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A knowledge of radiation dosage from radioactive substances deposited in the body is important both in tracer and in therapeutic applications of these substances. In tracer work, it must be assured that the radiation itself does not influence the phenomena being studied, and, in investigations with human beings, it must be certain that the radiation administered by the tracer is not sufficient to produce damage. In therapy the same considerations apply as with any other type of irradiation.

It would be highly desirable to express these doses in roentgens, but the roentgen as now defined applies only to x- and gamma rays. For the present, therefore, an interim unit is to be employed, called the equivalent roentgen, the amount of β radiation which (under proper conditions of measurement) produces the same amount of ionization in one gram of air as one roentgen of x-rays. (This is essentially the same as the rep.) For clinical purposes the roentgen and the equivalent roentgen may be considered as substantially the same, and for convenience when the sum of beta and gamma doses from a particular isotope is discussed, the total will be stated in roentgens.

For x-rays, dosage measurements may be made experimentally; this is also true for certain methods of using radium or radon in sealed containers. For these substances, moreover, dosage tables have been calculated, on the basis of the experimentally determined value for the radiation at 1 cm. from a defined point source. In the case of radioisotopes within the body, the situation is quite different; the materials are deposited with some degree of selectivity throughout cells or organs. However, when the physical factors of half life and radiation energies are known, together with physiological factors of uptake and excretion, it is possible in some cases to make satisfactory estimates of tissue dosage.

The mathematical approach to the problem is quite different for isotopes emitting only β particles and for those which also emit γ rays. The maximum range in tissue of the most penetrating β particles used in medical work is 19 mm for K-42, and the average range for radiation of this type only a few mm. Hence, in general, β -emitters give up their energy in the organ or tissue in which they are deposited. The γ -rays, on the other hand, may be very penetrating, so that most of their energy is removed from the region in which the isotope is deposited. The β -problem is relatively simple; the γ -problem quite complex.

β - and positron-emitters. Consider a mass of tissue large in comparison to the β -particle range (i.e., of linear dimensions more than a few mm.) having a certain β -emitting isotope distributed within it in a concentration of 1 μ c per gm. of tissue. 1 μ c emits 37000 β particles per second. Let \bar{E}_β be the average energy of these β 's, in kev. Then the total energy emitted per gram per second = $37000 \times \bar{E}_\beta \times 1000$. One equivalent roentgen = 1.62×10^{12} ion pairs, and each ion pair requires 32.2 electron volts for its production. Hence the equivalent roentgens per second =

$$\frac{37000 \times \bar{E}_\beta \times 1000}{1.62 \times 10^{12} \times 32.2} = 7.1 \times 10^{-7} \bar{E}_\beta \text{ e. RC}$$

The equivalent roentgens per minute =

$$60 \times 7.1 \times 10^{-7} \bar{E}_\beta = 4.25 \times 10^{-5} \bar{E}_\beta \text{ e. RC}$$

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If the radioisotope remains in the tissues for total decay, then the total e.r. are found by multiplying this number by the average life in minutes. (Average life = half life x 1.443.) If T is half life in days, then average life in minutes = $1.443 \times 24 \times 60T = 2080 T$. Hence the total e.r. = $4.25 \times 10^{-5} \bar{E}_\beta \times 2080T = 0.088 \bar{E}_\beta T$, where \bar{E}_β is in kev, T in days, and the concentration is 1 μ c per gram. For other concentrations, the dose is proportional to the μ c per gram.

Values of \bar{E}_β and of T , as well as other useful information, are given in Table 1.

As an example of this, consider a 70 kg. man to whom has been administered 4 mc. of P-32; assume that it is uniformly distributed throughout the tissues and that there is no excretion. $\bar{E}_\beta = 700$ kev; $T = 14.3$ days.
 $D_\beta = \frac{4000 \times 0.088 \times 700 \times 14.3}{70000} = 50.3.r.$

For any time interval less than total decay, the dose is proportional to the fraction of the atoms which have disintegrated. This can be obtained from the disintegration formula, or from a decay curve.

For different concentrations in different organs, each must be considered separately. In general, one is concerned mainly with the tissue of greatest concentration. Consider an individual who has received 1 mc. of Ca-45, in which the concentration in bone is assumed to be 20 times as great as in any other tissue. Assume also that it is uniformly distributed in the bone, and that the skeleton is 1/10 of the body weight. For 1/10 of the body to have a concentration 20 times as great as the remaining 9/10 means that the 1/10 must take up approximately 2/3 of the entire amount. For Ca-45, $E_\beta = 100$ kev; $T = 180$ days. The e.r. to the bone = $\frac{667 \times 0.088 \times 180}{700} = 150$

γ -ray emitters. As in the case of interstitial radium sources, the γ -ray dose depends on the distribution of the material within a given volume and on the absorption of the rays in the tissue. For radium, it has been determined experimentally that a point source at a distance of 1 cm., filtered by 0.5 mm Pt. gives 8.4 r per hour, and all dosage calculations are based on this. The corresponding value can be calculated for each γ -ray emitter, on a basis of the number and energy of the γ -rays emitted per disintegration, and the absorption and scattering coefficients of these in air. Some of these are given in Table 1 as I_γ in r per mc-hr. (For details of calculation, see Dosage Determinations with Radioactive Isotopes; II Practical Considerations in Therapy and Protection, American Jour. Roentgenology and Radium Therapy, Feb. 1948). The total γ -ray dose delivered per μ c at a distance of 1 cm. in air would then be $I_\gamma \times$ average life in hours, = $1.443 \times T \times 24 \times I_\gamma$. For 1 μ c, of course, it would be 0.001 of this or $34.6 I_\gamma T$. These values for 1 μ c destroyed, in air, are tabulated as K_γ . (Table I)

When the material is deposited in tissue, instead of air, and distributed throughout the volume, instead of being concentrated at a point, the dosage formula per μ c destroyed becomes $D_\gamma = K_\gamma \int \frac{e^{-\mu r}}{r^2} dV$, where μ is the absorption coefficient

in tissue, V the volume in which the material is distributed, and r the distance traversed in tissue by any individual photon. This integral is in general too complex to evaluate, but certain approximations may be made.

It can be denoted by g (geometrical factor) and the dosage formula then becomes $D_{\gamma} = K_{\gamma} g$. For a sphere, $g =$ approximately $4R$ ($R =$ radius). In Table II are given approximate values of g for a series of spheres and cylinders. These are reasonably satisfactory between 0.1 MEV and 3 MEV.

As an example of dosage determination with an isotope which emits both β and γ rays, consider a 70 kg. man who has received 1 mc. of Na-24.

$$E_{\beta} = 540 \text{ kev}; T = 0.62 \text{ days}; K_{\gamma} = 0.40; g = 200 \text{ (human trunk)}$$

$$D_{\beta} = \frac{1000 \times 540 \times 0.62 \times 0.088}{70000} = 0.42 \text{ e.r.}$$

$$D_{\gamma} = \frac{1000 \times 0.4 \times 2000}{70000} = 1.14 \text{ r.}$$

$$D_{\beta+\gamma} = 1.56 \text{ r.}$$

In the case just considered the γ radiation is considerably more important than the β . On the other hand, consider a 25-gram thyroid gland, in which 1 mc. of I-131 has been deposited.

$$E_{\beta} = 205 \text{ kev}; T = 8.0 \text{ days}; K_{\gamma} = 0.735; g = 17.6 \text{ (small sphere)}$$

$$D_{\beta} = \frac{1000 \times 205 \times 8.0 \times 0.088}{25} = 5800$$

$$D_{\gamma} = \frac{1000 \times 0.735 \times 17.6}{25} = 520$$

$$D_{\beta+\gamma} = 5800 + 520 = 6320.$$

In this case, most of the γ -ray energy escapes from the gland, and even from the body, and the β particle dose is much more significant.

Effective Half Life. In the foregoing analyses it was assumed that once the radioactive substance was deposited in a certain organ or tissue, it remained there until total decay. Actually this is seldom the case; due to the body's metabolic processes the material is constantly transferred from one part of the body to another, or eliminated. If, for example, the radioiodine content of the thyroid gland is properly measured in vivo day by day, it will be found to decrease more rapidly than the 8-day half life would predict. In some cases elimination proceeds much more rapidly in the first few days than it does later, and the only way to determine the effective rate of disappearance (due to both elimination and decay) is by repeated measurements. If values found in this way fall on a straight line when plotted on logarithmic paper, it is appropriate to consider an "effective half life" due to the two factors. This is an indication that elimination is proceeding at a constant rate, or that there is a definite biological half life which is independent of the physical half life. In such a case effective half life = $\frac{\text{physical half life} \times \text{biological half life}}{\text{physical half life} + \text{biological half life}}$.

Since the effective and physical half lives are known, the biological half life or the rate of elimination can be calculated.

The effect of this factor on dosage may be considerable. In the case of I-131 analyzed above, if the effective half life were 6 days, the actual dose would be only 6/8 of that calculated from the formula; the patient would actually have received 6/8 x 6320 = 4740r. Since in practice, for I-131 in thyroid glands, the measured effective half life varies from 3 to 7 days, it is evidently important to know it.

Safe Tracer Dose. When tracer studies are contemplated, it is important to know the dose which will result. This must be kept within low limits, especially for normal subjects, or when the procedure is to be repeated. The so-called "permissible dose" of 0.3 r per week is for continuous exposure, and may, of course, be exceeded when the results are sufficiently important, as is the case when radiological diagnostic procedures are carried out. A formula for the "safe tracer dose" can be developed by setting up a formula for the part of the total decay which will have taken place in a week. For any time t , the dose is $d(t) = D(1 - e^{-0.693t/T})$ e.r. per μc per gram of tissue, where D is the total dose per μc per kg., and T the half life in days. Then if S is the concentration in μc per kg which will deliver 0.3 r in the first week, the formula becomes $0.3 = D S (1 - e^{-7 \times 0.693/T})$, or if the term in parentheses is set = w , $S = \frac{0.3}{Dw}$

Values for S , D , and w , for distribution of the isotope throughout the body are listed for certain elements in Table I.

Some Personnel Safety Considerations. It is frequently desired to know the exposure to personnel from patients who have received therapeutic doses of radioisotopes. Also the question arises as to exposure from bottles of solutions, especially large bottles containing 24-hour urine specimens. It is usually possible to measure these with monitoring devices of some sort, but it is also of interest to be able to make approximate calculations. In these cases the β radiation is not important; it does not escape from the patient. The γ radiation at the surface of the body may be taken as half that at the center, and calculated on that basis. This dose, per hour, would be $1/2 \times \frac{I\gamma}{1000}$ per μc per gm.

Consider a 70 kgm patient who has just received 100 mc. of I-131 as a therapeutic dose for thyroid cancer. During the first few hours there will be little excretion and little concentration, and the material may be considered as uniformly distributed throughout the body. The dose in roentgens per hour $\frac{2.65 \times 0.001 \times 200}{2} \times \frac{100,000}{70,000} = 2.65$ r per hour at contact. (1 cm.)

For short distances from the patient, it is reasonable to assume decrease in intensity according to an inverse first power, rather than inverse square, because of the size of the source. On this basis, at 1 meter the intensity would be 26 milli-roentgens per hour. This is four times the permissible rate for continuous exposure, but it will decrease very rapidly as the radioiodine is excreted in the urine. Evidently one such patient does not constitute a real hazard in a ward, but it should not be the practice to group several in the same stage of therapy.

If the first 24 hour urine collection is placed in a cylindrical jar 12x18 cm, containing 2 liters of fluid, carrying 75 per cent of the above dose of 100mc. of I-131, the ratio at its surface is

$$\frac{2.65 \times 0.001 \times 100}{2} \times \frac{75,000}{2,000} = 5 \text{ r per hour at contact.}$$

Obviously one should not hold such a jar more than a few seconds, if at all.

TABLE I

PHYSICAL DATA PERTAINING TO CALCULATIONS OF RADIATION DOSEAGE FROM RADIOACTIVE ISOTOPES

Z = atomic number; A = atomic weight.

\bar{E}_β = average energy of β particles per disintegration.

K = equivalent roentgens due to β particles emitted during complete disintegration of 1 μ c of radionuclide per gr. of tissue.

I_γ = roentgens per mc-hr at 1 cm from unfiltered point source.

K_γ = roentgens at 1 cm in air from unfiltered point source, per μ c destroyed.

D = total roentgens ($\beta + \gamma$) delivered at center of body of adult human for 1 μ c of radionuclide completely destroyed per kg. of tissue. (Isotope uniformly distributed throughout body)

S = tracer dose, in μ c/kg. which will deliver whole body radiation of 0.3 r in the first week, the isotope being uniformly distributed. For greater differential uptake in a particular organ or tissue, corresponding reduction must be made in S for safe dose to most heavily irradiated tissue.

| Element | Z | A | radiation | \bar{E}_β half life - days | \bar{E}_β fraction absorb. per wt. | K_β r./mc. hr. per gr. | K_γ r./mc. hr. at 1 cm | K_γ r./ μ c. at 1 cm | D per μ c. per kg. | S μ c./kg. | |
|---------|----|-----|-------------------|---|---|---------------------------------------|---|--|------------------------------------|-------------------|------|
| C | 6 | 14 | β^- | 1.7×10^6 | neglig. | 30 | 2×10^6 | — | — | 8000 | 13 |
| Na | 11 | 24 | β^-, γ | 0.61 | 1 | 248 | 29 | 19.1 | 0.40 | 0.109 | 2.7 |
| F | 15 | 22 | β^- | 14.5 | 0.235 | 63 | 335 | — | — | 0.885 | 1.1 |
| S | 16 | 35 | β^- | 88 | 0.054 | 55 | 420 | — | — | 0.420 | 13.2 |
| K | 19 | 42 | β^-, γ | 0.915 | 1 | 1095 | 63 | 1.95 | 0.035 | 0.076 | 3.9 |
| Ca | 20 | 45 | β^- | 130 | 0.027 | 100 | 1930 | — | — | 1.58 | 6.9 |
| Fe | 26 | 55 | β^-, γ | 1500 | 0.005 | 3 | 780 | — | — | 0.78 | 130 |
| Po | 26 | 59 | β^-, γ | 47 | 0.098 | 120 | 490 | 0.55 | 10.7 | 2.04 | 1.1 |
| Br | 35 | 82 | β^-, γ | 1.5 | 0.901 | 150 | 20 | 15.1 | 0.79 | 0.13 | 1.7 |
| Sr | 38 | 89 | β^- | 55 | 0.030 | 370 | 1700 | — | — | 2.70 | 1.2 |
| Sr | 38 | 90 | β^- | 9000 | neglig. | 230 | 1.7×10^5 | — | — | 170 | 3.4 |
| I | 53 | 130 | β^-, γ | 0.925 | 1 | 170 | 12 | 13.05 | 0.237 | 0.00 | 5.1 |
| I | 53 | 131 | β^-, γ | 8.0 | 0.494 | 133 | 144 | 2.65 | 0.735 | 0.291 | 2.2 |
| Au | 79 | 198 | β^-, γ | 2.7 | 0.839 | 320 | 70 | 2.4 | 0.22 | 0.120 | 3.00 |

TABLE II

Approximate Values of Geometrical Factor "g" for γ -ray Dosage Calculations.

Spheres

| | | | | | | | | | |
|------------|------|------|------|------|------|------|------|-------|-------|
| Radius- cm | 1 | 2 | 3 | 4 | 6 | 8 | 10 | 15 | 20 |
| Vol- c.c. | 4.2 | 33.5 | 10.3 | 278 | 905 | 2140 | 4180 | 14150 | 27800 |
| g. | 12.6 | 25.2 | 37.8 | 50.4 | 75.6 | 101 | 126 | 189 | 252 |

Cylinders

| | | | | | |
|------------|-----|------|------|-------|-------|
| Diam- cm. | 6 | 10 | 16 | 24 | 40 |
| Height- cm | 10 | 16 | 30 | 40 | 60 |
| Vol- cc | 283 | 1260 | 6000 | 18000 | 76000 |
| g. | 455 | 73 | 108 | 135 | 184 |