed that this showed a current during the tetanus in a direction contrary to that during rest ; but this is not the case. Before the tetanus begins, the secondary polarity is evolved on the platinum plates in the conducting vessels. This polarity tends to produce a current in the opposite direction to the muscular current. As soon, then, as the muscular current, in consequence of the tetanus, diminishes to a certain degree, the current of the secondary polarity becomes the more powerful, and the needle is instantly deflected to the negative side.

If it be desired to have merely the current of the muscle when in the act of contraction, some means must be employed for closing the circuit easily and rapidly somewhere else than

between the cushions, as, for instance, a cup of mercury with two amalgamated hooks of copper wire dipping into it. If one of the hooks is taken out of the mercury, the muscle may be laid on the cushions without causing a current through the galvanometer, and without any polarization in the platinum plates. If the muscle be now tetanised, and then the circuit be closed at the mercury cup, the current of the tetanised muscle is obtained, and indeed the deflection occurs in the usual direction of the muscular current, but it is very much weaker than the deflection produced by the untetanised muscle.

This decrease in the current arises from a decrease in the electromotive power of the muscle in the act of contraction; but, to establish the truth of this assertion, du Bois-Reymond has controverted all objections that can be brought against it. From among his answers to various objections, the following are selected, showing that the decrease in the muscular current cannot arise from an increase in the resistance to conduction in the muscle, or from a change in its position on the cushions resulting from the contraction.

Du Bois-Reymond has disproved the first objection by the method of compensation. Between the conducting cushions an auxiliary cushion was placed, and the two spaces between the three cushions were bridged over with the *gastrocnemii* of the same frog, placed so that their muscular currents were opposed, and neutralized each other as perfectly as possible. If tetanus were now induced in either muscle the current of the other became paramount, a result which can only be explained by the decrease in the electromotive force of the tetanised muscle, and not by the increase in its resistance to conduction. Du Bois-Reymond, moreover, has found that instead of such an increase in the resistance of the muscular substance while in the act of contraction, there is a slight decrease perceptible.

To prove that no change in the position of the muscle could be the cause of the decrease in the current at the moment of the contraction, du Bois-Reymond fastened the muscle in an apparatus, by which it was stretched so tightly that when tetanised no perceptible change of

form could occur; and in this manner, when placed on the cushions, the decrease of force was still apparent.

He has also examined the decrease of the muscular current in the act of contraction, when the current was produced by means of the artificial transverse section instead of the natural one; the result of the experiment was the same as before.

If a muscle be tetanised whilst the cushions are applied to symmetrical points of its longitudinal or transverse section, the equilibrium of the needle is not disturbed by the contraction, and if the cushions are applied to unsymmetrical points, either of the longitudinal or of the transverse section, so as to have only a weak current in the circuit (p. 90-93), the deflection of the needle at the moment of contraction will also be a weak one. The negative deflection of the needle at the moment of contraction is therefore always proportional to the actual intensity of the current of the muscle when at rest.

In a paper communicated to the French Academy (*Annales de Chimie et de Physique*,

3^{me} Série, t. xxx.), du Bois-Reymond, moreover, briefly states that after the tetanus has ceased, the muscular current gradually, but not immediately, recovers its whole intensity.

In the above-mentioned paper on the par-electronomic layer of the muscle (p. 116) he also examines the electrical effect of tetanus on undissected muscles, in which the current has wholly disappeared, or even has been reversed, by the action of cold on the animal during its life. He establishes the fact, that such muscles if inactive become active in the negative direction at the moment of contraction; and that their negative power is increased if they possess a negative current. Hence du Bois-Reymond concludes that the negative electromotive force of the par-electronomic layer does not vary in the act of contraction, whilst the positive force of the rest of the muscles undergoes the negative variation which has already been explained.

CHAPTER XVIII.

ON THE SECONDARY CONTRACTIONS.

IN the experiments mentioned in the last chapter, the galvanometer was the rheoscope employed.

It will now be well to state how the rheoscopic limb reacts when subjected to the changes produced in the muscular current by tetanus.

This experiment may be made in two ways. Either the galvanometer may remain in the circuit, so that the current has to pass through the nerves of the rheoscopic limb and through the galvanometer when the indications on both rheoscopes will be simultaneously obtained; or the nerve of the rheoscopic limb may alone close the circuit.

In the first case an auxiliary cushion must be employed; one of the spaces is bridged over by the gastrocnemius to be tetanised, and the other by the nerve of the rheoscopic limb, which is

fastened with elastic rings on a slip of glass—as is seen in fig. 35.

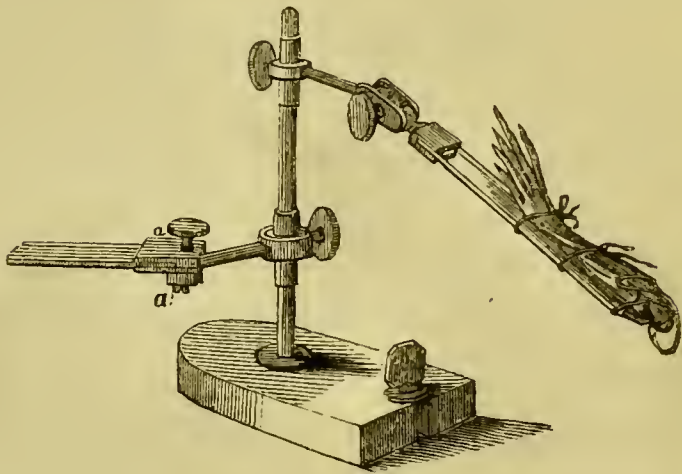


Fig. 35.

If the current be passed only through the nerve of the rheoscopic limb, the auxiliary cushion is unnecessary. The space between the two cushions is bridged over on one side with the nerve of the rheoscopic limb, on the other with the muscle.

It will be at once perceived that this is simply a more philosophical form of the experiment made by Matteucci for the production of his so-called induced contractions.

Fig. 36 is a plan of the various arrangements whereby the secondary contractions may be pro-

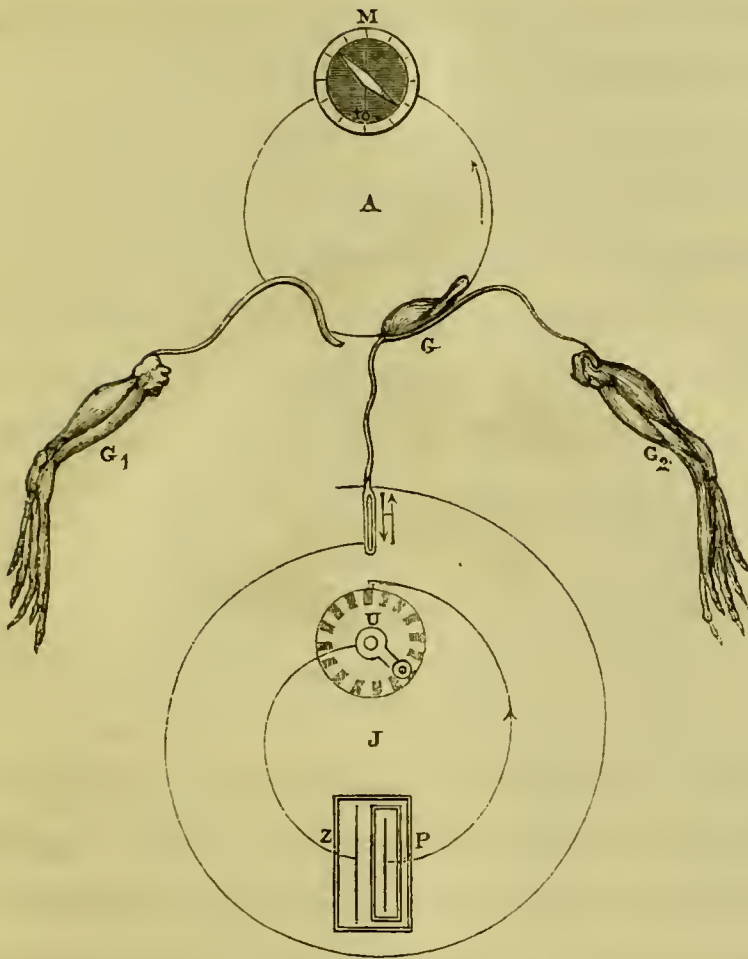


Fig. 36.

duced. The interrupting wheel (U) is included in the primary current (J) of the single element of Grove's battery (Z P). The ends of the induced circuit are bridged over with the nerve of the gastrocnemius (G); the muscular current of the gastrocnemius (G) is passed through the galvanometer (M), and a portion of the nerve

belonging to the rheoscopic limb (G_1); but the galvanometer may be quite left out of the arrangement, so that the limb (G_1) is the only rheoscope for the current produced by the gastrocnemius. If the nerve of the limb be laid on the gastrocnemius, as is the case in fig. 36 with the nerve of the limb marked G_2 , this nerve alone will form the circuit for the current of the gastrocnemius G , and this is the form in which Matteucci chanced to make the experiment.

If everything be thus arranged, a remarkable effect will accompany the production of tetanus in the gastrocnemius.

The rheoscopic limb will be seen to be attacked by tetanus during the whole time that the gastrocnemius is itself tetanised, and if the galvanometer be included in the circuit, it will at the same time show those phenomena described in the former paragraphs, but weaker, because the resistance of the circuit is increased by the interposition of the nerve of the rheoscopic limb. The same effect can be observed in the artificial transverse section, instead of the natural one; but of course the secondary tetanus in all these experiments is only obtained when

the primary contracting muscle is placed on the cushions, so as to send through the galvanometer wire a strong current ; that is to say, when the muscle is laid on the cushions with symmetrical points of the longitudinal or transverse sections, the secondary tetanus does not occur.

If it be desired to produce the secondary contractions as observed by Matteucci, the nerve of the rheoscopic limb must of course also complete the circuit between two heterogeneous surfaces of the muscle, whether artificial or natural ; or, in other words, the secondary contraction may occur in all those positions of the nerve of the rheoscopic limb upon the primary contracting muscle, in which on making or breaking the circuit, Galvani's contraction without metals may be observed.

In repeating the experiment in the way first described by Matteucci, this position of the nerve frequently happens by accident. But in order fully to demonstrate the proposition, the experiment must be repeated on some muscle which has a regular form, terminated at both ends by an artificial transverse section, as, for instance, on the adductor magnus Cuv., when the two

heterogeneous surfaces are easily seen, whereby the direction of the current can be easier foretold. Upon such a muscle the secondary contraction never occurs, unless the nerve of the rheoscopic limb be so placed upon it that a strong muscular current acts on the nerve.

By these experiments the true origin of the secondary contractions is placed beyond all doubt. They arise in consequence of those variations of the density of the muscular current in the nerve of the rheoscopic limb, which du Bois-Reymond has first demonstrated by means of the galvanometer.

Matteucci's theory, according to which the secondary contractions are some phenomena of induction caused by an unknown force circulating in the primary contracting muscle, is thus wholly overturned. Among the arguments which he brought forward in support of this opinion, there is one, however, which requires a closer examination. He contended that this hypothetical force of induction did not act through any solid body whatever, whether a conductor or non-conductor of electricity, when interposed between the primary contracting muscles and

the nerve of the rheoscopic limb; whilst it acted through an interposed layer of any liquid, whether a conductor or non-conductor of electricity.

Du Bois-Reymond shows that the latter statement is altogether incorrect, and that insulating liquids, even those tried by Matteucci, when the experiments are properly made, prevent the propagation of the secondary contraction. The former statement is indeed true; but nothing is easier than to account for it, in perfect accordance with the theory of secondary contractions given above, or with any other electrical theory of the contractions which may be proposed.

Becquerel long since gave the following explanation:—all solid bodies in Matteucci's experiment appear to intercept the secondary contractions, either because they are isolators of electricity, as mica, glazed paper, &c., or excellent conductors, as the metals. That the first should stop the secondary contractions is not to be wondered at; and that the latter should act in the same way depends on the peculiar mode which Matteucci employed of introducing

them into the circuit. For example, he coated the primary contracting muscles with gold leaf, and laid the nerve of the rheoscopic limb upon it. No secondary contractions were then obtained, because the greater part of the muscular current no longer circulated through the nerve but through the gold leaf. No contraction could have occurred under these circumstances from the action of the muscular current, whilst the muscles were in a state of rest. But if a true circuit is formed by the two heterogeneous surfaces of the muscle and the nerve of the rheoscopic limb, as is shown in the fig. 35, the presence of metals in the circuit most certainly does not interfere with the production of secondary contractions.

When the secondary contraction takes place in a limb, it can excite contractions in a third limb, just as the contractions in the first limb excited those in the second. Both Matteucci and du Bois-Reymond have made experiments on these contractions of higher orders. Matteucci has reached that of the fourth ; du Bois-Reymond that of the fifth order, perhaps in consequence

of his knowledge of the best position of the nerve upon the muscle.

The secondary tetanus obtained when the primary contracting muscle is tetanised gives a very different view of the electromotive action of a tetanic muscle. The inertia of the needle only admitted the observation of a decrease of the muscular current during the tetanus, but the mode of contraction of the rheoscopic limb in this experiment shows that the contraction of the muscle, though apparently so permanent, rather consists of a series of rapidly following single contractions, each of which is accompanied by an equal fall and rise of the intensity of the muscular current. Hence arises another most important question.

The comb-like curve in fig. 36 represents these oscillations of the muscular current during the tetanus. The abscissæ are proportional to the time; the ordinates to the intensity of the current; $o t$ is the axis of the abscissæ. The horizontal line from $+k$ to k' represents the permanent intensity of the current of the muscle when at rest. As soon as the tetanus com-

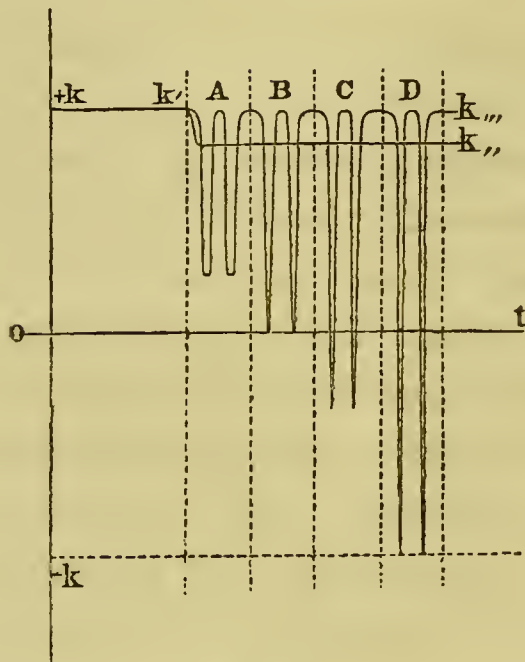


Fig. 36.

mences at k' in the figure, there is an alternate sudden fall and rise of the intensity, the effect of which upon the needle is the same as if the intensity had uniformly decreased, as is represented in the curve $k' k''$. Now it is undecided whether the teeth of the comb-like curve $k' k'''$ —do not reach the axis of the abscissæ $o t$, that is, if there is only a decrease in the intensity of the current; or whether these teeth really reach the axis, that is, if the direction of the current is reversed during the contraction; or lastly, whether these teeth reach the horizontal line

—k on the other side of the axis, that is, if the current, in changing its direction at the moment of contraction, attains the same intensity (in the opposite direction) which it had when the muscle was at rest. These four cases are represented in the four vertical columns of the figure A B C D. Du Bois-Reymond has hitherto tried in vain to find which of these cases represents the truth.

CHAPTER XIX.

ON THE NEGATIVE VARIATION OF THE MUSCULAR CURRENT IN THE ACT OF CONTRACTION, MADE APPARENT IN THE LIVING BODY OF MEN.

IN the living body of men du Bois-Reymond has succeeded in making the same variation of the muscular current apparent in the act of contraction as has been observed in frogs' muscles, of which the two last chapters treat. Unfortunately, his observations on this interesting discovery have only been published in an incomplete form. In a paper communicated to the French Academy, (*Annales de Chimie et de Physique*, 3^e Série, t. xxx.) he thus explains the reasons which induced him to make these new experiments. With frog's muscles he had finally observed the negative variation of the muscular current on contraction by putting the two feet of a live frog into the two conducting vessels. Both legs were undissected, but one was paralysed by cutting its ischiatic plexus. The

muscular currents of the two legs neutralised each other in the circuit. The frog was then poisoned with strychnia. Tetanic convulsions soon followed, but of course the paralysed leg remained motionless. Its current, therefore, became the stronger, and a deflection of the needle took place, indicating an upward current in the paralysed limb and a downward one in the tetanic one.

Du Bois-Reymond then repeated this experiment with his own arms, imitating, as it were by volition, the tetanic state of one leg of the frog, as well as the paralytic state of the other. He described his observations, in a letter to Baron Humboldt (*Comptes Rendus*, t. xxx).

The forefinger of each hand is dipped into the conducting vessels so that the two arms are included in an opposite direction in the circuit of the galvanometer ; just as in the previous experiment the two legs of the frog were included in the same circuit. Even before any contraction of the muscles is made, at the moment when the circuit is completed, the needle is more or less deflected in one or the other direction. This deflection is caused by some heterogeneity

of the skin of the fingers, and up to the time of the paper above quoted du Bois-Reymond had not succeeded in determining the law of its production. If there be ever so slight an abrasion of the skin of one of the fingers the deflection is said by du Bois-Reymond to be incomparably greater, and the current is directed through the galvanometer from the finger which was hurt to the unhurt one: in other words, if instead of the human body a heterogeneous metallic arch were placed with its two ends in the two conducting vessels, the wounded finger would act like the zinc or positive metal, and the sound finger like the platinum or negative metal. When one of the fingers has an abrasion, the permanent deflection which remains is so considerable, that it interferes with and prevents any more delicate observation. But when the two fingers are unhurt, the needle soon returns to the zero point, and becomes stationary at or near it. Du Bois-Reymond waits until this occurs. He then strongly, and permanently contracts all the muscles of one of the arms, so as to give them the greatest possible tension without changing the position of the arm. The

needle is instantly deflected, always indicating a current from the hand to the shoulder, that is, an upward current in the contracted arm; it consequently plays the part of the negative metal in the above-mentioned heterogeneous arch, in regard to the arm the muscles of which remained in a state of relaxation. Under du Bois-Reymond's direction many have succeeded in making the experiment. The current is, however, exceedingly weak, and, for rendering it perceptible, a very delicate galvanometer is requisite. The intensity of the current depends very much on the muscular energy of the experimenter, and even the greater power which the right arm usually possesses, becomes perceptible by means of a greater deflection of the needle.

It may be concluded from this experiment that the muscular current in the arm, *when in a state of rest*, is directed from the shoulder to the hand, or is a downward one; and that the muscular current of the arm in the act of contraction, undergoes the negative variation, whereby the current in the other arm becomes the stronger, the result of which must be an

apparent upward current in the contracted arm.

At first glance it may be thought remarkable that the muscular current in the arm of men, while in a state of rest, should be a downward one, whilst in the frog's leg it is an upward one. But it has already been shown that the muscular current has different directions in different kinds of animals: and, moreover, that its direction in a whole undissected limb of any animal is not of essential importance, but depends only on the form and arrangement of the muscles in the limb.

CHAPTER XX.

ON THE INFLUENCE OF THE EXTENSION AND OF THE COMPRESSION OF A MUSCLE ON THE MUSCULAR CURRENT.

DU BOIS-REYMOND, in his large book, has examined whether any effect was produced on the intensity of the muscular current by extending a muscle, or by compressing it in different directions, as, for example, parallel or perpendicular to its fibres. Only the extension of the muscle appears to have been attended with striking results. He found that the muscular current is a little weakened by extending the muscle, and that it recovers nearly all its former intensity when it is relaxed. This diminution of intensity is not caused by the increased length of the muscle when stretched, for du Bois-Reymond has repeated the same experiment, employing the method of compensation (see page 136). By this means the result is independent of any variations of the resistance in the circuit. An

explanation of this may be found in the fact that when a muscle is kept extended with any considerable force, its vital properties are most rapidly exhausted.

CHAPTER XXI.

ON THE DURATION AND DECREASE OF THE MUSCULAR
CURRENT AFTER DEATH.

THE muscular current continually decreases after the death of the animal, or after the separation of the muscle from the body.

The discovery of the law according to which this decrease takes place is surrounded with many difficulties. According to Matteucci the decrease is most rapid in the first eight or ten minutes after the muscles are prepared ; so that the action on the galvanometer after this period is only half as great as it was at first. He moreover contends that the duration of the muscular current is observed to be shorter, the higher the position of the animal in the scale of organised beings. Thus, for example, the electromotive force in the muscle of a rabbit is said by him to diminish much more rapidly, than in the muscle of a frog much more slowly, than the force in the muscle of a pigeon. To this he

adds that the amount of the power immediately after the preparations are made, follows a contrary law, viz., that it is greater in warm than in cold-blooded animals.

In regard to these statements of Matteucci's, du Bois-Reymond says that he has not been able to verify so rapid a decrease of the current in the first few moments after the preparation is made; and he thinks that in Matteucci's experiments on frogs, prepared according to Galvani's method, it depended on the drying of the nerves, which Matteucci had needlessly included in the circuit. As to the difference of the electromotive force of the muscles of different kinds of animals in the first few moments after the preparation is made, du Bois-Reymond is not disinclined to admit such a difference, but he thinks that such difficulties are opposed to the experimental proof of this statement that Matteucci has by no means been able to overcome them.

Du Bois-Reymond's own statements on this subject are these. The diminution of the muscular current after death is proportional to the diminution of the excitability of the muscle. Both the electromotive force and the excitability

have the same termination, that is, the rigor mortis; caused, as Brücke has proved, by the coagulation of the fibrin contained in the muscles external to the bloodvessels.

The phenomenon of the muscular current must, therefore, be considered as a phenomenon which can only take place in the living tissue. The current when once it has gone in consequence of the rigor mortis, never returns. Limbs in a state of decomposition after the relaxation of the rigor mortis, no longer possess any perceptible electromotive force.

By this most important statement, Matteucci's remarks concerning the relation between the duration of the muscular current after death and the rank of animals, is explained; for it is a long known fact, that the muscles of birds and mammalia lose their irritability much sooner than those of fish and of amphibia; and Matteucci is not correct when he states that the current lasts longer in birds than in mammalia, and longer in fish than in amphibia, because the mammalia precede the birds, and amphibia the fish in the scale of organic life. Du Bois Reymond has also made an extensive inquiry into the in-

fluence of a great many kinds of death from different causes on the duration of the current, and on the influence of certain physical and chemical agents on the muscular current ; as heat, cold, a vacuum, immersion in several poisonous liquids, gases, &c. The general result of these researches is only another proof of the above-mentioned law, that the electric power of a muscle is always proportioned to its contractility, inasmuch as those agents which do not influence its contractility also exert no influence on its current.

CHAPTER XXII.

ÓN THE ELECTRIC PROPERTIES OF DIFFERENT TISSUES,
COMPARED WITH THE ELECTRIC PROPERTIES OF
MUSCLE.

IT has already been said that after death the electromotive power of the muscle diminishes in the same proportion as its irritability decreases. The same law results from the comparison of different contractile tissues in respect of their electromotive power. This force is the weaker the less the mechanical power which they possess. According to this law the electromotive force is greatest in the striped muscles of the trunk and extremities, and in the muscular tissue of the heart. Matteucci first pointed out the electromotive action of the muscular substance of the heart. He experimented with a battery of transversely divided pigeons' hearts. Du Bois-Reymond made experiments on single hearts of frogs, land salamander (*salamandra maculata*), guinea-pigs, and on the common mouse. The

artificial transverse section is negative in regard to the longitudinal section. Also undissected hearts produced deflections.

The current caused by the muscle of a bird's gizzard is much weaker than the current of other muscles. The gizzard of a pigeon caused a current from the natural longitudinal section to the artificial transverse section through the galvanometer wire, much weaker than the current of the striped muscles. A piece of the muscular coat of the stomach or intestine of a frog when connected by a point of its outer surface with one cushion, whilst the other is connected with the edge of the section, gives an exceedingly slight deflection, but according to the law of the muscular current; whilst a similar piece from the intestine of the tench, which, according to Reichert's interesting discovery, has striped fibres, gives a very strong deflection.

The tendon of a rabbit with natural longitudinal and artificial transverse section, gave a scarcely perceptible action, which sometimes indeed followed the law of the muscular current, but soon became very irregular.

Pieces of lung, liver, and kidney, caused very

weak currents, which only partially obeyed the laws of the muscular current, and which continued evident with equal force long after death.

The contact of different tissues produced no electromotive action. In making this experiment it is plain that both tissues must be so placed that neither, by its own inherent electromotive power, can act on the needle. If, for instance, nerve and muscle be used, they must be placed on the cushions, as in the figure 37, when this

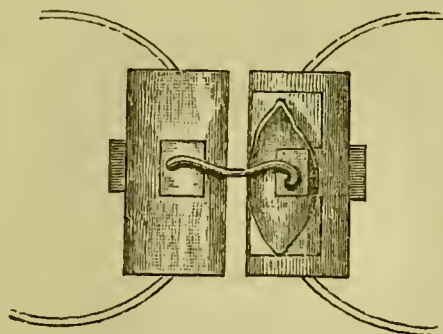


Fig. 37.

condition is fulfilled. Du Bois-Reymond has shown that no possible combination of muscle, nerve, tendon, skin and bone, produces any electric action. By this, Volta's explanation of the contraction produced by Galvani without metals is entirely refuted (see pages 15 and 51.)

CHAPTER XXIII.

ON THE NERVOUS CURRENT.

As the idea of the identity of the nervous power and of electricity, is an old and widely-extended one, it is natural that many endeavours should have been made to obtain electric action from the nerves. Du Bois-Reymond has brought together all the historic notices of this subject, which need not be mentioned here. Matteucci, after having published many confused and contradictory statements on the electric condition of the nerves, says, in the year 1844, (*Annales de Chimie et de Physique*, 3^me Série, t. xii. page 579), “Nous croyons être autorisés à conclure qu’il n’existe aucune trace de courants électriques dans les nerfs des animaux vivants, appréciable à l’aide des instruments que l’on possède aujourd’hui.”

Thus the honour of having discovered the current in the nerves belongs to du Bois-Reymond. Even in his “*Vorläufiger Abriss*” he announced

the discovery of the electromotive action of the ischiatic nerve in a frog and in a rabbit.

The following is the method employed by him for observing the *nervous current* and for determining its laws :—

A piece of the ischiatic nerve just cut from a recently killed frog is so placed on the cushions that it touches one of them with the natural longitudinal section, and the other with its artificial transverse section, as shown in fig. 38. In

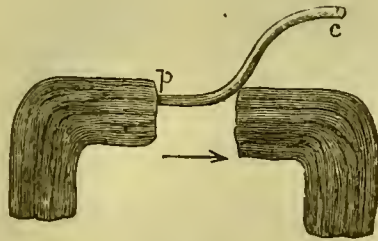


Fig. 38.

this manner a considerable deflection is produced, which, without exception, passes from the longitudinal section through the galvanometer wire to the transverse section of the nerve, that is, in the same direction as in the muscles.

The cushions in this experiment are of course to be coated with their albuminous guards, and upon that one which is to be in contact with the longitudinal section, a piece of mica must be

placed, upon which the end of the nerve, the transverse section of which is not to be in contact with the cushion, is laid.

It is indifferent, in regard to the direction of the current, which of the transversely cut ends is placed on the cushion, whether that near the origin of the nerve marked *c*, or that near the expansion of the nerve marked *p*, as in fig. 39.

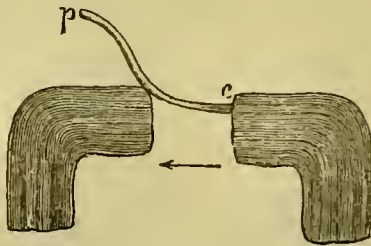


Fig. 39.

The nerve may also be doubled in the middle, and the two ends may be laid on one cushion and the loop on the other, as in fig. 40,

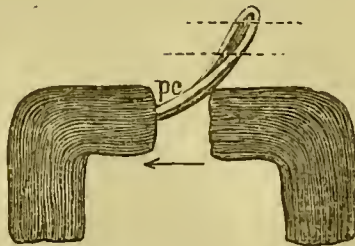


Fig. 40.

by which means a stronger current will be obtained.

If the cushion on each side be in contact with the artificial transverse section, as in fig. 41, the

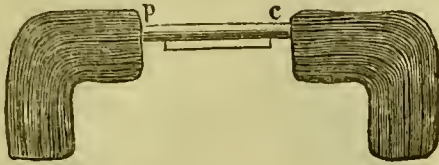


Fig. 41.

needle remains unmoved, if the experiment succeed. But there are generally weak currents, sometimes in one direction, sometimes in the other, which may easily be accounted for by the difficulty of getting the transverse section alone to be in contact with the cushions.

There is no possibility of obtaining the electromotive action of different points in the transverse section, on account of the smallness of its size; but the examination of the natural longitudinal section does not present any difficulty. It is to be examined in the same way as in the muscle, and it gives the same results. Slight deflections are obtained which are very weak in comparison with those obtained from the longitudinal and transverse sections. By these deflections those points of the longitudinal section of the nerve, which are nearer to the middle of the nerve, are

shown to be positive to those which are nearer to the ends, fig. 42.

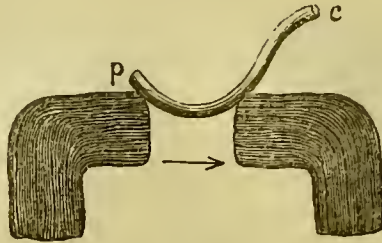


Fig. 42.

If two points equidistant from the middle of the nerve be laid on the cushions, no electromotive action ensues.

The influence of the length and thickness of the nerves on the intensity of their current is the same as has been stated in regard to the muscles. (See above, chapter xiv.)

These are the phenomena of the nervous current in the mixed nerves of the extremities, as a type of which the ischiatic nerve was chosen, because it is best adapted on account of its length for these experiments. It now remains to examine the condition of the nervous current in other parts of the system; of the central organ, as well as of the purely motor and purely sensory nerves.

The anterior and posterior roots of the nerves of the lower extremities in the frog, which are easily obtained 0·3 inch in length, offer excellent opportunities for studying the current in the purely sensory and motor nerves.

The electromotive action of the anterior and posterior roots, does not present any perceptible difference. The transverse section is negative in regard to the longitudinal section in the motor and sensory, as well as in the mixed nerves.

As to the optic nerve of the frog, it is difficult to make experiments with it, on account of its shortness. Du Bois-Reymond chose instead the optic nerve of fish—for instance, that of a great tench. It was found to possess electromotive action according to the previously stated law.

The same experiments that were made with the nerves, were made with the spinal marrow of the frog, and with the same results.

The brain does not present a longitudinal and transverse section properly so called; but every artificial section of the brain appears to be negative to every point of the natural surface of that organ.

Du Bois-Reymond has convinced himself of the existence of these laws of the nervous current by experiments on man, on the rabbit, guinea-pig, mouse, pigeon, tortoise, lizard, water frog, grass frog, leaf frog, salamander, tench, and crab.

Such, then, is the action of the nervous current on the galvanometer; moreover, du Bois-Reymond has succeeded in observing contractions in the rheoscopic limb, by the same current.

Two cushions soaked in a saturated solution of common salt, and with albuminous guards and mica, are placed at a short distance from each other on an insulating surface. The nerve of the rheoscopic limb fastened as in fig. 35, is made to bridge over the space between the cushions; at first so that it touches the cushions only with two points of its natural longitudinal section. If, then, the circuit of the cushions and of the nerve is completed by means of a connecting cushion, or is broken again after it has been closed, no contraction of the rheoscopic limb ensues; but if afterwards the position of the nerve

be changed so that it touches one of the cushions with its artificial transverse section, and the other with its longitudinal section, a contraction of the limb will take place every time that the circuit is closed, or when the frog is highly sensitive, even when it is broken.

CHAPTER XXIV.

CONSIDERATIONS REGARDING THE LAW OF THE
NERVOUS CURRENT.

IT has now been shown that the nervous current obeys the same law as the muscular current, and hence all the conclusions which were drawn from the phenomena of the muscular current, may be transferred to the nervous current, and it may be assumed that it is produced by electromotive molecules in the nerves.

The electromotive elements in the nerves, as well as in the muscles, must be considered as in the condition of a closed circuit, and every current produced by a nerve, must be considered as derived from a current circulating in the nerve itself; and lastly, as in the muscles, so in the nerves, the intensity of the current, as shown by the galvanometer, gives no indication of the intensity of the current in the immediate neighbourhood of the electromotive molecules.

It is evidently impossible to draw any exact conclusion as to the electromotive force of the nerves, as compared with that of the muscles ; but it may be observed with tolerable safety, that the force of the nerves is not less than that of the muscles.

CHAPTER XXV.

ON THE ELECTROTONIC STATE OF THE NERVES.

IT is time now to investigate how the nervous current is affected while the nerve is conveying to the muscle, or to the central organs, those material changes which become perceptible as sensation and motion. For this purpose, some method must be found for putting the nerve into a state analogous to tetanus in the muscle.

This condition in any motor nerve, is manifestly that which produces tetanus in its muscle; and in sensory nerves it is the state in which a violent sensation takes place uninterruptedly.

For shortness and convenience, when such a state is produced in a motor or sensory nerve, it will be said to be tetanised.

Before proceeding to these researches, it is necessary to study the influence of permanent currents on the nerves.

Let a nerve be placed with one of its ends upon the cushions, and with the other on the pre-

viously mentioned platinum ends, as shown in fig. 43. The current produced by the portion of the nerve between the cushions, will cause a constant deflection of the needle in the galvanometer.

If the rods on which the platinum plates are fastened be brought into metallic connexion with the positive and negative pole of a battery, so that a constant current passes through the portion of nerve between the platinum ends, according to the direction of the extraneous current, an increase or decrease of the nervous current, as indicated by the galvanometer, will occur. If the current of the battery have in the nerve the same direction as the nervous current in the portion of nerve between the cushions, as in the fig. 43, there will appear to be an increase in the intensity of the nervous current; and if the currents be in opposite directions, a decrease of the nervous current will appear to take place.

These variations in the intensity of the nervous current last as long as the extraneous current lasts by which they are produced; they cease immediately, when the circuit of that current is broken.

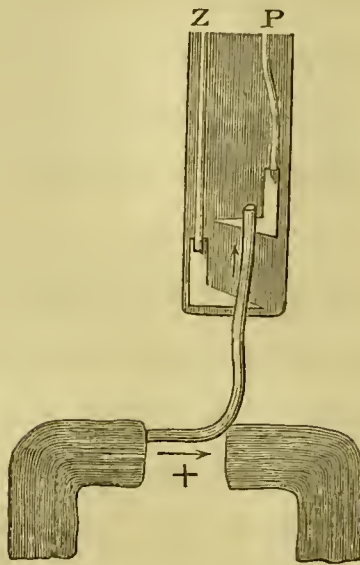


Fig. 43.

The current passed through the portion of the nerve between the platinum ends is called the *exciting current*.

The altered condition of the nerve which is produced by the extraneous current, and which shows its presence by the variation of the electromotive force of the nerve, du Bois-Reymond proposes to call the *electrotonic state of the nerve*.

That portion of a nerve in the electrotonic state, in which an increase in its original current is observed, may be said to be in the *positive phase* of the electrotonic state; while the

negative phase is ascribed to that portion of the nerve which shows a decrease in the intensity of the current.

That portion of the nerve which rests on the cushions, and from which the current in the galvanometer circuit is derived, is called the *derived portion* of the nerve; that which lies on the platinum ends, and is exposed to the exciting current, is called the *excited portion*.

Du Bois-Reymond begins a more minute examination of the electrotonic state by demonstrating that these phenomena, like those at page 132, cannot arise from the irruption of the exciting current into the circuit of the galvanometer.

From the above experiments it may be conjectured that when the nervous current is simultaneously derived from the two ends of a nerve, and the excited portion is situated between the two derived portions, about the middle of the nerve, as is shown in fig. 44, at one of the ends an increase of the intensity of the original nervous current will be observed, and at the other a decrease; still, according to the relation between the direction of the exciting current in the nerve,

section as in fig. 43, but touches both with points and the directions of the original nervous currents at the two ends of the nerve.

To perform this experiment, two galvanometers, and two pairs of conducting vessels are of course necessary.

Du Bois-Reymond really found that under these circumstances the permanent deflection produced by the nervous current in each galvanometer increased when its direction coincided with that of the exciting current; and decreased when the directions were opposed to one another.

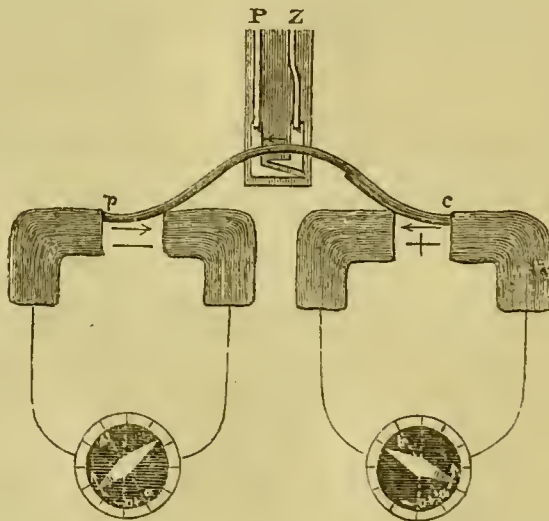


Fig. 44.

If the nerve does not touch one cushion with its longitudinal, and the other with its transverse

of its longitudinal section, so that the original nervous current is much weaker than in the previous case, the variation in the current on closing or breaking the exciting circuit does not appear to be diminished in comparison with its diminution in the former case. If the derived portion of the nerve is nearer to the middle of its length, the original nervous current becomes weaker and weaker. It wholly disappears, indeed, when the derived portion is placed just in the middle of the length of the nerve. On the contrary, the variation of the nervous current produced by the exciting current does not diminish in proportion to the intensity of the original nervous current; and if the derived portion is placed just in the middle of the length of the nerve, where there is no original nervous current, when the exciting circuit is closed a current appears in the circuit of the galvanometer, which has the same direction in the nerve as the exciting current itself.

All these phenomena are stronger the shorter the distance is between the derived and the excited portion of the nerve, the greater the inten-

sity of the exciting current, and the longer the excited portion of the nerve.

It is easy to account for them by admitting the following principle. *When any portion of the length of a nerve is traversed by an electric current, beside the usual electromotive action of the nerve, a new electromotive action takes place in every point of the nerve, which has the same direction as the exciting current itself. This action, the amount of which depends on the several circumstances just enumerated, produces a current in the derived portion, which is added to the original nervous current at that end of the nerve at which the direction of this current and of the nervous current coincide, and is subtracted at that end at which the directions are different.*

Thus the electromotive action of the nerve, which is superadded to its usual electromotive action when in an electrotonic state, may be compared to the action of a voltaic pile surrounded by a layer of moist conducting substance ; or, in other words, to explain the phenomena of the electrotonic state, it must be admitted that the exciting current throughout the nerve

sets in action electromotive elements, which turn all their positive poles in that direction in which the current goes, and their negative poles in that direction from whence the current comes, the current being supposed to continue in both directions throughout the whole length of the nerve.

This assumption may be understood thus:—it is obvious, indeed, that the extraneous current cannot produce electromotive elements, particularly in those points of the nerve where the extraneous current is altogether wanting. These elements, therefore, existed in the nerve previous to the action of any extraneous current, but as their electromotive action was not perceptible, it must be admitted that they were arranged in some way which did not produce any perceptible outward action. The phenomena of the electrotonic state might then be produced by the extraneous current polarizing, as it were, the electromotive elements in its passage through the nerve, thereby causing them all to turn their different poles in the way mentioned above. This action can last no longer than the exciting current itself lasts. Moreover it must extend, though with decreasing intensity, through the nerve beyond the excited portion.

It is easy to account for all these assumptions simply by supposing that the peripolar electromotive molecules, which produce the original nervous current, are composed of two dipolar electromotive molecules, as has already been stated when speaking of the electromotive molecules in the muscles (see page 122). Whatever may be thought of the electromotive action of these molecules, it is impossible not to admit that their positive faces are electro-positive and their negative faces electro-negative. If this be so, then, according to all theories of electrochemical decomposition, if an electrical current be passed through the nerve and electrolytic action begin in it, all the dipolar molecules must turn their positive poles in that direction in which the current goes, and their negative poles in that from whence it comes. But as the two dipolar molecules, which constitute a peripolar group, have their positive poles directed towards each other, one of the two dipolar molecules will always remain motionless, whilst the other must tend to turn round 180° .

Figs. 46 and 47 may serve to illustrate this view. Fig. 46 shows the molecular arrangement

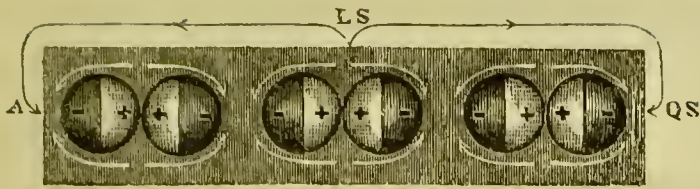


Fig. 46.

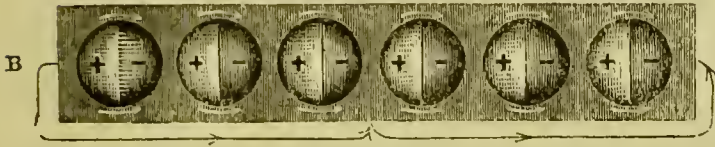


Fig. 47.

which the interior of the nerve is supposed to possess, when at rest. Fig. 47, the molecular arrangement, which may be supposed present when the nerve is polarised to the utmost by a current starting from B in the figure. Now, if it be allowed that this arrangement extends with decreasing regularity beyond the excited portion throughout the whole length of the nerve, this would be precisely the arrangement of the electromotive elements which was required above to explain the phenomena of the electrotonic state. But it is not necessary to admit that the dipolar molecules turn round 180° , as is shown in the figure; they may take an intermediate place between the two positions in-

dicated in the figures, and then the nerve will, at the same time, have an electromotive action according to the law of the nervous and muscular current, and to the law of the electrotonic state; and this is exactly what is found to be the case by experiment.

The physiological import of the electrotonic state may be stated thus:—

Ritter and Paul Erman, when proposing a theory of galvanic contractions, conceived that the action which caused contraction, and which arises at the moment of closing the circuit, is produced by the transition of the nerve into another state; and that the action of the current consisted in putting the nerve into this new condition, in which it remained as long as the circuit was closed, so that the contraction on breaking the circuit was caused by the return of the nerve to its original state.

Du Bois-Reymond supposes that the electrotonic state is actually such an altered condition of the nerves as was conjectured by Ritter and Erman.

When a current acts upon a nerve, the same thing happens in it as occurs in every other

moist conductor. Electrolysis is induced, which begins with a polarization of the electro-positive and negative elements of the electrolyte. The transit from the natural to the dipolar arrangement excites a disturbance of equilibrium which shows itself as contraction or as pain when the circuit is completed. The return from the dipolar to the natural arrangement causes the contraction and pain on breaking the circuit. The stimulation of the nerve by the galvanic current may indeed be nothing else than the first stage of electrolysis in the nerve.

In justification of the choice of the name for this permanent alteration in the nerve by the electric current, du Bois-Reymond recalls to mind the striking analogy, already pointed out, between the law of the galvanic contractions and the law which regulates the induction of currents in a circuit by moving a magnet, or by making or breaking another circuit in its neighbourhood. (See page 65).

Faraday supposed that in a conductor in which a current was induced a change took place which lasted as long as the inducing current itself continued. He regarded the current on making

contact as an evidence of this transit of the wire from its natural condition into an altered one ; whilst the return from the altered condition to the natural one announced itself by the shock on breaking the circuit. Faraday called this altered condition of the wire from the making to the breaking of the circuit the electrotonic state. At first he could give no actual proof of the real existence of this hypothetical state, but he afterwards, by optical means, proved that a real change in the molecular arrangement of different bodies occurred when they were subjected to magnetic influence.

If the comparison between the induction of currents in wires and the irritation of the nerves is to be fully carried out, it is clear that the permanent arrangement of the electromotive molecules produced by the current in the nerves would correspond with Faraday's electrotonic state of matter ; hence the state of the nerves treated of in this chapter, cannot be called by a better name than by that of the electrotonic state of the nerves.

CHAPTER XXVI.

BEHAVIOUR OF THE NERVOUS CURRENT ON
TETANISING THE NERVES.

IF a series of currents of short duration be passed in the same direction through the excited portion of a nerve, lying on the platinum ends, fig. 43, the derived portion still shows that positive and negative phase of the electrotonic state which was spoken of in the last chapter.

If an interrupting wheel be included in the circuit of the exciting current, variations will still occur in the same direction on turning the wheel, as occurred when the current was continuous; and this will be the case however short the time may be during which the circuit is closed. The interrupting wheel used by du Bois-Reymond was so constructed that he could make the period of each closure of the circuit equal to $\cdot 001$ of a second, while the time of interruption between two closures of the circuit was about nineteen times longer. As the phases of the electrotonic

state still occurred, the limit of the velocity with which the electrotonic state can be produced was not reached in this experiment. Even when a series of very short extra-currents is passed through the excited portion of a nerve, the phases of the electrotonic state still appear in their usual direction.

In these experiments, however, a disturbance becomes perceptible, inasmuch as the negative phase often appears much stronger than the positive one. Sometimes, in the positive phase no distinct action occurs. Sometimes, indeed, even a negative deflection is seen instead of a positive one, which, however, is much weaker than that which occurs in the negative phase.

These facts prove that the electrotonic state alone is no longer present. The difference between the above mentioned state, and the simple electrotonic state produced by the interruption of the current, indicates a negative variation in the current which modifies the phenomena.

In order to observe this negative variation without complication, it is necessary to cause the variations of the current produced by the electrotonic state to disappear. This may easily

be effected by tetanising the nerve by means of a rapid series of alternating shocks. The most convenient apparatus for producing such a series of currents is an induction coil, since the making and breaking of the primary current is accompanied by a current of equal amount in quantity, but in an opposite direction.

The consequence of tetanising a nerve with alternating currents, when the longitudinal and transverse sections are on the cushions, is that the needle goes back to the zero point, and in favourable circumstances is deflected to the negative side. If both ends of the nerve be derived, both needles will make this retrograde movement as in figure 48, provided the excited

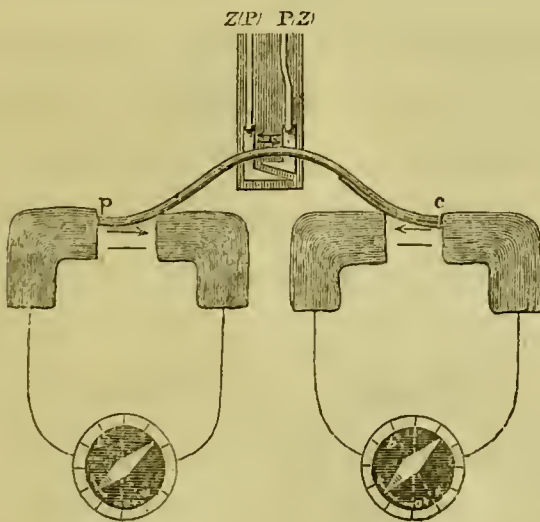


Fig. 46.

portion be tetanised by alternate currents ; while, as was before stated, by using a permanent current one half of the nerve shows the positive, and the other half the negative phase of the electrotonic state, so that the deflection of the needle in one galvanometer is increased, and in the other decreased.

If the derived portion of the nerve touches both cushions with points of its longitudinal section, the nervous current, as has been stated above, will be much weaker than when the cushions are touched one with the longitudinal and the other with the transverse section ; and it will wholly disappear when the two points which touch the cushions are equidistant from the middle of the length of the nerve.

The amount of the negative variation of the nervous current when the nerve is tetanised also depends on the position of the nerve on the cushions. So that it is much smaller when the two points of contact belong to the longitudinal section, and it disappears entirely when the points are equidistant from the middle of the length of the nerve. The amount of this negative variation, therefore, is always proportionate to

the intensity of the original current. It is on the other hand nearly independent of the distance between the excited and the derived portion of the nerve.

The amount of the positive and negative variations of the current to which the electrotonic state gives rise, has been found to be independent of the position of the nerve on the cushions, or of the intensity of the original current, so far as it is determined by the way in which this current is derived; and the same amount is very much influenced by the distance between the excited and the derived portion of the nerve.

Thus it is proved that the electric tetanus in a nerve is accompanied by a negative variation of the nervous current, entirely distinct from those variations which are caused by the electrotonic state.

The negative variation does not depend on any variation of the resistance of the nerve, for du Bois-Reymond has proved that this resistance remains constant during the most violent tetanic state of the nerve. The negative variation of the current, therefore, denotes a decrease in

the electromotive force of the nerve when tetanised; and it may with great probability be considered as being in some way intimately related to that molecular change in the interior of the nerve, which, when it reaches the muscle, will produce contraction, or when it reaches the brain will be perceived as sensation.

CHAPTER XXVII.

ON THE NEGATIVE VARIATION OF THE NERVOUS CURRENT ON TETANISING THE NERVE IN ANY OTHER WAY THAN BY ELECTRICITY.

IT might be asked, whether the same negative variation of the current which is produced by electricity would appear on tetanising the nerve by any other means, as for example by a mechanical stimulus, by a chemical corrosion, by heat, or by poisoning the frog with strychnia, &c.

On first trying these experiments by means of his galvanometer of 4650 coils, du Bois-Reymond obtained no distinct evidence of any action. But it soon occurred to him that this might only depend on the want of sensitiveness in his galvanometer, inasmuch as the excitation of a nerve by other means is far less effective than by electricity. He therefore constructed a new and much more sensitive instrument. This was the galvanometer already described of 24,160 coils; its sensitiveness bears the same

relation to the average intensity of the nervous current as the sensitiveness of the other galvanometer bore to the muscular current. For the current of an ischiatic nerve of a frog deflects the needle to the checks, just as the muscular current deflects the needle of the smaller instrument.

The formation of this instrument is most accurately described in du Bois-Reymond's work. By this means he succeeded in observing the negative variation of the nervous current, when the nerve was tetanised by some non-electric method. This observation is, however, among the most delicate which the province of experimental science can show.

Among other methods which du Bois-Reymond mentions, the following is one of the most remarkable, though at the same time one of the most difficult, because its success is in some respects a matter of chance.

In this experiment the tetanic state of the nerve is produced by poisoning the frog with strychnia. The frog is fastened on a suitable frame, and then poisoned with two or three drops of a saturated solution of nitrate of strychnia. The *arteria iliaca communis sinistra*

is tied. The ischiatic nerve is cut in the ham, and dissected out up to the vertebral column. Its lower end is then bridged over the two cushions, so as to touch one of them with the longitudinal and the other with the transverse section, as in fig. 49. At the moment when the

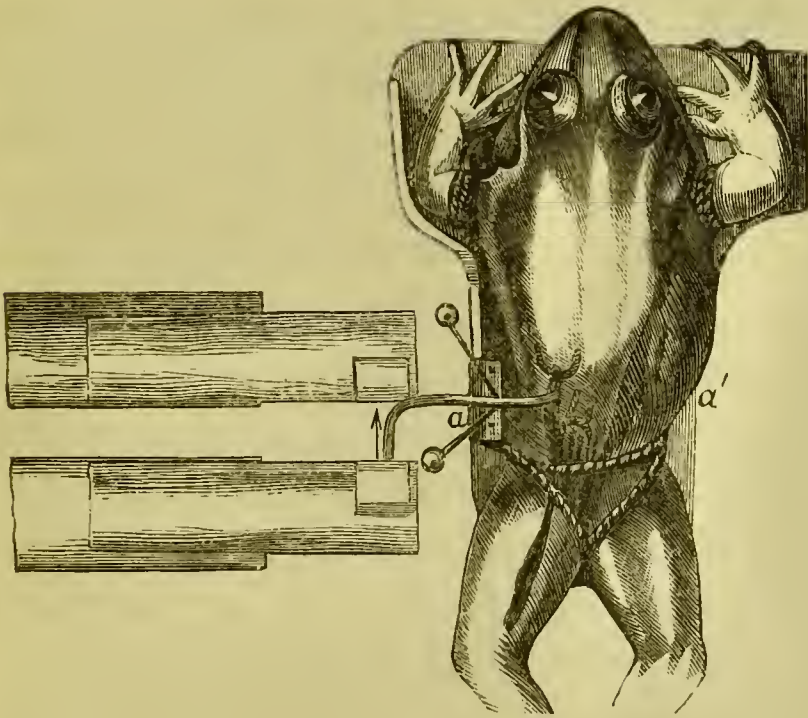


Fig. 49.

tetanus occurs, the needle recedes 4° nearer to the zero point, and on the relaxation of the muscles it comes back, although not quite to its original place. It does this not only with the first

and principal attack of the tetanus, which, after a certain time, spontaneously occurs; but also with the single shocks, which are of much shorter duration, and which can be produced by touching the frog when it is in the state of reflex action, before the principal attack of tetanus takes place.

If a nerve be cut away and laid in the manner described upon the cushions, under favourable circumstances a negative variation of from 1° to 3° is obtained when the other end is crushed or burnt.

The tetanic state of the ischiatic nerve from its branches upwards may also be produced in the following way. A rheoscopic limb on which the skin is left is placed in one limb of an inverted glass syphon; while its knee is held fast in a piece of cork fixed at the opening of the limb of the syphon. The nerve is placed with the longitudinal section upon one cushion, and the transverse section upon the other. A boiling solution of salt is poured into the funnel-shaped opening of the other limb of the syphon, it rises slowly in the opposite limb, and it thoroughly and gradually boils the leg of the frog. The action

on the needle then shows a negative variation. If it be for a moment supposed that the body of the live frog remained attached to the end of the nerve, it is evident that it would have suffered great torture. As the frog is killed and the body cut away from the nerve, a negative variation only is apparent.

Further minute details regarding these experiments are contained in du Bois-Reymond's work.

CHAPTER XXVIII.

ON THE SECONDARY CONTRACTIONS CAUSED BY
VARIATIONS OF THE NERVOUS CURRENT.

To determine whether the negative variation of the current of the nerves when tetanised be continuous or intermitting, as in the muscles, the galvanometer must be replaced by the rheoscopic limb. If the variation be continuous the rheoscopic limb will, under all circumstances, remain quiet, or at most be affected only at the beginning and end of the tetanus. If the variation be intermitting the rheoscopic limb will, on the contrary, show secondary tetanus, provided the single variations are large and rapid enough, and the limb possesses sufficient excitability.

The experiment is thus performed. The platinum ends of the apparatus are connected with the ends of a Grove's battery; an interrupting wheel is included in the circuit; an ischiatic nerve is spread on the platinum ends,

whilst the other end rests upon a carefully dried glass plate. The nerve of a rheoscopic limb closes with its longitudinal section the circuit between the longitudinal and transverse section of the primary excited nerve.

If the wheel be turned, secondary contraction is induced by the nerves.

In this experiment two different kinds of action take place in the primary excited nerve, namely, the electrotonic state and the negative variation of the nervous current.

It must, therefore, be determined whether this secondary contraction arises from the rapid appearance or disappearance of the electrotonic state; or from the negative variation. The following results are conclusive as to this point:—

The secondary contraction is obtained by simply laying the ends of both nerves together, as in fig. 50. Hence it is unnecessary that the primary excited nerve should touch the other with both its longitudinal and transverse section.

The distance between the excited and the derived portion of the nerve, that is, between the part of the nerve lying between the platinum ends, and the part between the two points of the

longitudinal section of the secondary excited nerve, has a great influence on the contractions. If this distance exceeds a certain amount, secondary contractions do not take place. Moreover, if the primary tetanus of the nerve is not produced by some electric method of excitation, the contractions are not observed.

From these facts it may be concluded that the secondary contractions are not produced by the negative variation of the nervous current, but by those variations of the current which arise from the electrotonic state.

The secondary contraction caused by nerves and that caused by muscles must, accordingly, be kept carefully distinct, on account of their origin. The secondary contraction caused by the muscles arises from the negative variation in the act of contraction ; and it is, therefore, independent of the peculiar origin of the primary contraction. On the other hand, the secondary contraction caused by the nerves appears solely to arise at the commencement and termination of the electrotonic state, and its production is, therefore, dependent on a peculiar mode of excitation of the nerves, namely, by the electrical current.

As to the question regarding the continuous or intermitting nature of the negative variation, it cannot be decided by these experiments.

There is one mode of observing the secondary contraction produced by a nerve which deserves notice, because at first glance it appears not only to be contrary to, but even wholly to subvert, a fundamental principle of nervous action. According to this well-known principle, the "*application of mechanical or galvanic irritation to one part of the fibres of a nerve does not affect the motor power of the whole trunk, but only that of the portion insulated from the rest to which the stimulus is applied.*"—Müller's Physiology, Baly's Translation, p. 681. Du Bois-Reymond, however, shows that this statement is incorrect as regards galvanic irritation.

The ischiatic nerve of the frog separates above the bend of the knee into two branches, the ramus tibialis, which chiefly ramifies in the gastrocnemius, and the ramus peroneus, which latter nerve is distributed to other muscles. If one of these two branches be divided above its insertion into the muscles, and a galvanic stimulus be applied to its lower end, the muscles

to which the other branch of the nerve is distributed will contract, as if their own nerve had been irritated. Of course the trunk of the ischiatic nerve must be divided in this experiment, or at least the spinal marrow must be carefully destroyed, otherwise the contractions which are observed might be considered simply as reflex actions.

Du Bois-Reymond has established beyond all doubt that these contractions are produced by the irritation of one of the branches of the nerve, as, for instance, of the ramus tibialis, by the beginning or ending of the electrotonic state in the other branch, the ramus peroneus. The experiment, of course, succeeds equally well wherever a similar anatomical disposition of the nervous ramifications gives the same opportunity of making it with equal convenience.

Du Bois-Reymond also shows that the electrotonic state of a primary excited nerve, produces a secondary electrotonic state in a contiguous nerve. Fig. 50, explains the mode of performing the experiment. In this figure the nerve on the cushions, in which the secondary electrotonic

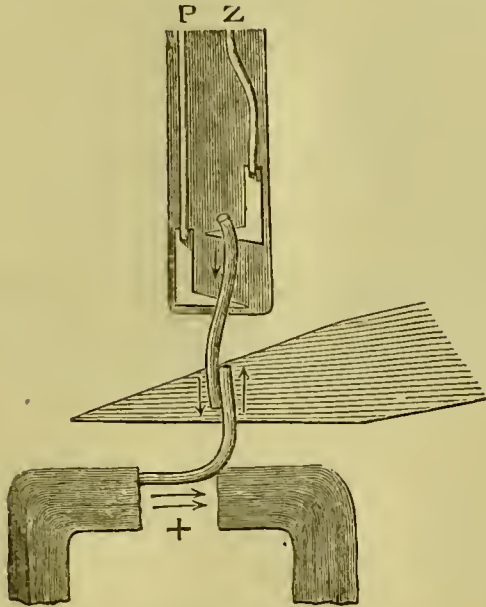


Fig. 50.

state is to be observed, is supposed to undergo the positive phase of this state, by the action of the negative phase of the electrotonic state in the primary excited nerve.

The electrotonic state may also be induced in a nerve by means of its own current. To prove this experimentally, a nerve is placed on the cushions so that one of its ends gives the nervous current, whilst the other end is bent on the nerve itself, so as to form a ring by means of the contact of the transverse section with the longi-

tudinal section. In this ring the nervous current circulates in such a direction that it tends to produce the negative phase of the electrotonic state at the end of the nerve upon the cushions. Accordingly, as soon as the ring is completed, a negative variation of the nervous current in the circuit of the galvanometer is seen to occur.

CHAPTER XXIX.

ON THE ELECTROTONIC STATE, AND ON THE NEGATIVE VARIATION OF THE NERVOUS CURRENT WHICH OCCURS ON TETANISING THE NERVE, IN DIFFERENT PARTS OF THE NERVOUS SYSTEM.

FINALLY, du Bois-Reymond proceeds to examine in different parts of the nervous system those variations of the nervous currents which have formed the subjects of the last chapters. Thus far only a mixed trunk, as the ischiatic nerve, has been taken as the subject of these experiments. The question arises, whether, on repeating the same experiments, on simply motor, or simply sensitive nerves, the same results would be obtained. Du Bois-Reymond has satisfied himself that between the anterior, or motory, and the posterior, or sensitive roots of the lumbar nerves of the frog, no difference can be detected. On tetanising both classes of nerves, the electrotonic state, and the negative varia-

tion of the current, are transmitted indifferently in both directions.

By these experiments a satisfactory answer can be given at last to the long-disputed question, whether, in each class of nerves, the irritation is propagated in one direction only or equally in both? Previously sensation and motion were the only two known means that could be employed for determining whether irritation were transmitted or not by a nerve. But as muscles do not exist at the expansion of the sensitive nerves, and as it is most probable that the parts of the brain and spinal marrow from which the motor nerves proceed are not able to perceive any sensation, it never could be determined whether the sensitive nerves were able to convey downwards, or the motor nerve to convey upwards the irritation produced by any stimulus applied to these nerves between their expansion and the central organs. This question may now be considered as settled, because the appearance of the negative variation of the nervous current in any part of a nerve on tetanising any other part of the same nerve, must be taken as a sign that

the irritation is actually transmitted from the latter to the former point.

Experiment also has shown that the electrotonic state and the negative variation of the nervous current on tetanising the nerve may be propagated through the spinal ganglia without any perceptible alteration of the phenomena.

CHAPTER XXX.

ON A MODIFICATION OF THE NERVOUS CURRENT
INDUCED BY SEVERELY INJURING THE NERVES.

IN the muscles of warm-blooded animals it sometimes happens that the direction of their current is reversed a short time before it wholly disappears, that is, before the death of the muscle. Du Bois-Reymond has observed the same phenomenon in the muscles of tadpoles : but in the muscles of full-grown frogs it never appears to occur. It may, however, be observed with a piece of the spinal cord, or of the brain of frogs.

A similar, although not quite identical, modification of the nervous current is often to be observed after severely injuring the nerves in different ways, either mechanically, or by thermal or chemical means.

If, for instance, a piece of hot metal is brought near to the nerve without touching it while it is on the cushions, the nervous current, either by the immediate action of the radiant heat, or by the dryness caused by it, will be seen to sink

rapidly, and to have its direction reversed, during which the property possessed by the nerve of conveying irritation to the muscle, though somewhat impaired, will not be destroyed; and if the nerve be placed between muscles, so as to recover its natural moisture, it will recover at the same time its usual electromotive power.

Du Bois-Reymond has demonstrated that the increase of resistance in the nerve, caused by the dryness of its surface, consequent on the action of the radiant heat of the metal, is not concerned in producing these strange variations of the electromotive power of the nerve.

If a nerve in this abnormal state is divided, every transverse section is found homogeneous or positive to the longitudinal section instead of negative. This annihilation, or subversion of the direction of the nervous current is therefore a totally different phenomenon from the annihilation or from the subversion of the direction of the muscular current in the parelectronic state, inasmuch as in the latter case any transverse section, except the natural one, preserves its proper negative condition in respect to the longitudinal section.

CHAPTER XXXI.

CONCLUSIONS.

FROM du Bois-Reymond's researches, as far as they are yet published, the following conclusions may be drawn :—

1. The muscles and nerves, including the brain and the spinal cord, are endowed during life with an electromotive power.

2. This electromotive power acts according to a definite law, which is the same in the nerves and muscles, and may be briefly stated as the law of the antagonism of the longitudinal and transverse section. The longitudinal surface being positive, and the transverse section negative.

3. As the nerves have no natural transverse section, their electromotive power, when they are in a state of rest, cannot be made apparent unless they have previously been divided.

4. The muscles having two natural transverse sections may show their electromotive power, without being divided. However, the electro-

motive power of the undissected muscles is often more or less concealed by the contrary action of a layer situated on the natural transverse section, called the parelectronomic layer. The contrary electromotive power of the parelectronomic layer may be increased by cooling the animal.

5. Every minute particle of the nerves and muscles acts according to the same law as the whole nerve or muscle.

6. The currents which the nerves and muscles produce in circuits, of which they form part, must be considered only as derived portions of incomparably more intense currents circulating in the interior of the nerves and muscles around their ultimate particles.

7. The electromotive power lasts after death, or in dissected nerves and muscles after separation from the body of the animal, as long as the excitability of the nervous and muscular fibre ; whether these fibres are permitted to die gradually from the cessation of the conditions necessary to the support of life, or whether they are suddenly deprived of their vital properties, by heat, chemical means, &c.

8. In the different contractile tissues the elec-

tromotive power is always proportioned to the mechanical power of the tissue.

9. Other animal tissues may, indeed, produce electromotive action : but it is neither so strong as the action of the nerves and muscles nor so regular ; nor does it vanish with the vital properties of the tissues ; nor does it, lastly, undergo those sudden variations of intensity and direction, which may be thus briefly stated :—

10. The current in muscles when in the act of contraction, and in nerves when conveying motion or sensation, undergoes a sudden and great negative variation of its intensity.

11. Muscles inactive from the contrary action of the pारेlectronic layer, when contracting become active in the opposite direction to that which muscles in a state of rest exhibit. Hence it must be concluded that the electromotive force of the pारेlectronic layer remains constant in the act of contraction.

12. The negative variation of the muscular current is not a permanent one during permanent contractions. It consists rather of a rapidly following succession of single and sudden variations of the intensity.

13. It has not yet been ascertained whether, in the act of contraction, the muscular current is only diminished or wholly vanishes, or whether it changes its direction.

14. After the contraction has ceased the current does not suddenly recover its original intensity, but the tetanus has a slight subsequent influence on the intensity of the current.

15. The negative variation of the muscular current in the act of contraction fully explains Matteucci's so called induced contractions.

16. If any part of a nerve is submitted to the action of a permanent current, the nerve in its whole extent suddenly undergoes a material change in its internal constitution, which disappears on breaking the circuit, as suddenly as it came on. This change, which is called the electrotonic state, is evidenced by a new electromotive power, which every point of the whole length of the nerve acquires during the passage of the current, so as to produce, in addition to the usual current, a current in the direction of the extrinsic current. As regards this new mode of action, the nerve may be compared to a voltaic pile, and the transverse section loses

its essential import. Hence the electric effects of the nerve, when in the electrotonic state, may also be observed in nerves without previously dividing them.

17. The electrotonic state of a nerve is the commencement of its electrolysis. The contraction on making the circuit is caused by the nerve passing into the electrotonic state, and that on breaking the circuit by the nerve passing out of this state.

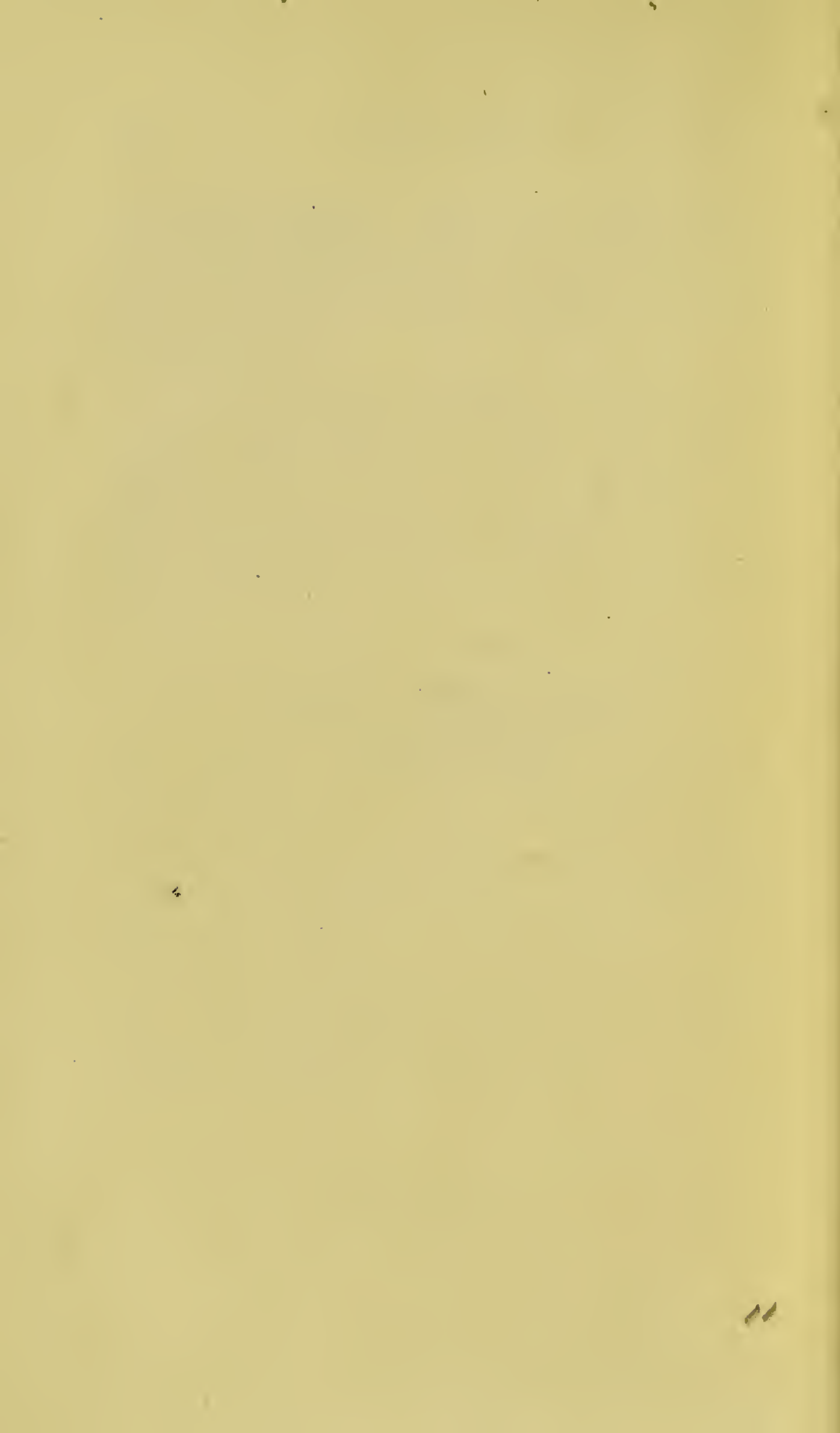
18. In the muscles the electrotonic state does not manifest itself as it does in the nerves.

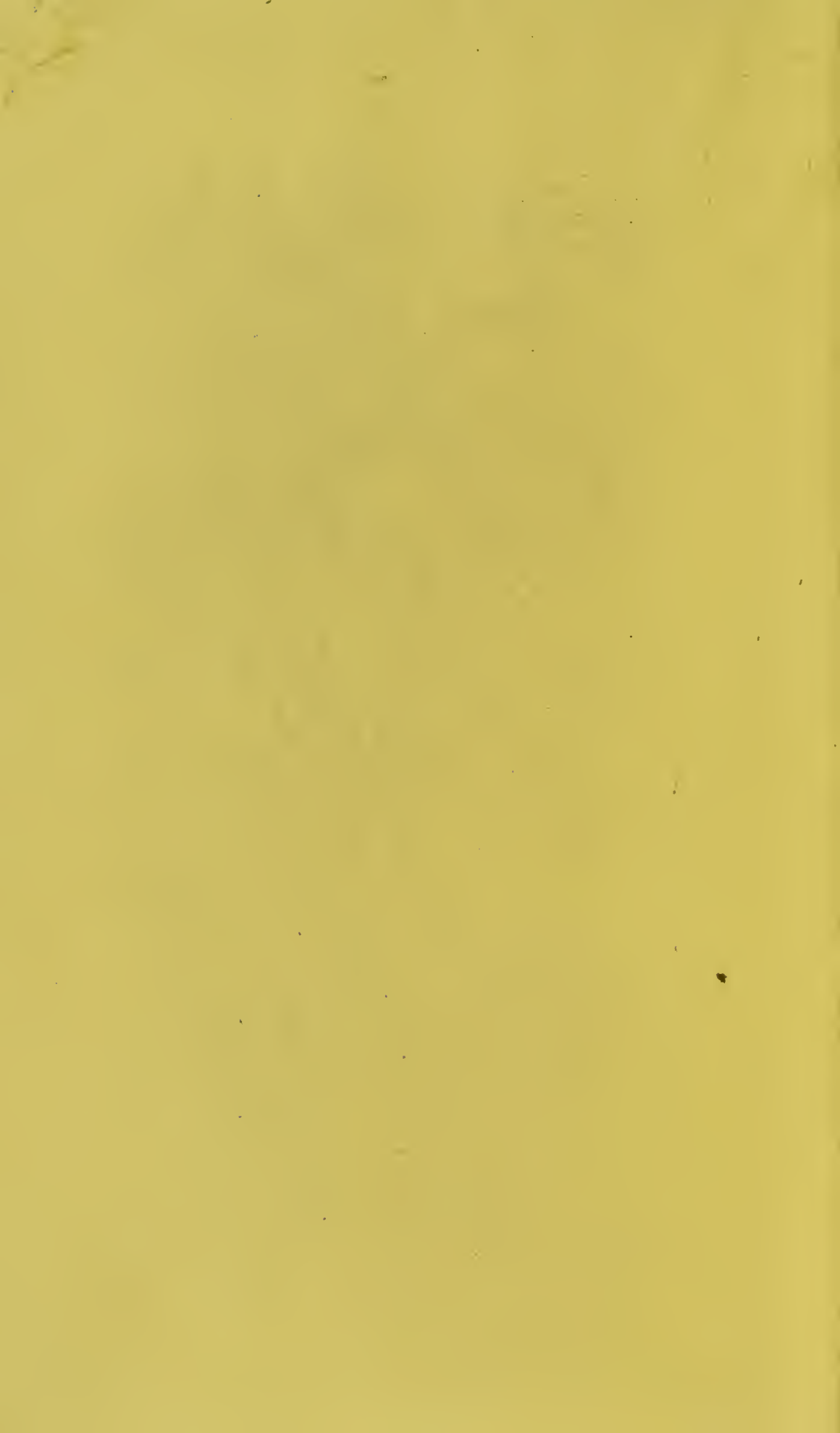
19. Approaching death, and severe injuries of the muscular and nervous tissue cause other modifications of the electromotive power of the nerves and muscles, of which some are permanent, and connected with the total extinction of that power; others are only transitory.

20. The electric phenomena of motor and sensitive nerves are identical. Both classes of nerves transmit irritation in both directions.

THE END.

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