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Technical Information Division, Oak Ridge Directed Operations

AEC, Oak Ridge, Tenn., 10-1-48-1500

Printed in U.S.A.  
PRICE 5 CENTS

19970221 175

## THE MEASUREMENT OF TISSUE DOSE OF IONIZING RADIATION

### I. Beta Ray Emitting Isotopes Uniformly Distributed in a Homogeneous Tissue

By G. Failla, H. H. Rossi, R. K. Clark, and N. Baily

In general it may be said that "irradiation equilibrium" exists at a point in an absorbing medium when in a small volume surrounding the point, the rate at which energy leaves the boundary is balanced exactly by the rate at which energy enters the small volume and is absorbed therein. In the case of a beta ray emitting isotope uniformly distributed in a homogeneous tissue, irradiation equilibrium exists everywhere except in a peripheral layer of thickness equal to the maximum range of the beta rays. Everywhere else in the tissue mass the energy absorbed per gram of tissue in unit time is equal to the energy liberated by the isotope in one gram of tissue in the same time. Therefore, knowing the number of disintegrations per second occurring in one gram of tissue and the average energy per disintegration, it is a simple matter to calculate the energy absorbed per gram of tissue.

Making use of the extrapolation ionization chamber method developed by one of us,<sup>1,2</sup> it is also possible to determine the energy absorbed per gram of tissue, by ionization measurements under suitable conditions. Since the two values must be equal we have:

$$N_{\text{dis}} E_{\text{av}} = W N_{\text{ion}} S \quad (1)$$

where  $N_{\text{dis}}$  = number of disintegrations per second occurring in one gram of the tissue equivalent wall material of the ionization chamber, in which the radioactive material is uniformly distributed.

$E_{\text{av}}$  = average energy per disintegration in ev.

$W$  = average energy lost by a beta particle in producing an ion pair in air, in ev.

$N_{\text{ion}}$  = number of ion pairs produced per second per gram of air in the effective volume of the ionization chamber.

$S$  = relative stopping power of the ionization chamber walls with respect to air on the basis of equal masses.

The value of  $W$  is generally taken as 32.5 ev. The value of  $S$  varies with the energy of the beta rays and the wall material. For tissue equivalent walls it is somewhat greater than one.

The experimental procedure to make the comparison indicated by equation 1 involves the preparation of two electrode plates with a known and uniform concentration of radioactive isotope. This is not so simple as it might be supposed. Accordingly, a different scheme has been developed, in which uniformity of concentration is assured and its magnitude in terms of the stock solution of the isotope is known accurately.

The method is based on the following considerations. The extrapolation chamber consists of two parallel plates separated by an air gap which can be varied from zero to a few millimeters. The collecting electrode is a small circle at the center of one plate surrounded by a guard ring of sufficient

spread to insure a uniform electrostatic field at the collecting electrode and comply with the condition of irradiation equilibrium. It is obvious that when the two plates contain the same concentration of the isotope, each plate contributes equally to the ionization current produced in the air volume (delimited by the area of the collecting electrode and the spacing between plates). Ionization is produced in this air volume by (1) beta rays emerging from each plate and (2) beta rays scattered back and forth because of the presence of the other plate. If only one plate contains the radioactive isotope and the other is made of the same material (including the same concentration of a nonradioactive isotope of the same element, when necessary), the ionization current is just one half of what it would be with the same concentration of radioactive isotope in both plates. Therefore, only one plate need contain the radioactive material. By using (thick) scattering plates of different materials (from beryllium to lead) it has been found, in the case of  $P^{32}$ , that the ionization current varies as  $\log(Z + 1)$ , where  $Z$  is the atomic number of the scattering material. This makes possible the use of any material for the second electrode, since the ionization current reading can be reduced to the appropriate value.

The simplest way in which to insure a uniform distribution of the radioactive material and a known concentration thereof, is to use a solution of the isotope as one plate of the ionization chamber. Water is already nearly tissue equivalent, but if desired other ingredients may be added to reproduce the elemental composition of tissue almost exactly. The final set-up consists of a glass dish containing the solution, to a height greater than the range of the fastest beta particles. Above this is suspended the collecting electrode and guard ring plate in a horizontal position, so that it is parallel to the surface of the liquid. These parts are made of aluminum mounted on polystyrene. Since it is necessary to take some readings with plate separations of about 0.5 mm, the ionization chamber must be set up in a place as free from vibration as possible. The spacing is determined accurately by measuring the electrostatic capacitance of the parallel plate condenser formed by the collecting electrode (of known area) and the surface of the liquid.

The practical case of most interest is that of  $P^{32}$ , since the average energy per disintegration for this isotope is known with considerable accuracy.<sup>3</sup> In a typical measurement the ionization current produced by a certain concentration of  $P^{32}$ , was found to be 0.01158 e.s.u. per cc at N.T.P. This corresponds to  $1.88 \times 10^{10}$  ion pairs per second per gram of air. The correction factor for the aluminum electrode is 1.15. Therefore, the number of ion pairs per gram of air for two water electrodes, only one of which contained the  $P^{32}$  is  $1.63 \times 10^{10}$ . If both water electrodes contained the isotope in the same concentration the reading would be  $3.25 \times 10^{10}$  ion pairs per second per gram of air. Therefore in equation 1 we have:

$$\begin{aligned} E_{av} &= 0.695 \text{ Mev for } P^{32} \\ W &= 32.5 \text{ ev} \\ N_{ion} &= 3.25 \times 10^{10} \\ S &= 1.1 \end{aligned}$$

and

$$0.695 \times 10^6 \times N_{dis} = 32.5 \times 3.25 \times 10^{10} \times 1.1$$

or

$$N_{dis} = 1.67 \times 10^6 \text{ disintegrations per second per gram of water}$$

This corresponds to  $4.53 \times 10^{-5}$  curie per gram of water. According to the Oak Ridge measurement of the  $P^{32}$  the concentration in the water electrode was  $4.62 \times 10^{-5}$  curie per gram.

The agreement between the two is better than should be expected. In the extrapolation chamber method of deriving  $N_{dis}$ , the quantity  $N_{ion}$  can be measured with as high an accuracy as desired. The accepted value of  $W$  is 32.5 ev but there is some uncertainty as to its constancy with respect to the energy of the beta rays. It appears probable that for low speed electrons it is somewhat greater than

32.5 ev. Since in the case under consideration the beta rays that ionize the air include a good proportion of low energy ones, it is difficult to appraise the error introduced by taking 32.5 ev as the average value. Perhaps the greatest uncertainty exists in the value of  $S$ , the relative stopping power of water with respect to air, per gram of material. Since the stopping power of a substance for beta rays depends largely on the electron density, we may use a value of  $S$  based on the relative electron content of the same mass of air and water. This makes  $S = 1.11$  and in view of the uncertainty we might drop the last figure ( $S = 1.1$ ).

At any rate if the Oak Ridge measurement really represents disintegrations per second at the rate of  $3.7 \times 10^{10}$  per curie of  $P^{32}$  and the average energy per disintegration is 0.695 Mev, the values of  $W$  and  $S$  cannot be appreciably different from those used by us.

Now we wish to point out certain experimental possibilities offered by equation 1 in conjunction with the extrapolation chamber method. We have five quantities of which in general only one ( $N_{ion}$ ) can be determined readily with high accuracy. It is evident that if we know accurately the value of the product  $N_{dis} E_{av}$  for one isotope, we can derive an accurate value of the product  $WS$ . It is expected that this will vary somewhat with the energy of the beta rays. Therefore, by using a few isotopes of widely different beta-ray energies, one could establish an empirical relation between "energy"\* and  $WS$ . If it turned out that  $WS$  is substantially independent of energy or the experimental points fall on a smooth curve, one could then determine the product  $N_{dis} E_{av}$  for any other isotope with high accuracy by the extrapolation chamber method alone. This would be sufficient for dosage purposes in terms of energy absorbed per gram of tissue.

An accurate value of the product  $N_{dis} E_{av}$  for a number of isotopes could be obtained by a suitable calorimetric method. It is obviously of greater interest, however, to know the values of all five quantities involved in equation 1. This can be done in a variety of ways none of which, unfortunately, is very simple.

The measurement of beta ray emitting isotopes in terms of disintegrations per second has been undertaken by numerous investigators using the Geiger-Mueller counter method. The inherent difficulties are many and in general the results have not been very concordant. To our knowledge, the method of measuring the charge carried away by the electrons leaving the source, has not been used heretofore.† Having available a large stainless steel tank (42 inches in diameter and 46 inches high) provided with fast diffusion pumps, we have made such measurements using  $P^{32}$ .

The source consists of about 0.1 mc of  $P^{32}$  deposited on aluminum foil about 0.0025 cm thick mounted on a thin aluminum ring. The source is suspended in the center of the tank by a fine wire, which makes contact with a Lindemann electrometer outside of the tank through a polystyrene bushing. In order to investigate the low energy spectrum of the electrons leaving the source (whether primary or secondary) and the influence of secondary electrons from the walls, provisions have been made to surround the source with wire cages of different sizes and to apply positive or negative potentials to them in the range of zero to 3600 volts. It has been found that with the screen at a negative potential with respect to the source of a few hundred volts, the current decreases by about 5%, and remains at substantially the same value when the screen voltage is increased to 3600. With the screen positive, the current increases 2 to 3% in a similar manner. The difference with the polarity of the screen is attributable in large measure to low energy electrons liberated by the primary electrons from the source, the supporting structure and surrounding material. It would appear from these results that the rate of emission of beta particles from  $P^{32}$  can be determined by this method with a precision of about  $\pm 5\%$ . Further study of the method should improve the precision considerably. In this connection it is interesting to note that determinations of the disintegration per second by this method in the case of  $P^{32}$ , agree within 5% with the value derived from measurements made at Oak Ridge. Of course, once

\* Whether for this purpose one takes the maximum or the average energy of the beta rays of a given isotope is immaterial.

† The principle is essentially the same as in the operation of the so-called radium clock described by Strutt.<sup>4</sup>

the apparatus has been set up, it is a relatively simple matter to make similar measurements with other isotopes emitting charged particles. We are planning to use  $S^{35}$  next because the beta rays are of much lower energy.

Mention was made earlier of the fact that in order to determine the energy absorbed per gram of tissue by the ionization chamber method, the walls of the chamber should be made of tissue equivalent material. Various close approximations to exact tissue equivalence are possible. The error introduced by not duplicating the elemental composition of a given tissue (that is, taking into account all the elements in the tissue in the proper proportions) depends largely on the laws governing the absorption of radiation by matter, for the particular types of primary and secondary ionizing radiations involved. In some cases it is necessary to duplicate quite accurately the relative proportions of at least the principal elements of the tissue. This is especially true when the ionization chamber is to be used for the measurement of neutrons (of any initial energy) in terms of the energy absorbed per gram of tissue. In addition to tissue equivalence of wall material there are other conditions that must be fulfilled. A full discussion of this problem will be given in a subsequent report. For the present it is sufficient to point out that we have been unable to find or prepare a dry solid material of the desired composition. However, a wet solid material can be prepared by using gelatine and formaldehyde to bring about "solidification" of a water solution of several organic compounds. The important point is that satisfactory ionization chambers lined with any desired thickness of this material can be made, in spite of the presence of saturated water vapor. Since the tissue equivalence of the material depends largely on its water content, (about 2/3 by weight), it is obvious that chambers of this type must be hermetically sealed to prevent evaporation. Thimble chambers lined with this material have been constructed, which show surprisingly little insulation leakage when used in conjunction with a Victoreen electrometer (initial fiber voltage about 400 volts).

For some purposes it is desirable to fill the ionization chamber with a gas mixture having the same constituent elements as tissue. Preparation of such a gas mixture is a simpler problem than making a solid tissue equivalent wall material. There is a serious complication, however, in that a mixture containing the right proportions of hydrogen, oxygen, carbon and nitrogen, is explosive.

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