# THE RELATION OF FREQUENCY TO THE PHYSIOLOGICAL EFFECTS OF ULTRA-HIGH FREQUENCY CURRENTS.

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It is known that the physiological effects of alternating currents can be profoundly changed by changes in frequency. D'Arsonval (1) first showed that as the frequency of alternations is increased a point is reached where stimulation no longer occurs, and the subject merely feels a sensation of warmth and prickling in the skin. This critical frequency lies between 5,000 and 10,000 alternations per second, depending on the strength of the current (2). As the frequency is still further increased, the prickling sensation disappears till at $10^6$ cycles per second heat production is the only effect which can be demonstrated. Accompanying the change in the physiological response with an increase of frequency, there is a change in the path of the current through the tissues. Whereas low frequency alternating currents confine themselves almost solely to the extracellular fluids, at a frequency of $10^6$ the current actually penetrates the living cell. It does this by reason of the thinness of the dielectric layer surrounding the cell, which transmits the current by means of its capacitance (4). The heat produced at these frequencies can be wholly accounted for on the basis of ohmic resistance and dielectric loss (3).

The modern development of the vacuum tube oscillator has opened up a new field, as it has made it possible to investigate frequencies ranging from 1,000,000 to 158,000,000 and more cycles per second (300 meters to 1.9 meters). Very little analytical work has been done on the biological effects of these currents but it is believed that they differ fundamentally from those produced by any other type of electric current. The literature on the subject is apparently confined to three papers:

Gosset and his coworkers (5) in 1924 published a report on the effect on plant tumours of radiations from a vacuum tube oscillating at 150,000,000 cycles per second. They observed that massive exposures to these rays killed various types of plant tumours, death being preceded by an acceleration in their rate of growth. More recently Schereschewsky (6) has studied the effect of these rays on mice. With the apparatus at his disposal he was able to subject mice to lethal exposures at frequencies varying from 8.3 to 135 million cycles per second. He claimed to have shown that the lethality was maximal when the frequency lay between 20 and 80 million cycles. This phenomenon he ascribed to some selective action of these wave-lengths, suggesting that this might be in the form of electromechanical vibration of the living cell caused by the rapid alternations in polarity of the field. He also observed that while the rectal temperature of a live mouse could be raised 5–6°C. by these currents, that of a freshly killed mouse could only be raised 0.1–0.7°C. in a similar length of time. This he believed was evidence to show that the heating effect with these currents was different from the diathermic effect observed at lower frequencies.

Having shown that there might be a differential action upon tissue cells with regard to frequency, Schereschewsky proceeded to investigate the effects of these radiations on transplantable tumours. A total of 403 mice with the mouse sarcoma were treated by radiation at a frequency of about 67,000,000 cycles per second,—the frequency which had been found to be most lethal to healthy mice. The radiations were strictly localized to the mass of the tumour, so that any systemic effect was excluded. Out of the total of 403 mice treated only 5.5 per cent actually died of the tumour, 23 per cent recovered, and the remainder died from other causes. In 203 control mice, no case of spontaneous recession of the tumour was observed. Somewhat similar results were obtained with chickens that had Rous sarcoma. Microscopic sections of tumours removed after radiation gave a picture resembling coagulation necrosis.

In a small series of experiments a frequency of 135,000,000 cycles was employed, but these radiations were found to have no demonstrable effect on the tumours, which seems to him to support his hypothesis that a specific frequency may be essential.

In short, Schereschewsky thinks that there are certain wave-lengths which have a specific lethal action on living cells. This specific band of frequency lies, he says, between 20,000,000 and 80,000,000 cycles per second (*i.e.* between wavelengths of 15 and 3.8 meters). This same band he says also destroys transplantable tumours in mice and frequencies outside this band have no demonstrable effect.

These observations, if confirmed, may obviously have a wide range of interest in biology and medicine. Previous work, however, had convinced us that the biological effects of currents of lower frequency could be explained solely on the basis of heat production. It was of great interest to us, therefore, to find out whether the same was true of currents of higher frequency, or whether some specific action on living cells existed.

## *Apparatus.*

### *1. Generation of High Frequency Oscillations.*

As is well known, the natural frequency of an oscillating circuit is made as high as possible by reducing the value of its inductance and capacity to the lowest possible limit. The technique of constructing oscillating circuits of ultra-high frequency (above 100,000,000 cycles per second) radiating relatively large amounts of power is rather new and has not been generally described outside of the literature dealing with radio transmission.

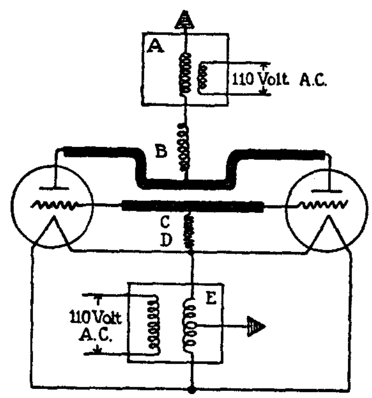

FIG. 1. Circuit used for wave-lengths less than 14 meters: *A*, plate transformer delivering 2,000 volts to the plates. *B* and *C*, radio frequency chokes. *D*, 10,000 ohm grid leak. *E*, filament transformer.

To obtain a frequency of 150,000,000 cycles per second (2 meters wave-length) we use two No. 852 radiatrons. These tubes are rated at 75 watts each and are especially designed for high frequency work as the grid capacity has been made as small as possible and this is the only capacity in our oscillating circuit. The inductance is a short straight piece of heavy copper tubing 6 inches long directly connecting the grids of the two tubes (see Fig. 1). To lessen the frequency it is only necessary to substitute a longer piece of copper tubing.

The plates are connected by another piece of copper tubing as shown in the diagram and the inductive coupling to the grid is varied by rotating the U-shaped piece until the position of maximum power output is obtained. These tubes radiate a very considerable amount of power. An ordinary 50 watt tungsten lamp with a small copper loop fastened to the base is lighted to full brilliancy when held near the oscillator. If a receiver is made by taking a thermoammeter and fastening two short pieces of copper tubing to the binding posts thus making an antenna 1 meter long (*i.e.* a half wave-length) with the meter in the center and placed 30 feet from the oscillator a deflection of over 50 milliamperes is observed on the meter.

The exact wave-length of the radiation is measured by the usual method, on 'Lecher wires." Two parallel wires are strung near the oscillator and the system of standing waves induced in these wires is determined with a neon light and a movable bar connecting the wires; the distance between each nodal point is a half wave-length. For wave-lengths longer than 14 meters we have used the conventional Hartley circuit with a 250 watt tube.

### *2. Utilization of Oscillator Output.*

To utilize the oscillator output a simple resonance circuit was used in which the size of the condenser plates was kept constant, and the inductance varied to attain resonance.

At wave-lengths of 6.0 to 1.9 meters an ammeter was placed in the center of the inductance and at 14 to 38 meters the ammeter was placed adjacent to one plate of the condenser. (An exception was made in this procedure in the first series of experiments when at 2 meters the ammeter was placed adjacent to the condenser plate.) By inserting any poor dielectric, such as a mouse, in the electrostatic field between the plates of the condenser there will be considerable dielectric loss, leading to the production of heat. In other words, a mouse suspended in this field will be subjected to an alternating current of the same frequency as that emitted by the vacuum tube oscillator. As the electrostatic field between the condenser plates is certainly not a homogeneous one, it was obviously necessary to maintain the position of the mice in the field constant with regard to the condenser plates. To do this they were inserted into a Pyrex glass tube of such dimensions that a 20 gm. mouse was able to crawl into the tube but could not move from side to side. With the mouse in the fundus of the tube, its movements were still further limited by the insertion of a glass disc supported by a rod which was embedded in a rubber stopper in the open end of the tube (Fig. 2). It was found that the condensation of moisture from the mouse on the walls of the tube could lead to considerable heating of the glass, when the current was turned on. The condensation of moisture was especially marked round the animal's buttocks. To prevent this the air used for ventilation was warmed and kept as dry as possible (*vide infra*) and a small vent for the escape of air was made through the cork as well as at the fundus of the tube (Fig. 2). By this means more ventilation was brought to bear on the animal's buttocks than elsewhere and heating of the glass was satisfactorily prevented. The tube containing the mouse was inserted between the plates so that it lay horizontally, with the mouse as nearly as possible in the center of the electrostatic field.

### *3. Measurement of Current.*

In a resonance circuit such as has been described we do not believe that, with changing frequency, an ammeter gives any indication of the intensity of the radiations between the condenser plates. The inductive part of the circuit has considerable capacitance, so that the actual amount of current flowing in different parts of the inductance will vary widely. The ammeter will give a maximum reading at a point in the center of the inductance and a minimum reading at the point where the inductance joins the capacitance. Even if the ammeter is kept in the center of the inductance, a change in frequency would of necessity alter the amount of capacitance in the inductive part of the circuit. This in turn would alter the ratio of the current flowing in the ammeter to the intensity of the field between the condenser plates. From theoretical principles it is then obvious that any change in the inductance or capacitance of a circuit renders an ammeter reading meaningless with regard to the amount of energy delivered between the plates of the condenser. As will be shown later, it is easy to vary the ammeter reading and the energy between the plates quite independently by changing the inductance, capacitance, or position of the ammeter. It is only when the position of the ammeter and the structure of the circuit are kept constant that the ammeter reading is of any significance and this is obviously impossible if the frequency is to be changed. Also, any "skin effect" in the thermocouple will introduce an error, the magnitude of which will change with frequency. It was evident therefore that some method must be devised whereby the energy between the condenser plates could be measured directly. To do this we used as our standard the heat produced in a simple electrolyte when suspended between the condenser plates.

The rate of heat production in an electrolyte under these conditions will constitute a direct measurement of the radiant energy between the plates, irrespective of frequency (7).

In our first series of experiments on mice, we used as our standard the rate of heat production in 100 cc. of $\frac{M}{10}$ NaCl in a glass cell. By this method successive observations under as far as possible similar conditions gave checks which only corresponded to within $\pm 10$ per cent. This was due in part at least to irregularities in heat production at the phase boundary between the electrolyte and air, and to the fact that the fluid had to be stirred. To obviate these sources of error a device like a large thermometer was constructed with the bulb containing 20 cc. of $\frac{M}{20}$ NaCl, coloured with safranine, and the stem graduated to from 15–35°C. When the bulb of the thermometer was suspended in the field between the condenser plates, it was found that at any frequency checks agreeing within ±1 per cent could be obtained provided the position of the thermometer and the various constants of the circuit remained unchanged. In the first series of observations $\frac{M}{10}$ NaCl in a cell was used to gauge the strength of the radiations to which the mice were being submitted. At each frequency the tuned circuit was so arranged that with the cell in position, the $\frac{M}{10}$ NaCl heated at a rate of approximately 0.5°C. per minute. The cell was then removed and the mice subjected to the radiations. In the second series of observations a somewhat different

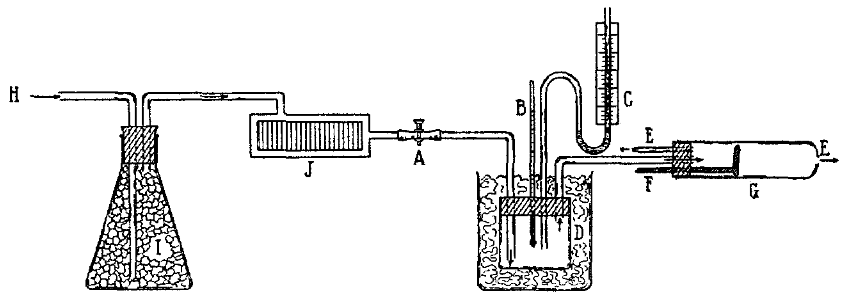


FIG. 2. Apparatus used to maintain a mouse under constant atmospheric conditions while suspended in the magnetic field. *A*, screw clamp to regulate air pressure. *B*, thermometer. *C*, water manometer. *D*, insulated mixing chamber. *E*, openings for escape of air. *F*, rod to keep mouse in position. *G*, mouse holder. *H*, source for air pressure. *I*, calcium chloride. *J*, electric heater.

procedure was adopted. During each experiment the $\frac{M}{20}$ NaCl thermometer was suspended vertically in the field, immediately above the center of the mouse so that both were being heated simultaneously. The heat produced in the thermometer was taken as an index of the strength of the field between the condenser plates.

### 4. *Maintenance of Constant Effective Temperature.*

Since it is known that the production of heat is one of the effects produced by these radiations, it was thought advisable to keep the atmospheric conditions around the mouse as far as possible constant.

For this purpose air of constant humidity and temperature was forced through the mouse chamber at constant pressure (Fig. 2). The humidity was reduced to approximately zero by passing the air through calcium chloride. The temperature was then raised by means of an electric heater to from 22–24°C. This warm dry air was then passed into the mouse chamber at a pressure of 30 mm. of water. The air was especially suitable for ventilation as it was below the "comfort zone" (8), and prevented moisture from condensing on the walls of the mouse chamber.

Even under these standardized conditions it was found that a considerable variation existed in the response of mice to any given quantity of current. Some mice made efforts to escape from the chamber and soon died while others compensated by quietly panting and survived for a longer time. Since variations due to this individual factor diminished as the current strength was increased, we decided to use more powerful radiations than did Schereschewsky. Also since the effectiveness of the heat-regulating mechanism of a mouse varied greatly with slight changes in the current strength, we believe that measurements of the amount of current required to kill the animal in a given length of time are of more significance than measurements of the time taken by a fixed quantity of the current to kill the animal. However, both methods were used in the experiments about to be described.

### 5. *Measurement of Temperature in Mice.*

To obtain a record of temperature changes in a mouse, special thermometers were constructed, of such dimensions that they could be inserted into the mouse's rectum. This was perfectly satisfactory for a live mouse, but it was early found that with a dead mouse which had been subjected to the radiations, a wide range of error existed. The distribution of heat was very irregular, so that if the bulb of the thermometer were held just inside the rectum a higher temperature was recorded than if it were inserted into the abdominal cavity. In the first series of experiments the rectal thermometer was used to measure the temperature after death. Care was taken to have the bulb lying in the abdominal cavity, not touching the spine. Even with these precautions a considerable margin of error undoubtedly persisted in the dead mice which were radiated, as a slight movement of the thermometer often caused a change of as much as 2°C.

To obviate these sources of error a method was devised whereby the temperature of the mouse could be estimated calorimetrically.

For the purpose a Dewar flask was used, of such dimensions that when closed with a rubber stopper, it could just hold a 20 gm. mouse and 130 cc. of water. In the stopper were two openings through one of which was inserted a thermometer and through the other a glass tube to allow for the escape of air when the stopper was inserted. The technique for estimating the caloric increase in a mouse after subjecting it to the radiations was as follows: The rectal temperature of the mouse was taken before radiation, and immediately after death the animal was plunged into the Dewar flask which had been filled with 120 cc. of water at room temperature. The stopper was then inserted and the flask allowed to stand for 20 minutes, being gently agitated every 5 minutes. By this time an equilibrium had been reached and the increase of temperature in the water could be read. The weight and specific heat of the mouse being known, it was possible to calculate the increase in calories brought about by exposure to the radiations. This was done by subtracting the number of calories as calculated from the rectal thermometer reading, from the number of calories as measured in the calorimeter. From the caloric increase, the temperature increase could be calculated. As no figures were available for the specific heat of mice, this had to be determined directly. To do this 8 dead mice of known weight were placed in an incubator at 40°C. for 6 hours. They were then placed in the calorimeter and the increase of temperature in the water observed, as described above. It was found that on an average the observed temperature increase was 69.2 per cent of what one would expect if an equal weight of water at 40°C. were poured into the flask. The actual figures obtained varied from 64.7 per cent to 73 per cent, but as all the data obtained by this method were used in a relative rather than in an absolute manner, a mean of 70 per cent was considered sufficiently accurate for our purpose. When we say that 0.7 represents the specific heat of mice we realise that this factor includes corrections for various sources of error in the method, but we consider this to be of advantage, since it is in the increase of temperature and not in the specific heat of mice that we are interested.

## EXPERIMENTAL.

The experiments about to be described naturally fall into three groups which can conveniently be considered separately. The first series of experiments were planned to find if the lethal nature of these radiations was strictly proportionate to their intensity, irrespective of frequency, or if certain frequencies had a specific lethal action on living cells. These experiments indicated the need for certain refinements of technique which were incorporated in the second series. The third series was planned to find the actual cause of death in animals subjected to these radiations.

### *First Series.*

The procedure in this series of experiments consisted of subjecting live mice to the radiations by means of the tuned auxiliary circuit and ventilated mouse chamber described above. The amount of current flowing in the auxiliary circuit was measured by means of an ammeter and also by the amount of heat produced in 100 cc. of $\frac{M}{10}$ NaCl (*vide ante*). The condenser plates were kept about 3 cm. apart. Temperature measurements were made on the mice before and after radiation by means of a rectal thermometer. In all, four wave-lengths were investigated: 2, 6, 14, and 38 meters. In the last three of these several different current strengths were used. At each current strength, from 2 to 10 live mice and from 3 to 13 dead mice were radiated and the temperature increase in each

TABLE I.

*Effect on Live Mice of Lethal Exposures, and on Dead Mice of Exposures of Similar Duration and Intensity. First Series.*

| Frequency $\times 10^6$ | Wave-length | Current strength | Rate of heating of M/10 NaCl in cell per min. | Number of mice | | Average duration of exposure | | Average temperature increase | | Average temperature increase per min. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Alive | Dead | Alive | Dead | Alive | Dead | Alive | Dead |
| *cycles per sec.* | *meters* | *amperes* | *°C.* | | | *min.* | *min.* | *°C.* | *°C.* | *°C.* | *°C.* |
| 150 | 2 | 1.35 | 0.54 | 9 | 12 | 4.79 | 4.71 | 4.99 | 5.77 | 1.05 | 1.39 |
| 50 | 6 | 1.6 | 0.08 | 2 | 2 | 20.8 | 20.5 | 4.3 | 8.1 | 0.21 | 0.40 |
| 50 | 6 | 3.0 | 0.47 | 10 | 13 | 4.90 | 4.86 | 5.17 | 5.17 | 1.05 | 1.06 |
| 21.4 | 14 | 1.0 | 0.40 | 6 | 6 | 5.05 | 5.11 | 4.28 | 3.6 | 0.86 | 0.70 |
| 21.4 | 14 | 1.6 | 0.98 | 8 | 7 | 3.76 | 3.71 | 4.63 | 3.97 | 1.21 | 1.08 |
| 21.4 | 14 | 1.8 | | 4 | 5 | 3.47 | 3.36 | 5.62 | 4.08 | 1.55 | 1.20 |
| 21.4 | 14 | 2.2 | | 5 | 7 | 2.62 | 2.58 | 5.18 | 3.95 | 2.01 | 1.76 |
| 7.9 | 38 | 0.55 | 0.45 | 6 | 3 | 5.3 | 5.3 | 5.35 | 5.30 | 1.01 | 1.00 |
| 7.9 | 38 | 0.65 | | 2 | — | 4.25 | — | 5.35 | — | 1.25 | — |

mouse was recorded. It was found at all frequencies that, within the limits of error, the rate of heating of the $\frac{M}{10}$ NaCl was proportional to the rate of heating of live and dead mice, and also to the time taken to kill the live mice (Table I). The amperage on the other hand bore no relationship to any of these figures when the frequency was changed. For example, with the current of such a strength that the salt solution heated at 0.4–0.54°C. per minute, mice were killed in from 4 to 5 minutes at all frequencies and their rate of heating was approximately 1°C. per minute. The amperage, however, varied from 0.55 to 3.0 as the frequency was changed.

The rate of heat production in dead mice was found to be on an average approximately the same as that of live mice at all frequencies. This is contrary to what was found by Schereschewsky. The discrepancy can readily be explained by the fact that we deliberately allowed the dead mice to cool down to room temperature before being radiated, while Schereschewsky radiated them immediately after death. We found that a dead mouse at 38°C. loses heat at a rate of more than 1°C. per minute, so that in Schereschewsky's experiments heat was being lost by the mice almost as rapidly as it was being generated in them. This obviously only applied to dead mice, as the metabolism of a live mouse is in itself sufficient to maintain a constant temperature. To show experimentally that this explanation is valid, we subjected three groups of mice to radiations at 2 meters wave-length, the auxiliary circuit and the average duration of exposure in each group being kept constant. The first group consisted of live mice, the second of freshly killed mice, and the third of dead mice which had been allowed to cool to room temperature. The temperature increase in these three groups averaged 4.42°C. for the live mice, 1.2°C. for the freshly killed mice, and 5.9°C. for the cooled dead mice.

It is apparent from this experiment that Schereschewsky's observation that currents of certain frequencies will raise the temperature in living mice to a greater degree than in dead mice can be explained not on the basis of specific properties of the radiations, but simply by the fact that the dead mice lost heat during exposure to the rays while the live mice did not.

### *Second Series.*

The technique used in this series was similar to that used in the first with three exceptions.

The temperature of the mice after radiation was measured calorimetrically; the strength of the current was measured with the $\frac{M}{20}$ NaCl thermometer; and measurements were made of the distance between the plates of the condenser in the auxiliary circuit. As we believe that the observations in this series have a much higher degree of accuracy than those in the first series, they will be given in greater detail. Observations were made at 5 wave-lengths, 1.9, 3.2, 6.0, 14.0, and 36.1 meters. At each frequency a group of mice were radiated with the current at such a strength that the $\frac{M}{20}$ NaCl thermometer was heated at a rate of 0.5°C. per minute. Under these circumstances it was found that between 6.0

and 36.1 meters the animals were killed in from 3 to 5½ minutes while at 3.2 meters they were killed in from 6 to 12 minutes and at 1.9 meters in from 8 to 13½ minutes (Table II, Fig. 3). The rate of heat production in these mice and also in dead mice exposed to the same amount of current was found to bear the same relationship to the heating of $\frac{M}{20}$ NaCl at the various frequencies. At 36.1, 14.0, and 6.0 meters the rate of heating in the groups of live mice averaged 1.95°, 1.88°, and 1.90°C. per minute and in the groups of dead mice 2.64°, 2.75°, and 2.55°C. per

TABLE II.

*Effect on Live Mice of Lethal Exposure and on Dead Mice of Exposures of Similar Duration and Intensity. Second Series.*

| Frequency × $10^6$ | Wave-length | Current strength | Rate of heating of M/20 NaCl per min. | Distance between plates | Number of mice | | Average duration of exposure | | Average temperature increase | | Average temperature increase per min. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Alive | Dead | Alive | Dead | Alive | Dead | Alive | Dead |
| *cycles per sec.* | *meters* | *amperes* | °C. | *cm.* | | | *min.* | *min.* | °C. | °C. | °C. | °C. |
| 158 | 1.9 | 4.3 | 0.52 | 4.2 | 6 | 6 | 9.6 | 10.1 | 5.59 | 14.5 | 0.563 | 1.46 |
| 158 | 1.9 | 3.4 | 0.59 | 2.9 | 2 | — | 7.2 | — | 6.60 | — | 0.895 | — |
| 158 | 1.9 | 3.8 | 0.65 | 2.9 | 6 | — | 4.83 | — | 5.53 | — | 1.115 | — |
| 158 | 1.9 | 4.2 | 0.74 | 2.9 | 2 | — | 3.35 | — | 6.40 | — | 1.90 | — |
| 93.7 | 3.2 | 1.4 | 0.37 | 4.9 | 2 | — | 29.8 | — | 4.90 | — | 0.16 | — |
| 93.7 | 3.2 | 1.7 | 0.53 | 4.9 | 7 | 6 | 9.8 | 10.18 | 5.96 | 11.9 | 0.626 | 1.16 |
| 93.7 | 3.2 | 2.0 | 0.65 | 4.9 | 2 | — | 6.6 | — | 4.70 | — | 0.73 | — |
| 93.7 | 3.2 | 4.9 | 0.74 | 4.9 | 9 | — | 5.1 | — | 4.60 | — | 0.94 | — |
| 50.0 | 6.0 | 1.5 | 0.48 | 2.9 | 6 | 6 | 4.58 | 4.53 | 8.53 | 11.50 | 1.90 | 2.55 |
| 21.4 | 14.0 | 1.2 | 0.51 | 2.9 | 6 | 6 | 4.1 | 3.97 | 7.69 | 10.87 | 1.88 | 2.75 |
| 8.3 | 36.1 | 1.0 | 0.30 | 4.2 | 3 | 3 | 11.2 | 11.6 | 8.60 | 11.43 | 0.79 | 1.00 |
| 8.3 | 36.1 | 1.0 | 0.49 | 2.9 | 6 | 6 | 4.35 | 4.73 | 8.27 | 11.83 | 1.95 | 2.64 |
| 8.3 | 36.1 | 1.05 | 0.60 | 2.9 | 2 | — | 2.25 | — | 4.70 | — | 2.58 | — |

minute. At 3.2 and 1.9 meters, however, the live mice heated at 0.63° and 0.56°C. per minute and the dead at 1.16° and 1.46°C. per minute respectively (Table II, Figs. 4 and 5).

The significance of these figures will be discussed later, but, in brief, it would appear that the lethal nature of the radiations and the amount of heat that they generate in mice, remain constant up to a frequency of about 50,000,000 cycles (6 meters wave-length). When this frequency is exceeded, however, both the heat production and the lethality diminish. Observations of a similar nature to those described above but with other rates of heating of the saline thermometer pointed to the same conclusions (Table II). For additional confirma-

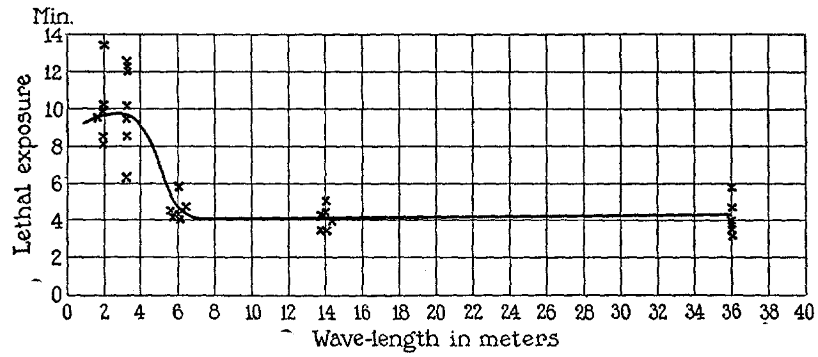


FIG. 3. Curve showing duration of lethal exposure for mice. The ordinates represent time in minutes; the abscissæ the wave-length in meters of the radiations to which the mice were exposed. At each wave-length the radiations were of such strength that the $\frac{M}{20}$ NaCl thermometer was heated at the rate of 0.5°C. per minute.

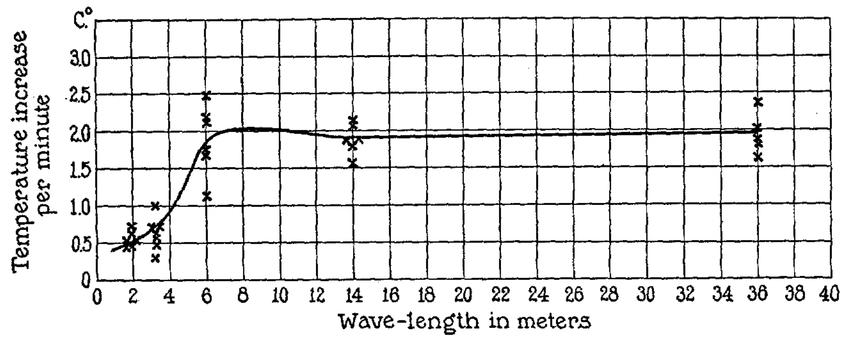


FIG. 4. Curve showing the rate of heating in mice when subjected to a lethal exposure. The ordinates represent the rate of heating in °C. per minute; the abscissæ the wave-length in meters of the radiations to which the mice were exposed. At each wave-length the radiations were of such strength that the $\frac{M}{20}$ NaCl thermometer was heated at the rate of 0.5°C. per minute.

tion observations were made on the amount of current required to kill the mice in approximately 5 minutes. Under these circumstances the saline thermometer heated at a rate of 0.5°C. per minute at 36.1, 14.0, and 6.0 meters, at 0.74°C. per minute at 3.2 meters, and at 0.65°C. per minute at 1.9 meters (Table II, Fig. 6). This diminution in lethality at the higher frequencies was also suggested by the experiments made in the first series, although the change was within the limits of experimental error.

In this series of experiments we also found that the elevation of temperature in dead mice was considerably greater than that found in

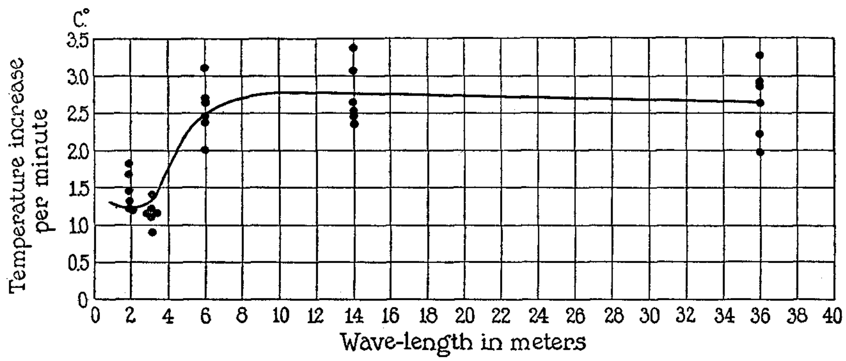


FIG. 5. Curve showing the rate of heating in dead mice when subjected to the same exposures as had been shown to be lethal to live mice. The ordinates represent the rate of heating in °C. per minute; the abscissæ the wave-length in meters of the radiations to which the mice were exposed. At each wave-length the radiations were of such strength that the $\frac{M}{20}$ NaCl thermometer was heated at the rate of 0.5°C. per minute.

live mice. The average increase in 59 live mice was 6.31°C. while the average increase in 33 dead mice subjected to an equal amount of the current was 12.01°C. The discrepancy is what one would expect if heat were being generated in both the live and dead mice at the same rate. Heat loss in the dead mice was reduced to a minimum, while in the live mice the heat-regulating mechanism was allowed to operate unhampered. It will be remembered that in the first series we found live and dead mice to heat at much the same rate. The method used for making temperature measurements was admittedly inaccurate in this series, especially when dead mice were employed.

As in the first series so in this, we could find no direct relationship between the amperage, the lethal effect on mice, and the heating of saline. It will be seen from Table II that the amperage as shown by the meter may be varied by altering the constants of the tuned circuit while the current passing between the plates as measured by the rate of heating of the saline thermometer remains unchanged or changes independently. This is in accord with the theoretical considerations given earlier in the paper, and demonstrates the fallacies underlying the use of the ammeter in an investigation of this type.

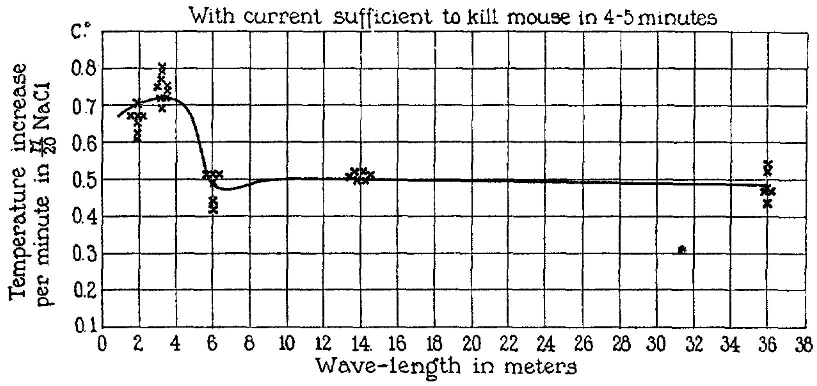


FIG. 6. Curve showing the rate of heating in the $\frac{M}{20}$ NaCl thermometer, when subjected to radiations of such strength that mice were killed in from 4 to 5 minutes. The ordinates represent the rate of heating in °C. per minute; the abscissæ the wave-length in meters of the radiations to which the mice and thermometer were exposed.

## *Third Series.*

It has been shown that radiation with these currents is always accompanied by heat production. In the 120 mice which are included in Series I and II the increase in temperature observed when mice were killed by the radiations ranged from 2–9°C. with an average of 5.7°C. (Fig. 7). Before we could ascribe the death of these animals to the increase of temperature it was obviously necessary to find exactly what increase could be tolerated by the normal mouse. To do this two series of experiments were performed.

In the first experiment 4 mice were placed in an incubator at 60°C. and immediately after death, which occurred in 8 to 10 minutes, the temperature increase was found to average 6.65°C. In another series 6 mice contained inside

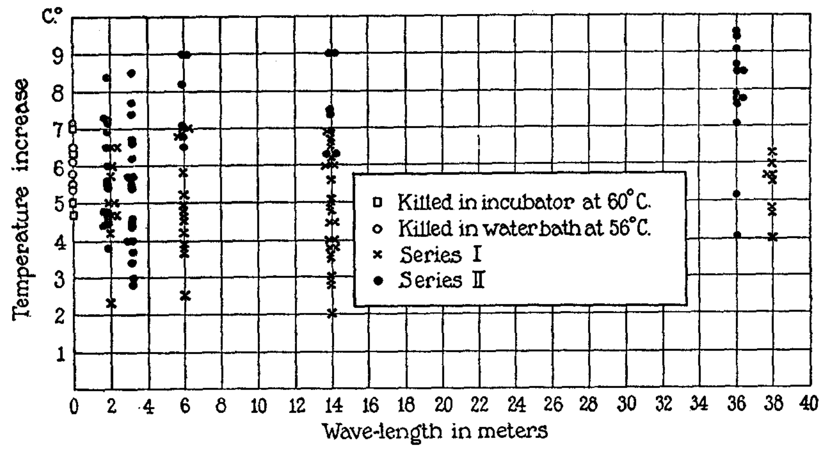


FIG. 7. The black dots and crosses represent the temperature increase at death in mice which had been subjected to lethal exposures of the radiations. The circles and squares represent the temperature increase at death in mice killed by exposure to environmental heat. The ordinates represent the temperature increase in °C.; the abscissæ the wave-length in meters of the radiations to which the mice were exposed.

TABLE III.

*Effect of Sublethal Exposures on Frogs.*

| Wave-length | Current strength | Duration of exposures | Temperature increment | | | | | Highest temperature reached |
|---|---|---|---|---|---|---|---|---|
| | | | 1st exposure | 2nd exposure | 3rd exposure | 4th exposure | 5th exposure | |
| *meters* | *amperes* | *min.* | *°C.* | *°C.* | *°C.* | *°C.* | *°C.* | *°C.* |
| 2 | 1.35 | 10 | 10.04 | 10.03 | 8.10 | 7.60 | — | 34.2 |
| 6 | 3.0 | 5 | 15.3 (10 min.) | 8.05 | 6.2 | 7.3 | 9.4 | 37.0 |

ventilated tubes were introduced into a water bath at 56°C. The average time taken was 4.47 minutes and the temperature increase 6.08°C. These experiments are represented in Fig. 7. The close agreement between the temperatures leading to death in the experiments and resulting from the radiations is apparent.

Several experiments were performed to show that these currents are harmless apart from their heating effect. In the first experiment 2 mice were subjected to 2 meter radiations of a strength to produce death in about 5 minutes. At 2 minute intervals the current was stopped for 2 minutes. Each mouse readily endured a total of 10 minutes radiation. Because of the poor circulation in the tail, overheating of this organ occurred with the result that it was lost (9).

In the next experiment frogs were used.

The technique of exposure to the currents was the same as that used with mice. Radiation was continued for from 5 to 10 minutes, when the groin temperature was taken, and the frog immersed in cold water. After the animal had cooled, the procedure was repeated. At 2 meters 4 exposures were without harmful effect although the temperature rose from 7.5–10°C. at each exposure. At 6 meters 5 exposures were borne although at the first, a temperature of 37°C. was reached and the animal lay as if dead (Table III). Thus if the systemic temperature be kept within tolerable limits, no ill effects result from even prolonged exposures to these radiations.

## DISCUSSION.

The results of these experiments are definitely at variance with those obtained by Schereschewsky. They show that the lethal nature of these radiations is proportionate to the intensity of the field up to a frequency of about 50,000,000 cycles. At frequencies higher than this, the lethality of the radiations appears to diminish. It must be realised that the standard of current strength was the intensity of the electromagnetic field and not necessarily the amount of current induced in the mouse. We believe that in this lies the explanation of the apparent diminution in lethality and that changes in the dielectric constant of the mouse cause a diminution in the amount of current induced in it. From Debye's equation for the dielectric constant as a function of frequency and viscosity it is apparent that in the region of the shorter wave-lengths it is possible that the highly viscous elements of the mouse (fat, epidermis, bone, etc.) begin to play an important part in its dielectric properties, and either diminish or increase the power loss. An analysis of the causes of deviation in this region is impossible, both because the dielectric properties of the constituent parts of the living organism are unknown (10) and the power loss in simple solid dielectrics has not yet received adequate theoretical treatment. It should be noted, however, that at wave-lengths less than 6 meters a mouse ceases to behave in the same manner as an electrolyte, since a deviation of the type found requires the introduction of heterogeneity. Changes in the dielectric constant of the mouse at these very high frequencies would entail a readjustment of the field in the condenser, causing a change in the ratio of power loss between the mouse and the saline thermometer. Curves of the type observed in Figs. 3 to 6 might easily be obtained with a system more simple than a mouse, and hence although it is not at present practicable to analyse the factors causing changes in the dielectric properties, the phenomenon in essence is not at all incomprehensible in its physical aspect. The results of our experiments certainly do not suggest that any specificity exists with regard to the action of any particular wave-lengths on living cells. They do indicate that the lethal effect of these radiations is diminished at the very low wave-lengths, but we believe that this is due to less current being induced in the mouse.

We have mentioned the errors involved in the use of a thermocouple ammeter for measurement of the intensity of the eletrostatic field between the condenser plates. In the auxiliary circuit used by Schereschewsky the error due to skin effect would increase with the frequency while the error due to the capacity of the inductance would decrease with frequency. In his experiments he kept the milliammeter reading constant but the intensity of the field between the plates was certainly changing. Since this change would be, in part at least, governed by the two factors mentioned above, the type of curve which he obtained for the lethal effect of these radiations on mice, might only represent changes in the intensity of the field.

The lethal effect of these currents can be fully accounted for on the basis of heat production. We believe that the production of this heat is strictly analogous to that observed in diathermy, being generated by the resistance of the tissues and dielectric loss. Considerable evidence is at hand to support this statement. Lethal doses of the current, at all frequencies are accompanied by the same degree of temperature elevation. Heat production in dead mice parallels that in live mice irrespective of frequency. Sublethal doses given to mice are without ill effects apart from those which can be accounted for by the local accumulation of heat. Animals which are poikilothermic can be given prolonged exposures without any harmful effect provided the systemic temperature be kept below the lethal point. Moreover, we believe that the data presented by Schereschewsky can also be explained on the basis of heat production by the induced alternating currents. Our interpretation of what he believes to be a specific band of wave-lengths has already been described and a simple explanation has been furnished for the fact that in his experiments dead mice heated less readily than live ones. The effect of these rays on tumours may also in all probability be accounted for on the basis of heat production. Schereschewsky states that the tumours did not feel hot but on the other hand the microscopic picture of the tumours after radiation suggested coagulation necrosis. It should be borne in mind that any heat developed in the tumour would rapidly be disseminated after the current was turned off. Direct temperature measurements in the substance of the tumour during radiation would be necessary to rule out the probability that the structural changes observed were not the result of heat. In fact in our opinion the burden of proof still lies on those who claim any biological action of high frequency currents other than heat production.

## SUMMARY AND CONCLUSIONS.

1. Biological effects of electromagnetic waves emitted by a vacuum tube oscillator have been studied at frequencis ranging from 8,300,000 to 158,000,000 cycles per second (1.9 to 38 meters wave-length).

2. The effects produced on animals can be fully explained on the basis of the heat generated by high frequency currents which are induced in them.

3. No evidence was obtained to support the theory that certain wave-lengths have a specific action on living cells.

4. At frequencies below 50,000,000 cycles, the effect of these radiations on animals is proportionate to the intensity of the electromagnetic field. As the frequency is increased beyond this point, the amount of induced current is diminished and the apparent lethality of the radiation is decreased. This can be explained by changes occurring in the dielectric properties of tissues at low wave-lengths.

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