A Physical Measurement of X-Rays.

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Introduction.

The use of Roentgen rays by the medical profession has increased very rapidly during the past few years, but, as yet, no method of measurement has been generally accepted. At present a large variety of instruments, methods, and units are used. For adding another method to the number already too large, the writer finds his justification in the fact that he not only employs a physical measurement of some accuracy, but also that is it not too complicated for practical use. All the physical principles used are old and have been used before.

The problem was suggested to the writer several years ago by Dr. G. P. Girdwood of Montreal, but a satisfactory galvanometer was not available at that time. The galvanometer needed for this work should be of the D'Arsonval type with a sensitiveness of at least 5×10^{-10} amperes per scale division, but should not be delicate mechanically. The resistance of the galvanometer is unimportant, but it should have as short a period as possible and at the same time be critically damped on open circuit. Dr. Edward Weston has recently developed an instrument which just meets these requirements. One of these he very kindly loaned for this work. The other things essential for satisfactorily carrying out this work were supplied by Dr. W. H. Eagar of Halifax, who was kind enough to place his office and most excellent X-Ray equipment at my disposal. In addition to this, experiments were carried on at Dalhousie University and at the Nova Scotia Technical College with the apparatus belonging to these institutions.

Roentgen rays are commonly used for two distinct purposes:

(1) For diagnostic work by means of fluoroscope and radiograph;

(2) For their therapeutic action.

In each case it is important to know both the quantity or intensity and the quality or hardness of the rays furnished by the tube. There are two *general* methods of measurement:

(1) The electric energy delivered to the bulb is measured and it is assumed that all or a constant fraction of this leaves the bulb as X-rays. A recent article by Dr. G. W. Holmes* shows that experience would seem to justify this assumption. This method does not distinguish directly between the quantity and quality of the rays, but the applied potential is taken as a measure of the hardness:

(2) The quantity and quality of the rays themselves may be directly measured; the quality by some form of penetrometer, which involves the comparison of the intensity of illumination of two surfaces; the quantity by the change produced in the color of some substance, such as barium platino-cyanide, in which case a color comparison is involved.

In a few cases the ionization produced in air has been used as a means of measuring the strength of the rays. Except for experimental difficulties, this should be the ideal method as practically all the evidence indicates that the various effects of Roentgen rays are directly related to their ionizing action. A simple direct reading instrument, making use of this principle, has been recently described by Dr. B. Szilard†. For some purposes this instrument should prove very useful, but for others the length of time necessary to get a reading would be objectionable. The instrument is calibrated to give directly the total number of ions formed in 1 c.c. of the air exposed to X-rays during the time of an exposure.

*The American Journal of Roentgenology, May, 1914.

†Archives of the Roentgen Ray, June, 1914.

The writer also makes use of the ionizing action of X-rays, but employs quite a different method for measuring it. He is able in a few seconds to determine with considerable accuracy the intensity and hardness of the rays, as well as the time of exposure necessary to obtain radiographs of proper density, even under very unfavorable conditions.

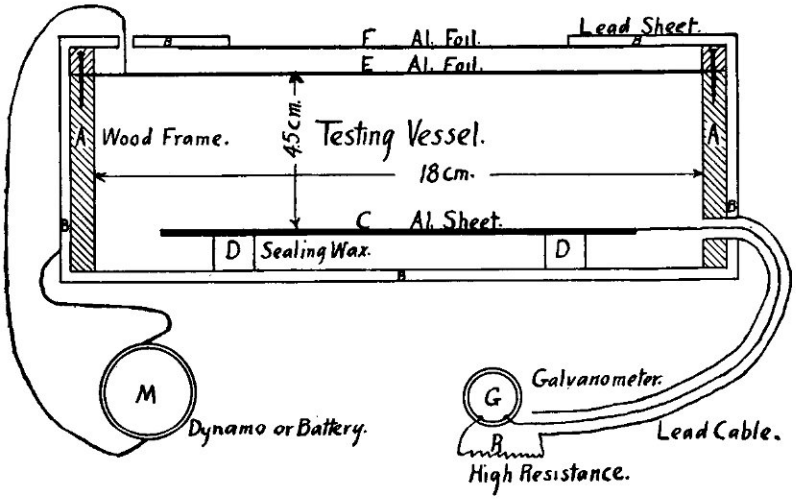

Fig. 1.

APPARATUS.

Figure 1 shows a section of the testing vessel drawn approximately to scale and gives a diagram of connexions. The galvanometer was a Weston Model 89, having a tripod base, and was very easily adjusted by means of an attached spirit level. It was mounted on a window-stool, shelf or mantel according to circumstances, and its deflection was read by means of a lamp and scale. With the scale at a distance of one meter, it gave a deflection of 1mm. for a current of 3×10^{-10} amperes. The high resistance R. of about 10^6 ohms, was made by a pencil line on ground glass and was used merely to protect the galvanometer. The resistance of

the testing vessel was so high in comparison that R can be neglected in the calculations. M may be any fairly steady source of potential, high enough to produce practical saturation. It should be at least 100 volts and was about 200 in the present experiments. Sometimes it was obtained from storage cells and sometimes from a small 220 volt D. C. motor used as a dynamo and driven by a small A. C. motor.

One potential terminal was connected to the outside lead covering of the testing vessel and the other to the insulated aluminum foil E. The foil F was used to protect E from possible electrostatic action, and both were too thin to produce appreciable absorption of the X-rays. The aluminum plate C was very carefully insulated on sealing wax so that the galvanometer would be sure to measure the current due to the X-ray ionization between the plates E and C. The wire leading from C to the galvanometer was a small lead covered cable. The lead cover was connected through the high resistance R to one terminal of the galvanometer and to the lead case of the testing vessel, thus completing the circuit.

The X-ray tube was mounted at any desired distance directly above the opening F. The size of the bundle of rays entering the vessel was determined by placing on top of the vessel a lead sheet with suitable opening. Six tubes of various makes and construction were used and similar results were obtained with all. The smallest tube was about 13cm. in diameter and had a light platinum target, and the largest was about 18cm. in diameter and had a heavy tungsten target.

The different sources of power used included a large and a small induction coil with both Wehnelt and mechanical interrupters and a high tension transformer and commutator (Waite and Bartlett Mfg. Co.), giving an interrupterless current. The current through the tube was measured by a milliammeter, but the spark gap was the only means at

my disposal of estimating the potential on the tube. In the various experiments the currents used varied from 5 to 0.3 milliamperes and the spark gap from 8 to 18cm.

Experimental Methods and Results.

The present investigation may be divided into three distinct parts:

(1) To discover whether the action of Roentgen rays on a photographic plate is proportional to the ionization in the air near the plate, and thus to be able to determine the proper length of time for an exposure;

(2) To compare the action of the rays on a Sabouraud pastille with their ionizing action;

(3) To find an accurate method of comparing the hardness or penetrating power of the rays.

(1)

In order to test the first point the ionization current was measured with some object, for example several sheets of glass, aluminum or lead, covering the opening F of the testing vessel. Then a photographic plate, covered by the same object, was exposed to the action of the rays, produced under the same conditions as before. The X-ray plates used were either Ilford or Wellington, the developer was carefully prepared according to the maker's directions, and great pains was taken to always use the same quantity of fresh developer at the same temperature and to develop for the same length of time.

It was discovered by preliminary experiments that an exposure of 5 sec. gave a satisfactory negative, when the deflection of the galvanometer was 40mm. with a bundle of rays 100 sq. cm. in area. Thereafter the time of exposure of any plate was adjusted to be inversely proportional to the current through the galvanometer, that is, the product of the

time of exposure and the deflection of the galvanometer was always 200.

The procedure in a particular case where six sheets of lead foil, each .026mm. in thickness, was to be the subject radiographed, was as follows: The six sheets of foil were first placed over the opening F, the tube was started up and the galvanometer deflection was 30mm. The foil was then removed from F and a small photographic plate was placed at C. Upon this there were placed, side by side, three strips of lead containing respectively 4, 6 and 8 thicknessess of the above foil. The strips with 4 and 8 thicknesses each were used merely to have some contrast on the negative. The plate was then exposed for $\frac{200}{30} = 7$ sec., with the tube working under as nearly as possible the same conditions as previously.

Over one hundred radiographs were taken as described. Various thicknesses of glass, aluminum and lead were used as the subjects for the radiographs and the rays in the different experiments differed widely in their characteristics, but the negatives showed practically the same photographic action on those portions covered by the materials under examination. Table I gives a record of six plates, all having lead foil for the subject of the radiograph, but taken with rays which were very different for the different plates. The first three were taken with a 17cm. tube having a tungsten target and using an interrupterless current and the last three with a 13cm. tube having a platinum target and operated by a small induction coil and a mechanical interrupter. The density of the negatives appeared to be alike within the limits of accuracy of the various measurements.

TABLE I.

Plate No.	Milliammeter.	Spark Gap.	Lead.	Gal. Defl.	Exposure.
91	1.1	unknown	.104mm.	23	9 sec.
95	4.1	unknown	.208mm.	16	12.5 sec.
96	3.1	unknown	.208mm.	29	7 sec.
10	0.38	18cm	.104mm.	7	29 sec.
10	9.38	18cm	.156mm.	5.5	36 sec.
107	0.50	9cm	.104mm.	5	40 sec.

A comparison of the currents through the tube with the galvanometer deflections, in the cases of 95 and 96 and of 105 and 107, shows how unsafe it is to judge the intensity of the X-rays by the milliammeter alone. In both cases the current through the tube increased, but the galvanometer reading decreased, and the radiographs showed that the desired results were obtained by increasing the time of exposure, as was actually done. We must conclude then that the relative action of Roentgen rays on a photographic plate and in ionizing the air near the plate remains practically constant, however the rays themselves may be altered.

In order to compare the absorbing power of various parts of the body with various thicknesses of lead foil, radiographs of the knee, the thigh and the chest were taken with lead foil of varying thicknesses on the same plates. The results were rather unsatisfactory, because somewhat different results were obtained with rays of different hardness, and in practice it would be better to use aluminum sheet in place of lead foil for this purpose. However, the negatives showed about the same density for the following when the penetration was 8 or 9 Benoist:

Knee joint and 8 thicknesses of foil each .026mm.
Thigh bone and 10 " "
Flesh of thigh and 8 " "
Ribs and 10 or 12 " "

By making such a comparison once for all, and using aluminum instead of lead, it would be possible in a few seconds by a single reading of the galvanometer, with proper thickness of aluminum over the testing vessel, to determine the time of exposure necessary to obtain a satisfactory radiograph of any part of the body. Of course, this would be of no practical value for powerful installations, where exposures are for only a second or two, but might be of great value where exposures for a considerable time have to be made.

(2)

In order to investigate the second point, a Sabouraud pastille was placed on the aluminum foil at F and exposed, sometimes to the direct action of the X-rays and sometimes with slight aluminum screening. During the time of exposure the deflection of the galvanometer was read at regular intervals The average of these readings multiplied by the time of exposure and by the galvanometer constant gave the charge that passed through the galvanometer, and this divided by the volume of air ionized and by the number representing the change in color of the pastille, as measured by Dr. Hampson's radiometer, should give a constant K, if the effect on the pastille is proportional to the ionization produced in the testing vessel. The last nine comparisons gave the following values for K: 2.4, 2.6, 2.7, 2.4, 2.5, 2.6, 2.4,2.4, and 2.6, all multiplied by 10^8 Thus, we see that this method furnishes an accurate and quick method of testing the therapeutic action of any tube. In these experiments only the interrupterless current was used, but hard and soft tubes were tried with currents varying from 1 to 5 milliamperes.

(3)

Less attention was paid to the measurement of hardness than to the previous parts of the work, but a number of experiments were tried to see how the ionization current

through the testing vessel is changed by various thicknesses of lead or aluminum placed over the opening F, and in each case the hardness was measured by a Benoist penetrometer. Table II shows the nature of the results obtained in a single experiment.

TABLE II.

Hardness.	Sheets of Lead Foil, each .26mm thick.	Gal. Defl.	% of Max. Defl.
9 Benoist	0	178	100
	1	83	47
	2	51	29
	4	25	14
	6	15	8

Table III gives a summary of the results obtained with different tubes of various degrees of hardness. Columns 3 and 4 give the thickness of lead and aluminum necessary to reduce the ionization to half value. Column 5 gives the ratio of the ionization when there are two and when there is only one sheet of lead foil over F, and column 6 gives a similar ratio of the ionization for 4mm and 2mm of aluminum.

TABLE III.

Tube.	Hardness.	3	4	5	6
No. 1.....	9 Benoist	.036mm	4.4mm	62%	73%
No. 2.....	7 Benoist	.....	3.5mm	.....	64%
No. 2.....	6 Benoist	.023mm	.....	45%	.....
No. 2.....	5 Benoist	.018mm	1.7mm	28%	43%
No. 4.....	7 or 8 Benoist	.030mm	3.6mm	55%	68%

In practice it would be much easier and quicker to obtain the hardness of a tube from the data of column 5 or 6 than from 3 or 4. It is a well known fact, which is also clearly shown in Table III, that X-rays become less and

less easily absorbed the more lead they pass through. It is for this reason that the figures in columns 3 and 4 have been made to apply to rays which have already passed through .026mm of lead or 2.0mm of aluminum respectively.

Table III shows that the apparatus is well suited to make comparisons of the hardness of X-rays. It is only necessary to take two readings of the galvanometer, first with one sheet of foil and then with two sheets. The ratio of the readings may then be used as a measure of the hardness. By obtaining foil of the right thickness, it would be possible to arrange a simple scale which would correspond with any of the various penetrometers now in use.

Discussion of Results.

The experiments above described show how a single instrument may be very simply used to determine both the quantity and quality of the Roentgen rays from any tube, as well as the length of time of exposure needed to produce radiograms of proper density. In each case the ionizing action of the rays is made use of and the measurements are all made with a galvanometer, which avoids the uncertainty and difficulty of comparing the color or the equality of illumination of two surfaces.

The physical explanation would seem to be that the magnitude of the effect produced by the rays on the photographic plate, the pastille and in ionizing the air depends on the energy used up in each case, and that the relative amounts absorbed in the three processes remain practically constant for rays differing widely in their characteristics.

The nature of the apparatus makes it comparatively easy to calculate the number of ions produced per c.c. near the photographic plate during the time of exposure or near the pastille during the time of some definite change in color.

Let V = volume of testing vessel exposed to the ionizing action of the rays.

t = time of exposure in seconds of either plate or pastille.

N = total number of ions per c.c. produced in the testing vessel during time t.

e = charge on an ion—4.7×10^{-10} E. S. units.

k = galvanometer constant—3.0×10^{-10} amperes per mm. deflection.

d = deflection of galvanometer.

q = charge passing through the galvanometer in time t.

Then $q = NeV$ E. S. units (if there is no recombination).

also $q = kdt$ coulombs

and $NeV = (kdt)\ 3\times10^{9}$.

In the experiments with the photographic plates, as has been stated, t was so chosen that $dt = 200$, and V was 100 x 4.5 = 450c.c.

$$\therefore N = \frac{3\times10^{-10}\times200\times3\times10^{9}}{450\times4.7\times10^{-10}} = 8.5\times10^{8}$$

Of course the value of N necessary to produce a satisfactory radiograph depends on the plate used and upon the method and time of development.

The average value of the constant $K = \frac{k\,dt}{V}$ found in the experiments with the Sabouraud pastille was 2.5×10^{-8}.

As above

$$N = \frac{k\,dt\ 3\times10^{9}}{V\,e}$$

$$= \frac{2.5\times10^{-8}\times3\times10^{9}}{4.7\times10^{-10}} = 1.6\times10^{11}.$$

This, then, gives the number of ions per c.c. formed in the air immediately surrounding the pastille during a change in tint corresponding to one number on Hampson's radiometer. Now the normal or epilation dose is determined by tint B, as it is called, and corresponds to a change equivalent to four numbers. Therefore, the number of ions per c.c.

produced in air surrounding the pastille during normal dose is 4N or about 6.4×10^{11}. In measuring this dose the pastille is ordinarily placed half way between the anticathode and the skin. Therefore the number of ions per c.c. produced near the surface of the skin during an epilation dose would be 1.6×10^{11}. This value is apparently very much smaller than that obtained by Dr. Szilard (loc. cit.), although there is some confusion in the part of his paper dealing with this calculation. A small part of this difference is due to the small value, 3.4×10^{-10} which he used for e, but the chief difference is due to the nature of the testing vessels used in the two experiments.

The vessel used by Dr. Szilard had a volume of 1 c.c. and was lined with lead. In a vessel of this kind the ionization due to secondary rays would be very large. Some of the secondary rays are very easily absorbed, but produce an intense ionization for a millimeter or two in air, so that their relative effect is especially great in a small vessel. The effect is also much greater with a lead than an aluminum vessel. Even in the large vessel used in the present investigation, the ionization was doubled by covering the plate C with lead foil. In the smaller vessel the ionization caused by the secondary rays might be several times as large as that due to the X-rays themselves. That the effect of the secondary rays from the aluminum plate C was small, was shown by covering C with a sheet of wet tissue paper, which reduced the ionization current less than 10%.

There is a still greater objection to using lead instead of aluminum for the interior of the testing vessel; namely the fact that the relative amount of secondary ionization depends on the hardness of the rays. The extra ionization in the testing vessel also requires the use of a higher voltage in order to prevent recombination.

Summary.

1. It has been shown that the action of Roentgen rays on a photographic plate and on a Sabouraud pastille is

proportional to the ionization produced in the air immediately surrounding them.

2. A simple apparatus, making use of this principle, has been devised for measuring the intensity and hardness of the rays.

3. It has also been shown that this same apparatus can be easily used to determine the length of time of exposure needed to produce radiographs of suitable density.

In conclusion, I desire to express my indebtedness to Dr. Edward Weston for his kindness in fitting up and loaning me a galvanometer suitable for this work; to Principal Sexton and Professor Ayars of the Nova Scotia Technical College for the use of their X-ray apparatus, and especially to Dr. W. H. Eagar for his many helpful suggestions and for the use of his office and equipment.

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