ELECTROMOTIVE FORCES AND ELECTRIC CURRENTS CAUSED BY METALLIC DENTAL FILLINGS

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ELECTRICAL phenomena in oral cavities have been described and discussed in many papers published between 1878 and the present time. Solomon, Reinhard, and Goodale[1] abstracted the 24 most important papers published before June, 1933.

The papers up to late 1933 describe different cases and suggest explanations of the observed symptoms. Cases are described in which certain pathologic conditions in the oral cavity were relieved when the metallic restorations were changed so that all were made of one kind of metal, or were completely removed.

Lain and Caughron[2] reported their use of a Weston Model No. 440 microammeter having a range of 75 microamperes, and stated that in only a few cases did they require an instrument having a greater range. They also state correctly that the potential difference of the two restorations could be calculated by taking the product of the observed current and the resistance of the microammeter. They state neither the resistance of the meter nor the magnitude of a potential difference. The chief concerns of the paper are case histories and general observations.

Solomon, Reinhard, and Goltz[3] reported the results of laboratory experiments in which they used saliva and six different restoration metals. They suggest that a current would exist in a normal oral cavity provided an external circuit exists and that soft tissue might supply the external circuit. They state further that it is "obviously impossible" to measure such a current in vivo and then suggest an experiment in vitro, which they performed. This experiment consisted of immersing a gold and an amalgam electrode in saliva. When a microammeter was connected to the electrodes it indicated a current. When both a copper wire and the ammeter were connected in parallel to the two electrodes, the meter indicated "no current." They state that the copper wire simulates the soft tissue external circuit and that therefore "this may be considered evidence that no external circuit exists in the soft tissues of the mouth." This conclusion appears to be quite incorrect. The resistance of the copper wire undoubtedly was very low compared to that of the ammeter and therefore the current through the meter was too small to cause the meter to deflect appreciably. Further, if the copper wire had had a resistance of thousands of ohms, as is the case for the resistance between a pair of dental restorations

through the soft tissues, then the meter would have recorded a large deflection. It is clear that these workers were not aware of the fact that the bone fluid* in the tooth and jaw also supplies a very good external circuit.

Solomon, Reinhard, and Goltz then observed the decrease in current with time when the microammeter alone was connected to the two electrodes. From these experiments they concluded that, although an e.m.f. exists between metallic restorations in the mouth, "no current is normally flowing." They suggested that polarization and oxidation of the restorations together with film formation prevent the flow of current. It is evident that their experimental results do *not* lead to this conclusion which rests on the copper wire data. Since the copper wire simulated the soft tissue and since a relatively large current did go through the wire, that current also went through the saliva and the bone fluid between the two electrodes. Thus it appears that their conclusion should have been that a current *is* normally flowing.

Lain, Schriever, and Caughron[4] described experiments which demonstrated the electrical conditions that exist in the case of two fillings made of different metals. It was shown that the bone fluid acting on the two fillings produces an e.m.f. which is nearly as great as that produced by the saliva, each of them being from amalgam to gold through the respective electrolytes. It was shown also how these electromotive forces might be measured and that the two of them would combine in parallel to furnish a current through a microammeter connecting the two restorations. It was pointed out why the current through such a meter would be much greater than that which would exist in the oral cavity under normal conditions.

Reed and Willman[5] described some experiments with pieces of platinum, gold, copper, and amalgam immersed in several solutions including the saliva in an oral cavity. They also connected a large amalgam filling and a gold inlay in an oral cavity, with a gold wire. Hours later they connected the galvanometer to these restorations and then broke the gold-wire connection. The current was then observed to be one microampere. They concluded from these experiments that under truly average conditions in the mouth appreciable currents do not exist. They also stated that currents from 1 to 100 microamperes may exist if a gold and an amalgam filling come in contact. They considered currents of the order of one microampere not to be harmful. It appears that Reed and Willman neither measured the magnitude of an electric current in a normal oral cavity nor measured quantities from which such a current could be calculated. They demonstrated that polarization effects build up relatively rapidly when the fillings are connected with a wire (ammeter), and that these tend to reduce the current.

Reed and Willman also referred to a paper by Mills[6] who found in a statistical survey of 1,000 patients that the incidence of irritation of the oral mucosa was essentially the same for patients with dissimilar metal restorations as for patients having restorations of only one metal or no restorations at all.

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*In this paper we shall define "bone fluid" to mean all those electrolytes in the dentin, bone, and tissue through which the electric current passes in going from the bottom of one filling through the tooth and jaw, then through the other tooth to the bottom of the second filling.

Venable, Stuck, and Beach[7] described experiments in which they placed screws, made of various pure metals and alloys, in the fractured radii of dogs, two screws being placed near each other in each radius. Their work convinced them that galvanic action did occur and that the metals were transported as would be expected from their positions in the electromotive series.

MacGreagor and Fickling[8] described three cases in which electrolytic action between Cu-Ag dental splints and Cr-plated steel pins caused ulcerations, bone necrosis, and delayed healing of mandibular fractures treated by bone grafting and extraoral fixation. The grafts survived but sequestra developed from one-half to one inch around the pins. Ulceration, considered to be due to electrolysis, occurred around the screws, projecting points, and soldered connections in the intraoral splint. A recording galvanometer indicated potential differences of 40 to 50 mv, with surges up to 200 mv, between a pin and a splint while in position in the patient. In one case where there existed some inflammation but no ulceration the potential differences were 5 to 10 mv. In seven additional cases treated by using acrylic resin junctions and stainless steel pins no ulceration or necrosis occurred.

Since 1933 several papers have appeared in which are described cases of stomatitis, leukoplakia and oral cancer which were believed to have been caused by electrogalvanic action of dental restorations. One must admit that much of the evidence presented hardly justifies the statement that electrolytic action of dental restorations was the undoubted cause of the pathological conditions.

Aasgaard* reported the potential differences of pairs of restorations of various kinds measured in 21 oral cavities with a vacuum-tube voltmeter of special design. Data on some 170 pairs were given. The largest, 950 mv, was between an aluminum splint and a gold crown; the next largest, 770 mv, was between two amalgam restorations. The average of the potential differences was approximately 135 mv. It can be inferred from his report that he used platinum-iridium tipped probes to contact the restorations and that the restorations were wet with saliva as they are under normal oral conditions.

Aasgaard also reported his experience with a patient who had a four-piece gold bridge and two large amalgam fillings with a potential difference of 330 mv between the bridge and one amalgam filling. Symptoms, such as irritation of the gingiva and the tongue, existed and the patient complained of pain in the tongue and in the palate. When the two amalgam fillings were replaced by baked porcelain the pain in the palate disappeared and the pain in the tongue diminished. The gold bridge was removed and an amalgam filling was found under a gold crown. When this amalgam restoration was replaced with gold the pain disappeared, the tongue regained its normal appearance, and the patient has remained without symptoms ever since. The potential difference between two gold restorations was around 70 mv. This report indicates that the galvanic electrical effects due to dissimilar metallic dental restorations may cause pathologic conditions in the mouth.

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*Private communication to Dr. E. S. Lain of Oklahoma City from G. Aasgaard, Bergen, Norway, March 9, 1939.

Venable and Stuck[9] reviewed the literature concerning the use of metals in the fixation of fractures, in the ligation of vessels, and in the support of soft tissues. They state that, ''brass, carbon steel, nickel-plated steel, and many other metals and alloys have been tried, but in each case irritation of the tissues, delayed healing, swelling, and sinus formation have resulted. These phenomena, formerly attributed to infection, pressure necrosis, or foreign-body reaction, are now known to be due to intense electrolytic reactions caused by the effects of the body fluids on the dissimilar metals contained in the alloy. . . . Steel appliances plated with nickel, silver or copper usually caused the most severe reactions of all. The plating became cracked or chipped so that two dissimilar metals were side by side in the body fluids. There was much electroactivity in these batteries and tissue damage and bone necrosis inevitably followed . . . So far, we know of only three metals which are sufficiently passive for use in the body, vitallium, tantalum, and 18-8-SMo stainless steel, and of these vitallium is the only one which appears to be uniformly inert.''

BASIC CONSIDERATIONS

Several possibilities for sources of electric current exist in an oral cavity containing two or more metallic fillings. First, an electric cell will be formed by two fillings, one gold and one amalgam for example, together with the saliva which is an electrolyte wetting the exposed surfaces of the fillings. Second, these same two fillings also contact the bone fluid through the teeth. Since the bone fluid is also an electrolyte, it, together with the amalgam and gold fillings, constitute another electric cell. Each of these two types of cells has the direction of its e.m.f. from amalgam to gold through the respective electrolyte. A third type of possibility for an electric cell exists. Since a single metallic filling under normal oral conditions contacts saliva at its exposed surface and bone fluid down in the tooth, and since the saliva and the bone fluid are in contact through the tissues, the requirements for a liquid-junction cell are fulfilled. This is illustrated in Fig. 4.

A careful survey of the literature reveals that in no instance has an e.m.f. caused by dental fillings, or the resulting normal current in an oral cavity, been measured, and that in no instance have measurements been reported from which these quantities could have been calculated.

PURPOSE OF THIS INVESTIGATION

The purpose of this investigation was to devise methods, including the necessary theory and apparatus, for determining electromotive forces, electrical resistances, and electric currents associated with metallic dental fillings in place in oral cavities under normal oral conditions. It was also proposed to make such determinations on a large group of persons having normal mouths, and to make measurements in as many pathologic oral cavities as might become available.

EXPERIMENTS

Part I. Pairs of Metallic Fillings.—Attempts to measure the electrical potential differences between pairs of fillings with a standard precision potentiometer having a sensitive galvanometer as a balance indicator, were unsuc-

cessful because duplication of results was not possible. The fillings had such small areas of contact with the saliva and the bone fluid that intolerable polarization effects were caused by the tiny currents required for the galvanometer. It was necessary to devise an apparatus which required the fillings to deliver much less electric charge per measurement.
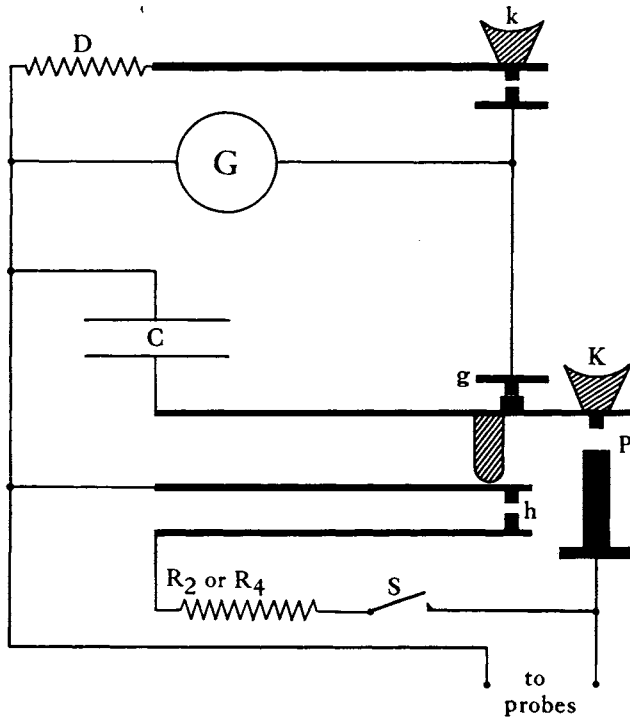

Fig. 1.—Schematic diagram of the electric circuit for the condenser-ballistic-galvanometer potential-difference meter.

k, galvanometer damping key
D, damping resistance
G, ballistic galvanometer
C, a one mf condenser
R_2 or R_4, a resistance which may be connected to probes by closing switch S
K, a special triple-contact key which connects R_2 and C to probe and, on release, connects C to G

A schematic diagram of such an apparatus is shown in Fig. 1. This apparatus might be termed a condenser-ballistic-galvanometer potential-difference meter. It does not require a continuous current for its operation, as did the potentiometer galvanometer. G is a Leeds & Northrup Type ''P'' ballistic galvanometer having a sensitivity of 0.004 microcoulomb per mm. deflection on the scale which was 50 cm. from the mirror. While the galvanometer coil was swinging back to the zero position it was damped by closing the auxiliary key (k) which connected a critical damping resistance (D) across its terminals; this made it possible to bring the galvanometer coil to rest quickly.

The two probes which contacted the two fillings were connected to the terminals marked ''to probes.'' The construction of a platinum-tipped probe is shown in Fig. 2.

When the triple-contact key (K, Fig. 1) was depressed it connected the probe terminals directly across the condenser (C) through contact (P), thus charging the condenser which was a high grade oil-filled condenser having a capacitance of one microfarad. When the key (K) was released to the position shown in Fig. 1, the charged condenser was disconnected from one probe and then connected through contact (g), so that it discharged through the galvanometer.

When it was desired to connect a resistor (R_2), across the probes, the switch (S) was closed. Then when the key (K) was depressed the resistor (R_2) was connected by the closing of the contact (h); this occurred before the condenser was connected by the closing of the contact (P). When the key was released the condenser was isolated before the contact (h) opened; had this not occurred the condenser would have discharged through R_2 instead of through the galvanometer.
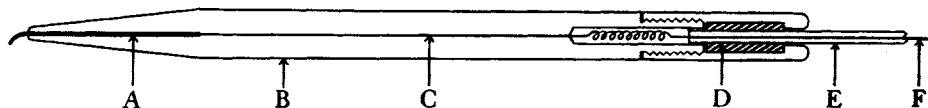

Fig. 2.—Scale drawing of a 7 inch platinum-tipped probe which was used to make electrical contact with a metallic filling.

A, a platinum wire sealed with plastic cement
B, polystyrene rod, 0.5 inch in diameter
C, copper wire sealed with plastic cement
D, a rubber gasket which grips E
E, shielded lapel-microphone cable, polyethylene insulation
F, flexible copper conductor within cable

Preliminary measurements indicated that the resistance between a pair of fillings was approximately a half megohm. It requires appreciable time to charge a 1 mf condenser by the e.m.f. generated by two fillings, through a total circuit resistance of ½ megohm. In order to have the condenser at least 99 per cent fully charged, it was necessary to keep the key (K) closed for five seconds. It was convenient to observe the charging time on a sweep second-hand electric clock.

When the resistor (R_2) was connected, the two fillings had to supply current through it as well as to charge the condenser. Since the passage of current through the resistor caused polarization effects at the fillings it was necessary to reduce this current as much as possible. Thus the polarization could be reduced by increasing R_2 and decreasing C. On the other hand, each of these changes decreased the accuracy of the measurements. Experience showed that a good compromise occurred when C was 1 mf and R_2 was 1 megohm. The charging current for the condenser (C) was so small and lasted such a short time that fairly satisfactory reproduction of data was possible.

This condenser-ballistic-galvanometer potential difference measuring apparatus was calibrated by connecting known potential differences, varying from 10 to 1000 mv, to the probe terminals. It was found that the deflection of the ballistic galvanometer was directly proportional to the applied potential difference and that the deflection to the right was the same as the deflection to the left for the same potential difference. The sensitivity of the instrument was found to be 3.3 mv per mm. deflection.

Experimental Procedure.—Students in the School of Medicine, and nurses, both graduate and undergraduate, served as "normal" subjects. Their ages ranged from 18 to 30. A small number of older people also served as subjects. Gold fillings were found to be relatively scarce, especially in the mouths of the younger men and women.
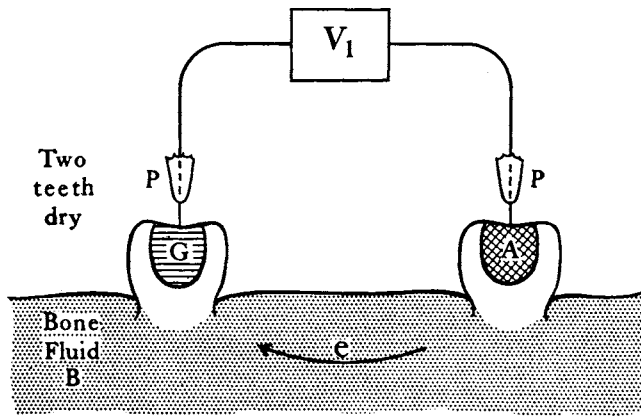

Fig. 3.—Circuit for measuring the e.m.f. caused by the action of the bone fluid on two fillings.

G, a gold alloy restoration
A, a silver amalgam restoration
e, e.m.f. due to contacts of G and A with the bone fluid
V_1, the potential difference indicated by a meter which does not require a continuous current. Since no current exists, $e = V_1$
P, two platinum-tipped probes which make electrical contacts with the restoration

It was of greatest interest to locate the largest existing electrical effects in each of the mouths studied. Since it was necessary to repeat measurements of potential differences in order to be certain of reproducible results, only a few pairs of fillings could be studied in any one mouth in an hour. Preliminary measurements of V_3, the potential differences between pairs of saliva-wet fillings, were made on various pairs of fillings in an oral cavity, and those pairs were selected which exhibited the greatest potential differences. Some pairs exhibited nearly zero potential difference.

The electrical measurements were carried out with the subject sitting in a reclined position in a barber chair. The two platinum-tipped probes were pressed firmly against the pair of fillings by one research assistant while all the teeth were wet with saliva. The second research assistant pressed down the key (K, Fig. 1) for five seconds, released it, and read and recorded the

deflection of the galvanometer. This result was checked by making one or more additional determinations. From this galvanometer reading the potential difference V_3 was later computed.

Next one oral pack (or two if necessary) was put in place, the two teeth were carefully swabbed with 95 per cent ethyl alcohol, and air was blown on both teeth. The potential difference of the dry fillings in the dry teeth was measured as described above. This potential difference is designated V_1 (Fig. 3). The switch (S, Fig. 1) was closed and the potential difference of the two fillings, when connected by a 1 megohm resistor (R_2), was determined. This potential difference is designated V_2. Each measurement was repeated in order to check the work and also to learn whether too great a polarization had occurred; if this did occur then reproducible results were not obtainable.

This same procedure was repeated for one or more additional pairs of fillings in the mouth of this same subject. In some cases it was necessary to swab a pair of teeth several times and to blow air on them from time to time in order to keep them dry. Occasionally it was found impossible to keep the desired teeth sufficiently dry, in which case they were abandoned and another pair was selected.

Other data concerning the subject were also obtained and these together with the three galvanometer deflections were recorded on a report form. This form included blanks for serial number of subject, date, name, age, sex, address, phone number, date and nature of last illness, pH of the subject's saliva, and pertinent information concerning past lesions in the subject's mouth. On a conventional chart of the teeth the locations of all fillings and all missing teeth were marked. Each pair of fillings which was studied was connected with a line which in turn was numbered. For each pair the electrically positive filling was marked with a plus sign. The approximate ages of the fillings were also indicated. On the reverse side of the form were four columns headed: Pair Number, V_3, V_1, and V_2; here the observed galvanometer deflections were recorded. The probes were so placed that V_3 always gave a deflection to the right; if any of the other deflections were to the left this was indicated by the use of a minus sign in the recorded deflection.

Results (Part I).—Since the teeth were dry the potential difference V_1 (Fig. 3) was the e.m.f. *(e)* caused by the action of the bone fluid on the two fillings, i.e.,

$$e = V_1.$$

The resistor R_2 was connected from one probe conductor to the other (by closing switch S, Fig. 1), thus closing the electric circuit. Since R_2 was of the order of 1 megohm (1,000,000 ohms) whereas the resistance of the two probe-conductors was only a fraction of 1 ohm, the entire electrical resistance in the circuit could be considered as $R_2 + R_B$, where R_B was the unknown resistance between the two fillings through the bone fluid. Ohm's laws apply to this single-path circuit; they yield the two equations:

$$i_2 = V_2/R_2, \text{ and } i_2 = e/(R_2 + R_B),$$

where V_2 is the measured potential difference between the two probes, i.e., across R_2, and i_2 is the current through R_2 and the bone fluid.

These three equations may be solved for the resistance through the bone fluid in terms of the measured and known quantities. Thus:

$$R_B = R_2 \ (V_1/V_2 - 1).$$

In the early work many data were found to be useless because of excessive polarization effects which were caused by the use of too large a condenser (C) or too low a resistance R_2. Also the proper technique and care in drying the teeth had not been perfected. In the later work some data were rendered useless because of excessively rapid polarization effects for tiny fillings in some subjects. Usable data were obtained on 213 pairs of fillings in 137 subjects having ''normal'' mouths. These results are summarized in Table I.

TABLE I
SUMMARY OF RESULTS FOR PAIRS OF FILLINGS

137 INDIVIDUALS 84 MALE; 53 FEMALE	AMALGAM AMALGAM		GOLD AMALGAM		GOLD GOLD	
125 Pairs *Male*	83		32		10	
88 Pairs *Female*	72		13		3	
213 Pairs *Total*	155		45		13	
AVERAGE VALUES	MALE	FEMALE	MALE	FEMALE	MALE	FEMALE
Potential difference wet, V_3 mv	142	162	207	271	63	91
Bone fluid e.m.f., e						
positive mv	147(80)*	156(69)	215	271	65	101
negative mv	41(3)	30.5(3)	—	—	—	—
Bone fluid resistance R_B megohms	1.30	1.32	0.465	0.89	0.85	0.82

*Number in parentheses means number of pairs of restorations. Positive direction is the same as that of potential difference V_3.

The two greatest observed potential differences (V_3) of pairs of fillings when wet with saliva were 564 and 511 mv. There were six others above 400 mv. The two greatest observed e.m.f.'s (e) caused by the bone fluid were 560 and 510 mv. There were five others above 400 mv.

The pH of each saliva was determined with a paper indicator, the observed values ranging from 6.2 to 7.4. None of the electrical quantities indicated any dependence on the pH of the saliva.

Nearly all the subjects fell in the 18 to 30 age range but there were some in the 35 to 60 range. There was no indication of a dependence of the electrical quantities on age. It also appears that there was no significant dependence on sex.

Five subjects had severe pathologic conditions in their mouths; one had a large white patch on the cheek. Six pairs of fillings were studied in the mouths of three of the patients. These yielded potential differences (V_3) and bone fluid e.m.f.'s (e) which were 2 to 3 times the average for normal subjects. However, a number of subjects having apparently normal oral cavities yielded values of these quantities which were even larger. The other two patients

yielded values which were about half the average values obtained from normal subjects. There was no convincing evidence that any of the lesions were caused by the dental restorations.

A study of the records did not indicate any connection between recent illness and the magnitudes of the measured electrical quantities. The same was true for subjects who reported occasional lesions occurring in their mouths.

An important fact was established by examining the results obtained in oral cavities in each of which two or more suitable pairs of fillings were studied. The three types of pairs chosen were: (1) The two teeth were adjacent or very near each other in the same jaw; (2) the two teeth were in the same jaw but across the mouth from each other; (3) the two teeth were across the mouth from each other but one was above and the other below. More than 20 cases
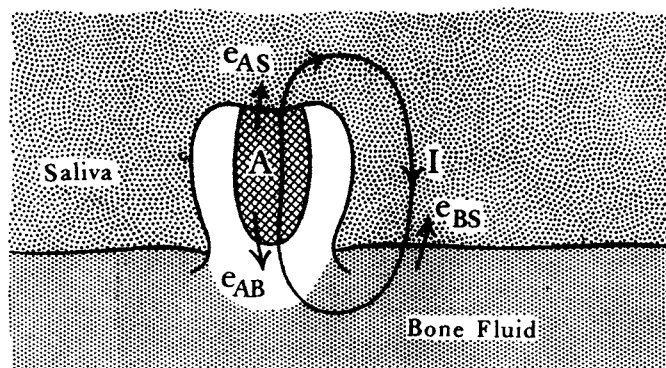

Fig. 4.—An electrical current results when a single metallic dental filling contacts the two electrolytes, saliva and bone fluid, which are themselves in contact.
A, an amalgam filling contacting saliva above and bone fluid below
Net e.m.f. in the circuit is the algebraic sum of e_{AS}, e_{AB}, and e_{BS}, the e.m.f.'s generated at the metal-saliva, metal-bone fluid, and bone fluid-saliva contacts.
I, shows the direction of the net e.m.f. and the resulting electric current

of each of these types were found among our data. The average value of the resistances through the bone (R_B) was calculated for each of the three types of pairs. These three average values indicated that the resistance between a pair of fillings under normal oral conditions is independent of how far apart they are in the mouth. In fact, in several cases the higher resistance was associated with two fillings that were nearest each other. This confirms the long-known fact that the resistance between small electrodes immersed in a large body of electrolyte is concentrated almost entirely in and very near the electrode-electrolyte contacts. Thus it is evident that the electrical resistance associated with a filling in a tooth is concentrated in and very near the metal-saliva and the metal-bone fluid contacts. That part of the resistance out in the bone and the tissues is negligible in comparison.

Part II. Phenomena Associated With Single Fillings.—

Fundamental considerations.—When a piece of metal contacts two different electrolytes and these two electrolytes contact each other, through a porous substance for example, then a net e.m.f. exists in that circuit and an electric current passes through the metal and through the electrolytes.

In Fig. 4 is shown an amalgam filling which contacts both of the electrolytes, saliva, and bone fluid. Since the saliva and the bone fluid are also in contact through tissue, one would expect an electric current through the filling as is indicated by I in Fig. 4.

Fig. 5 shows the electric circuit which is equivalent to that associated with an amalgam filling in an oral cavity containing three other fillings. The significant experimental fact stated above, that the resistances are concentrated at and near the metal-electrolyte contacts, makes this equivalent circuit relatively simple. The resistance and e.m.f. of the amalgam-saliva contact are indicated respectively as R_{AS} and e_{AS}, and those of the amalgam-bone fluid contact as R_{AB} and e_{AB}. The e.m.f. of the bone fluid-saliva contact is shown as e_{BS}. This last contact and the path through the saliva and bone fluid have relatively negligible resistances.
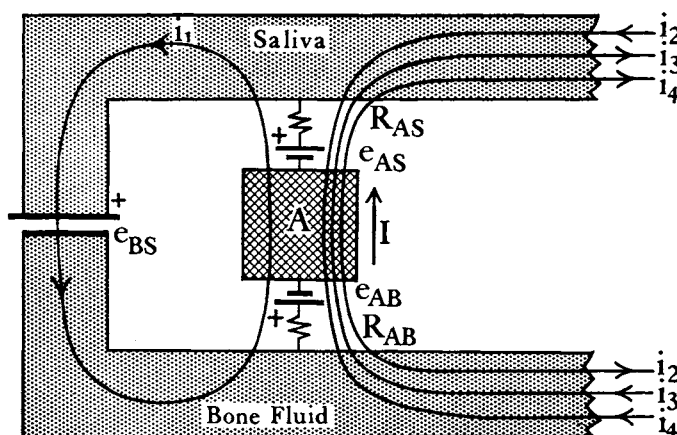

Fig. 5.—Possible electrical phenomena associated with an amalgam dental filling in an oral cavity having three other fillings.

A, an amalgam dental filling

e_{AS} and e_{AB}, the e.m.f.'s of the amalgam-saliva and amalgam-bone fluid contacts
e_{BS}, the e.m.f. of the saliva-bone fluid contact

R_{AS} and R_{AB}, the resistances of the amalgam-saliva and amalgam-bone fluid contacts

i_1 electric current caused by $e_{AS}-e_{BS}-e_{AB}$.

i_2, i_3, and i_4, currents caused by three other fillings in the same mouth

$I = i_1 - i_2 + i_3 + i_4$, the net current through the filling A

Also in Fig. 5 are shown three other currents i_2, i_3 and i_4 which may pass through the filling. Each of these currents may be caused by A and another filling in that mouth, acting as a pair of fillings in accord with the findings in Part I of this paper. Thus, the total net current (I) which passes up through A is the algebraic sum of the individual currents. Therefore:

$$I = i_1 - i_2 + i_3 + i_4$$

Obviously if any number (N) other fillings exist in that oral cavity, I is the algebraic sum of i_1 and the N other resulting currents (if they exist).

Around any closed path in an electrical network the sum of the electrical potential drops must equal the sum of the electrical potential rises (Kirchhoff's

Law). The closed loop marked i_1 in Fig. 5 is along such a closed path. Thus it is possible to write the following equation:

$$R_{AS}I + R_{AB}I + e_{BS} + e_{AB} = e_{AS}$$

This may be solved for I, thus:

$$I = (e_{AS} - e_{BS} - e_{AB})/(R_{AS} + R_{AB})$$

It is evident that the net e.m.f. in the closed path is $e_{AS} - e_{BS} - e_{AB}$; that the total resistance in that path is $R_{AS} + R_{AB}$; and that I is the total (or net) current that passes through the filling.

It is also clear that R_{AS} and e_{AS} depend only on the natures of the filling and the saliva; that R_{AB} and e_{AB} depend only on the natures of the filling and the bone fluid; that e_{BS} depends only on the natures of the saliva and the bone fluid; and that none of these depends on the presence or absence of other fillings in that oral cavity.
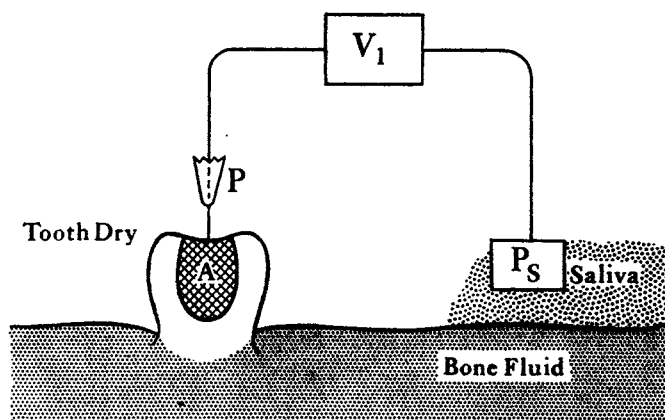
Fig. 6.—The use of the auxiliary electrode for measuring V_1 and V_2 of Part II.
    A, an amalgam filling
    P, a platinum-tipped probe which contacts the metal filling
    P_S, a large auxiliary platinum electrode which contacts the saliva
    V_1, the potential difference indicated by a meter which requires no continuous
        current

Thus the magnitude of the electric current through any metallic dental filling is independent of the number of fillings in that oral cavity, provided that particular filling does not make contact with another metallic filling. The magnitude of this current is given by the last equation above. This conclusion would be exact if the saliva and bone fluid had exactly zero resistance. Their resistance is not zero, but it is very small compared to R_{AS} and R_{AB}. Thus the conclusion above states a very close approximation to the actual situation in an oral cavity.

Theory for Determining the Desired Electrical Quantities (Part II).—Fig. 4 shows the current I which might pass through a metallic filling if that were the only filling in that oral cavity. If other fillings are present the current through the filling tentatively may be represented by I as shown in Fig. 5. It is possible by indirect means to make determinations of the net e.m.f., the

current and the contact resistances. The theory for these measurements will now be developed. In this development it will be assumed that an instrument is available with which electrical potential differences may be measured, without drawing any continuous current from the filling. It will also be assumed that it is possible to keep the tooth entirely free of saliva, and that it is possible to contact only the filling with a tiny drop of saliva so as to leave a dry ring of enamel entirely around the wetted filling.

In Fig. 6 is depicted a tooth which has been well dried and which contacts the bone fluid at its buried surface. The potential difference meter is shown connected to the filling through the platinum-tipped probe (P), and to the saliva through the large auxiliary electrode P_S. Let e_{AB}, e_{BS}, and e_{SP} represent the e.m.f.'s generated respectively at the amalgam-bone fluid, bone fluid-saliva and saliva-platinum contacts. Since the meter uses no current, the potential difference V_1 which it indicates, is the net e.m.f. in that circuit. Therefore:

$$V_1 = e_{AB} + e_{BS} + e_{SP} \quad - - - - - - \quad [1]$$
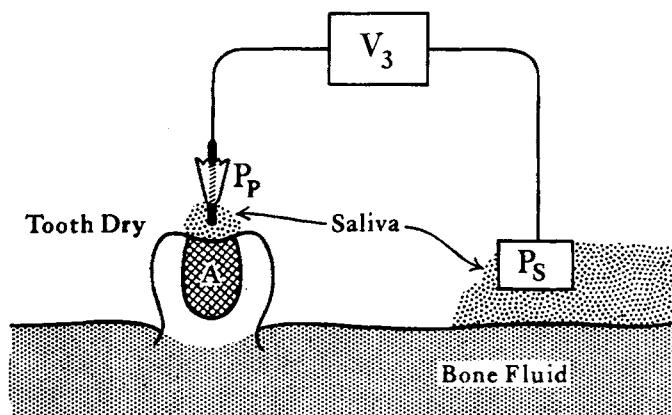
Fig. 7.—The use of the saliva probe and the auxiliary electrode for measuring V_3 and V_4 of Part II.

A, an amalgam filling
P_S, an auxiliary platinum electrode
P_P, a platinum probe which makes an electrical contact with the filling through a tiny drop of saliva.
V_3, the potential difference indicated by a meter which requires no continuous current

When a resistor R_2 is connected from the probe to the auxiliary electrode the e.m.f. in the circuit causes a current i_2 to pass through the resistor. Ohm's laws apply to this single-path circuit and yield the equations:

$$V_2 = R_2 i_2 \quad - - - - - - - - - - - - - - - \quad [2]$$

and

$$i_2 = (e_{AB} + e_{BS} + e_{SP})/(R_{AB} + R_2 + R_{PS}) \quad - - - - - - \quad [3]$$

where R_{AB} and R_{PS} are the resistances respectively of the amalgam-bone fluid and the platinum-saliva contacts. (It was shown in Part I that almost the entire resistance exists at the metal-electrolyte contacts.)

In Fig. 7 is shown the same setup as in Fig. 6 except that the platinum-tipped probe now does not contact the metallic filling directly but does make electrical contact with it through a tiny drop of saliva; the enamel surrounding the filling is kept dry. Here again the potential difference meter indicates (V_3) the net e.m.f. in that circuit. Thus:

$$V_3 = e_{AB} + e_{BS} + e_{SP} - e_{PS} + e_{SA} \ - \ - \ - \ - \ - \ - \quad [4]$$

where e_{PS} and e_{SA} are respectively the e.m.f.'s generated at the probe-saliva and the saliva-amalgam contacts.

When a resistor R_4 connects the auxiliary electrode and the saliva-probe electrode a current i_4 passes through the resistor. Here again Ohm's laws apply and yield the equations:

$$V_4 = R_4 \, i_4 \ - \quad [5]$$
$$i_4 = (e_{AB} + e_{BS} + e_{SP} - e_{PS} + e_{SA})/(R_{AB} + R_{PS} + R_4 + R_{PP} + R_{AS}) \ - \ - \quad [6]$$

where R_{PP} and R_{AS} are respectively the resistances of the probe-saliva and amalgam-saliva contacts.

The current in the normal oral cavity is shown in Figs. 4 and 5 and is given by:

$$I = (e_{AB} + e_{BS} + e_{SA})/(R_{AB} + R_{AS}) \ - \ - \ - \ - \ - \ - \quad [7]$$

The e.m.f., which may be introduced by the auxiliary electrode and the saliva-wet probe, occurs in equation [4] as ($e_{SP} - e_{PS}$). This can be measured directly by inserting the probe in the saliva near the auxiliary electrode in the mouth and measuring the resulting potential difference V_P with the meter. Thus:

$$V_P = e_{SP} - e_{PS} \ - \ - \ - \ - \ - \ - \ - \quad [8]$$

The magnitudes of the saliva-probe and the saliva-electrode resistances, R_{PP} and R_{PS}, can be measured by a special electric circuit which will be described in the next section. For the present development these two resistances will be considered to be known quantities.

These eight independent equations state relations involving the unknown quantities, R_{AB}, R_{AS}, net e.m.f., I, ($e_{SP} - e_{PS}$), e_{SP}, i_2, and i_4, and the measured and known quantities V_1, V_2, V_3, V_4, V_P, R_2, R_4, R_{PS}, and R_{PP}. The solutions of these equations for the desired electrical quantities, R_{AB}, R_{AS}, net e.m.f., and I are:

$$R_{AB} = (V_1/V_2 - 1) \, R_2 - R_{PS} \ - \ - \ - \ - \ - \ - \ - \ - \ - \quad [9]$$
$$R_{AS} = (V_3/V_4 - 1) \, R_4 - R_{AB} - R_{PS} - R_{PP} \ - \ - \ - \ - \ - \ - \quad [10]$$

(In the calculations the numerical value of R_{AB} from [9] would be used in [10].)

$$\text{Net e.m.f.} = V_3 - V_P \ - \ - \ - \ - \ - \ - \ - \ - \quad [11]$$
$$I = (V_3 - V_P)/(R_{AB} + R_{AS}) \ - \ - \ - \ - \ - \ - \quad [12]$$

(In the calculations, values from [9] and [10] would be used for R_{AB} and R_{AS}.)

R_{AB} is the resistance of the metal-bone fluid contact of the filling.

R_{AS} is the resistance of the metal-saliva contact of the filling.

Net e.m.f. is the algebraic sum of the e.m.f.'s generated at the metal-bone fluid, metal-saliva and bone fluid-saliva contacts.

I is the electric current which passes through a metallic filling in an oral cavity under ordinary oral conditions, regardless of the number and kinds of other fillings in that oral cavity.

Apparatus (Part II).—The condenser-ballistic-galvanometer potential-difference meter, described in Part I, was used for many measurements. However, it was found that the 1-mf condenser took so long to charge (5 sec) that the current through the resistor (R_2 or R_4) often caused intolerable polarization effects. These were indicated by the lack of reproducibility of the potential difference measurements when the resistor (R_2 or R_4) was being used. In fact, the reproducibility of the measurements made on single fillings was much poorer than that found in Part I where the apparatus was used with pairs of fillings. A smaller condenser would have used less charge and would have had a shorter charging time, but a sufficiently small condenser would not take enough charge to operate even a very sensitive ballistic galvanometer.

This difficulty was overcome by designing and constructing what is essentially a direct current amplifier which uses the recently developed Victoreen 5803 electrometer tube. With this tube a condenser of only 0.01 mf is required, for which the charging time is only a small fraction of a second. This short closed-circuit time made it possible to use a 0.25 megohm resistor for R_2 and R_4, and thus to increase the accuracy of the resistance determinations. This electrometer apparatus required a very highly insulated quadruple-contact key, two very highly insulated switches, highly insulated wires in the grid circuit, and a polystyrene base for the electrometer tube. Polystyrene rods and amphenol sheets and tubes furnished sufficiently good insulation. The steady deflections were indicated on a Leeds & Northrup Type "P" galvanometer. A circuit for calibrating the meter at hundred-mv intervals up to 600 mv, and at 800, 1000, 1200, and 1400 mv, was incorporated in the instrument. This instrument is entirely battery operated, and, after a warm-up period of a half hour, retains its "zero" and calibration for several hours without adjustment. It will be described in detail in a separate publication. All potential difference measurements were made with this vacuum-tube electrometer apparatus.

The platinum-tipped probe used for contacting the fillings for the potential difference measurements V_1 and V_2 as indicated in Fig. 6 was the same probe that was used in the experimental work described in Part I; its construction is shown in Fig. 2.

The construction of the tip of the saliva probe used in the measurements of V_3 and V_4 as indicated in Fig. 7, is shown in Fig. 8. The tip of this probe was dipped into the saliva in the mouth and then touched to the metallic filling so that the polystyrene pin, P_3, rested on the filling. The 15 wires W_2 made a large area of contact with the tiny drop of saliva which was held by surface tension and which also was in contact with the filling.

It was necessary to have the leads to each of these probes and to the auxiliary electrode exceedingly well insulated, and well shielded with a grounded metal sleeve. Shielded lapel-microphone cable having polyethelene insulation was found to be entirely satisfactory.

The auxiliary electrode, P_S, in Figs. 6 and 7, was made of 4 inches of $\frac{1}{16}$ inch diameter platinum wire. A $2\frac{1}{2}$ inch length of this wire was wound into a tight flat spiral, the outside turn of which had a diameter of $\frac{1}{2}$ inch; the remainder served as a lead out of the mouth where it joined the flexible copper lead in the shielded microphone cable. This junction was covered with gum-rubber tubing which was cemented to the platinum and to the cable with gum-rubber cement. This spiral electrode was placed in the saliva under the tongue at the side of the mouth.
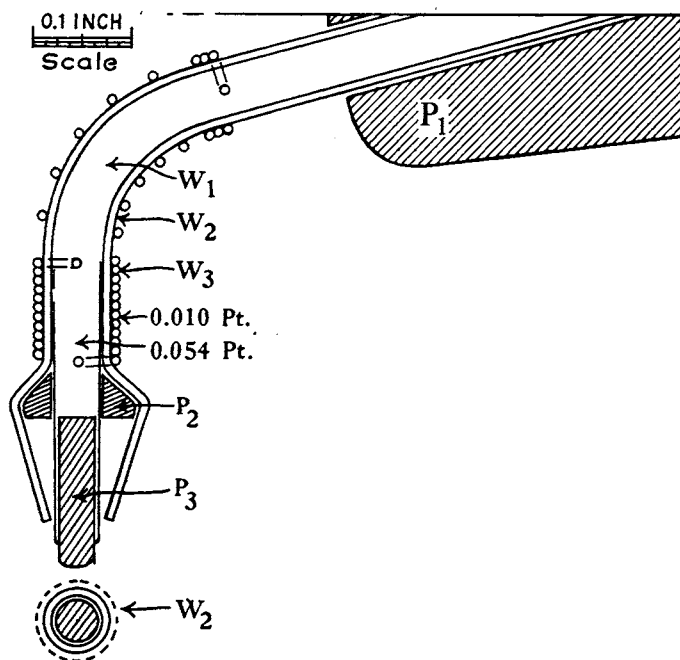
Fig. 8.—Construction of the tip of the saliva probe used for making a saliva contact with the metal filling while leaving a ring of dry enamel surrounding the filling

    W_1, 0.054 inch platinum wire
    W_2 and W_3, 0.010 inch platinum wire
    P_1, tapered end of half-inch polystyrene rod; this handle is like that for the probe described in Part I
    P_2, a polystyrene washer
    P_3, a 0.035 inch polystyrene pin which contacts the dental filling.

The circuit for measuring the resistance R_{PS} of a spiral auxiliary-electrode-saliva contact is shown by the schematic diagram, Fig. 9. Two exactly similar spiral electrodes were immersed in the saliva under the tongue in a

subject's mouth.   Since there were two electrode-saliva contacts the resistance between the two through the saliva was $2R_{PS}$.   For this circuit it is possible to write three independent equations.   These are:

$$R_0 i_0 = V \quad - - - - - - - - - - - - - - - \quad [13]$$
$$R_b i_b + R_a(i_b - i_0) = e_b \quad - - - - - - - - - \quad [14]$$
$$2R_{PS} i_0 + R_0 i_0 - R_a(i_b - i_0) = e_0 \quad - - - - - - \quad [15]$$

Substituting for i_0 and i_b in equation [15] from equations [13] and [14], we have:

$$2VR_{PS} = R_a R_0 e_b/(R_a + R_b) - R_0 V + R_a^2 V/(R_a + R_b) - R_a V + R_0 e_0 \quad - - \quad [16]$$

If the reversing switch in Fig. 9 is reversed then all currents will be reversed, all resistances will remain the same, and e_0 will not change in magnitude or direction because it depends only on the natures of the two electrodes and the saliva.   Consequently an equation exactly like [16] will result except that the last term, $e_0 R_0$, will be negative.

If V and V' are the observed values of the potential differences for the two positions of the reversing switch, the addition of the two equations like [16] eliminates the term containing the e.m.f. e_0 of the electrodes.   The resulting equation is:

$$2R_{PS} = 2 R_a R_0 e_b/(V + V')(R_a + R_b) - R_0 - R_a + R_a^2/(R_a + R_b) \quad - - \quad [17]$$

Since R_0 was 0.25 megohm, whereas R_a was 300 ohms and R_b was approximately 1200 ohms, the last two terms are very small compared to the first two on the right hand side of the equation [17].   These last two terms therefore may be neglected.   The resulting equation is:

$$R_{PS} = R_a e_b R_0/(V + V')(R_a + R_b) - 0.5 R_0 \quad - - - - - - \quad [18]$$

R_a, R_b, and e_b were adjusted so that the term, $R_a e_b/(R_a + R_b)$ was 300 mv.   Thus the resistance R_{PS} of a spiral electrode-saliva contact was given by equation [18] when V and V' were expressed in millivolts.

The resistance R_{SP} of a saliva-probe contact (Fig. 8) was measured with this same apparatus.

Experimental Procedure (Part II).—Students in the School of Medicine, and graduate and student nurses, all in the 18 to 30 year age group, served as subjects in this study of electrical phenomena associated with single metallic fillings.   Apparently, all had normal oral cavities.

Since it was necessary to maintain a ring of dry enamel entirely around each filling in the measurements depicted in Fig. 7 (both without and with R_4) in which only the filling made a saliva contact with a platinum probe, those fillings were selected which were situated near the centers of the teeth.

Each potential-difference measurement was repeated four times.   This was feasible because of the rapidity with which the vacuum-tube electrometer could be operated.   This repetition made it possible to detect polarization effects since these made reproduction of results impossible.   Very little difficulty with polarization effects was encountered, but the inability to keep a

ring of dry enamel entirely around a filling, while measuring V_3 and V_4 (Fig. 7), did cause the discarding of many sets of data. It just was not possible to find one or more ideally located fillings in each oral cavity.

Since polarization effects were usually negligible when the vacuum-tube electrometer was employed to measure the potential differences, the order of taking the potential differences was V_1, V_2, V_3, and V_4, and V_P. If a second filling in that oral cavity was investigated, measurements of V_P were not made again since it was found that they duplicated those made after the measurements on the first tooth.

The electrical measurements were carried out with the subject in a reclined position in a barber chair. The platinum spiral auxiliary electrode P_S was placed under and to the side of the subject's tongue. An oral pack was put in place and the selected tooth, together with the adjacent teeth, were dried carefully with the ethyl-alcohol-air-blast method described in Part I. While one research assistant pressed the platinum-tipped probe (P) (Fig. 6) on the filling, the second assistant pressed the quadruple-contact key of the vacuum-tube electrometer, released it immediately, and read and recorded the steady deflections of the galvanometer. This measurement was repeated 3 more times.
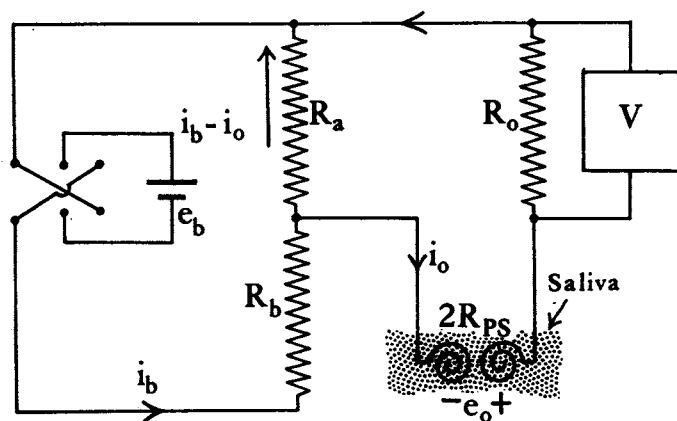

Fig. 9.—Schematic diagram of the electric circuit used to measure the resistances introduced by the auxiliary electrode and the saliva probe.
  e_b, e.m.f. of dry cell connected through a reversing switch
  R_a and R_b, Leeds & Northrup resistance boxes
  $2R_{PS}$, the resistance between the two spiral auxiliary electrodes in an oral cavity
  e_o, the e.m.f. caused by the possible dissimiliarity of the spiral electrodes; usually a few mv.
  R_o, a 250,000 ohm resistor
  V, the potential difference indicated by the electrometer-tube meter which uses no current

A resistor (R_2) of 0.25 megohm was connected across the probe and electrode leads, and the potential difference (V_2) was measured: this was repeated 3 more times.

The platinum-tipped probe was replaced with the saliva probe (P_P) (Fig. 7). This saliva probe was immersed in the saliva in the mouth until its tip was covered with a small drop. It was then pressed on the filling so that only the polystyrene pin $(P_3$, Fig. 8) touched the filling. The potential difference

V_3 was then measured 4 times. A resistor (R_4) was connected across the probe and electrode leads and the potential difference (V_4) was measured 4 times.

It is nearly impossible to get the surfaces of two pieces of platinum (or any metal) so nearly alike that they will not generate an e.m.f. when they are placed in an electrolyte (saliva). This possible e.m.f. (V_P) is indicated in equation [8], and was determined by measuring the potential difference between the saliva probe (P_P) and the auxiliary electrode (P_S) when these were near each other and both immersed in the saliva in the mouth. This measurement also was repeated 4 times.

The form for recording these data included all the items described for the form used in Part I except that the columns were headed V_1, V_2, V_3, V_4, and V_P. These potential differences were recorded as galvanometer deflections in millimeters. Usually measurements on two fillings were made in each oral cavity.

The resistance (R_{PS}) of the auxiliary-electrode-saliva contact was determined with the apparatus shown schematically in Fig. 9 and the use of equation [18]. It was found that R_{PS} was independent of the relative locations of the two auxiliary electrodes in the mouth. It was also found that this resistance was virtually the same when it was measured in the mouths of various people. Since it was small compared to the resistance of a filling-saliva or a filling-bone fluid contact, R_{PS} was considered a constant for the apparatus. Its measured value was 0.007 megohm.

The resistance (R_{PP}) of a saliva-probe contact was also determined with the apparatus shown in Fig. 9 and by the use of equation [18]. In this case a pair of identical saliva probes replaced the spiral electrodes in Fig. 9. These two probes were dipped into the saliva in the subject's mouth, and their tips were brought together out in the air so that the ends of the two polystyrene pins (P_3, Fig. 8) touched each other and so that the two tiny drops of saliva coalesced. Here again it was found that R_{PP} was essentially the same when determined with the use of saliva drops obtained from various oral cavities. It also was found that R_{PP} was independent of the size of the coalesced drops which connected the two probes. Since R_{PP} also was rather small compared to the resistances of the saliva-filling and bone fluid-filling contacts, it was considered an apparatus constant. Its measured value was 0.028 megohm.

From the data obtained for V_1, V_2, V_3, V_4, V_P, R_2, R_4, R_{PS}, and R_{PP}, were calculated the values of the four desired quantities, R_{AB}, R_{AS}, net e.m.f., and I by use of equations [9], [10], [11], and [12]. These calculations were carried out conveniently by use of a record form having 14 columns. The galvanometer deflections in millimeters were translated into potential differences in millivolts before recording them on this form. The electrometer apparatus was adjusted to a sensitivity of 2.5 mv/mm for these measurements.

Results (Part II).—Usable data were obtained on 78 fillings in the oral cavities of 66 subjects whose ages fell in the range 18 to 30 years. The results are summarized in Table II in which are given average values of the desired electrical quantities.

The magnitudes of the three largest observed values of each of the electrical quantities are: For Gold: R_{AB}:0.31, 0.19, 0.14; R_{AS}:1.4, 1.3, 0.87; (R_{AB} + R_{AS}):1.5, 1.3, 0.90; I:1.07, 0.44, 0.24; $e.m.f$:245, 160, 150. For amalgam: R_{AB}:0.42, 0.31, 0.30; R_{AS}:1.7, 1.5, 1.3; (R_{AB} + R_{AS}):2.0, 1.6, 1.3; $e.m.f.$:160, 151, 145; I:3.4, 2.8, 1.9.

TABLE II

SUMMARY OF RESULTS FOR SINGLE FILLINGS

78 Fillings in Mouths of 66 Persons

Average Values—Part II

78 FILLINGS	66 AMALGAM	12 GOLD
Resistance of the bone fluid contact, R_{AB}	0.067 megohm	0.097 megohm
Resistance of the saliva contact, R_{AS}	0.24 megohm	0.44 megohm
Total resistance	0.31 megohm	0.54 megohm
Net e.m.f. associated with filling		
Positive*	87 mv. (29)**	67 mv. (7)
Negative	54 mv. (37)	136 mv. (5)
Normal electric current through filling, I		
Positive*	0.48 microamp. (29)	0.30 microamp. (7)
Negative	0.48 microamp. (37)	0.22 microamp. (5)

*Positive direction of e.m.f. and current is from filling to saliva to bone to filling.
**In parentheses is given the number of fillings used to compute the average value.

The result that the resistance between a pair of platinum spiral auxiliary electrodes was independent of their relative positions in the oral cavity, also shows that the resistance introduced by such an electrode is concentrated in, and very near, the metal-saliva contact, and that the resistance offered by the saliva, bone and tissues is relatively negligible.

The similar result that the resistance between a pair of saliva-probes (Fig. 8) was independent of the size of the drop of saliva which connected them, also shows that the resistance introduced by such an electrode is concentrated at, and near, the metal-saliva contact.

Both of these results corroborate the experimental fact noted in Part I, that the resistance between a pair of fillings was independent of their relative positions in the oral cavity, which led to the conclusion that the resistance limiting the normal current through a filling is concentrated at and near its contacts with the saliva and the bone fluid.

While the electrometer-tube potential-difference meter was being constructed and perfected, many data on single fillings were taken with the aid of the ballistic-galvanometer-condenser potential-difference meter which is described in Part I. With this meter usable data were obtained on 127 fillings in the mouths of 77 persons. Eleven of the fillings were gold, 116 were of amalgam.

Since the charging time for the one-mf condenser was 5 seconds, serious polarization effects were present in spite of the fact that a 2 megohm resistor served for both R_2 and R_4. The measurements of the net e.m.f. did not involve the use of current through the resistor, and these measurements agree very well with those obtained with the electrometer-tube apparatus. In fact in both sets

of measurements the average value of the positive e.m.f. associated with an amalgam filling was 87 mv. The average negative e.m.f. for amalgam was 54 mv for the electrometer data and 60 mv for the ballistic galvanometer data. The number of gold fillings in each set was too small (5 to 7) to yield good agreement; they were respectively 67 and 136 mv, and 161 and 46 mv. This is an entirely satisfactory agreement for such small numbers of measures on such highly variable quantities.

The resistance measurements involved the use of current and the resulting polarization effects (with ballistic galvanometer apparatus) evidently caused the resistances of the metal-saliva and metal-bone fluid contacts to increase (or the existing e.m.f.'s to decrease, which would give the same effect). In fact the average computed resistances were several times those computed from electrometer data. The average currents were correspondingly less by the same factor. Again, these results may be considered in satisfactory agreement for they disagree by less than half an order of magnitude. This is far less disagreement than may occur between sets of measurements on two different fillings in the same oral cavity. Serious polarization (decrease in e.m.f. or increase in resistance, or both) was evidenced by the fact that successive values of both V_2 and V_4 decreased in size. This occurred very seldom with the electrometer apparatus.

Considerations of the results obtained with pairs of fillings in Part I, in the light of the results obtained with single fillings, are of interest. One also would expect that R_B of Part I, which is made up of two filling-bone fluid contacts, should be about twice as large as R_{AB}. Actually the former is some 5 times larger. This probably is due to the polarization effects which occurred when the resistor (R_2) was connected for the 5 second intervals and a 1 mf condenser was charged.

A few of the subjects reported electric shocks when two of their fillings were contacted with the probes (connected to the 1 mf condenser); evidently even the small charge taken by the condenser was sufficient to cause this disagreeable sensation. If two fillings, wet with saliva, are connected through an ordinary microammeter or galvanometer, both the e.m.f. caused by the saliva and the e.m.f. caused by bone fluid (acting on the pair of fillings) furnish current through the meter. Early workers reported such currents to be as much as 50 microamperes, and even much more in some cases. These facts indicate that contacts between metallic fillings in place in teeth, must be avoided. If necessary a plastic plug may be inserted in one of them at the point of contact.

The many case histories that have been reported in the literature lead one to conclude that serious pathologic conditions in the oral cavity have been caused by metallic dental fillings. There appears to be no evidence that such conditions are caused directly by the electric current. However, if the subject happens to exhibit hypersensitivity to certain metallic ions supplied by the dental fillings, then, since the electric current hastens the solution of the fillings and assists in transporting the ions to and through the tissues, it may exert an indirect detrimental effect on the subject.

The mere size of the electromotive force probably is not significant. Three of the five patients who had decided pathological conditions in their mouths exhibited electromotive forces much larger than the average from ''normal'' subjects, but quite a number of the subjects with apparently ''normal'' mouths exhibited even larger electromotive forces. However, the number of cases (5) exhibiting decided pathological conditions was too small to permit the drawing of final conclusions.

CONCLUSIONS

A critical survey of the literature since 1878 together with the results obtained in the present work, lead to the following conclusions:

1. There appears to be good evidence that serious pathologic conditions in the oral cavity have been caused by metallic dental fillings.

2. The mere size of the electromotive forces associated with metallic fillings is probably not of primary significance (this conclusion is based on only a few observations). A more important factor may be the hypersensitivity of the subject to the metallic ions supplied by the fillings.

3. Relatively large electric currents will pass through metallic fillings if two such fillings are in contact. Such contacts between metallic fillings should be prevented.

4. The magnitudes of the electrical phenomena associated with metallic dental fillings do not appear to depend on the pH of the saliva, on the sex or age of the subject, or on the existence or nature of recent illness.

5. In this report are shown: (a) that the bone fluid is just as important as the saliva in causing electric currents; (b) methods for determining the net e.m.f.'s associated with metallic dental fillings; (c) methods for determining the electrical resistances associated with metallic dental fillings; (d) that these resistances are concentrated at the metal-saliva and metal-bone fluid contacts; (e) a method for determining the net electric current passing through a metallic dental filling under ordinary oral conditions; and, (f) that the magnitude of the current through any filling is virtually independent of the number and kinds of other fillings in that oral cavity, provided that filling does not make contact with any other metallic filling.

SUMMARY

A critical review of the literature from 1878 to date is presented. The more important experiments are described and the more important conclusions are cited. Certain fallacies are pointed out.

The sources of possible electromotive forces for pairs of metallic fillings and for single fillings are described. The literature survey revealed that neither these e.m.f.'s, nor their resulting currents, had been measured, and that no measurements had been reported from which these e.m.f.'s and currents could have been calculated.

A condenser-ballistic-galvanometer potential-difference meter was developed, with which the electrical potential differences between pairs of metallic fillings could be measured. The scheme for carrying out the measurements and the theory for the calculations are given.

Measurements were made on 213 pairs of fillings in the mouths of 137 subjects. Average values of the results are given in Table I.

A study of these measurements (Part I) led to the conclusion that the electrical resistance associated with a filling is almost entirely concentrated in, and very near, the metal-saliva and metal-bone fluid contacts. This was confirmed in Part II for metal-saliva contacts.

This conclusion made it possible to prove, by use of the well-known principles applying to electric circuits, that the electric current through any metallic filling is virtually independent of the number and kinds of other metallic fillings in that oral cavity, provided that filling is not in contact with any other metallic filling.

This proof, together with the conclusion above, made it possible to develop a method, including the necessary theory, for determining the electromotive force, electrical resistance, and electric current associated with a single metallic filling. The theory calls for the measurement of five potential differences as well as the resistances introduced by an auxiliary electrode and a saliva probe.

A second apparatus for measuring the potential differences was developed: it incorporated a special highly-insulated electrometer tube. A potential measurement with this meter required a closed-circuit time of only a fraction of a second, and only a very small electric charge needed to be furnished by the source of the potential. This meter eliminated intolerable polarization effects.

The experimental procedure is described and the scheme for dealing with the data is given. Results were computed for 78 fillings in the oral cavities of 66 subjects whose ages fell in the range 18 to 30 years. These results are summarized in Table II.

These results are discussed and their relations to other results obtained with the condenser-ballistic-galvanometer meter on 127 fillings in the mouths of 77 persons, are described.

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