OBSERVATIONS ON ELECTRO-OSMOSIS

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The present investigation was undertaken with the object of throwing light upon the enquiry whether it is possible to introduce dissolved substances into living tissues by means of electro-osmosis. Early in the course of this work it became apparent that, so long as the investigation was confined to living tissues, serious limitations would be encountered as regards the number and duration of the observations possible, as well as in consequence of the relatively low strength of current necessarily employed when it was desired to preserve uninjured the vitality of the living surface to which the current was applied. Since living matter is largely colloidal it was determined to study as far as possible electro-osmosis in respect of colloidal membranes. In all of such experiments the degree of electro-osmosis was ascertained quantitatively, for it is obvious that the practical value of electro-osmosis, if it can be employed as a means of introducing dissolved substances, would depend upon the amount of fluid which could be made to pass into the living tissues under the conditions of experiment obtaining. The selection of the type of experiment performed is necessarily largely determined by current hypothesis as to the nature of this phenomenon, and the same applies to the interpretation of the results obtained.

It will be convenient, in detailing the results of this investigation, to exhibit first of all the degree of osmosis obtainable through living tissues, colloidal membranes and porous diaphragms under similar conditions of experiment. A short reference will then be made to the theory of electro-osmosis, after which some experiments bearing upon the possibility of employing electro-osmosis as a means of introducing dissolved substances into living tissues will be described. The latter are incomplete, but as the course of this work is temporarily interrupted, it has been thought best to present it in an incomplete form rather than delay for an indefinite period publication of the results already obtained.

DEGREE OF ELECTRO-OSMOSIS OBTAINABLE

The fluids employed in the experiments about to be described were alcohol and water. The latter was sometimes used in the form of distilled water, but more frequently contained dissolved salts.

The media in which electro-osmosis was studied were of three kinds; porous plugs, contained in glass tubes; colloids in the form of hydrogel or colloidal solid; and living tissues.

For convenience of comparison the degree of electro-osmosis is always given per square centimetre sectional area of the medium and in respect of a potential fall of one volt per centimetre length of the medium. It may here be observed that the amount of electro-osmosis with a given sectional area of medium is proportional to the potential fall per centimetre. So long as the potential fall is maintained constant, the degree of electro-osmosis per square centimetre is independent of the length of medium traversed by the current.

FIG. 1.

The experiments made with porous plugs were of two kinds; those made with filter paper or cotton wool and those in which powdered naphthalene or sulphur was employed.

In experiments made with filter paper the apparatus shown in fig. 1¹ was used. The description of this apparatus is given on p. 330. In the experiments made with cotton wool, naphthalene, and sulphur, Perrin's apparatus shown in fig. 2 was used. This consists of a glass tube (*a*), filled with the substance employed as diaphragm, and fitted by means of ground surfaces into (1) a vertical limb (*b*), provided above with a stopcock and connected with a horizontal measuring tube

1. Figs. 1 and 2 are approximately one-quarter, and Figs. 5 and 7 one-half the natural size. Figs. 3 and 4 are reduced to one-sixth and three-quarters, respectively, of the actual size.

(*d*), furnished with a bulb at its extremity; and (2) the curved limb (*c*), provided below with a stopcock. Two electrodes, marked + and –, are introduced into the apparatus as shown in the figure.

FIG. 2.

Some observations made with the above forms of apparatus are recorded in Table I, which serves to illustrate the degree of electro-osmosis observed. The latter ranged, it may be observed, between 0.015 c.c. and 0.2 c.c. per hour, being less marked when 70 per cent. alcohol was employed than when distilled water or a solution of glucose was used. In all cases the flow of liquid by electro-osmosis was from anode to kathode, that is to say, in the direction of the current.

TABLE I.—Electro-osmosis through various diaphragms. The amounts of fluid given below correspond to a sectional area of one square centimetre and a potential fall in the plug of one volt per centimetre. The first three experiments were made with the apparatus shown in Fig. 1; the remaining experiments were made with Perrin's apparatus, Fig. 2. The + sign indicates flow of fluid from anode to kathode.

No. of Experiment	Liquid in contact with diaphragm	Material of which diaphragm was composed	Amount of electro-osmosis per hour.
1	5 % solution of glucose in water	Filter paper	Approximately + 180 c.mm.
2	5 % solution of glucose in water	Filter paper	Approximately + 130 c.mm.
3	5 % solution of glucose in water	Filter paper	Approximately + 100 c.mm.
4	70 % alcohol	Cotton wool (<i>a</i>)	Approximately + 34 c.mm.
5	70 % alcohol	Cotton wool (<i>b</i>)	Approximately + 35 c.mm.
6	70 % alcohol	Cotton wool (<i>c</i>)	Approximately + 35 c.mm.
7	70 % alcohol	Powdered naphthalene	Approximately + 15 c.mm.
8	70 % alcohol	Powdered sulphur	Approximately + 44 c.mm.
9	Distilled water	Powdered sulphur	Approximately + 191 c.mm.
10	Distilled water	Powdered sulphur	Approximately + 197 c.mm.

When studying electro-osmosis through colloids immersed in watery liquids the apparatus shown in fig. 3 was employed. In this apparatus the colloid is used in the form of a diaphragm (*a*), 1 mm. or less in thickness, placed between two curved tubes (*bb*), in the lower part of which electrodes, marked + and -, are placed. Above are two graduated measuring tubes (*cc*), 3 mm. in internal diameter, by means of which the amount of fluid passing through the diaphragm is determined, the stopcocks shown in the figure being closed during the passage of the current. Fluid is introduced into the apparatus through the narrowed portion of the curved limbs, which are provided with stopcocks, or by means of a very fine capillary pipette introduced into the graduated vertical pieces (*cc*). The electrodes were usually made of copper immersed in a 10 per cent. solution of CuSO_4 , above which was placed the fluid in which the diaphragm was immersed; but in experiments with gelatine, silver electrodes were employed, immersed in a N/10 solution of AgNO_3 , between which and the liquid used for observing electro-osmosis a solution of NaNO_3 generally intervened.

The colloids employed for the diaphragm were three in number; a hydrogel of washed gelatine (10 per cent.); a hydrogel of agar (1.5 per cent.); and an insoluble colloidal solid consisting of parchment paper. These diaphragms were held in position by metal or vulcanite flanges, indicated in fig. 3, which were clamped together and rendered water-

FIG. 3.

tight by means of shellac. When gelatine or agar was employed, the diaphragm was formed by painting linen with the dissolved colloid which was then allowed to set. In some of our earlier experiments, instead of the diaphragm of gelatine or agar shown in fig. 3, a solid plug was employed several centimetres in length, but this was given up in consequence of a difficulty referred to later (p. 323). When a thin diaphragm is used diffusion readily occurs, so that an equilibrium between the salts contained in the colloid and those present in the surrounding liquid is very quickly obtained, but if a solid colloidal plug is employed it is difficult to secure such equilibrium.

The fluids employed when using the apparatus shown in fig. 3 consisted, in addition to distilled water, of varying concentrations of the monovalent, divalent and trivalent salts enumerated in Experiments 2 to 8, Table 2, and in Experiments 9 to 12, of a 0.01M to 0.02M solution of sodium sulphate or nitrate saturated with iodine and containing, in addition, in Experiments 9 and 10, 33 per cent. of alcohol. The results obtained in the former series (Experiments 2 to 8) are given in full elsewhere;¹ in the Table the amount of electro-osmosis obtainable with 0.02M and 0.01M solutions is given. The degree of electro-osmosis obtained should be compared with that exhibited in the preceding and succeeding Tables.

TABLE II.—Electro-osmosis through colloidal membranes immersed in watery liquids. The apparatus shown in Fig. 3 was employed. The amounts of fluid given below correspond to a sectional area of one square centimetre and a potential fall in the colloid of one volt per centimetre. The sign + indicates a flow of fluid from anode to kathode; the sign — indicates a flow of fluid from kathode to anode.

No. of Experiment	Concentration of electrolyte in liquid in contact with medium	Amount of fluid passing per hour by electro-osmosis through colloid. The electrolytes employed are given in brackets		
		Gelatine (10 %)	Agar (1.5 %)	Parchment paper
1	Distilled water	Could not be measured	Could not be measured	Could not be measured
2	0.02M		+ 365 c.mm. (Na_3PO_4)	+ 4.15 c.mm. (Na_3PO_4)
3	0.02M	+ 198.3 c.mm. (Na_2SO_4)	+ 374 c.mm. (Na_2SO_4)	+ 4.31 c.mm. (Na_2SO_4)
4	0.02M	+ 184.2 c.mm. (NaOH)	+ 370 c.mm. (NaOH)	+ 3.64 c.mm. (NaOH)
5	0.02M	+ 68.3 c.mm. (NaNO_3)	+ 362 c.mm. (NaCl)	+ 2.10 c.mm. (NaCl)
6	0.02M	— 171.4 c.mm. (HNO_3)	+ 103 c.mm. (HCl)	+ 1.08 c.mm. (HCl)
7	0.02M	— 286.5 c.mm. ($\text{Cu}(\text{NO}_3)_2$)	+ 103 c.mm. (CuCl_2)	+ 1.32 c.mm. (CuCl_2)
8	0.02M	— 693.0 c.mm. ($\text{Al}(\text{NO}_3)_3$)	+ 64 c.mm. (AlCl_3)	+ 0.15 c.mm. (AlCl_3)
9	0.01M	— 19.6 c.mm. (Na_2SO_4)*		
10	0.01M	— 28.5 c.mm. (NaNO_3)*		
11	0.01M	— 36.6 c.mm. (NaNO_3)*		
12	0.02M	— 54.8 c.mm. (NaNO_3)*		

1. Barratt, J. O. Wakelin, and Harris, A. B. 'Elektroosmose und Konzentration der Elektrolyte,' *Zeitschr. f. Elektrochemie*, Bd. XVIII, S. 221, 1912.

* In Experiments 9 and 10 the sodium salt employed was dissolved in water containing 33 per cent. of alcohol. In Experiments 11 and 12 a watery solution of sodium nitrate free from alcohol was used. In these four experiments the solution of sodium salt in contact with the diaphragm was saturated with iodine.

The amount of electro-osmosis observed ranges, it will be seen, from 0.693 c.c. to less than 0.0002 c.c. per hour. The direction of osmosis is that of the current, except in some observations made with gelatine, in which the direction is from kathode to anode. In Experiments 2 to 8 the influence of decreasing valency of anion and of increasing valency of kation in diminishing the rate of flow of liquid from anode to kathode or of reversing its direction (in the case of gelatine) is shown. When gelatine is immersed in a solution of sodium sulphate or nitrate, the flow of liquid is from anode to kathode; if iodine is added the direction of flow is reversed.

The observations made upon living tissues now remain to be described. In these experiments the human forearm was used, the apparatus shown in fig. 4 being employed. This consists of a flanged glass bowl, the mouth of which is applied to the skin, to which it is affixed by means of collodion. To the upper part of the bowl is attached a graduated glass tube, having an internal diameter of 2 mm., which is

FIG. 4.

kept in a horizontal position during experiment. Near this tube a platinum electrode is sealed into the bowl. Before use the electrode is covered thickly with electrolytically deposited zinc. When used for experiment the apparatus, after being attached to the skin, is filled with a 4 per cent. solution of ZnSO_4 , by means of a pipette introduced into the horizontal tube, all air bubbles being removed. The forearm is supported below in a dish containing a 4 per cent. solution of ZnSO_4 , into which an electrode is placed.

When a current is passed through the forearm a passage of fluid from anode to kathode occurs. So long as the circulation in the forearm continues this is not, however, recognisable, for oedema of the skin occurs, in consequence of which the fluid in the horizontal tube is driven towards the mouth of this tube whatever the direction of the current may be. This difficulty was removed by applying an indiarubber bandage to the forearm and elbow so that the tissues were largely emptied of blood, after which a ligature was placed on the middle of the arm, arresting the circulation beyond; the indiarubber bandage was then removed below

the ligature and the apparatus fixed in position. Under these circumstances no oedema occurred during the course of the experiment. The forearm and hand soon became numb, and after a time cold. The application of the ligature was attended with a certain amount of discomfort; it could be borne, however, for a period of about three-quarters of an hour.

The experiments were performed in the following manner. After the apparatus had been applied as above described, an interval of ten minutes was allowed to elapse in order to make sure that the level of fluid in the horizontal tube was nearly constant. A current was then allowed to pass for fifteen minutes and the movement of the meniscus in the horizontal tube noted. At the end of this period the current was passed in the reverse direction for ten to fifteen minutes, during which time a nearly equal movement of the meniscus in the opposite direction occurred. The current was then broken, and the position of the meniscus noted for a further period of ten minutes, during which no current was passing. Sometimes the current was passed for about twenty-five minutes in one direction only, the reversal of current being omitted. In these experiments it is essential that the forearm should be kept as free from movement as possible, the subject assuming at the beginning of the experiment a comfortable position, which is subsequently maintained unchanged. During the periods, at the beginning and end of the experiment, while no current is passing, the meniscus in the horizontal

TABLE III.—Electro-osmosis through forearm. The apparatus shown in Fig. 4 was attached to the skin. The amounts of fluid given below correspond to a sectional area of one square centimetre and a potential fall of approximately one volt per centimetre. The sign + indicates that the flow of fluid is from anode to kathode.

Subject of Experiment	Amount of fluid passing per hour by electro-osmosis through forearm.	
B	+ 11.3 c.mm. (kathode inside apparatus)	+ 5.0 c.mm. (anode inside apparatus)
B	+ 10.7 c.mm. (kathode inside apparatus)	+ 11.5 c.mm. (anode inside apparatus)
H	+ 9.0 c.mm. (kathode inside apparatus)	+ 7.9 c.mm. (anode inside apparatus)
A	+ 6.3 c.mm. (kathode inside apparatus)	+ 15.0 c.mm. (anode inside apparatus)
A	+ 26.0 c.mm. (kathode inside apparatus)	+ 17.5 c.mm. (anode inside apparatus)
W	+ 13.0 c.mm. (kathode inside apparatus)	+ 9.8 c.mm. (anode inside apparatus)
	Mean 12.7 c.mm.	Mean 11.1 c.mm.

tube exhibited slight variation in position, but no definite movement in one direction; during the passage of the current a movement was observed which was constant, its direction being determined by that of the current.

The results of a number of experiments of this type are given in Table III. With different subjects and strengths of current ranging

from 2 milliamperes to 4 milliamperes per square centimetre, some differences in the rate of flow of fluid were observed, and again on changing the direction of the current the reversed flow did not always take place at the original rate. Nevertheless, the variations observed were on the whole inconsiderable, the mean value for a potential fall of approximately one volt per centimetre being 11·9 c.mm. per hour per square centimetre of surface of skin. With currents exceeding 9 milliamperes per square centimetre of surface, superficial sloughing of the skin occurred. The duration of application of the current was, as already mentioned, about twenty-five minutes.

The direction of electro-osmosis through the forearm was from anode to kathode. For convenience of comparison the direction of flow of fluid in these and the preceding experiments is indicated in Table IV.

TABLE IV.—Direction of electro-osmosis (compiled from I, II and III).

No. of Experiment	Liquid in contact with medium	Medium employed and direction taken by fluid.				
		Plug of filter paper	Gelatine	Agar	Parchment paper	Forearm
1	Solution of glucose	+—>—				
2	Distilled water	No movement recognisable				
3	Solution of Na_3PO_4		+—>—	+—>—	+—>—	—
4	Solution of Na_2SO_4		+—>—	+—>—	+—>—	—
5	Solution of NaOH		+—>—	+—>—	+—>—	—
6	Solution of NaCl or NaNO_3		+>—	+—>—	+—>—	—
7	Solution of HCl or HNO_3		+<—	+—>—	+—>—	—
8	Solution of CuCl_2 or $\text{Cu}(\text{NO}_3)_2$		+<—	+—>—	+—>—	—
9	Solution of AlCl_3 or $\text{Al}(\text{NO}_3)_3$		+<—	+—>—	+—>—	—
10	Iodine in water		+<—			
11	Solution of zinc sulphate					+>—

When a current is passed as above described through the forearm, little or no sensation is ordinarily experienced, so long as the strength of the current does not exceed 3 milliamperes per square centimetre. With a current of 6 milliamperes, tingling is frequently produced. If still stronger currents are employed, a smarting or burning sensation is felt; such currents can, however, be borne provided the strength of current is increased very gradually, the passage of the current being after a time attended with some blunting of sensibility. When the circulation is re-established in the limb, transient swelling of the skin, generally attended by redness, occurs in the area of application of the current.

If the current has been too strong, blanching of the skin may take place, and superficial necrosis is likely to occur. When such injury follows the application of the current, it is generally irregular in distribution, the surface of the skin being unequally affected. Commonly necrosis, if it occurs, takes place around the mouths of the hair follicles, in which situation the current appears to enter more readily than elsewhere. The current which can be applied without injury, varies in different individuals. Any breach of surface which may be present at the time of application of the current is likely to be the seat of subsequent sloughing, even if a current of only 2 milliamperes per square centimetre is employed.

Before concluding this section, reference may be made to an effect of electro-osmosis, which at first exercised a disturbing influence upon the course of these experiments. It was sometimes found that when a current

FIG. 5.

was passed through a glass tube (*a*, fig. 5) partly filled with a hydrogel of gelatine (containing 40 per cent. of gelatine and 0.6 per cent. of NaCl), above which was a solution of an electrolyte, the degree of electro-osmosis diminished as the experiment proceeded, and after a time its direction¹ became reversed. In such cases, the upper surface of the gelatine (the condition of the lower surface could not usually be

1. To measure the rate and direction of flow the upper electrode was sealed into the vertical tube *a*, which was closed above and connected with a horizontal measuring capillary. Other forms of apparatus were also used.

observed) was seen to become cupped, and a few millimetres below the apex of the cup a crack appeared after a time in the gelatine. This phenomenon was observed when a 0.1M solution of CuSO_4 , containing a copper anode, or a 0.1M solution of ZnSO_4 , containing a zinc anode, was placed above the gelatine. In fig. 5, *b c d* represent the appearance of the gelatine in tube *a*, two hours, three hours, and four hours, respectively, after the commencement of the experiment. Below the surface of the gelatine is a dark-coloured green zone into which Cu^{++} ions have penetrated; beneath this is a lighter greenish zone indicated by a double contour in *b*, *c* and *d*, representing the advancing layer of these ions. Still lower a horizontal reflecting surface is seen (indicated in the figure by a horizontal line). This appears to be caused by removal of water by electro-osmosis from the upper portion of the gelatine, the refractive index of which is in consequence no longer the same as that of the more watery portion of the gelatine below. This boundary surface was found to travel, under a potential fall of one volt per centimetre, at the rate of 0.93 cm. to 1.05 cm. per hour. A crack, placed obliquely and reaching below to this boundary surface, is seen in *c* and *d*.

The explanation of this phenomenon was ultimately found to be as follows:—When Cu^{++} or Zn^{++} ions passed into the gel, causing it to become green in the former case, and somewhat opaque, the direction of electro-osmosis in this portion of the gel, in contact with the solution of CuSO_4 or ZnSO_4 , became reversed, while that occurring in the unchanged gel below continued its original direction unaltered. In consequence, at the junction of the two the gel became rapidly deprived of water and very marked cupping took place. As soon as the latter became unable to compensate for the contraction of the gelatine a crack appeared in the gelatine, attended with the formation of an air space. When the hydrogel of gelatine, instead of being made up with 0.6 per cent. NaCl solution or with distilled water, was made up with CuSO_4 solution of the same concentration as that used in the liquid above, cupping did not occur or was very slight, and no cracks formed.

It may be observed that the effect of adding an electrolyte to a gel of gelatine or agar is to cause contraction of the gel, which usually swells up again (though not necessarily to the original extent) when placed once more in distilled water. Some salts, however, such as HgCl_2 , cause permanent shrinking. Irreversibility is also conferred upon gelatine by Hg salts, formol and iodine.

NATURE OF ELECTRO-OSMOSIS

Electro-osmosis was observed as long ago as 1807 by Reuss.¹ It was re-discovered by Porret,² and was further studied by de la Rive,³ Becquerel⁴, Daniell,⁵ Napier,⁶ and Wiedemann.⁷

Reuss placed two tubes, containing electrodes immersed in water, in a mass of clay and found that the level of the fluid during the passage of the current rose in the kathode tube and sank in the anode tube. In consequence of this passage of fluid the phenomenon was compared to osmosis, but the resemblance is only a superficial one, since at the commencement of the experiment the fluids are of the same concentration. As the current continued to pass, the difference of level in the two sections of the cell increased up to a certain point and then remained unchanged, the hydrostatic pressure balancing the action of electro-osmosis. The

FIG. 6.

degree of electro-osmosis can therefore be measured in terms of the equilibrated height (H), which has been shown by G. Wiedemann,⁷

1. Reuss, F. 'Notice sur un nouvel effet de d'électricité galvanique.' *Mémoire de la Soc. imp. des Naturalistes à Moscou*, T. H., 1809, pp. 330-332.
2. Porret. Thomson, *Annals of Phil.*, VIII, p. 74, July, 1816.
3. de la Rive. *Traité de l'Electr.*, II, p. 379; *Ann. de Chim. et de Phys.*, XXVIII, p. 125, 1825.
4. Becquerel. *Traité de l'Electr.*, III, 102.
5. Daniell. *Ann. d. Physik. u. Chemie*, 1835, *Ergänzungsbd.*, I, 569.
6. Napier. *Phil. Mag.*, July, 1846.
7. Wiedemann, G. *Galvanismus*, I, S. 377; 'Über die Bewegung von Flüssigkeiten im Kreise der geschlossenen galvanischen Säule.' *Ann. d. Physik. u. Chemie*, Bd. LXXXVII, 321, 1852; 'Über die Bewegung der Flüssigkeiten im Kreise der geschlossenen galvanischen Säule und ihre Beziehungen zur Elektrolyse.' *Ann. d. Physik. u. Chemie*, XCIX, p. 177, 1856.

employing the apparatus shown in fig. 6,¹ to be directly proportional to the strength of the current (c), the specific resistance of the solution (r), and the thickness of the diaphragm (t), and inversely proportional to the sectional area S , according to the formula:—

$$H = \text{constant} \times \frac{Crt}{S}$$

Since $\frac{rt}{S}$ represents the resistance of the diaphragm the expression $C \frac{rt}{S} = CR$, i.e., the potential fall between the sides of the diaphragm (E), so that the formula may be written:—

$$H = \text{constant} \times E$$

Wiedemann concluded that the galvanic current caused a direct transport of fluid, in virtue of a traction which it exerted upon each element of volume of fluid which it traversed. This conclusion was contested by Graham,² v. Quintus Icilius,³ and Breda and Logemann,⁴ who pointed out that it was impossible to demonstrate the transport of fluid in the absence of a diaphragm.

Further investigations were made by G. Quincke,⁵ who studying electro-osmosis in capillary glass tubes provided with platinum wire electrodes, advanced an interpretation of electro-osmosis, which still remains the accepted explanation of this phenomenon. Quincke observed that when particles of clay were suspended in the liquid between the electrodes, a movement towards one or other electrode occurred (in water towards the anode). He therefore concluded that, at the surface of contact of solid and liquid, opposite electrical charges appeared, an electrical double layer resulting. A system of this kind would be affected by a potential gradient in such a way that the positively charged portion of the system is moved in one direction and the negatively charged portion in the other direction. If the solid were fixed, then movement of the

1. This consists of a porous clay cylinder, closed below and cemented above to a vertical glass tube provided with a horizontal capillary which delivers fluid into a receiver or, in another form of the apparatus, is continuous with a manometer tube. Passing through the vertical glass tube is a platinum wire connected with a cylindrical electrode of platinum foil, (*b*) placed in the clay vessel. The latter is contained in a beaker filled with water and is surrounded by a second cylindrical electrode (*a*) made of lead.

2. Graham. *Phil. Mag.*, VIII, p. 151, 1854.

3. v. Quintus Icilius. *Lehrbuch der Experimental-Physik*, S. 642, 1855.

4. Breda and Logemann. *Ann. d. Physik. u. Chemie*, Bd. C, S. 149, 1857.

5. Quincke, G. 'Üeber die Fortführung materieller Theilchen durch strömende Elektrizität. *Ann. d. Physik. u. Chemie*, Bd. CXIII, S. 513, 1861.

liquid alone would occur. Subsequently Helmholtz¹ advanced a mathematical theory of the electrical double layer and showed that Quincke's explanation was theoretically tenable.

Hardy² observed that particles of globulin of different size contained in solutions of varying concentration, the aspect of which ranged from transparency to opalescence, moved at the same rate. Since the velocity of the particles was, within the limits of concentration employed, independent of their size, it follows from Helmholtz's theory of electro-osmosis that the density of the charge per unit of surface is constant and the total quantity of electricity on each particle (Q) is directly proportional to the surface according to the equation

$$Q = \sigma 4 \pi r^2$$

Helmholtz showed that the potential difference E , at the junction of solid and fluid in a capillary tube was given by the equation

$$E = \frac{4 \eta \phi}{K r^2 H}$$

Where K is the specific inductive coefficient of the liquid,³ η the coefficient of internal friction of the fluid, (r) the radius of the tube, H the strength of the electric field, and ϕ the amount of liquid passing through the tube per second under the influence of the electric field.

Data respecting the amount of fluid carried by electro-osmosis are scanty. A few determinations of the amounts of fluid transported through a clay diaphragm immersed in dilute solutions of H_2SO_4 , CuSO_4 , $\text{Cu}(\text{NO}_3)_2$, and AgNO_3 by currents of a known strength were given by Wiedemann (1856).⁴ Further determinations of the relative rate of flow of fluid through hydrogels under a fixed potential gradient are given by Perrin.⁵ More recently Barratt and Harris⁶ have determined the absolute rate of flow of fluid by electro-osmosis through gelatine, agar, and parchment paper, when various concentrations of electrolytes are employed. From these observations the data given in Experiments 2 to 8, Table II, are selected.

1. Helmholtz. 'Studien über electrische Grenzsichten. Wiedem., *Ann. d. Ph. u. Ch.*, Bd. VII, S. 337, 1887.
2. Hardy, W. B. 'Colloidal solution. The globulins.' *Journ. of Physiol.*, XXXIII, p. 251, 1905-6.
3. K is introduced into the formula by J. Perrin, 'Mécanisme der l'électrisation de contact et solutions colloïdales.' *Journ. der Chimie Physique*, II, p. 601, 1904; III, p. 50, 1905.
4. *Loc. cit.*, p. 177.
5. *Loc. cit.*
6. Barratt, J. O. Wakelin, and Harris, A. B. *Loc. cit.*

The flow of fluid in electro-osmosis is obviously determined by the movement of the ions contained in the liquid at the surface of contact with solid. These ions, as they move under the influence of the potential gradient, cause a passive movement, in the same direction, of the molecules of liquid. The narrower the interval between the particles of which the diaphragm is composed, the more marked this movement of liquid will be. Further, the more numerous the ions in the liquid portion of the double layer, the greater the flow of liquid will at first be, though with continued increase in the number of ions a diminution of concentration of fluid will later occur and the flow will diminish; thus the curve obtained by plotting concentrations, as abscissae, against rates of flow, as ordinates, under a given potential gradient, will exhibit a maximum, corresponding in the case of agar to a concentration of electrolyte about 0.02M, while on each side of this maximum, with greater and lesser concentrations, the curve will exhibit a diminished rate of flow.¹

Up to the present it has been tacitly assumed that electro-osmosis has been brought about solely by the movement of unaltered ions. If, however, the ions in question became centres for the condensation or combination of water molecules, then an additional factor in the transport of fluid would come into play. Nernst² showed how the problem of ionic hydration might be investigated by means of diffusion and migration experiments in which an indifferent dissolved substance was used as indicator. Lotmar,³ employing one of Nernst's methods, showed that hydration of ions occurs. Lobry de Bruyn,⁴ using a solution of silver nitrate in aqueous methyl alcohol, was unable to obtain evidence of ion hydrates or alcoholates. Morgan and Kanolt,⁵ however, studying electrolysis of a solution of copper nitrate in water and alcohol by a procedure similar to Nernst's second method, concluded that copper ions were hydrated.

Obviously if the ions contained in the liquid portion of the double electrical layer are hydrated, the rate of flow will be much greater than would be the case if no hydration occurred. Usually the current

1. Barratt, J. O. Wakelin, and Harris, A. B. *Loc. cit.* Figs. 172-174, pp. 223-224.
2. Nernst, W. 'Zur Frage nach der Hydratation gelöster Substanzen,' I, *Nachr. d. k. Gesellsch. d. Wissensch.*, Göttingen, Math.-Phys. Kl., S. 68, 1900.
3. Lotmar, H. 'Zur Frage nach der Hydratation gelöster Substanzen,' II, *Nachr. d. k. Gesellsch. d. Wissensch.*, Göttingen, Math.-Phys. Kl., S. 70, 1900.
4. Lobry de Bruyn. *Jahrb. d. Elektrochemie*, Bd. X, p. 260, 1904.
5. Morgan and Kanolt. 'Über die Verbindung der Lösungsmittel mit den Ionen,' *Zeitschr. f. physikal. Chemie*, Bd. XLVIII, S. 365, 1904.

would not be conveyed wholly by the ions contained in the liquid portion of the double layer, though as an exceptional event this might conceivably occur if the particles of which the diaphragm was composed were in sufficiently close apposition. More usually the current would be in part conveyed by ions of the electrolyte employed, which do not form part of the double electrical layer at the surface of solid and liquid. In the latter case there would be, if the ions were hydrated, an additional transport of fluid representing the difference between the hydration of opposite ions involved. Presumably, also, the degree of ionic hydration would be different at the surface of liquid in contact with the solid, in which situation the concentration of water would be different from that obtaining elsewhere in the liquid. At the present time sufficient data are not available to enable an estimate to be formed of the extent to which electro-osmosis is affected by ionic hydration. If, however, an agar diaphragm is employed in the apparatus shown in fig. 3, the number of molecules of water passing when electro-osmosis is at a maximum is found to be from eighteen to three hundred and seventy times greater than the number of molecules of electrolyte decomposed by the current,¹ a circumstance which may be interpreted as indicating that conveyance of fluid by hydrated ions plays only a subordinate part in electro-osmosis.

THE INTRODUCTION OF DISSOLVED SUBSTANCES INTO LIVING TISSUES BY MEANS OF ELECTRO-OSMOSIS

The conditions under which experiments directed to this end are performed, are attended with limitations, which render investigation difficult.

Thus the amount of current which can be employed without damaging the skin is limited ordinarily to from one to three milliamperes per square centimetre, and even this current cannot usually be continued safely for more than twenty minutes. Again, since ions derived from dissolved electrolytes enter and leave the skin under the action of a potential gradient, the dissolved substances which can be employed in the investigation of the problem under consideration are limited to non-electrolytes of sufficiently simple molecular constitution to be able to pass through colloidal material. Further, such dissolved substances, after passing into the skin, must be capable, even in the very small quantities which in practice can alone be introduced, of producing a marked local or remote effect upon the organism. Unfortunately, it is in many cases

1. Barratt, J. O. Wakelin, and Harris, A. B. *Loc. cit.*, p. 225.

difficult, when employing dissolved substances in experiments on electro-osmosis, to be quite sure that an ionisation effect is wholly excluded.

It is obvious that a solution of the problem whether non-electrolytes can be introduced into the skin by electro-osmosis is best approached by first ascertaining if dissolved substances can be made to pass by electro-osmosis through colloidal membranes. This aspect of the enquiry will alone be dealt with in this section, experiments made with living tissues being reserved for a subsequent communication.

This problem has already been studied by Oker Blom,¹ who introduced I-ions by means of electrolysis into colloidal masses. As a want of correspondence between the calculated amounts I-ions which should have been introduced by the strength of current used, and the amounts actually present in the gel at different distances from the site of entry of the current occurred, Oker Blom concluded that evidence of a kataphoric action of the current had been obtained.

Our own experiments directed to the investigation of this problem have been made with two dissolved substances, namely glucose and iodine.

In the first series of experiments a plug of filter paper contained in a glass bulb was moistened with a 5 per cent. solution of glucose in distilled water, and an electric current caused to pass through it for a period of time sufficient to permit of the passage of so large an amount of liquid by electro-osmosis that any alteration in composition, such as would occur if water were carried to the complete or partial exclusion of glucose, would be readily determined.

The apparatus employed (fig. 1, p.316) consisted of a glass bulb, tightly packed with filter paper, and placed horizontally in a beaker containing a 5 per cent. solution of glucose. At one end the bulb was open, communicating with the liquid in the beaker; a platinum electrode was placed in the beaker opposite this open end. The other end of the bulb was sealed into a vertical tube, also filled with glucose solution, containing another platinum electrode. Connected with the vertical piece were two measuring capillary tubes of two millimetres internal diameter, one above, placed vertically, and the other, placed horizontally, used for measuring the amount of fluid passing by electro-osmosis. The latter tube terminated in a thistle funnel in which the fluid passing could, if desired, be allowed to collect.

1. Oker Blom. 'Beitrag zur Feststellung einer physikalisch-chemischen Grundlage der elektro-medikamentösen Behandlung mit besonderer Berücksichtigung der Jodsatzlösungen,' Kuopio, 1896; 'Experimentelle Untersuchungen über das unter Einwirkung des konstanten elektrischen Stromes stattfindende Eindringen von medikamentösen Stoffen in den Thierkörper,' Willmanstrand, 1898.

In the experiments made the strength of current passing was 8 milliamperes to 10 milliamperes per square centimetre, the potential gradient per centimetre being 23 volts. The amount of fluid passing per square centimetre by electro-osmosis, calculated for a potential fall of 1 volt per centimetre, was 0.10 c.c. to 0.18 c.c. per hour (Table I, Experiments 1 to 3). The current was allowed to pass for fourteen to sixteen hours, during which period the actual amount of fluid which passed through the plug of filter paper was 60 c.c. to 70 c.c.

The fluid passing by electro-osmosis was found to exhibit the same specific gravity as the solution of glucose in the beaker. These experiments, therefore, indicate that the water passing by electro-osmosis through the plug underwent no change in respect of its content of dissolved glucose. It is therefore proven that a non-electrolyte dissolved in water may be carried passively by electro-osmosis through a colloidal membrane. The actual amount of glucose transported during the period of experiment by electro-osmosis was, it may be observed, 3.0 g. to 3.5 g.

In the second series of experiments the dissolved substance employed was iodine in 0.01 N NaCl solution. In these experiments the plug of filter paper was discarded, and instead a hydrogel of gelatine was employed in the form of a thin diaphragm. Before use the gelatine was, in the earlier experiments, allowed to remain in contact with the iodine solution for some time; in some of the later experiments the gelatine was not previously exposed to the action of iodine. It may here be observed that iodine changes the condition of gelatine, rendering it after a time insoluble even in boiling water. It also causes reversal of the direction of electro-osmosis when Na_2SO_4 or NaNO_3 are employed as electrolytes (Table II).¹

The apparatus employed to determine, if the fluid passing by electro-osmosis contained iodine, is shown in fig. 7. It consisted of two short glass tubes, *a*, *b*, closed below by a membrane of gelatine half to one millimetre thick. These tubes were partially immersed in a 0.01M solution of NaCl, containing a small amount of starch solution. The current was conveyed to the cups by non-polarisable electrodes formed by two glass tubes, *c*, *d*, closed below by a plug consisting of a hydrogel of gelatine (10 per cent.), and containing above zinc electrodes, marked + and - in the figure, immersed in a saturated solution of ZnSO_4 . The potential gradient in these experiments was about 10 volts per centimetre,

1. Separate determinations of the direction and amount of fluid and the amount passing by electro-osmosis were made with the apparatus shown in Fig. 3.

the strength of current being about 5 milliamperes per square centimetre of gelatine membrane.

FIG. 7.

In carrying out an experiment the empty tubes, *a*, *b*, were partly immersed in the liquid contained in the beaker as shown in fig. 7, the electrodes, connected to the source of the current, being also placed in position. The iodine solution was then rapidly poured into the cups, *a*, *b*, thus completing the circuit. The object of the latter procedure was to avoid the passage of iodine, by diffusion through the gelatine diaphragm, into the liquid contained in the beaker before the circuit was closed, whereby a blue deposit or coloration would make its appearance in the liquid below the cups before electro-osmosis was set up.

When an experiment was made, as above described, it was found that at the kathode cup iodine passed into the liquid contained in the beaker, a blue deposit or cloud appearing at the under surface of the gelatine, while at the anode cup no blue coloration appeared. If the current was reversed, a blue coloration or deposit appeared below the gelatine diaphragm of the former anode cup, while no further coloration appeared beneath the former kathode cup. Thus the iodine passed in the direction of electro-osmosis, from kathode to anode.

It appears to be admissible to conclude that in these experiments the dissolved iodine passes in the unionised condition through gelatine under the action of electro-osmosis.