MEASUREMENT OF DOSAGE BY MEANS OF IONIZATION CHAMBERS*

BY WILLIAM DUANE, PH.D., SC.D.

Professor of Biophysics, Harvard University

BOSTON, MASSACHUSETTS

THE fact that different *x*-ray plants produce *x*-rays of different intensities and effective wave-lengths even though they may be running at the same voltage, as estimated by a sphere-gap, and with the same current through the tube, indicates that we must use a method of measuring something connected with the *x*-ray beam itself, if we wish to get reliable estimates of dosage.

Variations of 40 per cent and more in the intensity of the *x*-rays projected through the same filter and at the same distance from the tube with different machines are not uncommon, and in extreme cases one machine may produce twice as much *x*-radiation as another.

Without doubt, ionization chambers provide us with the most reliable methods of measurement, at present. Ionization chambers, however, are by no means perfect, and great care must be exercised in employing them.

I purpose, in this discussion, to describe the method we are using and to call attention to certain pitfalls into which one is apt to stumble, hoping that this may prove of use to those of you who are using ionization chambers, or who may be planning to purchase them.

When a beam of *x*-rays passes through a gas, such as air, it splits up the molecules of a gas into particles (called ions), some of which carry a positive charge of electricity, and others a negative charge. If left alone, these particles will recombine with each other, owing to the attraction of those charged positively for those charged negatively. By applying an electric force to the ionized gas, however, we can separate the positively charged particles from the negatively charged ones. For instance, suppose that the ionized air lies between two parallel metal plates, one of which is connected to the positive pole of a battery and the other to the negative pole. Under these conditions the positively charged plate attracts the negatively charged ions and draws them to it out of the air; similarly, the negatively charged plate attracts the positively charged ions and pulls them out of the air in the opposite direction. Thus, the battery produces a current of positive electricity through the air in one direction and a current of negative electricity through the air in the opposite direction. This current may be measured by a galvanometer suitably placed in the electrical circuit. We may use the electrical current as measured by the galvanometer as an indication of the intensity of the *x*-ray beam, for, in general, a strong beam of *x*-rays produces a larger number of pairs of ions than does a weak one.

The electrical current, as measured by the galvanometer, however, will not give reliable estimates of the intensities of *x*-ray beams unless in each case the electrical force acting on the ions suffices to remove practically all of them before they have time to recombine with each other. For example, if two equal and similar beams of *x*-rays pass through the air between the plates, the current will not be twice as great as that due to one beam alone, if an appreciable number of ions recombine with each other before they reach the plates; for with the two beams passing through the air, twice as many pairs of ions are produced per second as with one, and there is a much greater chance for the ions to recombine with each other. Those ions which recombine cease to produce their share of the electrical current. If, however, the electromotive force of the battery produces an electrical force on the ions of sufficient magnitude to remove practically all of them before they have time to recombine, then the electrical current due to two equal, similar beams of *x*-rays will be

* Read at the Midwinter Meeting of the Eastern Section of THE AMERICAN ROENTGEN RAY SOCIETY, Atlantic City, N. J., Jan. 25–27, 1923.

Discussion on this article will appear in June.

twice as great as that due to one of them alone. In this case we may take the currents as proportional to the intensities of x-ray beams.

If the electric force acting on the ions suffices to remove practically all of them before they can recombine, the ionization current is said to be saturated. Only saturated ionization currents should be used to measure x-ray beams.

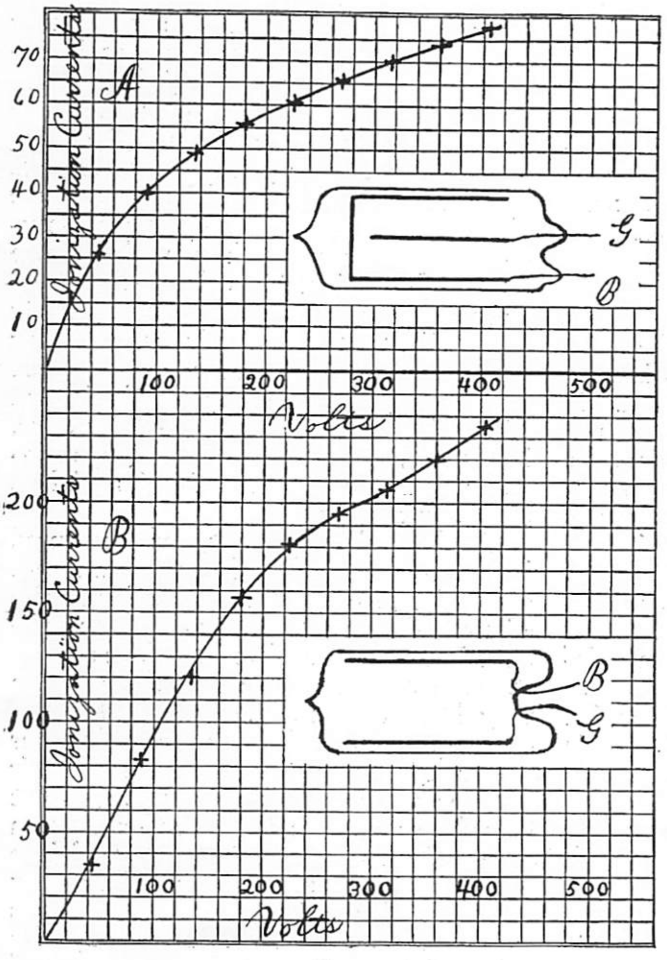

Fig. 1.

In some ionization chambers great difficulty may be encountered in producing the saturated current; in other cases, a small battery may produce such saturation. I will illustrate these points by describing several experiments, in some of which I could easily produce a saturation current and in others of which the batteries at my disposal were not sufficient to saturate the current.

The diagram in A (Fig. 1) represents a hollow, metal cylinder, closed at one end, with a rod lying along the axis of the cylinder, the cylinder being joined to a battery and the rod to a galvanometer, and the other pole of the battery being connected to the galvanometer so as to form a complete electrical circuit. The cylinder and rod lie in a closed, glass vessel, as indicated.

On sending a beam of x-rays through this ionization chamber and on changing the number of cells in the battery, that is, on changing the voltage applied to the cylinder, a number of different currents through the chamber were obtained. The curve in A (Fig. 1) gives the readings of the galvanometer at different voltages applied to the cylinder.

It appears that on increasing the number of cells in the battery, that is, on increasing the voltage applied to the cylinder, the ionization current, as measured by the galvanometer, keeps on increasing and does not reach a constant value. This means that, as the electrical force acting on the ions increases, more and more of the positive ions become separated from the negative ions before they have time to recombine. In this case, however, the electrical force applied was never sufficient to remove practically all of the ions before they could recombine with each other. In other words, a saturation current was not produced. An ionization chamber with these characteristics should not be used to measure x-ray beams. Cylindrical ionization chambers of this type should never be used, if the wire along the axis of the cylinder is very fine.

B (Fig. 1) represents an ionization chamber in which both electrodes are metal plates, one of them joined to the battery and the other to the galvanometer, as above. In this case, on increasing the voltage applied to the plates the curve in B was obtained. This curve also indicates lack of saturation; for the ionization current continues to increase as the size of the battery increases. In this chamber the metal plates did not cover the entire sides of the glass vessel containing them and left corners in the vessel from which the electric force was unable to withdraw all of the ions. The design of this chamber illustrates again a kind of ionization chamber that should not be used.

C in Figure 2 represents a chamber in which the parallel metal plates extended to the ends of the closed space, enclosing the air. They did not, however, extend to the sides of this enclosed space in a direction perpendicular to the diagram. Further, one of the plates joined, as indicated, to the galvanometer lay close to the metal sheet wrapped around the chamber for protection. The curve giving the current produced by different voltages indicates a much closer approach to saturation in this case than in the two preceding cases. In other words, the design of the chamber is better than those of the first two.

It is not quite as good, however, as that represented by D (Fig. 2) in which all three plates extend completely across the enclosed air. In this chamber the two outside plates go to the battery and the inside one to the galvanometer. The curve D (Fig. 2) indicates practically complete saturation by voltages above 20 volts. For saturation purposes this chamber represents the best type that I have examined. It is the one we are now using in our measurements of the intensities and effective wave-lengths of x-ray beams.

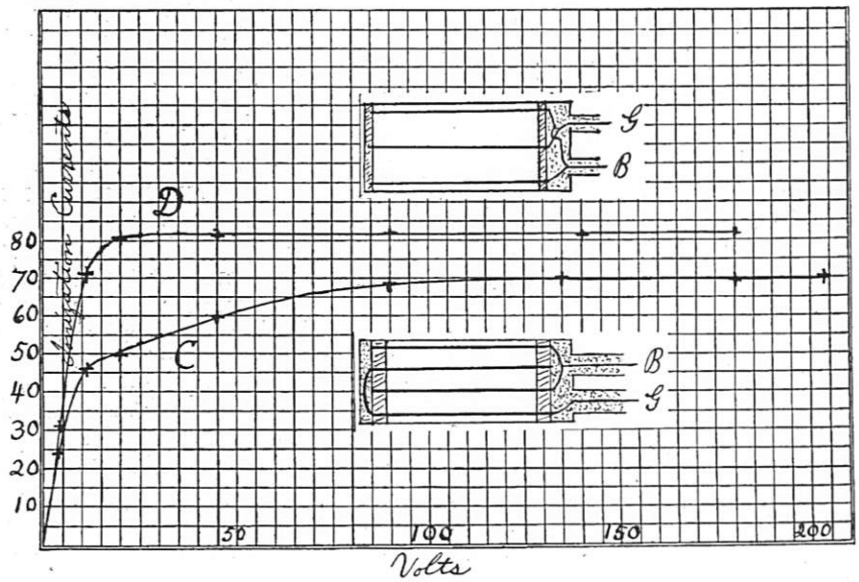

Fig. 2.

As indicated above, the question of saturating the ionization current becomes one of prime importance. No chamber should be used or purchased unless it has been proved experimentally that the electric force produces saturation.

If saturation currents are not obtained, the readings of the galvanometer do not give reliable measurements of x-ray beams. Intense beams will produce relatively smaller deflections than they should, and, vice versa, weak beams of x-rays will produce relatively too large deflections. Perhaps some of the exceptionally high depth dose readings obtained by certain observers may be due to the fact that they were not using completely saturated ionization currents.

In order that we may compare with each other measurements made in different laboratories and in different clinics it is desirable to have some standard unit of x-radiation and some standard method of measurement. The unit that I have been using for the last nine or ten years may be defined as: "That x-ray beam which would produce one absolute electrostatic unit of current in each cubic centimeter of air through which it passes, provided that the current has its saturation value."

Ionization chamber D (Fig. 2) does not appear to be suitable for measuring currents in terms of this unit, for two reasons. Firstly, a large part of the ionization arises from the secondary rays produced by the primary beam of x-rays in the plates and walls of the chamber. The secondary rays increase the ionization current and the readings of the galvanometer become, therefore, too high. This secondary ray effect may be greatly reduced by using some substance of low atomic weight in place of the metal plates. In the measurements of effective wave-lengths recorded in an article by Dr. Hunt and myself[1] we used sheets of thin paper with faint pencil-marks drawn across them. The plates, therefore, were very thin layers of carbon. A much better method, however, is that which I have previously employed to standardize the ionization chamber that we actually used. In this method I compared the current produced in the chamber to be standardized with that produced by the same beam of x-rays in a chamber so designed that the x-ray beam did not strike anything inside the chamber. Figure 3 represents one of these standard ionization chambers.

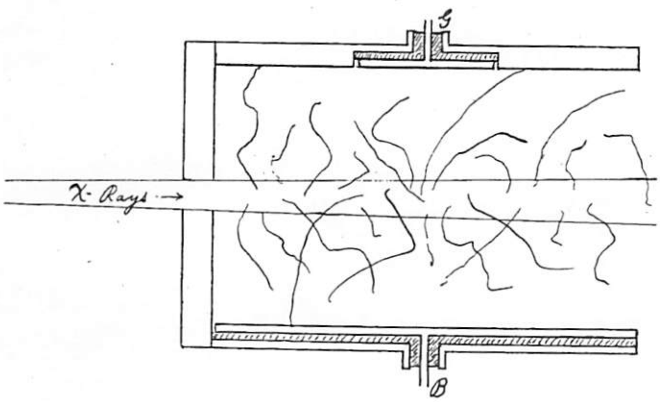

Fig. 3.

[1] *Phys. Rev.*, Aug. 1915, p. 166.

The x-ray beam enters the chamber through a hole of known area and passes between the plates without striking them. The plates are arranged in a manner similar to those in an instrument designed by Lord Kelvin and called a guard-ring condenser. One plate, connected with the battery through B, extends almost the whole length of the chamber. The other side of the chamber is divided into three sections. The two end sections are joined to the outside metal casing of the chamber, which, in turn, is connected to earth for purposes of protection. The middle section of the side, insulated from the casing, is connected through G to the galvanometer. The middle section has a certain definite breadth and draws its ionization current from an equal length of the x-ray beam. Since the x-ray beam has a definite, known cross-section, this means that the current going to the galvanometer comes from a certain volume of air. The volume of air in my instruments amounts to 25 c.c. If I get from this ionization chamber a current through the galvanometer of 25 electrostatic units, then each of the 25 c.c. of air produces one electrostatic unit and my beam has unit intensity, according to the above definition of unit beam. This is the standard ionization chamber that we use in calibrating the smaller chambers actually employed to measure the x-radiation during treatments.

There is one important point to be borne in mind in designing a standard ionization chamber of this kind. When x-rays produce ionization in a gas, a certain amount of secondary radiation is generated in the atoms and molecules of the gas by the primary beam. This secondary radiation produces a large amount of the ionization. The secondary rays, however, travel some distance from the path of the primary beam. They are of two kinds—corpuscular-rays and x-rays. The secondary x-rays are very penetrating and travel a long distance from the beam. The corpuscular rays, however, follow very crooked paths, somewhat as indicated in Figure 3, and only a few of them penetrate to a great distance from the primary beam.

In 1905 I pointed out that a correction must be made for the rays that strike the walls of a vessel and for secondary rays coming from those walls, if one wishes to measure quantities of radium emanation by the ionization method.[1] The correction, as determined by my experiments, proved to be proportional to the ratio of the surface of the ionization chamber to its volume. As this ratio becomes very large for small volumes it indicates a certain disadvantage in using very small ionization chambers. Theoretically, a standard ionization chamber should be indefinitely large so as to include all the ionization produced by all the secondary rays. Practically, however, the vast majority of secondary rays travel along such crooked paths that they do not get very far from the primary beam. It is not, therefore, necessary for therapeutic purposes, at least, to use very large standard ionization chambers. Those that I was using nine years ago had volumes varying from 500 to 2,000 c.c., and this appeared to be sufficient for the x-rays that were being produced at that time in practice.[2]

In order to test the suitability of a standard ionization chamber it is necessary, firstly, to make sure that the ionization current is saturated, and secondly, that it includes practically all of the secondary radiation coming from the molecules of gas struck by the primary beam.

The curves in Figure 4 represent the ionization currents passing through two of our standard ionization chambers of different sizes when different voltages were applied to them. The curves indicate that the current in the smaller one became saturated at about 300 volts and that the current in the larger one became saturated at about 500 volts. When using either of these chambers I employ about 800 volts, so as to be sure of their saturation.

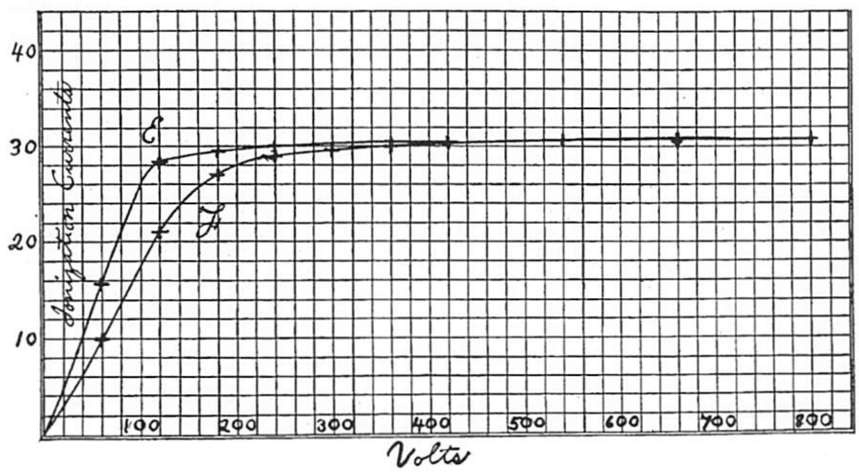

FIG. 4.

In the experiments represented by the curves in Figure 4 the voltage applied to the x-ray tube amounted to about 100,000 volts, and I was unable to detect any difference between the ionization current in the larger chamber and that in the smaller chamber. Either chamber, therefore, appeared to include practically all of the x-ray effect due to the secondary rays coming from the air in the chamber.

On using 200,000 volts, however, x-rays of much shorter wave-length were produced and the secondary radiation became more penetrating. In this case I found a difference of about 5 per cent between the currents through the two chambers. The larger chamber produced the larger current. On increasing the distance between the plates of the larger chamber, however, no perceptible increase in the ionization current occurred. It

[1] *Compt. rend. Acad. d. sc.*, and *J. de Physique*, 1905.
[2] Friedrich employs standard ionization chambers somewhat similar to those described here.

appears, therefore, to be large enough to use as a standard, even with rays produced by 200,000 volts. A distance of 10 cm. between the plates of an ionization chamber seems to be sufficient, if 200,000 volts are applied to the tube.

It is, perhaps superfluous to call attention to the fact that in estimating dosage (erythema dose, for instance) it is necessary to measure the effective wave-length of the beam as well as its intensity, for the amount of *x*-ray energy absorbed by the tissues depends upon the wave-length.

These wave-length measurements may be made with either a standard ionization chamber or with one of the smaller metal chambers. It appears, however, necessary to standardize the smaller chamber for wave-length measurements by comparison with the standard ionization chamber.

One important feature of the method I am describing lies in the fact that the reading of the galvanometer gives the intensity of the *x*-ray beam and not the total dose received by the patient. In order to get the total dose we have to multiply the intensity by the time of exposure.

The large, standard ionization chambers are not suitable for measurements of the intensity during a treatment. We invariably use one of the smaller ionization chambers to measure the intensity of the beam received by the patient several times during the treatment. We measure the intensity of the rays at the surface where they enter the patient's body, and also where they emerge. This gives us an estimate of the secondary radiation coming from the patient's body. The estimate, however, is too low. Estimates may be made by means of water phantoms, placing the small ionization chamber in the water itself. This estimate is always too high. The real dose received by the patient's skin lies between the two. We have obtained quite variable estimates of the secondary radiation from different patients made by measurements taken during the treatments themselves. The secondary radiation appears to depend not only upon the size of the portal of entry but also upon the size of the patient and upon the shape, content, etc., of the portion of the body radiated. In estimating erythema doses all of these factors must be taken into consideration. The safest method appears to be to make the measurements while the patient is actually being treated.

In many of the ionization methods of measuring dosage one determines the ionization current by timing with a stop-watch the passage of the leaf of an electroscope across a scale. In methods of this kind some difficulty often arises in determining whether the current is saturated or not. Very particular attention should be paid to this point.

I might mention, also, another very common source of error in electroscope measurements. In such measurements one should always determine the "leak" in the instrument. This should be done with the *x*-ray tube running: for the *x*-rays may produce ionization currents in the electroscope (if it is not completely protected), or in parts of the apparatus other than the ionization chamber itself. Corrections must be made for the "leak," when it exists.

If one makes percentage depth dose measurements in a water phantom, one should determine the "leak" with the ionization chamber at the surface of the water, and also, at the various depths used below it. Perhaps the best way to measure the "leak" is to place a thick sheet of lead over the opening that determines the cross-section of the *x*-ray beam (the lead being thick enough to stop practically all of the *x*-rays), and then to measure the current. The leak current must be subtracted from the ionization current (obtained after removing the lead sheet), the two currents being inversely proportional to the lengths of time during which the leaf in the electroscope moves from one point on its scale to another.

If one measures percentage depth dose, the following well-known formula may be employed to correct for the leak. With the ionization chamber at the surface of the water phantom let L_0 be the number of seconds corresponding to the "leak" (i.e., when the lead plate stops the *x*-rays) and let T_0 be the number of seconds corresponding to the ionization current (after the lead plate has been removed). Further let L_1 and T_1 be the corresponding numbers of seconds, when the ionization chamber lies at any distance (say 10 cm.) below the surface. The formula for the percentage depth dose may then be written:

$$\text{P.D.D.} = \frac{\frac{1}{T_1} - \frac{1}{L_1}}{\frac{1}{T_0} - \frac{1}{L_0}}$$

If no correction be made for leak currents, and the depth dose is determined simply by dividing one length of time by another, a large error may be introduced. In one experiment that came under my observation the uncorrected depth dose amounted to considerably over 40 per cent with the tube running at approximately 200,000 volts. When the correction was made, however, the measured depth dose fell to about 34 per cent.

A great many important investigations have been carried on in connection with the question as to whether the biological effects of *x*-rays are proportional to ionization currents, when rays of different wave-lengths are used. One speaks of the biological dose. In particular cases biological doses are definite quantities. Before we can speak of a biological dose in general, however, it will be necessary to show by experiments that a large number of different biological effects are proportional to each other, when *x*-rays of different wave-lengths produce the effects.