THE PHENOMENA OF CATAPHORESIS.

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IN this paper we will confine ourselves to the consideration of the phenomena attending the application of an electric current to the human body, *with* and *without* an interposing medicament, and especially its application to the dental organs.

There are three distinct theories as to the forces at work and their particular action in these processes, and, since there is such a diversity of nomenclature and variety of method for the application of these forces, we will include in this consideration all the methods of applying an electric current to the dental organs for producing anesthesia, whether used in conjunction with a medicament or not.

These theories are,—

First. The polarization of the tissue, producing an inhibition of the sensory impulse.

Second. Osmosis.

Third. Electrolysis.

The first theory provides that when an electric current is applied to a tooth, with or without a medicament, the conditions produced are due entirely, or almost entirely, to the effects of the current and not due to the medicament, other than its assistance in conducting a current. The supporters of this theory are here divided into two classes, from a difference of opinion of the exact method of this inhibition,—whether the decreased excitability is due to the polarizing effect of the current on the tissue, or to its inhibition of the normal sensory impulse by its passage through the nerves.

So far as I know, the leading advocate of the former theory is Professor Neiswanger, of the Post-Graduate Medical School of Chicago. I have also heard Drs. Husted, Oberlin, and Heise, of Cincinnati, and some others favor this theory.

Professor Neiswanger said, in the discussion of an allied subject at the Ohio State Society meeting last December, that owing to the liberation of hydrogen at the negative pole and of oxygen at the positive pole there would be at these two regions respectively a condition of increased and decreased excitability, due to the production of an acid condition at the positive pole and of an alkaline condition at the negative pole, and that the zone of neutrality would be the median of resistance, and consequently that the negative or indifferent electrode should be placed as far as possible from the polarizing electrode. He detailed minutely the action of the gases on the tissue.

The adherents of this polarization theory maintain that the amount of current used is not great enough to produce sufficient electrolysis of the medicament used to produce its effect on the tissue. We will not stop to discuss the various theories until we have stated them all.

The other division of this first theory is, that a constant current applied to the dental branches of the trifacial nerve, with the positive pole applied to the tooth and the negative pole over the Gasserian ganglion, inhibits the normal sensory impulse. The leading advocates of this theory maintain that a certain and intricately definite amount of current, applied in the manner just described, will produce a condition of anesthesia in the tooth, and that either too little or too much will not produce this condition. They call it "short-circuiting the nerve." For its application the positive pole of the constant current is attached to the dental engine in such a manner as to make the bur the electrode, the handpiece being insulated and the negative pole applied over the Gasserian ganglion, on the same side as the tooth to be operated upon, which is perfectly insulated. The chief supporters of this theory are Drs. Horton, of Cleveland, and Lyder, of Akron, with a host of sympathizers. No medicament is used in either of these two processes except moisture in the former, the polarization theory, to reduce the resistance of the dentin. In the latter, the Horton method, the cavity is dehydrated.

The next theory provides that the medicament, which is applied under the electrode, is the agent which does the work, but that it is carried in by a physical force; that in some way, just as a stream of water carries sediment with it, so the electric current carries the ingredients in solution with it through the solvent and through the tissue. The advocates of this theory have furnished almost all the literature that has been written on the theory of cataphoresis since its advent, and in its ranks are to be found many of the foremost men in the dental and medical professions. The most exhaustive articles bearing out this theory have been written by Drs. Morton, Peterson, and Phillips, while a number of shorter articles have appeared from other writers.

To secure the conditions best suited for the development of this process, the positive pole is placed in the cavity or on the tissue to be anesthetized, with an interposing layer of the obtunding medicine, and the negative pole placed at any more or less remote place.

Dr. Morton has said (see Proceedings of the First District Dental Society, New York, December, 1895), "You may even drive solid particles into tissue, and solid particles will move through fluids by the aid of electricity." He says in the same article, "You cannot be too sure of your osmosis."

Dr. Peterson, in his introduction to his valuable article in "The International System of Electro-Therapeutics," says, "From a medical standpoint, we understand by cataphoresis the introduction of medicaments, by means of electricity, into the body through the skin or mucous membranes. It seems to be a *purely physical process*, and has nothing to do with electrolysis." Very many others could be quoted from as supporting this theory with which doubtless you are familiar, but we will pass to the statement of the last theory, namely, electrolysis.

This theory provides that practically all the effect produced in passing an electric current through a medicament as applied in cataphoresis or in any other way is electrolytic. I have not been able to find a single person except one among the writers for the medical and dental profession defending this theory. It may, however, be worthy of consideration.

As the next steps let us consider,—

First. The physiological effect of a constant current on nerve-tissue.

Second. The laws governing osmosis.

Third. The laws governing electrolysis.

For the study of the first, take, for convenience, the sciatic nerve of a frog. Apply the electrodes of a polarizing current to two distant points from each other on the nerve. Before considering the phenomena of muscular contraction let us observe the conditions this current produces in the nerve, relative to any other irritant applied to that nerve. Suppose the irritant to be mechanical, not electrical, to prevent confusion with the polarizing current. The negative pole of the polarizing current is placed nearest to the muscle. The following phenomena will be observed:

First. That the nerve at different points has altered excitability. At some places less than the normal amount of stimulation will produce a contraction of the muscle, while at other points it will take far more than the normal amount of stimulation to produce this contraction, due to the passage of a current.

Second. It will be found that these regions of increased and decreased excitability are confined to the vicinity of the particular electrode,—the region of decreased excitability about the anode, or positive electrode, and the increased excitability about the cathode, or negative electrode.

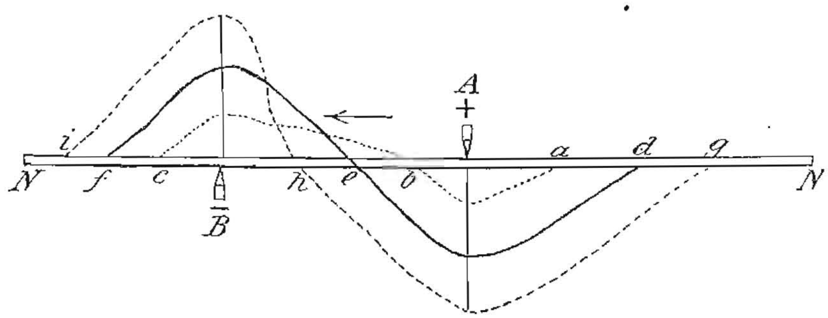
Third. There is a point between the electrodes of normal excitability, which point *varies* in distance from the respective electrodes according as the current is *weak* or *strong*.

Fourth. The *degree* of *decrease* or *increase* of excitability is in *direct proportion* to the strength of the polarizing current.

Fifth. This condition ceases practically at the instant the current is broken.

The alteration of excitability in the region of the poles we will know as electrotonus; that at the positive pole, or anode, as anelectrotonus, and that at the negative pole, or cathode, as catelectrotonus. These terms have been used by different physiologists to express two different conditions.

In 1843 Du Bois-Reymond discovered that the passage of a constant galvanic current through a portion of a nerve produced a change in the electro-motive forces existing between the longi-



tudinal and transverse surfaces, whereby the resulting *nerve-current* was either increased or diminished, according to the direction of the constant current. To this condition he applied the term electrotonus. It was subsequently shown by Pflüger, in 1859, that a definite change in the irritability of the nerve is also caused by the passage of a constant galvanic current, and as it is intimately related to the change in the electro-motive forces he applied to this *alteration of excitability also the term of electrotonus*. This will be the application of the term in this paper. He showed very clearly by the diagram the relative effects of different currents. "The abscissa line *N N* represents the nerve, the decrease in the excitability of which is indicated by an ordinate directed downward, and the increase in excitability by an ordinate directed upward. The electrodes conveying the current to the nerve are represented by *A*, the positive, and *B*, the negative pole. The relative extent of the alterations of the excitability, as revealed by the energy of the muscle contraction following the application of a uniform stimulus, is shown by the curves, the size and extent of which represent the changes produced by a weak, medium, and strong current. The curve also shows that with a weak current *(a, b, c)* the excitability in the anodal (positive) zone is decreased and in the cathodal (negative) zone increased, and that the neutral point *b* lies close to the side of the positive pole. From this point the changes in excitability gradually increase, and reach their maximum in the neighborhood of the electrodes, from which both phases gradually decline. The position of the neutral point also indicates that by far the larger portion of the intra-polar region is in a condition of increased excitability, or catelectrotonus. The curve *d, e, f*, similar in its general form to the preceding, represents the alterations in the excitability produced by a current of medium strength; in direct proportion with the increase of current strength, there is an increase in the amount of anelectrotonus and catelectrotonus and the distance to which they spread themselves into the extra-polar regions. The indifferent point has advanced toward the center of the intra-polar region, indicating that this portion of the nerve is almost equally occupied by the opposite states of excitability. The curve *g, h, i* represents still further the changes following the employment of a strong current. The neutral point has now been shifted toward the cathode, and the intra-polar region is in a condition of anelectrotonus." These changes in excitability are not dependent upon or related to the special nature of the electrical stimulus, for they exhibit themselves upon the application of all forms of stimuli, whether mechanical, chemical, or thermal. The degree of electrotonus is in direct proportion to the strength of the constant current, even to the point of the destruction of the continuity of the nerves. This is a very important fact.

The foregoing laws pertain to motor nerves. Nothing analogous has yet been observed in secretory nerves, but Donders confirmed it in his experiments upon the inhibitory fibers of the vagus. *Does an analogous condition exist in sensory nerves?* This will be observed later.

These preceding laws, as also the laws of contraction produced by an electrical stimulus, have been established on the isolated nerves of frogs under abnormal conditions. Can they be verified on the living human body? Yes and no. Not, of course, under the same conditions, though they can under very complicated conditions. Why can they not? Because of the nerves being surrounded by tissues of different degrees of resistance. This will be the key to the answer of one of these theories.

Suppose the positive pole be placed in a tooth and the negative over the Gasserian ganglion, and suppose, for argument's sake, that the sensory impulse is inhibited, just as the motor is. Will the current travel on the nerve or on the surrounding tissue? To determine this I chloroformed a dog, and with expert assistance dissected out the inferior dental nerve from near the base of the skull to the inferior dental foramen and insulated. The lower cuspid on the same side was excised and insulated, and an electrode placed in the pulp-tissue. With very great care the current through the path, the "pulp and nerve," was determined and found to be 23,630 ohms. The resistance through the path, "the pulp to a point equidistant away on the muscle," with the same electrodes, was determined and found to be 18,570 ohms, which was 5060 ohms less than that of the nerve.

What does this mean? Simply that if the Gasserian ganglion were right on the surface and the negative pole applied to it, the amount of current passing through each, the nerve and muscle, would be inversely in proportion to their resistance. But the nerve does not come to the surface, hence the current to pass through the nerve must travel along on it to a point opposite the negative electrode and then pass out through the tissue to the surface, which the advocates of this theory claim it does. But an electric current always seeks out the path of least resistance, so to fulfill the requirements of this theory the resistance through the nerve would have to be infinitely lower than the resistance of the surrounding tissue. A point of interest here is that the cross-section resistance of a nerve is still five times greater than its longitudinal resistance. The facts are that the current would diffuse throughout the entire tissue of that side of the face, and the amount of current flowing through the nerve at any point in cross-section would be less than that flowing through the same cross-sectional area of the tissue at any point around it within a wide area. Hence the theory of *short-circuiting a nerve* is inconsistent, and its accomplishment in dental therapeutics clearly impossible.

I have demonstrated this same fact on the inferior maxillary of a sheep and on the sciatic nerve of a frog. This is a very important consideration, since it determines to a greater or less extent the possibility of the realization of the fundamentals of both the inhibition and the polarization theories. It was because of this fact that Erb, in 1867, failed to verify on the human body the laws established by Pflüger in 1859. (See *Deutsches Archive für klin. Med.*, Band III, S. 238, 513.) He found as a constant result of many experiments that there occurred a diminution of excitability in the extra-polar catelectrotonic region and an increase in the extra-polar anelectrotonic region.

Helmholtz subsequently demonstrated that the cause of this deviation from Pflüger's law is the position of the nerve in the uninjured body. He says, "Since the nerve is in a position surrounded by a well-conducting medium, even better than itself, the current density in the nerve must rapidly decrease with distance from the electrode. While, of course, under the polarizing electrode the current density in the nerve is the greatest, this density, on account of the moist conductors surrounding the nerve, so rapidly decreases that it becomes almost *nil* for the nerve at even a small distance from the electrodes. At a small distance from the positive pole, therefore, the density is so slight that it may be assumed without error that the current now leaves the nerve, or, in other words, that the cathode, so far as the nerve is concerned, is to be found at this point. It is to be expected, therefore, that the effects of the opposite pole would be observed at only a short distance from the applied pole."

Erb, at this suggestion, renewed his investigations, eliminating this error, and got results harmonizing perfectly with the laws established by Pflüger. For his method of eliminating this error, see Bigelow's "International System of Electro-Therapeutics."

This fact was more thoroughly established by Waller and De Waterville (Physiological Transactions of the Royal Society, 1832), to which reference can be made, or to Waller's "Human Physiology," 1891, page 363.

Now to return to the application of a constant current to the dental organs. Where will the current leave the dentinal nerve if the positive pole be upon the exposed pulp and the negative elsewhere? I need not go into the anatomical structure of the pulp; with that you are certainly all familiar. Nearly two-thirds of a pulp-chamber consists of blood-vessels and their contents; much less than one-third of nerve-fiber, and the remainder of connective tissue, etc.

The blood has a greater conductivity than the nerve-tissue for the same cross-sectional area, consequently most of the current will travel through the surrounding tissue and not through the nerve-tissue. The size of the apical foramen and the resistance through the walls of the pulp-chamber are of some importance in this connection, but time will not permit of their discussion here. In the case considered above but a very small per cent. of the entire current flowing would travel for any distance on the nerve-fibers, since it would go direct to the less resistant tissue. Suppose the current applied just as in the last case, except that the pulp is not exposed and the current must pass through the dentinal tubes. Here, it seems to me, would be an ideal condition for the demonstration of either the polarization or the purely inhibition theory. We would expect that since these tubes contain chiefly the projected fibers of the odontoblastic or spindle-shaped nucleated cells surrounding the pulp, and which are supposed to be the periphery endings of the dentinal nerves, the current would of necessity have to pass through this structure to the pulp before it could disseminate to the other structures. Of course, the lime-salts of the dentin are a non-conductor. If any effect is produced by applying the current in this manner through the drill, it must be on this structure in the tubes, for it would disseminate immediately on arriving at the pulp-tissue. We shall not discuss whether or not these cell projections fill completely the space of these tubuli; probably so, or very nearly so. However, the fact we wish to establish can be easily clinically demonstrated.

Will the current applied under these conditions produce anesthesia of the part to any considerable extent, and why? This is to be answered clinically and theoretically. I give my answer guardedly and after giving the question a very thorough investigation to my own perfect satisfaction, *No.* From a physiological standpoint it would not be possible, since we are dealing with a sensory nerve, whose function is to produce the sense of pain with the very slightest irritation, and with the most sensitive one in the whole human structure.

If the sensory nerve did not respond in the form of pain to the passage of the current we should expect even then that the amount of current necessary to produce this condition, judging from motor nerves, would be many milliamperes.

But you say that the impulse which carries the sensation of pain in the sensory nerve is related to the internal nerve-current of the nerve discovered by Du Bois-Reymond, and why could not this impulse be interposed by an artificial current, thus preventing the pain impulse to pass? This can be answered in two ways: First, this *nerve-current* always travels from center to periphery in motor nerves and from periphery to center in sensory nerves, always in the direction of the impulse; hence it would be in the same direction as the polarizing current, which really increases this *nerve-current* when in the same direction. We should then expect on this theory an increase of sensitiveness.

Again, the normal sensory impulse has no connection with this *nerve-current*, and again even the origin of this *nerve-current* would answer this question. It is to my mind the height of unreasonableness to expect to be able to pass enough current through that sensory nerve to produce the condition of anelectrotonus, since the pain limit will permit scarcely the thousandth part of so great a quantity of current to be passed as would be necessary to produce that same condition in a motor nerve, provided the sensory nerve were capable of an analogous reaction. For the clinical answer to this question I have tried in vain to produce this condition, using every variety of conditions in the tooth and combinations of potential and resistance possible in instruments on the plan of this theory. It is very simple, and would be ideal if possible. Any good cataphoric apparatus will produce every possible combination of any of these instruments that I have seen that are in use at the present time, though not as they were first used. The Horton instrument has a possible total potential of less than six volts and has a variable resistance of less than 50,000 ohms in series, and divided into twenty-four divisions in such a way as to make almost any combination up to that total possible.

I have demonstrated elsewhere and verified repeatedly that the resistance through a tooth, accordingly as the cavity is wet or dry, will vary all the way from thousands to hundreds of thousands of ohms. I have measured cavities in dentin after dehydrating, and found them to vary from 20,000 ohms to over 1,000,000 ohms, and in different parts of the same cavity almost that amount of variation over the surface of the dentin alone, while through the enamel, of course, these figures would be multiplied by thousands.

Two things must be evident to every one at a glance,—viz, that in delivering the current to tooth, from the bur as the positive electrode, it is impossible to have a uniform amount of current flowing as the bur is moved to different parts of the cavity, owing to the variableness of the resistance of the different parts of the cavity, and that with so very high a resistance it would be impossible to have more than an extremely weak current flowing unless the potential were very many times that used.

With the instruments I use, which have been specially constructed, I can measure with precision and express in amperes any amount of current, from the one-hundred-and-twenty-five millionth of an ampere to one-twentieth of an ampere. I have measured the actual amount of current flowing in amperes in the use of two of these instruments as used by their exponents, and found it to vary from six-millionths of an ampere to one twelve-millionth in one case with one instrument, and from one six-millionth to one sixty-millionth of an ampere in one case of another instrument. In my own subsequent investigations I have collated considerable data showing a much greater variation than the above. In view of the fact that this condition of anelectrotonus is in direct proportion to the amount of current flowing, I have passed as high as two milliamperes of current through a healthy live pulp and tried to work on it at the same time, but could not produce this condition of anelectrotonus, even while so strong a current was flowing. I have let it flow for fifteen minutes and not been able to produce any such condition to a sufficient degree to permit of touching the pulp, even slightly, without pain. We saw from the law established by Pflüger that this condition was in direct proportion to the amount of current flowing; hence how impossible for the millionth part of an ampere to produce this condition if two thousand times as much could not.

Another law enters at this point making the realization of the anelectrotonic condition of the dental nerve impossible, which is the law of stimulation of an electric current. This is, that it is the sudden variations of current strength which excite muscular contraction in a motor nerve or in a sensory nerve that produce its normal impulse, pain; hence when the current is delivered to the tissue from a revolving bur every blade brings with it an interruption of the current strength, which, if the current strength were great enough to produce anelectrotonus, would produce such pain as would be positively unbearable. You could scarcely imagine anything more excruciating.

I have an abundance of reserve proof for sustaining this position, among which are the personal experiences of two different afternoons' use of this process on my own teeth by the original introducer and a couple of other similar applications of the method by other advocates, also using it myself on very many patients. Try it yourself. The only precautions are to insulate the tooth and the hand-piece perfectly, and begin with a minimum amount of a constant current and gradually increase.

What are the laws governing osmosis? This theory provides that when we apply an electric current to tissues with an interposing layer of some medicament under the positive pole, the medicament will be carried into the tissue by means of a physical force possessed by the current.

What is osmosis? It is the diffusion of a dissolved substance in a solvent to equalize the concentration.

If a layer of pure water be placed over a solution of sugar, the system immediately commences to suffer a change. The particles of sugar immediately rush from places of a higher up to places of a lower concentration. This diffusion process, as the phenomenon is called, does not cease till the concentration has become the same in all parts of the solution. Let us imagine the sugar to be separated from the pure water by a semi-permeable membrane, such as will allow of the passage of the water, but not of the sugar. Of course the sugar will exert a pressure, and since it cannot go to the water it will produce a hydrostatic force against the partition, which will be moved upward if the apparatus be so arranged that it can; or if the partition cannot move and the chamber in which the sugar is confined be arranged with a capillary tube, the water will pass into the sugar solution through the membrane, increasing the volume of the confined solution, causing it to rise in the tube to a height equal to the osmotic pressure of the sugar. The fact is, that all the conditions just assumed can be realized. This condition exists in any possible solution, and is influenced by many conditions.

The osmotic pressure of cane sugar in water has been demonstrated by Pffefer, using cupric ferro-cyanide as the semi-permeable membrane. He has shown that a saturated solution exerts a pressure of about four atmospheres, which would, at the ocean level, be about sixty pounds to the square inch. The osmotic pressure is in a definite proportion to the concentration and temperature.

This condition is perfectly analogous to that of a gas confined within inclosing walls. It exerts a definite pressure, which is influenced both by temperature and density. The molecules of the gas tend to fill all possible space, each endeavoring to get just as far from every other molecule as possible. Just the same condition exists among the molecules of the dissolved substance; every molecule endeavors to get as far from every other molecule as possible, thus filling the greatest possible space, and they will continue so to do just as long as more pure solvent is provided.

It has been demonstrated by Nernst and Van-Hoff and others that "the osmotic pressure *is independent of the nature of the solvent,* and in general obeys the laws of gases." The various proofs for establishing this law are given in Nernst's "Theoretical Chemistry," 1895. It has also been demonstrated that "solutions having the same osmotic pressure can be obtained by dissolving equimolecular quantities of the most various substances in the same solvent."

It has long been noticed that a coincidence existed between the osmotic pressure of a substance and the gas pressure of the same substance. It is now known that "the osmotic pressure is exactly the same as the gas pressure which would be observed if the solvent were removed and the dissolved substance were left filling the same space in the gaseous state at the same temperature." There is a constant relation between the osmotic pressure, the freezing point, and the vapor tension of substances of the same molecular species.

Nernst says that "the question as to how the nature of the solvent influences the osmotic pressure of the dissolved substance is at once settled by the fact that insomuch as it is identical with the gas pressure there is no dependence at all between the osmotic pressure and the solvent." Which fact is easily demonstrated.

The laws governing the phenomena of osmosis are very clearly understood, and so perfected that the exact constancy and temperature coefficient are known for a large number of substances.

Time will not permit of anything but the most hurried *résumé* of the laws governing osmosis, but from even the few just quoted we can make some valuable deductions as to the *rôle* this force plays in the process of cataphoresis.

Since the nature of the solvent has nothing to do with the osmotic pressure, it at once becomes obvious that,—

First. It does not matter what solvent we use for our cocain, provided it is the force of osmosis that accomplishes the work.

Second. Since the osmotic pressure is in direct proportion to the concentration, the solution should be as nearly saturated as possible.

Third. Since the osmotic pressure is increased to a definite extent by each degree increase of heat, the solution should be kept as hot as possible.

These above observations hold good for practical application *if* the force we are dependent upon is osmosis. We can make our deductions both from a clinical and theoretical standpoint. Will osmosis carry cocain into dentin to any considerable extent? To answer this, I have sealed a saturated solution of cocain into cavities for two days and again for two months without producing anesthesia except on the very surface of the cavity. I have also applied it for some time on an exposed pulp, and could not cut very far into it. Sulfate of strychnia and bichlorid of mercury applied on cotton to the chest of frogs produced no physiological effect, while with a current death was produced in a few minutes. This at one stroke seems to answer the question as to whether osmosis alone can produce this condition.

Now for the theoretical suggestions. We know that if a saturated solution of cocain be placed in a cavity there will be a difference of concentration between the cavity and dentin and the cavity and pulp. We know also that the velocity of migration of the dissolved salt will depend on two things: the osmotic pressure or "head," and the resistance. We have all observed how slowly a very fine precipitate settles. This is the resistance of the solution. Just so the resistance of any solvent to any dissolved substance can be determined from the osmotic pressure and velocity.

Now, as a matter of fact, all cell-tissue and porous partitions offer great resistance to osmosis, and many cells have the power of permitting some substances to pass, while excluding others. This is the foundation of plant-life physiology, and largely of our own physiology. It is for this reason that some bacteria are so difficult of destruction.

In the dentin we have both of these conditions, and it would be expected that a very great barrier would exist here to the osmosis of the cocain. So far as I know, no scientific study has been made of dentin in this connection. It is a good field for some one.

We are forced to conclude, from the clinical observations and theoretical probabilities, that osmotic pressure is not the force on which depends the transmission of cocain through dentin into the pulp. This brings us to a consideration of the last question,—viz,

What are the laws of electrolysis?

What is electrolysis?

"It is the change that is effected by the passage of an electric current, in so far as the electricity exhibits itself as such." How is electricity conducted? As expressed by Nernst and translated by Palmer, "The conveyance of electricity in conducting substances may happen in two different ways,—viz, *with* or *without* the associated transportation of matter. The latter happens in the case of metallic conductors (first class), the former in electrolytic conductors (second class); hence these are called conductors of the first and second classes respectively."

The nature of conduction in the first class (metallic) is unknown, but the nature of conduction in the second class, namely, electrolysis, is quite perfectly understood. From the above author I quote that "The process of the conduction of a current, as a result of electric forces, consists in the displacement of free ions." "By free ions we mean those which are not united with each other to form electrically neutral molecules; the positive ions migrate in a direction from anode to cathode, the negative ions in the opposite direction."

A solution conducts electricity the better the more numerous the ions and the smaller the friction which the ions encounter in their migration. This conception may be applied unchanged to every substance which conducts electrolytically,—whether gaseous, liquid, or solid, whether simple or mixture. Insomuch as it is impossible for a weighable quantity of a substance to consist solely of positive or negative ions,—because this would signify the accumulation of such immense quantities of electricity that the substance would at once be dissipated, in consequence of the repulsion,—therefore only *compound substances*, but no elements, have the property of electrolytic conductivity. Moreover, the molecules of the conducting substances must be dissociated in order that there may be free ions present; *and the free ions are divided into two classes, which are sharply contrasted*, accordingly as they are positively or negatively charged.

The electrolytic charges of the ions are equally great and equivalent, whether they occur in solution or in substances having a simple composition. This would be anticipated, because the fundamental laws of Faraday hold good both for water solution and also for fused salts. It is very remarkable that *we do not know of any electrolyte which in the pure state and at ordinary temperatures has the power of electrolytic conductivity to any marked extent.* Thus, *e.g.*, neither liquid hydrochloric acid nor pure water can conduct electricity noticeably; but when they are mixed they become conductors. The reason for this certainly is not that the ions in the pure liquid experience too great a resistance to their movement, but rather that the liquid electrolytes in the pure state are dissociated only to the very slightest extent. In the passage of a current through any liquid, then, except a metal, the current can pass only by dissociating some of the molecules, called the ionization of the medium, and these ions, which are equal in quantity, migrate in their respective directions. The measure of the ions traveling in either direction is the exact measure of the ions traveling in the other direction and the measure of the current flowing.

This is expressed by Nernst as follows: "When the galvanic current passes through conductors of the second class,—viz, electrolytes, then, in addition to the liberation of heat, there occurs a transportation of matter,—migration of the ions,—and also on the limiting surfaces between the conductors of the first and second classes there occur peculiar chemical processes; these latter consist primarily in the solution of the electrodes or in the separation of the ions from the electrolytes, but they are usually complicated by secondary reactions between the electrolyte and the separated products."

This latter phenomenon, with associated reactions, has been by some thought to be a movement of solid particles.

The quantity of the ion separated in a unit of time upon the electrode is proportional to the intensity (strength) of the current, and the same quantity of electricity will in the most various electrolytes electrolyze chemically equivalent quantities of ions. In those cases where the chemical value of the ions is capable of changing, of course the meaning of *chemical equivalents* changes; thus, the same current which separates two hundred grams of mercury from a solution of $Hg\ (NO_3)_2$ will separate one hundred grams of mercury from a solution of $HgCn_2$. The above author says, "It is only in the rarest cases that the ions themselves are obtained as the product of electrolysis,—*i.e.*, products which have the same composition as the ions as they are primarily separated, which differ from the ions only by having given up their electric charges. Thus the hydrogen ions appear in the form of H_2, the ions of certain metals in the form of metals, and under suitable conditions the ions of the haloids (viz, acidiferous elements) in the form of metaloids." "But much more frequently the ions either act upon each other on being separated, as, *e.g.*, in the decomposition of the acetic acid ion according to the equation,—

$$2\ CH_3\ COO = C_2\ H_6\ CO_2,$$

producing ethane and carbon dioxid; or the ions may react upon the water as when separated sodium gives off secondary hydrogen, or, finally, the ions may react *upon the metal of the electrode*, as when separated chlorin forms the respective chlorid" (or when graphite is put in a silicate of soda solution).

The (freshly separated) ions, which have been deprived of their charges by the aid of the passage of powerful electric energy, are illustrations of substances containing a large quantity of free energy,—that is, illustrations of great affinity. The (freshly separated) ions are capable of performing reactions of which they are quite incapable in the ordinary state. Thus, for example, freshly separated hydrogen, unlike ordinary hydrogen, can reduce nitric acid,—the so-called "nascent state." It is especially worthy of our notice here that electrolytic dissociation as compared with ordinary dissociation is influenced but slightly by temperature. In fact, it sometimes happens that with rising temperature it diminishes, or it may slightly increase, which is in strong contrast with ordinary dissociation, which always rapidly increases with rise of temperature.

Let us now apply some of these laws of electrolysis to the particular process with which we are interested. Suppose the positive pole to be applied to the dentin of a tooth and the negative to the cheek. An interposing layer of medicament, say cocain in water solution, is between the metallic positive electrode and the dentin. Now the only way electricity can get from the metallic positive electrode to the metallic negative electrode is by the dissociation of some of the molecules in every substance of the second class through which it passes. In every part of the course, through the cocain solution, the dentin, the pulp, the connective tissue, the blood-vessels, the muscle-tissue, and the sponge on the negative electrode, there will be a cleavage of some of the molecules of the various chemical compositions into a positive and a negative ion. These ions, with equal force and chemical equivalents, start on their respective journeys toward their opposite poles. They meet with friction which varies for different ions, and since they have the same force behind them, pushing them, their velocities will vary with their resistance. If in their course they meet a new ion or an element or compound for which they have a greater affinity than the force which separated them, they will unite with it until they are again called into service. Unless an ion found such an affinity it would keep on going until it got to the metal plate of the negative electrode, and, if it could unite with it, would do so; if not, would be deposited upon it or be liberated in the form of gas.

Now the question we have heard raised so often, Is the current we use strong enough to produce any electrolysis? must be settled, for if we have no electrolysis we cannot have any current flowing, and the measure of the current is the measure of electrolysis, and *vice versa*. In the case above the hydrochlorid of cocain would probably be broken up as follows: The acid radical will be negatively charged and will go to the positive pole, and the alkaloid will be positively charged and will go to the negative pole. As it passes into the tissue it will doubtless meet ions of oxygen coming toward the positive pole, and at once there will be formed in the tissue a new product, a compound of cocain. Now it is a fact that only a small per cent. of the molecules will ionize or dissociate; hence we see why there has been practically no difference in the effect we observed from using a saturated solution of cocain or a one per cent. solution.

Here again we can make our deductions both from clinical observations and theoretical calculation.

I have observed the following results by applying the cocain solution as stated above:

First. In nearly fifteen hundred cases of which I have kept a record (and in many a complete record of the ampereage, the voltage, and the resistance at both the beginning and the ending of the operation; also the time, size of cavity, and medicine used), the per cent. of perfectly successful cases has been between 95 and 100; and of late, with the increase of experience, all cases have been successful on the second application, if not on the first. Of these fully one hundred were cases in which the pulp was entirely removed at the time, and in about two hundred more the pulp was drilled into and partly removed and a devitalizing agent used to complete the destruction.

Second. In almost all cases of single-rooted teeth the pulp was entirely removed at the time.

Third. No sensation of pain was felt from the devitalizing agent applied after using cataphoresis.

Fourth. Not a single case, as yet, of a dead pulp from the use of cataphoresis.

Fifth. No difference has been noted in the time required for different concentrations of cocain or any other agent.

Sixth. The average time required was about thirteen minutes.

Seventh. The amount of current tolerable in a case of unexposed healthy pulp is determined by the effect of the current on the pulp-tissue and not on the dentin.

Eighth. The resistance through the wet dentin varies all the way from a few thousand to five hundred thousand ohms.

Ninth. The amount of current tolerable has been found to vary from one two-hundred-thousandth of an ampere to two-thousandths of an ampere, the average being less than two ten-thousandths at the beginning of the operation and four ten-thousandths at the finish. Of course, where pulps were devitalized a very much stronger current was used for the finish, but seldom more than that amount was used where the continued life of a pulp was expected.

Tenth. There are no constant symptoms that will give any indication of the amount of current flowing. Each case has a different pain limit; hence the *absolute* necessity of using a milliamperemeter.

Eleventh. No effect has ever been noted in the tissues beyond the tooth except where a very strong current was used; then slight periostitis.

What deductions can we make from the above clinical results? And the foregoing laws of nerve excitability, the laws of osmosis, and the laws of electrolysis?

We know that when a solution of cocain is supplied to the dentin of a tooth under the positive pole, with a negative elsewhere, we do get anesthesia not only of the dentin, but of the pulp-tissue, if applied long enough.

Will the current alone produce this condition? Answer, *No.*

Then it is not the current that does the work.

Will the medicine alone produce this condition? Answer, *No.* Then it is not a simple osmosis.

Does the current so applied produce any change in the cocain solution? Answer, *Yes.* It cannot pass through it except by changing it.

Is there a transmission of matter in this solution under these conditions by simple osmosis? Answer, probably very slight.

Is there a considerable transmission of matter at all? Answer, *Yes*, by the migration of the ions.

Do these ions produce currents which carry the unchanged medicine with them? Theoretically, yes, but practically, *very* slight.

Are these currents produced in both directions? Answer, *Yes.*

Can an osmosis be produced from a negative to a positive pole? Yes, in some solutions. (An analogous phenomenon is observed, though by a different force, when a globule of mercury is placed between two electrodes in water; the globule goes to the positive pole.)

According to the older theories, there was supposed to be a physical force exerted in some manner by the electric current applied in this manner, and this theory has its advocates yet. There is a newer theory, however, which is made by its introducer to explain all the phenomena. Its author is Nernst, of Göttingen, Germany. He maintains that there is no transmission of matter except the ions themselves. Of course, the accumulation of the ions at the electrodes will produce a difference of concentration of the products they form, which would set up osmotic currents. These are granted, but there is a different opinion as to their strength, which is probably extremely slight.

Now to follow this same argument in this connection, if it is the force of osmosis on which we are dependent, what will be the effect of the new molecules of hydrochlorid of cocain formed in the pulp-tissue by electrolysis on the osmosis from without? Of course, if such is formed it would diminish the difference of concentration within and without the pulp-chamber, and by doing so would lessen the force of the osmotic pressure, which is in direct proportion to the difference of concentration at different points. In this case it would not seem that the current was helping the process. It is certain that we are not dependent on a difference of concentration for the development of the force that carries the cocain through the tissue. Do we know that a medicament can actually be forced into the pulp at all? Answer, yes, in many ways. I have put sulfate of morphin with the cocain, and after extracting the pulp on a broach been able to detect the morphin by the nitric acid test under the microscope. I have killed a frog in twenty minutes with sulfate of strychnin with the current, when neither the current alone nor the medicine alone, left for a considerable time, produced any noticeable effect. I do not believe the medicine was in any case carried in as the original chemical species, but was changed by electrolysis; and further, with the conditions under which we use cataphoresis, I believe the forces upon which we are dependent are the dissociation of the molecules and the increased energy of these dissociated products. These ions, by their increased energy, by their migration, and by the new chemical species they form, are capable of producing just such phenomena as are produced in cataphoresis, as will be seen by this simple experiment.

The final goal is, of course, to diminish the time. I do not believe this will be done by seeking directly for a substance that has a high osmotic pressure, but rather by seeking for a reaction that will produce the most active ion. It is true, however, that substances that have a high osmotic pressure have good conductivity. Since the amount of current we can use is limited by the pain limit of the tissue, and the amount of electrolysis is a constant expression of the strength of current, of course the amount of chemical energy we can liberate is fixed, and we cannot hope to change this unless we can change some of the laws of either *physiology, electrolysis,* or *chemistry.* We have left these unfixed conditions to modify,—viz, to select the ions with greatest migration velocity, and which themselves, or the compounds which they will form, will produce the greatest physiological effect upon the tissue for the same unit of concentration in the tissue. There is no reason why great advancement should not be expected along this line, and it is my opinion that when it does come it must come along this line.

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