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Urinary Excretion of Tritium following Exposure of Man to HTO—a Two Exponential Model

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ABSTRACT. Data on urinary excretion of tritium by a 41-year-old male who accidentally inhaled (or ingested) tritium, presumed to be in the form of HTO, are presented along with an interpretation of these data and an estimate of the radiation dose delivered to tissues. Measurements of levels in urine were made as long as 255 days after the intake of the tritium. The data could be represented as a sum of two exponential terms, one with a half-life of about 9 days, the other of about 34 days. The total dose to body water was estimated to be about 16 rem, the long-term exponential contributing about 2% of the total. A two-compartment model was applied to the data. Equations were derived for the amounts of tritium in each compartment, and an estimate was obtained for the total dose in any tissue, based on a comparison with the content of hydrogen in the tissue. This method of estimating the dose may be applicable for other radionuclides and compounds. It assumes the stable element and its radioactive isotope behave similarly, or identically, in the body, but does not involve assumptions concerning the mathematical form of the retention function.

1. Introduction

The metabolic course of HTO in the body may be considered to be relatively well understood. Numerous animal experiments supplemented by experiments on humans suggest that HTO introduced into the body becomes a part of the general pool of body fluids and is eliminated from the body via the urine, perspiration, breath, and other avenues of elimination of water from the body. The experimental data prior to 1957 are summarized in the comprehensive review of the problem by Pinson and Langham (1957). In addition, there is a wealth of experience gained in working with tritium which has revealed other factors which influence the metabolism of HTO, in particular, age and seasonal variations.

Nevertheless, there are some data to suggest that the metabolic model which assumes HTO to enter and be non-preferentially eliminated from the general pool of body water is not entirely accurate. Thompson (1953) exposed mice and rats to HTO and observed that retention in a variety of tissues could be represented by a sum of two exponentials which were distinct from the single exponential representing the retention in body water. In addition to experimental work on mice which gave a multi-exponential retention, Pinson and

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Langham report an experiment in which one human subject was exposed to tritium over a period of 8 months, and dried biopsy specimens of skin and fat taken 51 days after the end of the exposure showed a higher concentration of tritium per g of H than did urine at the time of the biopsy. Thus, there is the implication that in man, as in experimental animals, some fraction of the HTO entering the body is not eliminated at the rate characteristic of the elimination of water from the body, and that this fraction may be more closely incorporated in certain tissues of the body. Subsequent to the inhalation of HTO by a human subject, we have been able to measure the concentration of tritium in various body fluids and, in particular, have found that concentration in urine does follow a pattern described as a sum of two exponentials during 255 days following an intake.

2. Human tritium excretion following accidental exposure

The exposure occurred in our laboratory (ORNL) when an individual, working with a source of HTO in a hood, inhaled some of the material. The subject is a senior scientist, a male of age 41 years, weight 66·5 kg, height 161 cm, and apparently enjoying good health. He was aware of the general nature of the problem posed by HTO in the body, and we are indebted to him for his co-operation which made this extended study possible.

During the first 11 days, samples of urine, blood serum, and sputum were obtained and analysed for tritium. No significant difference in the levels found in these various body fluids was noted, and this is in line with measurements reported by Pinson and Langham (1957). Also, the data appeared to follow a single exponential as expected, but indicated a half-time for elimination of something under 9 days. The data for the first 13 days are shown in fig. 1.

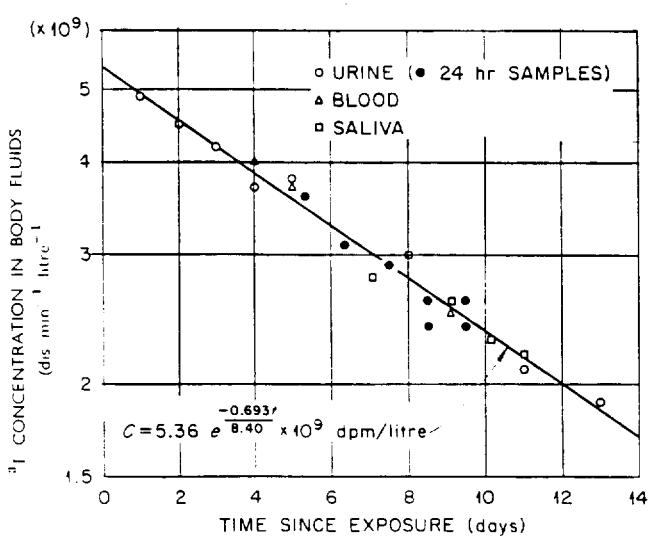

Fig. 1. Tritium concentration in body fluids.

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Table 1. Concentration of tritium in body fluids

Time after exposure (days)	Concentration (dis min^{-1} ml^{-1})[a]		
	Urine	Blood serum	Sputum
1	$4{\cdot}9\times10^6\pm5{\cdot}1\times10^3$		
2	$4{\cdot}5\times10^6\pm5{\cdot}1\times10^3$		
3	$4{\cdot}2\times10^6\pm3{\cdot}5\times10^3$		
4	$3{\cdot}7\times10^6\pm4{\cdot}6\times10^3$	$4{\cdot}0\times10^6\pm3{\cdot}4\times10^3$	$3{\cdot}3\times10^6\pm4{\cdot}4\times10^3$
5	$3{\cdot}8\times10^6\pm3{\cdot}4\times10^3$	$3{\cdot}7\times10^6\pm3{\cdot}3\times10^3$	
6[b]	$3{\cdot}6\times10^6\pm3{\cdot}3\times10^3$		
7[b]	$3{\cdot}1\times10^6\pm3{\cdot}0\times10^3$		$2{\cdot}8\times10^6\pm2{\cdot}9\times10^3$
8[b]	$2{\cdot}9\times10^6\pm2{\cdot}9\times10^3$		$3{\cdot}0\times10^6\pm3{\cdot}1\times10^3$
9[b]	$2{\cdot}6\times10^6\pm2{\cdot}8\times10^3$	$2{\cdot}5\times10^6\pm1{\cdot}5\times10^3$	$2{\cdot}6\times10^6\pm8{\cdot}8\times10^2$
9	$2{\cdot}4\times10^6\pm2{\cdot}7\times10^3$		
10[b]	$2{\cdot}6\times10^6\pm2{\cdot}8\times10^3$		$2{\cdot}3\times10^6\pm3{\cdot}8\times10^3$
10	$2{\cdot}4\times10^6\pm3{\cdot}9\times10^3$		
11	$2{\cdot}1\times10^6\pm3{\cdot}6\times10^3$		$2{\cdot}2\times10^6\pm3{\cdot}9\times10^3$
13	$1{\cdot}9\times10^6\pm3{\cdot}4\times10^3$		
18	$1{\cdot}0\times10^6\pm2{\cdot}0\times10^3$		
24	$7{\cdot}9\times10^5\pm1{\cdot}8\times10^3$		
29	$5{\cdot}4\times10^5\pm1{\cdot}0\times10^3$		
36	$3{\cdot}2\times10^5\pm7{\cdot}8\times10^2$		
42	$1{\cdot}9\times10^5\pm6{\cdot}2\times10^2$		
53	$9{\cdot}4\times10^4\pm3{\cdot}8\times10^2$		
64	$4{\cdot}6\times10^4\pm2{\cdot}8\times10^2$		
70	$3{\cdot}0\times10^4\pm2{\cdot}2\times10^2$		
73	$2\ 3\times10^4\pm2{\cdot}0\times10^2$		
77	$1{\cdot}8\times10^4\pm1{\cdot}8\times10^2$		
80	$1{\cdot}5\times10^4\pm1{\cdot}7\times10^2$		
84	$1{\cdot}1\times10^4\pm1{\cdot}5\times10^2$		
87	$9{\cdot}2\times10^3\pm1{\cdot}7\times10^2$		
91	$6{\cdot}7\times10^3\pm1{\cdot}3\times10^2$		
98	$4{\cdot}6\times10^3\pm1{\cdot}3\times10^2$		
101	$4{\cdot}2\times10^3\pm92$		
105	$3{\cdot}5\times10^3\pm86$		
108	$3{\cdot}0\times10^3\pm82$		$3{\cdot}0\times10^3\pm47$
112	$2{\cdot}3\times10^3\pm71$		
115	$2{\cdot}2\times10^3\pm75$		
119	$2{\cdot}1\times10^3\pm73$		
122	$1{\cdot}9\times10^3\pm74$		
126	$1{\cdot}7\times10^3\pm59$		
129	$1{\cdot}7\times10^3\pm58$		
133	$1{\cdot}5\times10^3\pm56$		
147	$1{\cdot}1\times10^3\pm47$		
150	$1{\cdot}0\times10^3\pm46$		
154	$1{\cdot}0\times10^3\pm49$		
163	$9{\cdot}2\times10^2\pm30$		
164	$8{\cdot}3\times10^2\pm29$		
168	$6{\cdot}3\times10^2\pm28$		

Continued

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Table 1 (*continued*)

Time after exposure (days)	Concentration (dis min^{-1} ml^{-1})[a]		
	Urine	Blood serum	Sputum
172	$6{\cdot}9\times10^2\pm28$		
189	$4{\cdot}9\times10^2\pm24$		
200	$4{\cdot}8\times10^2\pm26$		
203	$4{\cdot}4\times10^2\pm25$		
206	$3{\cdot}8\times10^2\pm24$		
210	$3{\cdot}2\times10^2\pm23$		
213	$3{\cdot}2\times10^2\pm23$		
217	$3{\cdot}2\times10^2\pm24$		
220	$3{\cdot}4\times10^2\pm25$		
224	$2{\cdot}8\times10^2\pm23$		
226	$2{\cdot}9\times10^2\pm25$		
231	$2{\cdot}3\times10^2\pm23$		
235	$2{\cdot}7\times10^2\pm22$		
240	$2{\cdot}1\times10^2\pm17$		
245	$1{\cdot}7\times10^2\pm17$		
248	$1{\cdot}9\times10^2\pm16$		
252	$2{\cdot}4\times10^2\pm16$		
255	$1{\cdot}9\times10^2\pm17$		

[a] Mean disintegration rate $\pm$ one standard deviation.
[b] 24-hour samples; all others are spot samples.

An early evaluation of the dose to be expected was made and indicated no apparent need for measures to hasten elimination. After discussion with the subject, it was agreed that he would not attempt to alter deliberately his normal habits for the purpose of hastening the elimination of the tritium.

Urine specimens were collected periodically during 255 days post-exposure and analysed by liquid scintillation counting. All counting times were for 30 minutes. All the urine data are shown in fig. 2, and all the post-exposure data are given in table 1. During these 255 days, the subject had not been working directly with tritium. However, prior to this incident, he had shown urine concentrations in excess of the later values reported here. For example, the last sample taken before the incident was on October 25, just 3 days before the incident. and a concentration of $6{\cdot}1\times10^4$ dis min^{-1} ml^{-1} was measured. It is possible that this earlier exposure may have some influence on the data.

From fig. 2 it appears that at least two exponential terms are required to fit the urinary concentrations observed in this case. By the courtesy of C. R. Richmond of Los Alamos Scientific Laboratory, we have obtained a least-squares fit of the data to a sum of two exponentials using the LASL code (Richmond 1964) which does not require a logarithmic transformation of the concentrations. This fitting procedure yielded a formula for concentration in urine of

$$R(t)=5{\cdot}3\times10^6\,e^{-\alpha t}+2{\cdot}3\times10^4\,e^{-\beta t}, \qquad (1)$$

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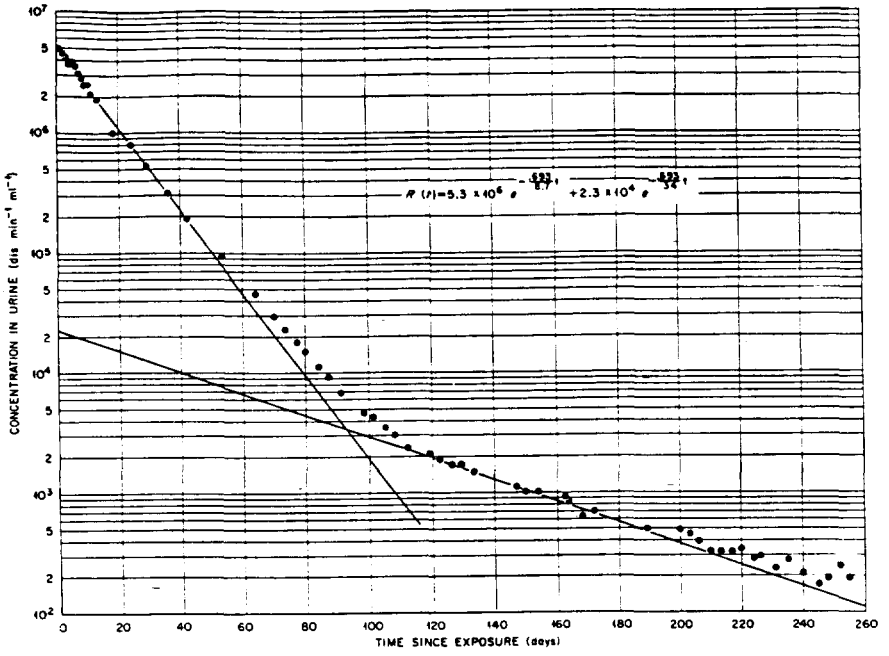

Fig. 2. Tritium concentration in urine.

with

$$\alpha = \frac{0{\cdot}693}{8{\cdot}7} \quad \text{and} \quad \beta = \frac{0{\cdot}693}{34}.$$

3. Estimation of internal exposure

Cases of internal exposure at ORNL which warrant special consideration of dose and intake are evaluated by an internal dose evaluation committee. This subject's total body water was estimated by that group on the following bases:

1. On weight basis: From the regression line relating body water to body weight, there are 0·52 litres of water per kilogramme for a 66·5 kg man (Biological Handbook 1961). Thus the body water $= 0{\cdot}52 \times 66{\cdot}5 = 34{\cdot}6 \approx 35$ litres.
2. On age basis: From the regression line relating body water to age, there are 0·525 litres of water per kilogramme in a 41-year-old human (Biological Handbook 1961). Thus the body water $= 0{\cdot}525 \times 66{\cdot}5 = 34{\cdot}9 \approx 35$ litres.
3. On the basis of weight-to-height ratio: Weight/height $= 0{\cdot}41$ kg/cm, the male human body weight is 18 to 37% fat (mean 28%). Lean body weight (LBW) $\approx (1 - 0{\cdot}28) \times 66{\cdot}5 = 47{\cdot}9$ kg (Forbes, Gallup and Hursh 1961). The same reference suggests: total body water $= 0{\cdot}72$ LBW $= 34{\cdot}5 \approx 35$ litres.
4. On the basis of total potassium content: The subject was counted in the ORNL Whole-Body-Counting Facility on November 8, 1963, and contained an estimated 121 g of potassium based upon ^{40}K measurement.

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Total potassium content = 0·28% of LBW; LBW = 121 g/0·0028 = 43·2 kg (Anderson 1957). This reference indicates that 72% of the lean weight and 20% of the fat weight are made up of water; thus, total body water = $0{\cdot}72 \times 43{\cdot}2 + 0{\cdot}2 \times 23{\cdot}3 = 35{\cdot}76 \approx 36$ litres.

The committee decided to use 36 litres as the amount of body water. Assuming a concentration of $5{\cdot}3 \times 10^6$ dis min^{-1} ml^{-1} initially, and that all the tritium is in the body water at early times post-exposure, this yields $5{\cdot}3 \times 10^6 \times 36 \times 10^3 = 1{\cdot}9 \times 10^{11}$ dis/min, or 86 mCi, as the initial intake. The total dose to body water is then

$$\mathrm{D} = \frac{51 \times f_2 \ \epsilon \ q(0)}{m \times 5{\cdot}3 \times 10^6} \int_0^\infty \mathrm{d}t \ \mathrm{R}(t) = 15{\cdot}5 \text{ rems}, \tag{2}$$

where $f_2 = 1$, $m = 3{\cdot}6 \times 10^4$ g, $\epsilon = 0{\cdot}01$ Mev, $q(0) = 86 \times 10^3$ μCi, and

$$\int_0^\infty \mathrm{R}(t) \ \mathrm{d}t = \frac{5{\cdot}3 \times 10^6 \times 8{\cdot}7}{0{\cdot}693} + \frac{2{\cdot}3 \times 10^4 \times 34}{0{\cdot}693}$$
$$= 6{\cdot}68 \times 10^7 + 1{\cdot}13 \times 10^6 = 6{\cdot}79 \times 10^7.$$

It is apparent that the second exponential term contributes only about 1·7% to the total dose. The dose in various body tissues may be somewhat less, since no allowance has been made for the presence of organic material. However, there are some tissues in which water constitutes a preponderant part of the mass, and so the estimate is substantially, although not precisely, correct for such tissues. On the other hand, there remains the probability that some tissue may accumulate a higher concentration than body water, particularly at times much later than the exposure. In an attempt to explore this possibility, even partially, a two-compartment model was set up to see if such a model would fit the available data.

4. A two-compartment model for tritium metabolism

The model is shown schematically in fig. 3. It is assumed that a unit amount (1 μCi) of HTO is taken into the system at time $t = 0$. The functions $A(t)$ and $B(t)$ represent the amount of activity present in the respective compartments (see fig. 3). The exchange rates α, β and the excretion rate γ represent fractions of the compartment contents exchanged or excreted per unit time and, therefore, are non-negative constants.

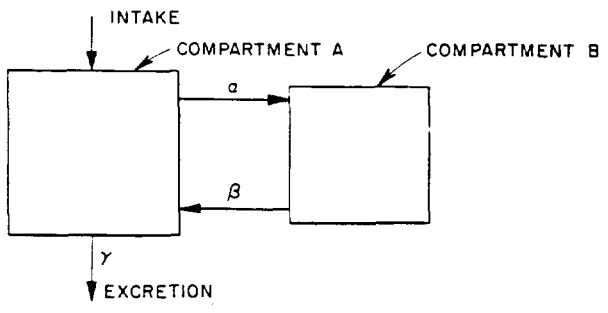

Fig. 3. Schematic diagram of a two-compartment system.

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The differential equations governing such a system are the following:

$$\frac{dA}{dt} = \beta B - (\alpha+\gamma)A$$
$$\frac{dB}{dt} = \alpha A - \beta B. \tag{3}$$

The solution of these equations with $A(0)=1$ and $B(0)=0$ as initial conditions is given by

$$A(t) = [(\beta-h)\,e^{-ht} + (k-\beta)\,e^{-kt}]/(k-h)$$
$$B(t) = \alpha[e^{-ht} - e^{-kt}]/(k-h) \tag{4}$$

where k and h are the two roots of the quadratic equation

$$x^2 - (\alpha+\beta+\gamma)x + \beta\gamma = 0. \tag{5}$$

To fix the notation, we let

$$k = [\alpha+\beta+\gamma+\sqrt{\{(\alpha+\beta+\gamma)^2 - 4\beta\gamma\}}]/2$$
$$h = [\alpha+\beta+\gamma-\sqrt{\{(\alpha+\beta+\gamma)^2 - 4\beta\gamma\}}]/2. \tag{6}$$

These roots are easily shown to be positive, and k is greater than h. It is also easy to show that

$$\beta - k < 0 < \beta - h \tag{7}$$

so that $A(t)$ is the sum of two exponential terms with positive coefficients and $B(t)$ the difference of two such terms.

From the least-squares fit of the data, it is observed that the coefficients of the exponentials fitted to the excretion data are $5{\cdot}3\times10^6$ and $2{\cdot}3\times10^4$ dis min^{-1} ml^{-1}. Although fig. 2 represents excretion data, the pool of body water, represented by compartment A, is at the same concentration as urine, and thus the function represented in fig. 2 is proportional to $A(t)$. When normalized for unit intake, the intercepts in fig. 2 are given by

$$r = 0{\cdot}9957 = (k-\beta)/(k-h)$$

and

$$1 - r = (\beta-h)/(k-h). \tag{8}$$

The values of k and h may be determined from the slopes of the lines on fig. 2 or by the least-squares fit of the data. From eqns. (8) and (6), one obtains

$$\alpha = \frac{r(1-r)\,(k-h)^2}{rh+(1-r)k} = 7{\cdot}3\times10^{-4}$$
$$\beta = rh + (1-r)k = 0{\cdot}021 \tag{9}$$
$$\gamma = \frac{hk}{rh+(1-r)k} = 0{\cdot}079.$$

The numerical evaluations given in eqns. (9) have been obtained by using the values

$$k = \frac{0{\cdot}693}{8{\cdot}7}, \quad h = \frac{0{\cdot}693}{34}, \quad r = \frac{5{\cdot}3\times10^6}{2{\cdot}3\times10^4 + 5{\cdot}3\times10^6} = 0{\cdot}9957.$$

It appears that it is possible to select parameters in such a way that the model fits the excretion data.

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It is possible to compare the excretion predicted by the model and the excretion of the subject, and thus further test the validity of the model. Using the estimated 36 litres of total body water and the value of γ obtained from the model, one would predict a daily excretion of 2·84 litres. ICRP Publication 2 suggests that standard man has a total daily excretion of 2·5 litres of which 1·4 litres is excreted as urine. If the same proportion held for this subject, one would expect a daily urinary excretion of 1·6 litres. If one assumes urinary excretion is proportional to body weight, then the subject should excrete about 1·3 litres of urine per day. Only five 24-hour urine samples were collected during the study, and these averaged 1·3 litres. While neither extrapolation can be considered as highly accurate, it appears that the model is in reasonable agreement with the volume of urine excreted per day by the subject, as far as this can be estimated.

To estimate a dose to the tissues representing the two compartments, the mass of these tissues is needed. In the absence of any direct biological evidence on the compartment represented by $B(t)$, it was assumed that the HTO metabolized in the same way as H_2O. This unsupported assumption can be used to calculate an estimate of the H_2O in compartment B, and a dose can be computed on the basis of this water content. The surprising result was that this estimate did not involve the parameters α, β, γ of the model, although the model was used in making the estimate. It was found then that a quite general argument could be used, and this is outlined below.

5. Estimates of dose to individual compartments

Assume HTO is taken into the body and metabolized in exactly the same way as H_2O until the moment when the tritium disintegration takes place. Because of the long radioactive half-life of tritium, the decay will be neglected. Let $R_i(t)$ μCi be the burden of ingested tritium present in tissue i at time t following intake of 1 μCi at time 0. The dose rate (rem/day) to tissue i at time t is then

$$\frac{R_i(t) \times 3{\cdot}2 \times 10^9 \times \epsilon}{M_i}$$

where

$R_i(t)$ = the tissue burden in μCi
$3{\cdot}2 \times 10^9$ = (dis/day)/μCi
ϵ = effective energy (Mev) $\times 1{\cdot}6 \times 10^{-8} \times$ QF (g rem)
M_i = mass of tissue i(g).

The total dose, D, to tissue i is then

$$D = \frac{3{\cdot}2 \times 10^9 \times \epsilon}{M_i} \int_0^\infty R_i(t)\, dt \text{ rem.} \tag{10}$$

Assuming an intake of I g of H_2O per day and that tissue i is in equilibrium for intake of H from H_2O, then tissue i contains

$$\frac{I}{18} \int_0^\infty R_i(t)\, dt \text{ g} \tag{11}$$

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of hydrogen which was ingested in the form of H_2O, I being the daily intake of water (g/day). Whether one uses 1/9 or 1/18 in eqn. (11) depends on whether both hydrogen atoms or only one of them in the H_2O molecule is retained to the same degree as is tritium from HTO. For example, if the HTO molecule transfers intact to the compartment of interest, then the hydrogen transferred to the compartment from the daily intake of H_2O is 1/9 of the total water mass; but if the HTO molecule dissociates at some stage of the pathway to the compartment, so that only one of the ions, possibly after combining with some other radical, arrives at the compartment, and if the other ion does not go to this compartment, then water following similar pathways would contribute only 1/18 of its mass to the compartment. The infinite range of integration is unrealistic, but it is used only to indicate effective equilibrium. The total hydrogen content, say, h_i g, of tissue i must be at least the amount indicated by eqn. (11). In general, there is not a great range of variation of hydrogen content among the soft tissues, 10% being a representative value. Table 2 presents data from several sources on this point. Thus from eqn. (11) we have

$$0{\cdot}1\, M_i \sim h_i \geqslant \frac{I}{18}\int_0^\infty \mathrm{R}_i(t)\,\mathrm{d}t. \tag{12}$$

Combining eqns. (12) and (10), one obtains

$$\begin{aligned} \mathrm{D} &= \frac{3{\cdot}2\times 10^9\times\epsilon}{h_i}\int_0^\infty \mathrm{R}_i(t)\,\mathrm{d}t\times\frac{h_i}{M_i} \\ &\leqq \frac{3{\cdot}2\times 10^9\times\epsilon\times 18}{I}\times\frac{h_i}{M_i}\sim\frac{5{\cdot}8\times 10^9\times\epsilon}{I}\,\mathrm{rem} \end{aligned} \tag{13}$$

since

$$\frac{h_i}{M_i}\sim 0{\cdot}1.$$

If the compartment represented by $A(t)$ is considered to consist essentially of water and if we denote this compartment by taking $i=0$, then the amount of water in the compartment is at least

$$I\int_0^\infty \mathrm{R}_0(t)\,\mathrm{d}t\ \mathrm{g}.$$

This follows from the assumption that HTO and H_2O metabolize in the same way and because $\mathrm{R}_0(t)$ being the fraction of intake present at time t, one atom of tritium corresponds to one molecule of HTO. Since

$$M_0 = I\int_0^\infty \mathrm{R}_0(t)\,\mathrm{d}t,$$

eqn. (10) becomes

$$\mathrm{D} = \frac{3{\cdot}2\times 10^9\times\epsilon}{I}\,\mathrm{rem}. \tag{14}$$

It will be noted that the estimated dose to any tissue i given by eqn. (13) cannot exceed the dose to body water as given by eqn. (14) except by the factor

$$\frac{18\,h_i}{M_i},$$

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where h_i/M_i is the fraction of the mass M_i due to hydrogen. hydrogen is all present in the form of water, then the facto by the data of table 2, there is no tissue known to the au hydrogen is much in excess of 10%. The data of Forbes based on a single subject who was 23% underweight, but are not greatly different from those reported by othe particular, by Spector (1956). Thus it seems unlikely that dose from ingested HTO that is markedly in excess of do This conclusion, while only suggested by the above indire provide some guidance in attempting to assess the significa physicist of the existence of tissues where the elimination o in the case of body water.

Table 2. Hydrogen content of some body tis

Tissue	Tissue weight (g)	Per cent water by weight
Bone	7,000[b]	28·2[c]
Fat	10,000[b]	23·0[c]
Skeletal muscle	30,000[b]	70·1[c]
Skin	2,000[b]	57·7[c]
GI tract	2,000[b]	77·4[c]
Liver	1,700[b]	75·0[e]
Brain	1,500[b]	77·5[e]
Lungs	1,000[b]	77·3[c]
Kidneys	300[b]	70·6[e]
Heart	300[b]	63·0[e]
Spleen	150[b]	78·5[e]
Pancreas	70[b]	73·1[c]
Spinal cord	30[b]	70·0[e]
Eye, lens	~0·45[e]	68·0[e]
Blood plasma	3,200[g]	92·0[f]

[a] Computed from the per cent hydrogen for a typical fat, c protein as given in Zoethout and Tuttle (1949), together with (1) t from column 3 and (2) the per cent ash and the fat, carbohydrate an of each tissue as taken from the references in this column.

[b] Report of Committee II on Permissible Dose for Internal Radia

[c] Forbes *et al.* (1953).

[d] Woodard (1962).

[e] Spector (1956).

[f] Sunderman and Boerner (1950).

[g] Houssay (1955).

6. Discussion of dose estimates

It is evident that the assumption that tritium taken in the fo hydrogen taken in as H_2O will metabolize in exactly the same fa expected to be highly accurate. The ratio of the masses of ^3T a than for any other pair of isotopes, and this may be expected t

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difference in the distribution of these isotopes. In addition to the mass difference is the evident fact that there is only one T atom per molecule of HTO, but two hydrogen atoms per molecule of H_2O. Certainly one would not be surprised if the doses in various tissues differed by a factor of 2 or even 5. Whether the isotopic difference may produce a disparity of an order of magnitude or more seems doubtful. Thus, the analysis serves only to make it somewhat implausible that any tissue receives a dose vastly higher than the dose to body water.

Brues and Tyler (1959) have discussed the variation of dose and dose rate in a multi-compartment system which is in a state of equilibrium. They find that " there is a predictable maximum radiation given by any compartment of any steady-state multi-compartment open system in which the 'external' compartment is specified as to its specific activity in time ". Marshall has generalized the argument of Brues and Tyler in his discussion of the metabolism of the alkaline earths (1964). However, his discussion applies almost without change for other elements. In the present note a related result is obtained without the assumption of a multi-compartment or mammillary system, and the final estimate of dose does not directly involve the rate constants of the various compartments. Thus, the present result appears to be somewhat more general than those mentioned above. On the other hand, the argument presented above demands a knowledge of the daily intakes and of the mean concentrations in the organs involved of a stable isotope of the radionuclide in question. In this sense, the argument may be more special than those of Brues and Tyler or of Marshall. Finally, it may be noted that the data on composition are all from analysis of gross tissue masses, and thus do not provide information on dose to microscopic volumes such as cell nuclei.

The authors have no direct evidence concerning the tissue which might be represented by the second compartment of the model. The argument above suggests that the equilibrium amount of hydrogen in this tissue is at least

$$\frac{\alpha}{hk} I \text{ g} \tag{15}$$

where I is the daily intake of H in the form of H_2O. Taking

$$I = 36{,}000 \times \frac{0{\cdot}693}{8{\cdot}7} \times \frac{1}{9}\text{g} = 320 \text{ g}$$

as the daily intake of this person, one obtains an equilibrium amount of 144 g of H in this tissue. The total mass of the tissue might then be about 10 times this or 1440 g, but there is an uncertainty in this value of at least a factor of 2, because it does not seem clear whether both hydrogen atoms in H_2O or only one of them will follow the pathway of the tritium atom in HTO. This estimate of mass is, at best, only an indication of the mass of the second compartment and, even if accurate, would not suffice to identify the tissue which perhaps might be some fraction of the protein, fat, etc., which is exchanging tritium with the body water. The authors are indebted to Dr. A. M. Brues for pointing out that Prentice, Siri, Berlin, Hyde, Parsons, Joiner and Lawrence (1952)

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found a difference between the HTO and antipyrine volumes in man which suggested a non-water compartment of the same order (0·5–2% of the total) similar to compartment *B*.

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Résumé

Elimination du tritium par voie urinaire quand l'homme était exposé au HTO—Un modèle à deux courbes exponentielles

On présente les données relatives à l'élimination par voie urinaire du tritium par un patient âgé de 41, qui avait par accident inhalé (ou absorbé) du tritium, probablement en forme de HTO, ainsi que l'interprétation de ces données et une évaluation de la dose de radiation, fournie aux tissus. Les mesures des niveaux en urine étaient conduites même 255 jours après l'absorption du tritium. Les données pouvaient être présentées comme une somme de deux termes exponentiels, dont un ayant une période de demi-vie de 9 jours environ, et l'autre—de 34 jours environ. La dose totale fournie à l'eau du corps était évaluée comme 16 rem environ, la courbe exponentielle au terme plus long contribuant 2% du total environ. Un modèle à deux compartiments était employé pour les données. On a déduit des équations pour les quantités de tritium dans chaque compartiment, et on a obtenu une évaluation de la dose totale dans n'importe quel tissu, basé sur la comparaison avec le contenu d'hydrogène dans le tissu. Cette méthode d'évaluation de la dose peut être employée à d'autres radicisotopes et composés. On présuppose que l'élément stable et son isotope radioactif se comportent d'une façon analogue ou identique dans le corps, mais il n'est pas nécessaire de faire des suppositions relatives à la forme mathématique de la fonction de rétention.

Zusammenfassung

Ausscheidung von Tritium im Harn nachdem ein Mann der Einwirkung von HTO ausgesetzt war—ein zweifach-exponentielles Modell

Es werden Angaben dargestellt betr. Ausscheidung von Tritium im Harn eines 41-jährigen Mannes, welcher zufällig Tritium eingeatmet (oder absorbiert) hatte, höchstwahrscheinlich als HTO, sowie eine Deutung dieser Angaben und eine Abschätzung der den Geweben zugeführten Dosis. Die Niveaus im Harn wurden bis 255 Tage nach der Tritiumeinnahme gemessen. Die Angaben konnten als Summe von zwei exponentiellen Gliedern dargestellt werden, und zwar hatte das eine eine Halbwertszeit von ungefähr 9 Tagen, das andere aber von ungefähr 34 Tagen. Die gesamte dem Körperwasser zugeführte Dosis war mit ungefähr 16 rem eingeschätzt, wobei der exponentielle Term mit längerer Halbwertszeit etwa 2% des Gesamtwertes ausmachte. Es wurde ein Zweiabteilmodell für die Angaben verwendet. Es wurden Gleichungen für Tritiummegen in jedem Abteil abgeleitet, und ein Schätzungswert wurde für die Gesamtdosis in einem beliebigen Gewebe erhalten, auf grund eines Vergleichs mit dem Wasserstoffgehalt des Gewebes. Dieses Verfahren zur Einschätzung der Dosis kann auch für andere Radionuklide und Verbindungen anwendbar sein. Es wird hier vorausgesetzt, dass das stabile Element und sein radioaktives Isotop sich im Körper in analoger Weise oder identisch benehmen, doch sind keine weiteren Annahmen betr. die mathematische Form der Rückstandfunktion erforderlich.

Резюме

Выделение трития с мочой после облучения человека НТО—двухпоказательная модель

Представлены данные о выделении в моче трития 41-летним мужчиной, который случайно вдыхал (или проглотил) тритий, вероятно в виде НТО, вместе с интерпретацией этих данных и оценкой дозы излучения, доставленной тканям. Измерения уровней в моче производились

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до 255 дней после поглощения трития. Данные можно было представить как сумму двух экспоненциальных членов, один из которых имеет период полувыведения около 9 суток, а другой—около 34 суток. Полная доза, полученная водой тела, оценивалась как около 16 биологических эквивалентов рентгена, причем экспонента с дольшим периодом полувыведения составляля около 2% целого. К данным применялась модель с двумя отделениями. Выводились уравнения для количеств трития в каждом отделении, и получалась оценка для полной дозы в любой ткани, основывающаяся на сравнении с содержанием водорода в ткани. Этот метод оценки дозы может применяться для других радиоизотопов и соединений. Он основывается на предположении, что поведение устойчивого элемента в теле аналогично или идентично с поведением его радиоактивного изотопа; нет необходимости делать предположения, касающиеся математической формы функции удержания.

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