AN EXPERIMENTAL STUDY OF DIATHERMY.

I. The Measurement of Lung Temperature.

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INTRODUCTION.

The word "diathermy" means heating through. It was coined by Nagelschmidt (1) to describe the effects of the passage of certain electrical currents through the human body. Tesla[1] (2) is responsible for perfecting apparatus whereby high tension alternating currents of high frequency can be produced. In the *Electrical Engineer* for December, 1891, Tesla says: "Without vouching for all the results, which must of course be determined by experience and observation, I can at least warrant the fact that heating would occur by the use of this method of subjecting the human body to bombardment of alternating currents of high potential and high frequency." He goes on to throw out the suggestion that such heating of the body may some day find an important place in therapeutics. This prediction is in a sense correct. Diathermy has come to be one of the most widely used of the so called "physiotherapeutic modalities." Moreover, a copious literature, mostly of an empirical and casuistic kind, has sprung up, dealing with the therapeutic application of diathermy in a variety of clinical conditions. Much of this prolific literature attributes the beneficent action of these currents solely to the production of local deep heat, though some writers go as far as to stress the value of "cellular massage," which they claim the current produces. Medical diathermy, as distinguished from fulguration and cauterization, is today being used in the treatment of many diseases,

[1] We have since learned that Dr. Elihu Thomson of the General Electric Company was probably the first to construct a dynamo capable of producing high frequency currents.

such as angina pectoris, arteriosclerosis, arthritis, asthma, bronchitis and bronchiectasis, cholecystitis, essential hypertension, gonorrhea, gout, hemorrhoids, impotence, intermittent claudication, lumbago, lupus, myocarditis, neuralgia, paresthesias, pneumonia, Raynaud's disease, scleroderma, sciatica, tabes, tuberculosis, uterine displacements, varicose veins, whooping cough, and xanthelasma. For the successful treatment of each one of these conditions there are one or more enthusiastic champions.

Such a list naturally gives one pause and makes for skepticism, especially as it is so extraordinarily difficult to arrive at sound judgments in regard to remedial measures. Still, it should be borne in mind that the application of heat with the production of hyperemia is a time-honored medical procedure and one which may well have unsuspected usefulness. In the treatment of pneumonia, particularly, reports of the successful application of diathermy have been numerous, widespread, and enthusiastic. Stewart's (3) work is especially suggestive. The rationale for the use of diathermy in pneumonia has been variously ascribed to the hastening of resolution, the stimulation of the normal defenses of the body, and the direct lethal action on the microorganisms of the heat developed in the lung.

We were led to a study of the bodily responses to high frequency currents as a preliminary to an investigation of the value of diathermy in pneumonia. D'Arsonval (4) made the fundamental observation that when this type of current is passed through the human body muscle contraction is felt up to about 5000 interruptions per second. At 5000 interruptions muscle contraction is feeble, disappearing beyond 10,000.[2] At these frequencies, however, there occurs an unpleasant feeling of heat. The problem which confronted us was to find out whether deep localized heat could actually be produced in the body. Before presenting an account of our experiments and the

[2] Nernst (5) developed mathematically a generalization stating that the physiological threshold for relatively weak alternating currents varies inversely as the square root of the frequency. The number of times a current must alternate if it is to lose its stimulating and electrolytic powers depends upon its strength. Strong currents must have a higher frequency than weak ones. The Nernst formula is $I = \sqrt{NC}$, where I = intensity of alternating current, N = number of complete cycles per unit of time, and C = a constant.

results obtained from them, it will be well to consider briefly the character of the so called diathermy current and some of the laws governing its use.

The Nature of the So Called Diathermy Current.

The diathermy current is an alternating current of high voltage and low amperage, very rapidly reversed in its polarity. Usually the voltage employed in the secondary circuit is approximately 30,000 to 40,000, the voltage in the body being lower, but not accurately ascertainable. The current is from 1 to 2 amperes, and the frequency of oscillation about 1,000,000 to 2,000,000 cycles per second.[3] Such currents can be produced by suitable apparatus consisting essentially of the parts shown in Fig. 1.

In this diagram *b* is the core of a transformer which transforms the low voltage current in the primary coil (*a*) into a high voltage current of the same frequency in the secondary coil (*c*). This current charges the condenser (*d*) to a voltage sufficient to break down the insulation of the spark-gap (*e*). The condenser (*d*) then discharges through the circuit *d e f* with an alternating current of high frequency determined by the small capacity of (*d*) and the small inductance of (*f*). The current induces in the oscillator (*g*) a current of the same high frequency but of again increased voltage.

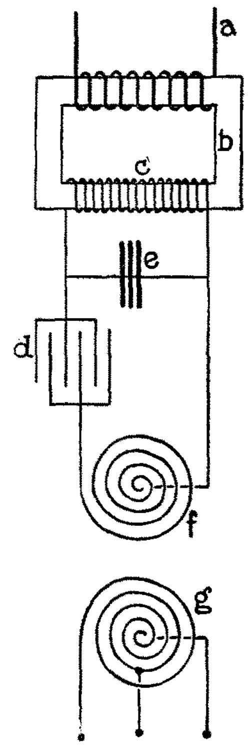

FIG. 1. Diagram of high frequency apparatus after Cumberbatch (6). (*a*) primary coil, (*b*) transformer, (*c*) secondary coil, (*d*) condenser, (*e*) spark-gap, (*f*) oscillator, (*g*) resonator.

[3] The physical constants of the apparatus which we used were:
Primary voltage, 110.
Secondary transformer voltage, 36,000.
Frequency in primary circuit, 60 cycles per second.
Frequency in secondary or oscillating circuit, 1,250,000 cycles per second.
Amount of capacity in secondary circuit about 900 cm.
Damping factor in secondary circuit, or logarithmic decrement, slightly below 0.5.

It is not unlikely that modern radio equipment may soon be used to advantage to replace this type of spark-gap machine.

The frequency of oscillatory discharge will depend upon: (1) the amount of self-induction in the spiral oscillator, (2) the capacity of the condenser, and, to a slight extent (3) the resistance of the circuit.

When a current traverses a conductor, heat is generated. The number of units of heat developed in the conductor is proportional to (1) its ohmic resistance, (2) the square of the current strength, (3) the duration of flow. For a continuous current the heating effect is proportional to I^2R, where I is the steady current and R the normal resistance of the conductor at any definite temperature. With diathermy high frequency currents the heat is again proportional to I^2R, but in this instance I denotes the average flow of current throughout the successive cycles, and R is the ohmic resistance plus the effect of dielectric loss.

The heating effects of these currents have for the most part been studied in non-living systems. A favorite experiment has been the coagulation of egg albumin or the cooking of meat and potatoes. Two statements are frequently made concerning the diathermy current, first, that the current always flows through the shortest path between the electrodes regardless of the resistance it encounters; second, that the heating occurs first at the center of the current path and later at the two ends. In another communication (7) we will present evidence to show that neither of these statements is strictly accurate.

Arguments from analogy based on such *in vitro* experiments have been carried over to the clinical application of diathermy, and have been responsible for many false assumptions. The living body is not a sausage, nor yet a tube filled with albumin water. It is a heterogeneous system composed of tissues with different specific conductivities and heat capacities. Moreover, these tissues are variously placed and must therefore lose heat at different rates, according to the efficiency of their circulation, and the opportunity afforded them for heat loss by radiation, convection, and conduction. Thus far, it has not been definitely established either that deep local heat can be produced by the diathermy current or, indeed, that the current penetrates into the deeper portions of the body.

Recently, Bethman and Crohn (8) have presented evidence which they believe indicates that the so called "skin effect" is a factor in keeping the current near the surface of the body. Moreover, these authors state that in experiments with anesthetized dogs they have "found it extremely difficult at any time to raise the systemic temperature more than a few fractions of a degree." Such has not been the case in our experiments, as will be brought out later, nor in the experiments reported by Lonergan (9). Dowse and Iredell (10), applying the formula developed by Lord Rayleigh, A. Russell, and others, "assume that no measurable skin effect will be present" in the passage of a current of 10^6 periods per second through the human body. They emphasize, further, the unreliability of attempting to measure current strength in the body accurately by means of a hot wire ammeter.

The fact of the passage of current through tissue can best be established by proof of heat development in the tissue. That this heat will be quickly dissipated, and that it may be conveyed to the tissue from adjoining structures, are two complicating conditions which need to be carefully controlled.

It has been the object of this study to learn whether or not local deep heat is developed in the living animal body by the passage of the current, and if so, under what conditions.

EXPERIMENTAL.

I. Effect of Diathermy Current on the Rectal Temperature.

There can be no doubt that the general systemic temperature as measured by a rectal thermometer can be raised by the passage of the diathermy current. This has been shown by Setzu (11), von Zeynek and his coworkers (12), and Lonergan (9), as well as frequently in our own experiments. In Table I it will be seen that in unanesthetized individuals of three different species the rectal temperature as observed by us was raised from 1–2°C. in as many hours.

In anesthetized animals (dogs) we have frequently seen a rise in rectal temperature of as much as 5–6°C. This increased heating effect must be due to inability to provide for heat loss, owing to partial paralysis of the heat-regulating mechanism by the anesthetic. Normally an animal will compensate for a moderate decrease or increase in the systemic temperature by increasing the heat loss or varying the metabolic rate. Under the influence of an anesthetic, however, this mechanism may be impaired, and the systemic temperature will fall rapidly unless heat loss be prevented (13). This phenomenon is well shown in the control periods of most of our experiments. Careful wrapping of the dog in blankets prevents heat loss to a fair degree and similarly assures a greater rise in systemic temperature during the passage of the current.

TABLE I.

Species	Milliamperes per sq. inch of electrode surface	Duration of current flow	Rise in rectal temperature
			°C.
Rabbit	100	2 hrs.	2.7
Dog	90	2 hrs. 13 min.	1.1
Man	66	1 hr. 21 min.	1.0

II. Effect of Diathermy Current on Deep Temperature.

(*a*) *Intraabdominal Temperature.*

Experiment D 8.—A male mongrel terrier was anesthetized by the intravenous injection of 2.97 gm. of barbital-sodium dissolved in physiological salt solution. The sides of the abdomen were shaved and lead-tin electrodes measuring 8 × 10 cm. were applied laterally. A mercury thermometer was inserted into the rectum, a second thermometer was placed outside of the electrical field by passing it through the abdominal wall so that its bulb lay in the abdominal cavity 5 cm. from the superior edge of the electrodes. A third thermometer was so placed that its bulb lay in the abdominal cavity at a point midway between the two centers of the parallel electrodes. A diathermy current of 1000 milliamperes (with a current density of less than 100 milliamperes per square inch) was passed through the abdomen for 1 hour. The result was a rise in rectal temperature of 1.76°C., a rise of temperature in that part of the abdomen outside the electrical field of 1.76°C., and a rise of temperature in the abdominal cavity between electrodes of 2.62°C. The dog was then suddenly killed, while the diathermy current was flowing. After death the temperature in both rectum and upper abdominal cavity continued to rise at approximately the rate previous to death, while the temperature in the midabdomen between electrodes suddenly shot up and in the next hour showed an increment of 17.73°C., or nearly seven times as great a rise as recorded during life. This latter fact is in agreement with the temperature changes observed by Lonergan

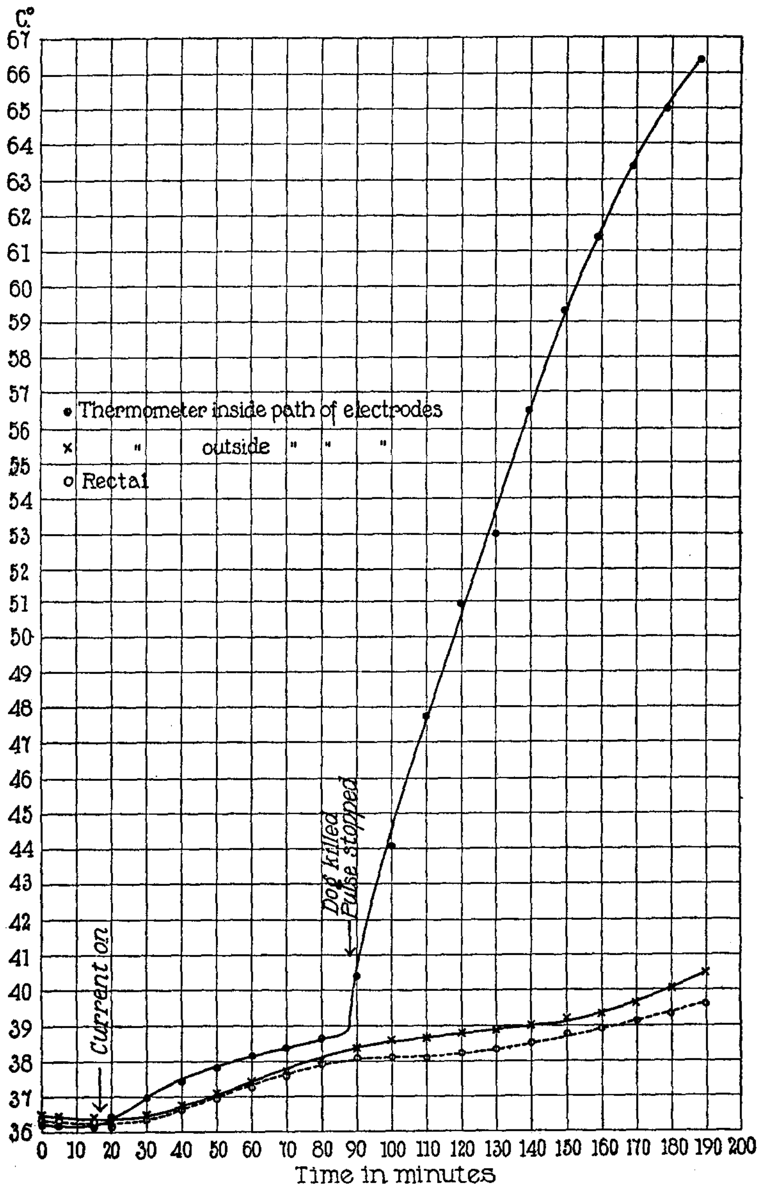

FIG. 2. Curve showing effect of death on heat recorded by thermometer placed in abdomen between electrodes.

(9) during diathermy of a dog's hip joint before and after death. The temperature changes recorded in the experiment just described (D 8) are graphically shown in Fig. 2.

This experiment brings out several points of interest. The temperature rise during life in that portion of the abdominal cavity situated between the electrodes was only a little greater than the rise in the upper abdomen and rectum. After death, however, there was a great and sudden heating up of the abdomen between the electrodes, suggesting that a compensatory cooling mechanism had ceased to operate with the cessation of life. The rectal thermometer reading here cannot be regarded as a true record of the systemic temperature because of its proximity to the heated area.

(*b*) *Intrapleural Temperature.*

In another similar experiment (D 9) in which a thermometer was inserted into the left pleural cavity between electrodes placed laterally on the shaved chest wall, the temperature during 1 hour of current flow rose by 1.88°C. with a rise in rectal temperature of 1.21°C. After death, another hour of diathermy produced an elevation in intrathoracic temperature of 11.62°C., whereas the rectal temperature increased by only 0.08°C. Death, therefore, appears to permit a local heating in the deep tissues between electrodes which does not occur during life. It seemed fairly obvious that the interruption of normal circulation would be found accountable for this discrepancy.

To study the relation of local circulation and heat production experiments were planned in which the temperature of the lungs could be measured by thermocouples. Previous work (14) had provided us with methods for modifying and interrupting the pulmonary circulation. A description of the application of these methods to the present problem will be found in a companion paper (15).

Technique for Measuring Lung Temperature.

The accurate measurement of lung temperature in the living animal during heating by diathermy was not easy to accomplish. After discovering and ruling out a number of sources of error, we achieved a method which has proved satisfactory.

The dog is anesthetized by the intravenous injection of a solution of barbital-sodium. The sides of the thorax are shaved. Lead-tin electrodes, measuring in most instances 3 × 4 inches, are applied to the chest wall with the superior edge well up in the axilla. The interposition of 8 to 12 layers of gauze soaked in a solution consisting of equal parts of glycerol and saturated salt solution assures a good contact. Great care is taken to have the planes of the electrode surfaces as nearly parallel as possible in order to prevent the so called "edge effect"—*i.e.*, the current passing largely between the proximal edges of the electrodes. A convenient method for holding the electrodes in place was accomplished by encircling the thorax with two or three rubber tubes and slipping the electrodes under them. These tubes permit the free motion of the chest wall and still, by their elasticity, hold the electrodes firmly against the skin.

Thermocouples were made by twisting together 5½ foot lengths of No. 31 gauge enamelled copper wire and double silk-covered "constantan" wire treated with one coat of shellac. These were then shellacked and allowed to dry. The two wires were threaded through the shank of a No. 20 gauge hollow Luer needle 11.5 cm. long. The exposed tips of the wires were soldered to the point of the needle in such a manner that the solder closed smoothly the bevelled opening of the needle. The wires were protected by covering them with thick walled rubber capillary tubing, the end of which was passed over the butt of the needle. The free ends of the exposed wires were connected with a galvanometer through a constant temperature junction obtained by a thermos bottle thermostat as described by Clark (16). Thermocouples such as these can be easily prepared in the laboratory. Before use they were calibrated against a Bureau of Standards thermometer which could be read to 0.02°C. When prepared from the same materials and in identical manner, the calibration curves agreed so closely that one curve could be used for all the thermocouples. The calibrations were made at known resistances and each resistance required its own curve. Resistance was supplied by an ordinary Leeds and Northrup resistance box.

The position of these thermocouple needles in respect to the electrical field was found to be of great importance. To obtain accurate temperature measurements the needles must be so placed that they cut the electrical field at right angles. In other words, they must be parallel to the planes of the electrodes, otherwise a concentration of the high frequency current occurs at the needle point, which is then heated more than the surrounding tissue. To avoid this contingency the needles were inserted into the thoracic cavity either from its anterior or posterior aspect so that the final disposition of electrodes and thermocouples was as shown in Fig. 3.

In all experiments it was made certain that turning the current on or off caused no sudden fling in the galvanometer due to concentration of current at the thermocouple. The error introduced by heat loss due to conduction through the needle shank seems a negligible one in view of the very close agreements between temperature so measured and temperature measured by Bureau of Standards thermometers inserted in the rectum. That this source of error was negligible was shown by heating a portion of the needle shank which lay under the skin or projected outside the body wall. This caused no change in the galvanometer reading, showing that sufficient heat to cause an error in reading was not conducted along the needle to the thermocouple.

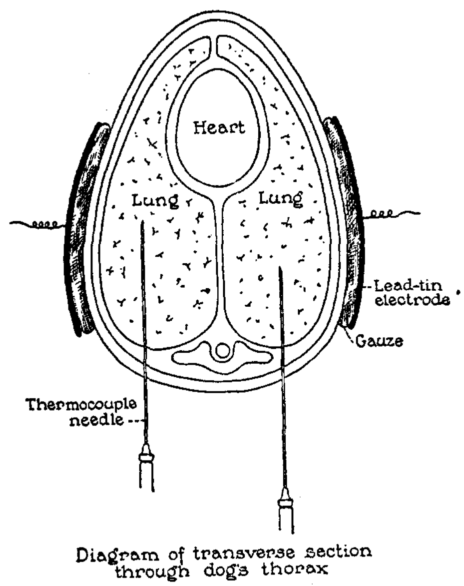

FIG. 3. Diagram of transverse section through a dog's thorax, showing relative positions of electrodes and thermocouples.

(c) *Intrapulmonary Temperature.*

Experiment D 12.—An experiment in which we used the general technique just described was performed on a male American bulldog weighing 14.7 kilos. Thermocouple needles were inserted into the right lower lobe, the right ventral lobe, and the left lower lobe. The position of the thermocouples was verified at the close of the experiment. Simultaneously the rectal temperature was recorded with a mercury thermometer. The average of the three lung temperature readings which agreed within ±0.05°C. before the current was turned on was 0.39°C. below the rectal temperature. During diathermy the lung temperature rose slightly above the rectal, not exceeding it by more than 0.4°C. Toward the close of the experiment, after 3 hours of diathermy, this difference was even less. The temperatures are shown graphically in Fig. 4.

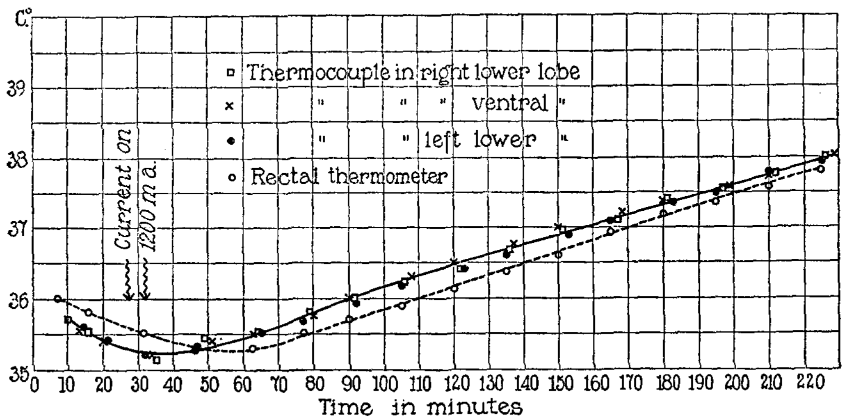

FIG. 4.

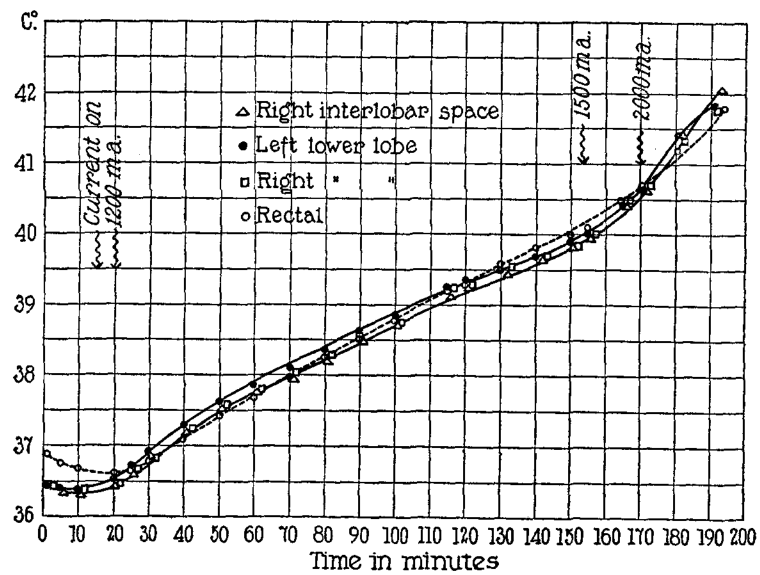

FIG. 5.

FIGS. 4 and 5. Curves showing temperatures recorded by thermocouples in the lungs and by rectal thermometers, in anesthetized dogs subjected to high frequency currents.

Experiment D 11.—This experiment was repeated on another dog. Three thermocouples were again inserted into the thoracic cavity. One of them lodged in the left lower lobe, one in the right lower lobe, and one lay between the right ventral and lower lobes in contact with the visceral pleura. The readings on these three thermocouples seldom varied by more than 0.1°C. Before turning on the current the three readings were: left lower lobe 36.45°C., right lower lobe 36.43°C., right visceral pleura 36.42°C. At this time the rectal temperature measured by a mercury thermometer was 36.88°C. After 2¾ hours of diathermy, the lung temperatures had risen respectively to 41.43°C., 41.35°C., and 41.43°C., while the rectal temperature was 41.21°C. Fig. 5 shows the lung and rectal temperatures in graphic form.

This kind of experiment has been done repeatedly, and in some cases rectal thermocouples were used in conjunction with rectal thermometers. The same type of curve was always obtained.

DISCUSSION.

Examination of Figs. 4 and 5 will show that whereas the lung temperature in the anesthetized dog normally lies 0.3–0.4°C. below the rectal temperature, this relationship is reversed during the passage of high frequency currents of strengths equivalent to those usually employed in therapy. The lung temperature now exceeds the rectal temperature, but only by a few tenths of a degree. Moreover, there is a tendency for the lung to cool and gradually to approximate the rectal temperature again unless the current strength is augmented. This is well shown in Fig. 4, where the lung temperature crosses the rectal temperature first at the start of current flow, gradually falling below it, but again crosses it when the milliamperage is increased. In the light of subsequent experiments this gradual fall in lung temperature may be interpreted as resulting from increased blood flow through the lung and increased pulmonary ventilation.

The fact that death allows a sudden increase of heat in the deep tissue between the electrodes, and that this occurs in the abdominal organs as well as in the thoracic, suggests that the circulation rather than the respiration is chiefly responsible for the removal of heat from the lungs. Whether or not the heating of deep tissues is the result of the passage of current through them or is due to conduction from the more superficial structures has not yet been established. This question will be considered in another communication.

SUMMARY AND CONCLUSIONS.

1. Experimental evidence is furnished to show that in normal animals the rectal temperature can be elevated by the passage of high frequency currents.

2. During life the intraabdominal and intrathoracic temperatures can be increased only slightly above the rectal temperature.

3. The lung temperature in the anesthetized dog normally lies 0.3–0.4°C. below the rectal temperature. During the passage of diathermy currents of strengths equivalent to those used in therapy this relationship is reversed—the lung temperature exceeding the rectal temperature by about the same value.

4. Immediately after death, the temperature rises abruptly in the deep tissues between the electrodes.

5. For the measurement of deep temperature special thermocouples have been devised. Their method of preparation and mode of use are described.

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