The Goulstonian Lectures

ON DEATH BY ELECTRIC CURRENTS AND BY LIGHTNING.

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LECTURE I.—DEATH BY ELECTRIC CURRENTS.

IN these lectures I propose to consider, first, the subject of death by electric currents, and next, death by lightning. I do this because a good deal is known for certain as to the way in which industrial and domestic electric currents bring about death in man, and much valuable experimental work has been done illustrating the effects of such currents upon the lower animals. In the case of lightning, however, although plenty of observations upon its victims have been made, the nature of lightning itself has always prevented the making of experimental observations of its effects upon living creatures. It is true that in the middle of the eighteenth century a few desultory experiments were made with the electric discharges brought down from heaven during thunderstorms by kites and lightning conductors of various kinds. But all experimentation of this kind came to an abrupt end when, in 1763, Professor Richmann of St. Petersburg was killed outright in his own laboratory by a miniature lightning stroke a foot long, while investigating the nature of the discharges collected by a lightning-rod set up on his roof above and brought down into his room (Arago).

Death by Electric Currents.

I believe that no loss of human life from industrial currents of electricity occurred before 1879, though currents strong enough to have caused death were employed in lighting the operatic stage in Paris (at the first performance of Meyerbeer's *Le Prophète*) as long ago as 1849, and in lighthouses on and off the coast of England in 1857. In 1879 a stage carpenter was killed at Lyon by the alternating current of a Siemens dynamo that was giving a voltage of about 250 volts at the time. The man became insensible at once and died in twenty minutes; artificial respiration was not applied. The first death in this country took place at a theatre in Aston, outside Birmingham, in 1880, where a bandsman short-circuited a powerful electric battery, became insensible, and died in forty minutes. Since that date the annual number of deaths from electric shock has steadily increased, particularly during this century, in which the industrial employment of electricity has extended so widely, and is now quite large. In the ten years 1901–10 the Registrar-General's returns show a total of 183 such deaths in England and Wales, the population having risen from 32½ to 36 million during that period. In the three years 1901 to 1903 there were 25 such deaths; in 1908, 25; in 1909, 29; in 1910, 26. Only 2 of these 183 victims were females, because women are so much less exposed to contact with dangerous electric currents than are men. Many deaths by electricity occur annually on the Continent, though I can only bring forward a few scattered figures to prove it. In Germany, 33 were killed in 1908, 52 in 1909, 46 in 1911. In Austria, 11 were killed by electricity in 1907, 10 in 1910, 10 in 1911. In Switzerland, 21 were killed in 1905, 19 in 1906. I think it probable that about 200 persons are killed by electricity annually over the whole of Europe. As regards the United States of America, where electricity is so very extensively employed, I have not been able to find any statistical records. As long ago as 1888 Brown estimated that during the past five years some 200 people had been killed by handling live electric wires. One must remember that in America life is held very cheap, and that safeguards and protective legislation tend to be regarded as undue restrictions upon industry

and commerce. I imagine that not less than 200 persons are accidentally killed by electric currents every year in America.

As a rule, only a single person is killed by electricity in any single accident; but in an accident occurring in 1909 at Olginate, a village in Lombardy, 10 people were killed outright by a three-phase current at 3,000 volts. One was saved by artificial respiration, and about a dozen more were severely injured (Hoest).

It is necessary before going further to explain the meaning of certain technical terms that cannot be avoided when electric currents are under discussion. Any given electric current is maintained by an electromotive force or pressure that for practical purposes is measured in volts; to give a hydraulic analogy, the pressure or voltage, or, as it is still sometimes confusingly called, tension, that drives the current through an electric lamp corresponds to the head of water, or pressure measured in pounds per square inch, that causes water to run out of a turned-on tap. The rate at which a current of electricity flows, or the quantity (measured in coulombs) flowing in unit time, is measured in amperes; to give the hydraulic analogy, an electric current of so many amperes may be compared to a stream of water or so many gallons per second. The resistance met with by a current as it flows through a circuit or any part of it is measured in ohms; electric resistance is analogous to the frictional resistance met with by water flowing through pipes or in partially choked channels. An electric current that flows steadily in one direction is called "direct" or "continuous." For technical reasons it is often found more convenient to use currents that frequently and regularly reverse, flowing first in one direction round the circuit and then round in the opposite direction, say from 50 to 150 times a second; these are called "alternate" or "alternating" currents of electricity. An alternating current that reverses the direction of its flow 100 times a second is described as an alternating current of fifty periods or cycles a second, or as having a frequency or periodicity of fifty cycles; the frequency of an alternating current is of great importance in considering its dangerousness to life. Electric energy, or the power of doing work, is measured in joules; one joule represents the energy expended in one second by one ampere in one ohm.

Post-mortem Evidence as to the Cause of Death.

The interest of men of science, of physicians and pathologists, in deaths due to industrial electric currents was first shown in France. In 1882 the celebrated French medico-legal expert and pathologist, Brouardel, made a careful *post-mortem* examination of a man killed in Paris at the Tuileries by a 250-volt alternating current, and he decided that death was fulminating, due to the electric discharge, and directly caused by arrest of the heart. Bourrot at the same time examined a second and similar case *post-mortem*, and came to the conclusion that death was due to violent excitation of the vagus nerve and consequent arrest of the heart, with the result that the heart could not resume its functions, and death by asphyxia followed. In 1885 a man killed instantaneously by electric shock at the Health Exhibition in London was examined forty hours after death by Sheild and Delépine. Rigor mortis was marked; extreme fluidity of the blood was observed, even the right heart being free from clots. The authors came to the conclusion that "No doubt the vital spots at the base of the brain are in such cases markedly implicated." As the result of a *post-mortem* examination made by Pla in 1891, he concluded that death by electric shock was due to an instantaneous suppression of all the organic functions. The brain and its membranes were hyperaemic in this case; the blood was fluid, but showed no microscopical change. The victim had died twenty minutes after receiving the fatal shock. In 1892 Buchanan described the case of a man who came in contact with a 2,400-volt alternating current, and fell back insensible with one cry for help. Ten minutes later he was found to be livid, with dilated pupils and blood-stained mucus coming from the nares. Artificial respiration was performed; the man inspired slightly three times and then died, becoming quite rigid in about four minutes. The *post-mortem* examination was made thirty-one hours later; rigor mortis was still marked, the blood was liquid and tarry, the brain was congested, the spinal cord was

congested but healthy. Buchanan remarked that the cause of death was evidently asphyxia. In the same year Crossland recorded the case of a youth of 17, who was killed by a current at a pressure of 115 volts. *Post mortem* the blood was found to be "fluid-inky," but no other lesion could be discovered.

It is well to say something at this point as to the infliction in America of the death penalty on criminals by means of electricity, which had been widely discussed in the lay press and the medical papers of America and this country since 1889, and was first put into practice in the State of New York in August, 1890. Various suggestions had been made as to the strength and nature of the current to be used, and the methods and sites of its application to the body of the criminal. The upshot was that alternating currents of high electromotive force—1,200 to 1,700 volts, while Carleton recommended 3,000 volts—were used, with large electrodes fixed to the head, neck, arms, legs, and elsewhere; the current was turned on several times in each case, and for periods lasting up to 70 seconds or more. Each execution, or "electrocution" as it was first called in 1892, lasted from 3½ to 8 minutes. Enormous quantities of electricity were employed in these executions. To quote one example, an alternating current of 7 amperes was maintained for 70 seconds through the body of one criminal, at a pressure of 1,500 volts; assuming that the man weighed 10 st., here was enough energy expended to raise the temperature of his whole body through more than 5° F., quite apart from any heat generated by the prolonged contraction of the electrically-stimulated muscles. Spitzka states that within twenty minutes of an electrocution the temperature of the body rises to 120° or 129.5° F. in many cases, and that coagulation of the myosin of the muscles takes place. The whole muscular system was thrown into complete tonic rigidity, we are told, when the current was turned on, and this was maintained until it was turned off. The *post-mortem* examinations of persons thus electrocuted showed, among other things, extensive capillary hæmorrhages in the brain and in the floor of the fourth ventricle, and it was assumed that death was due to injury to the brain. No doubt these hæmorrhages were caused by the rupture of small vessels following on the great rise in the blood pressure produced by the prolonged tonic spasm of the muscles; they are not a common feature after death by electric shock. But I think it is obvious that the *post-mortem* changes observed in such electrocutions as these are not of much use in explaining the mode of death by electric shock in industrial accidents, in which the voltage of the current is often much less, the quantity of current passing through the body of the victim is very much less (probably rarely approaching 7 amperes), and the duration of the contact is not often more than a few seconds. The conditions in which electrocutions have been performed and the electrical quantities involved in them are so very different from those ordinarily obtaining in death by accidental electric shocks, that as a matter of fact electrocutions have thrown no light at all on the mode in which deaths by misadventure with electric currents as they commonly occur are brought about. The objects of the responsible authorities were to produce instant insensibility, in the first place, and in the second place death, and both of these objects were attained by the method of electrocution adopted. It was generally supposed that death in electrocution was due to asphyxia or injury to the brain; although, and to my mind quite unjustifiably, it was also argued that it was the subsequent *post-mortem* examination, and not the electrocution, that was the real cause of death, a view that was upheld again and again from time to time in the public press of America until at any rate as late as the year 1905.

During the last twenty years a great many *post-mortem* examinations have been made in cases of sudden death by electric shock, but I do not think that any useful purpose would be served by going through them in detail, as they do not in general throw light on the exact way in which death has been brought about. Stress may, however, be laid on a few points commonly observed. In the first place, burns of greater or less superficial extent are generally seen at the points where the electric current has entered and left the body. They have been carefully studied by Shield and Delépine, and by Mally, and are due to the relatively great resistance offered by the skin to the

passage of the electric current, which is transformed into heat in proportion to the amount of resistance it meets and to the square of the current. If the current is at a low voltage and the contact is brief, the resulting burns may be so slight as easily to escape notice. But if contact with the electric conductor is prolonged, the burning may be very extensive and deep—in extreme cases it has even been found necessary to send for the fire brigade to extinguish the burning victim, who is kept alight by the transformation into heat of the electric energy being poured into him. In the second place, abnormal fluidity of the blood has often been found *post mortem*; in this, those cases of sudden death by electric shock resemble cases of sudden death by asphyxia. In the third place, no pathological changes are regularly found in the heart muscle, although there are good reasons for believing that in most instances death is directly due to paralysis of the heart. In the fourth place, the central nervous system often shows neither macroscopical nor microscopical changes of importance, except in the cases where relatively large quantities of electricity have passed through the body for long periods of time; when this happened, capillary hæmorrhages have often been found in the brain and cord, with chromatolysis or destruction of the Nissl bodies in the nerve cells. In a word, the *post-mortem* evidence as to the cause of death by electric currents in industrial accidents is generally negative, but may suggest asphyxia in some cases, in others organic vascular and nervous lesions in the brain and cord.

Evidence from Anatomical and Electrical Considerations.

When one comes to look into a number of both fatal and non-fatal instances of accidental shock by industrial electric currents, it becomes apparent that the part of the body through which the current flows is extremely important in determining the result of the shock. Practically speaking, there is not the smallest danger of sudden death if the current enters one foot or leg and leaves it by the other or by the lower part of the trunk, however high the voltage and however great the current thus forced through the lower part of the body and the legs. But there is a danger, even with electric currents of as low a voltage as 65 volts, when the current travels through the thorax, and so has the chance to pass through the substance of the heart. The degree of danger here depends upon two factors—first, the resistance presented to the flow of electricity by the skin at the points at which the current enters and leaves the body, and, secondly, upon the voltage of the current. The resistance of the skin varies very widely in any given case, being high when the skin is greasy or dry, or when the area of contact with the electric conductor is small, and relatively low when the skin is wet or the area over which it comes into contact with the conductor is great. To give a single example illustrating my meaning, one may handle a bare wire carrying, say, an electric lighting current at a pressure of several hundred volts with complete impunity, so long as the hands by which the current enters or the feet or boots by which it leaves the body are dry, because in these circumstances the amount of current flowing through the body is too small to be dangerous. But if the hands and feet are damp or wet, the electrical resistance of the skin at the points of entry and exit of the current may be so much lowered that a relatively strong current will flow from the hands through the body to the feet; and if the proportion of this current that passes through the heart is strong enough to paralyse it, then sudden death will occur.

Hence the cardiac region in the thorax is the chief danger area of the body in cases of dangerous or fatal electric shock. Experimental evidence obtained from animals makes it certain that the central nervous system constitutes another area of danger; but for practical purposes the number of industrial accidents recorded in which the current entered by the head and left the body without traversing the region of the heart would seem to be small—at any rate, I have not been able to find any.

The direction in which an electric current flows through the body, whether from right to left or left to right, or whether from the head to the feet or the feet to the head, has no influence on the effects it produces. As a matter of convenience one always speaks of a current as

"entering" at the point where the body comes into contact with the uninsulated electric conductor carrying the current, and "leaving" at the place where it is in contact with some indifferent but conducting substance—with the earth in the case of a person who is standing—by means of which the current after passage through the body is conveyed back to the source whence it came. But it must be understood that these words "entering" and "leaving" are used without prejudice to the actual direction in which the current flows through the body in any given case.

Experimental Evidence.

It is upon the evidence obtained by the experimental electrocution of animals that most of our knowledge as to the modes of death by electric shock rests. No electrical apparatus capable of producing currents strong enough to kill animals was invented before about the middle of the eighteenth century. At that time electricity suddenly developed into a popular and spectacular science in France and Germany, just as in the middle of the nineteenth century table turning, spiritualism, and clairvoyance were popularly taken up all over England and America with the greatest energy. In neither case was much real scientific progress made by this arousal of popular interest; birds, beetles, and other living creatures were electrocuted by frictional electricity by Gordon (1745), Gralath (1746), Nollet (1749), and many others (Benjamin). It was noted that the birds exhibited ecchymoses where the electric sparks struck them, much like the ecchymoses seen on persons killed by lightning (Nollet). Priestley in 1767 killed kittens and dogs with the discharges of condensers, and tried without success to resuscitate a kitten by artificial respiration, distending the lungs by blowing with a quill into the trachea. Abildgaard (1775), using condensers and Leyden jars, tried without success to electrocute a 3-months-old foal; he succeeded in killing cocks and hens by electric discharges sent through the head, and made the important observation that fowls treated in this way and to all appearances dead could be brought back to life by electric shocks sent through the body from breast to back, but remained dead if not treated in this manner. Thus, a cock received the discharge of a Leyden jar through its head, and fell down apparently dead at once, blood coming from its nose and throat, no doubt in consequence of the rupture of some superficial vessels by the mechanical violence of the spark; but when a second Leyden jar was discharged into its breast the cock leaped up and flew away with alacrity, upsetting and breaking the Leyden jar. Abildgaard concluded that when death took place in the fowls it was due to syncope brought on by nervous shock.

Brodie (1828), in some experiments made to explain the mode in which death is produced by lightning, was led to suppose that electric shocks caused death by destroying the functions of the brain. He speaks of restoring to life the guinea-pigs apparently killed by electric discharges by means of perseveringly inflating their lungs by bellows. Brown-Séquard (1850) expressed the opinion that animals killed by electric discharges died by asphyxia, tetanus being set up and preventing respiration till death ensued. It must be remarked, however, that this explanation does not account for the many instances in which death occurs without the establishment of tetanus, but with simple failure of the heart or respiration.

Some important experiments on the electrocution of animals by sparks from the large induction coil belonging to the Polytechnic were made in 1869 by Richardson. They led him to believe that death could take place in two ways—either by failure of the respiration or by failure of the heart; in each case as a consequence of injury to the nervous centres. The heart was the last organ to be brought to rest. In the case of a pigeon anaesthetized with methylene bichloride and killed by a six-inch spark from the induction coil, and apparently killed outright, all four chambers of the heart went on beating for an hour and a quarter after death. Discussing the *post-mortem* observations he made, Richardson was finally led to a number of conclusions that are certainly erroneous. "Death," he said, is due "in all cases where it is instantaneous to the sudden expansion of the gaseous part or atmosphere of the blood, combined in extreme degrees of

shock with a sudden conversion of animal fluid from the fluid into the gaseous condition." He had found that the vessels of the brain were distended, the arteries contracted, and that sometimes there were slight serous or haemorrhagic effusions beneath the arachnoid; "often, on lifting up the brain and medulla, there is a free escape of bubbles of gas," but he does not say whence this gas came. I cannot find that any other observer (except Corrado in a couple of instances) has observed gas in the blood vessels as the result of electrocution, either in animals or man. The large Apps induction coil Richardson used gave sparks up to 29 inches in length, and even with 29-inch sparks could produce no fatal effects unless reinforced by the use of Leyden jars; the currents he obtained would have been very small, presumably a few milliamperes at most, though the voltage would have been very great—tens or hundreds of thousands of volts; and these facts explain to some extent the inconclusive character of Richardson's results.

The fact is that electricity is a science in which beyond all others science is measurement. For all practical purposes accurate measurements of the strengths of currents, of electromotive forces and of resistances, were luxuries at the command of a few physical laboratories only until the end of the Seventies of last century. Until after the year 1880 the men of science who investigated the subject of electrocution never even thought of giving any precise figures whereby one could calculate the electrical dimensions of the currents they employed. Their statements are qualitative and not quantitative, and so are of historical rather than practical interest in any discussion about the cause of death by electricity.

One of the first experimenters to give accurate measurements of the voltages and currents he used was Grange (1884). He failed to kill guinea-pigs by continuous currents at 31 and 48 volts, and rats with currents of 62 volts; with an alternating current at 825 volts he failed to kill a dog weighing 17 lb., but some of his other attempts at electrocution were more successful. His failures were due to the want of skill with which he affixed the electrodes to the dogs, for he found the resistance of his dogs to be as much as from 50,000 to 80,000 ohms, while later experimenters have observed resistances of only a few hundred ohms when the electrodes were rationally applied to the animals. Grange found capillary haemorrhages in the central nervous systems of the animals he killed, and concluded that these haemorrhages were the cause of death. The fact that later experiments have shown that alternating currents at voltages as low as 10 or 15 volts suffice to kill dogs if electrodes are used so as to reduce the resistance of the animals to a minimum, proves what care is necessary in drawing definite deductions as to the possibilities of death by electric shocks; for here we have Grange failing to electrocute dogs with alternating currents of no less than 825 volts electromotive force.

In 1885 Mann made some interesting experiments on the effects of electricity on the action of the human heart. He applied the electrodes to the praecordia and back, and found that a slowly alternating current of from 15 to 30 milliamperes did not prejudice the heart's action. His method of experimentation was admirable, and failed to give more positive results only because the voltage he employed between the two electrodes was not large enough to drive stronger currents through the thorax, fortunately for the person on whom the experiments were made. It would be of the greatest interest to know how high a voltage can be used, and how large a fraction of an ampere can be passed with impunity through the human heart, from front to back through the thorax, with electrodes applied to the best advantage; because it is the strength of the current passing through the heart that is the main factor in determining death in the large majority of industrial accidents as they actually occur, and it is a quantity that has never yet been measured. Experiments to determine these points, however, in human beings would be far too dangerous to be justifiable—unless, indeed, some American criminal condemned to death were to offer to take on the task and were allowed to do so.

In 1885, and further in 1887, d'Arsonval made some interesting remarks on deaths caused by industrial electric currents, advancing the views as to their mode of

production that he has continued to hold faithfully ever since. These deaths, he said, were brought about in one of two ways:

- (1) By direct action, the mechanical effect or disruptive action of the electric current on the tissues; or
- (2) By indirect or reflex action on the nervous centres.

In the first case death is final; in the second it is often apparent only, so that the victim may recover if treated by artificial respiration immediately after receiving the shock. Most of the victims of industrial electric accidents had died of asphyxia, he believed.

In 1889 Donlin published some details of ten autopsies made on electrocuted criminals in America, and advanced the view that death was due to action of the electric current (conducted by the blood) upon the ganglia of the heart, causing a spasm of the heart muscle; in other cases it was produced by disorganization of the blood and interference with the circulation. I cannot find that these two theories ever had much vogue, or that the spasm of the heart muscle and disorganization of the blood have ever been observed experimentally, either before or after Donlin's elaboration of these views. An editorial in the *Lancet* (1890) brought forward the explanation that electrocuted persons died "by concussion of the brain and explosion within the closed cavity of the skull"; here, again, we have a theory of the cause of death that lacks any experimental evidence in its favour or even rational support. As a contrast may be quoted the excellent experiments made in 1890 by Tatum, upon dogs for the most part. He found no *post-mortem* lesions unless he used current densities many times in excess of those needed to produce death; weak currents might produce death by arresting respiration, strong currents by a permanent arrest of the heart without influencing respiration, while currents of intermediate strength might kill by arresting both the heart and the respiration simultaneously. Tatum appears to me to have been the first to give due prominence to the fact that death by electricity is generally due to paralysis of the heart, and depends on injury of the heart muscle rather than of the nerves of the heart. He also showed that section of the vagi and the use of atropine or curare gave no protection against the fatal result in these electrocutions—observations that are hard to explain on the theory that death by electric currents is due to nervous inhibition. Tatum also showed that a given current would be most fatal when the two electrodes were placed in the neighbourhood of the heart.

One may say that from the year 1890 onwards three main theories of the cause of death by electricity have held sway. The first was d'Arsonval's theory, that it was due to nervous inhibition of the heart and respiration. The second, as advanced by Tatum, attributed death to direct paralysis of the cardiac muscle by the passage of the electric current through it. The third, based mainly on the *post-mortem* examinations of electrocuted criminals in America, put death down to the gross lesions—haemorrhages—found in the brain and bulb of the victims, and produced by the vast quantities of electrical energy employed to procure an easy death.

In France the first theory was, naturally enough, generally adopted, and it was supported by many others besides the French (Biraud, Jenks, Hankel, Cunningham, Witz, Hedley, Durand, Verhoogen, Gardé, Jones, Dürck). The second theory was supported by a number of authors, some of whom held that both were true in given instances (Witz, Gardé, Hedley (1895), Dürck, Kratter, Oliver and Bolam, Cunningham, Bordier and Lecomte, Lebrun). The third met with comparatively little support outside America (MacDonald, Goelet, O'Neill, Corrado), but was reiterated with some elaboration in a modified form by Jellinek (1903). But the subject has always had great attraction for the abstract philosopher, and so it is not surprising to find that the industrious production of what may not unfairly be called "freak theories" of death by electricity has continued. Thus, Shettle (1895) attributed such deaths to the fact that the electric current deprives the arterial blood of its active magnetic properties, and prevents the corpuscles from constantly inducing magneto-electric currents in the nerves. Bennett (1897) put them down to a violent, rapid, and excessive disturbance of the

normal atomic electrical equilibrium of the body, to such an extent as to cause complete and instantaneous disease and death. Coulter (1899) quotes the view that the whole volume of the blood seems to be suddenly forced to the head in the electrocution of criminals; "this alone in each and every case would explain the cause of death." I quote these views to show that the old principle of explaining *obscurum per obscurius* dies very hard.

Towards the end of the nineteenth century it became apparent that more extended experiments on animals were required to settle the mechanism of death by electric shock. In 1898 Oliver and Bolam published some investigations made upon etherized dogs and rabbits with an alternating current at 100 volts. They came to the conclusion that the deaths produced by currents of such voltages were by a primary cessation of the heart's beat as a rule, while currents at higher voltages might paralyse both heart and respiration together. Under no circumstances did these authors produce a primary failure of the respiration, and they note that it had been frequently recorded by bystanders that the persons killed by accidental shocks from industrial electric currents had breathed a few times after receiving the shock, although to all appearances dead.

Fibrillation of the Heart Muscle.

It had long been known (Ludwig and Hoffa, 1850) that one effect of electric currents on the mammalian heart might be to paralyse the ventricles by throwing them into a state of fibrillation, also known as *Herzdelirium*, fibrillary contraction or tremulation, consisting in a fine and rapid but inco-ordinate twitching of the separate muscular bundles. Kronecker and Schmey (1884) had produced fibrillation in the dog's heart by the mechanical stimulation—a pin-prick—of a certain point on the anterior aspect of the ventricle, also by ligation of the coronary arteries and by electrical stimulation. They attributed it to the destruction or paralysis of a nervous co-ordinating centre located in this particular part of the heart's muscle. McWilliam (1887) made further investigations into cardiac fibrillation, and denied that it was in any way a nervous phenomenon. He believed that it depended on physical or chemical changes in the substance of the heart muscle itself. The subject was very carefully examined again by Prevost in 1898, and it demands further consideration here because there is little doubt that cardiac fibrillation is the immediate cause of death in the majority of cases of death by electric shock in man. Prevost found, as McWilliam had found before him, that cardiac fibrillation was produced with much greater ease in certain varieties of animals and birds than in others; that in some—the dog or pigeon, for example—it was generally fatal and irremediable, while in others it tended to cease spontaneously after a longer or shorter period, the heart beginning to beat normally again; and that in the young of any given species cardiac fibrillation was more readily recovered from than in the adult. Thus, guinea-pigs weighing 1 lb. would often recover from cardiac fibrillation spontaneously; while with heavier animals weighing 2 lb. the heart would fail to begin again to beat normally, the guinea-pig dying of asphyxia with great dilatation of the heart, though long massage of the heart might enable it to recover. As to the exact mechanism whereby cardiac fibrillation was produced, Prevost expressed himself as uncertain; he did not think it due either to stimulation of an intracardiac nervous centre or to anaemia of the muscle substance, as Kronecker at one time believed. It is explained by Boruttau as due to the different excitability of the different muscular bundles composing the heart wall and the various length of their refractory periods; all the bundles are strongly stimulated by the electric current, and so contract with their maximum frequency, but as these maxima are unequal the contractions are not synchronous. Why these small and rapid local contractions are not propagated in such a way as to make the heart beat as a whole remains unknown. They may be excited by the local ionic dissociations caused by the passage of the electric current, Professor Gotch tells me, as is also the case in the analogous Porret's phenomenon observed in the frog's sartorius muscle, and may fail to be transmitted to the adjoining bundles because, although excitability remains, the power of propagating the stimulus to contract may be lowered. Fibrillation is also to be seen in

the auricles of the heart, but does not seem to be of any great importance here.

Later Experimental Evidence.

An illuminating and most extensive series of experiments on the electrocution of animals was published by Prevost and Battelli in 1899. The great merit of these authors was that they varied the electrical conditions of their experiments far more widely than any of their predecessors, and gave measurements not only of the voltages they employed but also of the amperages of the currents they passed through the various animals; they also registered the arterial blood pressure and the respiratory movements. Perusal of the published works of the vast majority of the other writers on this subject is apt to leave one with the impression that their authors were not particularly skilled physiologists or physicians in some instances, in others that they were not electrical experts or men of science. The work of Prevost and Battelli is both sound and brilliant, and shows a degree of competence in both physiological and electrical matters that inspires great confidence in their conclusions. They employed both alternating and continuous currents, and took great pains to ensure adequate electrical contacts between the terminals of their electric apparatus and the animal under experiment. In many cases one electrode was placed in the mouth, the other in the rectum; the resistance in different dogs with this arrangement varied between 250 and 400 ohms. Electrical contact was made for a few seconds or for a fraction of a second in different cases. An alternating current at five volts was painful to dogs when passed thus between mouth and rectum, but did not affect the respiration or the action of the heart. The current at a pressure of 10 volts in two seconds caused almost certain death, the ventricles of the heart being irremediably thrown into a state of fibrillation while the auricles continued to beat normally. Respiration stopped, owing to general muscular tetanus, during the passage of the current, beginning once more when it was cut off, but soon dying away again for want of irrigation of the respiratory centre in the bulb with blood, for after the current was turned on the blood pressure fell steadily away to nothing in about 15 seconds. Using metal electrodes covered with wetted cotton, suitably shaped and applied to the shaved chest-wall, they found the resistance of three dogs from one side of the chest to the other was about 300 ohms in each case, and these dogs were killed by alternating currents at 10 to 15 volts pressure. Fibrillary contractions of the heart muscle was found to be almost invariably fatal in dogs; life could be preserved for a time by massage of the heart and artificial respiration, but death ensued when these manipulations ceased, as the heart could not be induced to begin to beat spontaneously again. In the guinea-pig of medium size, however, massage of the fibrillating heart through the chest wall would sometimes restore the animal to life, the heart beginning its normal action again; the resistance of the guinea-pigs as arranged for electrocution was from 700 to 900 ohms, and pressures of from 20 to 120 volts were found to be fatal by heart failure, as a rule. It was noted that in the case of the rabbit cardiac fibrillation tended to spontaneous recovery in most cases, and in the rat always. Hence alternating currents up to a pressure of 120 volts were not often fatal to rabbits, under the conditions of experimentation employed by Prevost and Battelli, and were never fatal to rats, as the fibrillation of the heart would cease spontaneously, and the respiration would begin again soon after the current was turned off in both these animals. But death could be procured by the use of these relatively low voltages if the contact was prolonged and the current kept on until asphyxia from prolonged arrest of the respiration occurred.

Using alternate currents at higher voltages—120 to 4,800 volts—Prevost and Battelli found that the effects produced were quite different, so far as life was concerned, and that death, when it occurred, might be caused in a different way. Thus, with the dog, alternating currents sent from the head to the legs at pressures of from 240 to 600 volts caused arrest of the heart (with ventricular fibrillation) and arrest of the respiration also, the animal inevitably dying. At higher voltages, however, 1,200 to 4,800 volts, the ventricles of the heart continued to beat vigorously, though the auricles were paralysed in diastole,

and respiration ceased; hence at these high voltages death was due to asphyxia from failure of the respiration, and not, as at low voltages, from heart failure, or, as at intermediate voltages, by failure of both heart and respiration together. The very important observation was made that a dog killed by the ventricular fibrillation caused by a current at 40 volts could be brought to life again if a current at a much higher pressure—4,800 volts in the present example, or 240 volts in other instances quoted later—was sent through its body so as to pass by way of the heart. Very similar results were obtained with rabbits; alternating currents at 240 volts killed by throwing the heart into a state of ventricular fibrillation, but at pressures from 600 to 4,800 volts the heart was not paralysed, but went on beating with rising arterial blood pressure, though respiration was brought to a standstill. Death in these conditions was due to asphyxia from failure of the respiration, and prolonged artificial respiration was needed to bring the rabbit back to life, and was not always successful. Analogous results were obtained in the experiments on guinea-pigs and rats. It was noted that, using these high voltages, phenomena were produced in all these animals indicating that the nervous system received injuries; general convulsions might be produced, or the respiratory movements might be upset for half an hour or more with loss of sensation and the reflexes, and the severity of the nervous symptoms was more or less in proportion to the voltage and the length of time for which the current was applied. No such phenomena depending on injury to the central nervous system were seen in the experiments at voltages up to 120 volts.

Prevost and Battelli also experimented in much the same way with the continuous electric currents of dynamos and of primary batteries. They found that continuous currents at pressures below 50 volts were not fatal to dogs even in five seconds, whereas with alternating currents pressures of 10 to 15 volts were fatal in two seconds. Between 50 and 550 volts the continuous current was uniformly fatal to dogs, causing irremediable ventricular fibrillation; artificial respiration was useless. No continuous current at voltages higher than 550 volts was available; but if it had been the authors thought that at some higher voltage it would have had the effect of stopping the cardiac fibrillation and restoring the normal action of the heart, just as was the case with the alternating current. In the case of guinea-pigs, the direct current was fatal by ventricular fibrillation at pressures of from 100 to 350 volts; but higher pressures, 400 to 550 volts, were not thus fatal, because although the heart fibrillated during the passage of the current, the extra shock of turning it off suddenly (the "extra-current at break," which d'Arsonval thought so important and fatal) restored its normal action to the heart. With rabbits, as with dogs, direct currents at pressures from 50 to 550 volts threw the heart into ventricular fibrillation, from which the rabbit might or might not recover spontaneously. With rats, the heart was thrown into ventricular fibrillation by currents at from 200 to 550 volts, but only for so long as the current was passing; when it was turned off the ventricles resumed their normal mode of beating, but the auricles were paralysed in diastole for perhaps two or three minutes before they set to work again.

It is clear, then, from these experiments that direct electric currents are much less dangerous, *ceteris paribus*, than alternating currents, for dogs, rabbits, guinea-pigs, and rats. The experiments also show clearly the importance of reducing as far as possible the resistance offered to the passage of the current through the animal, and of placing the electrodes on it in the most favourable position for producing a fatal result—in other words, of placing them so that the current passes as much as possible through the substance of the heart, when the minimum fatal voltage is to be determined.

A further series of experiments was made in 1899 by Prevost and Battelli to determine the mode of death in animals by electric shocks from induction coils and condensers. These shocks were mostly at voltages varying from 1,500 to 33,000 volts, and the electric energy available was up to 1,000 joules per shock. The duration of each shock was no doubt exceedingly brief—at a guess, perhaps a thousandth of a second. One may summarize their results by saying that the fatal effect of these

electrical discharges were in proportion neither to their voltage nor to the quantity of electricity (in micro-coulombs) they contained, but to their electric energy measured in joules, taking the presence of thoracic respiration as evidence of life or death. It is worth noting that no such connexion between the amount of electric energy employed and the occurrence or not of a fatal result can be worked out in the case of animals exposed to shocks from the ordinary electric currents used industrially, or in the numerous experiments on animals already described. Young animals were generally more easily killed than old, weight for weight; the direction in which the shock passed made no difference to the result. Death was generally due to asphyxia, from central inhibition of the respiration without inhibition of the heart's action. A curious *post-mortem* lesion was sometimes found, especially in young guinea-pigs—namely, a loss of the elasticity and retractility of the lungs, which rendered recovery by the performance of artificial respiration impossible. It occasionally happened in the guinea-pig that the heart was thrown into a transient state of ventricular fibrillation; the amount of electrical energy available was not large enough to kill dogs.

In 1899 Cunningham independently made some experiments on the electrocution of etherized dogs, somewhat similar to those described a few minutes ago, and, so far as they went, with similar results. Using a continuous current at 115 volts, he found great differences in the strength of current that could be passed with impunity through different dogs; thus a large Newfoundland was killed by 300 milliamperes, while a small shaggy terrier survived 700 milliamperes, and currents smaller than 200 milliamperes were never fatal. Other experimenters have found direct currents of 200 to 300 milliamperes to be fatal to dogs; very possibly the discrepancy here may have been due to the occasional use by Cunningham of larger electrodes that did not serve to concentrate the current and make a sufficiently large proportion of it pass through the heart—a supposition confirmed by the fact that the recorded resistance (77 ohms) of one of his dogs from side to side of the chest was only a quarter of the resistance commonly found in their own experiments by Prevost and Battelli and by Weiss. Such deaths he attributed to the immediate and permanent cessation of the co-ordinated contraction of the heart caused by the electric current. He then went on to investigate the effect of electric currents applied directly to the central nervous system of the etherized dogs. He found that strong currents (1.6 amperes) through the brain caused a deep inspiration, and cessation of respiration while the current flowed; the heart kept on beating and the blood pressure rose steadily to two or three times its original value, returning again to the normal when the current was cut off and respiration began once more. But if the current was kept on for as long as four or five minutes, the heart gradually stopped. He therefore argued that death by the action of electric currents on the brain and medulla was due to asphyxia, and not to heart failure. The strength of the ordinary electric currents that may be sent through the dog's head without causing rapid death is surprising; Houston found that even 6 amperes were not necessarily fatal.

A few more recent investigations remain to be mentioned. Battelli, in 1902, electrocuted dogs, rabbits, guinea-pigs, and rats with discharges from large Ruhmkorff induction coils giving sparks up to 15 and 45 cm. in length. He was able to kill the smaller animals either by arrest of the respiration, or, using a condenser as well, by throwing the heart into fibrillary contraction. With the larger animals, however, death could only be produced by asphyxia after prolonged electrification, the available current—measured in milliamperes—being too small to cause the heart muscle to fibrillate. Battelli stated that no human being had ever yet been killed by the discharge of an induction coil, and estimated that the larger of his two coils would have required a minimum time of two minutes to kill a man, when death, had the experiment been successful, would have been by asphyxia and not by heart failure.

The fact that d'Arsonval believes death by electricity to be due to inhibition, or paralysis of the central nervous system, has been mentioned already. In 1910 he recorded a further experiment that appeared to him to prove that

death by electricity, if not due to material lesions of the nervous centres and the heart, was due to Brown-Séquard's inhibition or the action of electric shock on consciousness and the psychical functions. A dog is anaesthetized with chloroform and the cerebral cortex is exposed; stimulation of the cortex with the current from a single Daniell cell (1.1 volts) is found to produce movements of the limbs. If the dog is now killed by a current at 110 volts the heart is thrown into fibrillary contractions, the respiration stops, and the cortex ceases to be excitable by the Daniell cell. At the end of a few minutes respiration begins again, and then the cortex again becomes excitable, and, lastly, in some cases the heart begins to beat spontaneously once more. This experiment d'Arsonval takes to prove that all the vital functions are affected at the same time by an electric shock, so that in his view it is superfluous to inquire whether death is due to a paralysis of the heart or not. He admits that the recovery or death of an animal from a shock that may or may not be fatal depends entirely on the question whether the cardiac fibrillation is transient or is followed by permanent loss of the ability of the heart to beat spontaneously; and as it has been found that section of the vagi has no influence on the occurrence of this cardiac fibrillation, it is, in my opinion, impossible to agree with d'Arsonval when he attributes great importance to nervous inhibition in the large majority of the fatal accidents brought about by industrial electric currents.

NOTE.—The references to the literature will be given at the end of the third lecture.

THE USE OF PHYSICAL CONSTANTS IN TOXICOLOGY.

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In the course of toxicological examinations it is frequently necessary to identify various organic compounds, and the increasing use of synthetic remedies renders it imperative that toxicologists should have at their disposal methods by which such drugs can be recognized with the greatest possible certainty. In cases where reasonable amounts of the substance can be obtained there is usually no great difficulty, since quantitative analyses may be made of both the original substance and its derivatives.

It sometimes happens, however, that, after a compound has been separated from some food substance or excretion, the amount available for examination is exceedingly small, and becomes still smaller after it has undergone purification. In such cases, unless some definite chemical or physiological reaction can be applied, colour tests and other purely empirical methods are adopted, and consequently, although the investigator might be satisfied with the results he had obtained, such results might not carry, and very often do not carry, such weight with others.

It is, therefore, desirable to ascertain if any physical methods are available for a more satisfactory elucidation of such problems.

One constant—the melting point—stands out pre-eminently, since it can be obtained with a very small amount of material. During recent years a modification of the usual method of identifying a substance by taking its melting point has been largely used by organic chemists.* This method may be called that of "mixed melting points."

Speaking broadly, a pure organic substance that is fusible within ordinary limits will melt sharply—that is, at one particular temperature it will be a definite solid, and when the temperature is raised gradually it will assume the liquid phase within 1° C., or possibly 2° C. Now the admixture of foreign substances with the material under examination will totally upset this state of things, and instead of fusion taking place at a definite temperature characteristic of the pure substance, it will commence at an entirely different temperature. This is

* The mixed melting point method was apparently first used by Kipping and Pope (*Trans. Chem. Soc.*, 1893, 63, 558).