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THE FATE OF RADON INGESTED BY MAN*

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Abstract—Four experiments were performed in which two subjects on two occasions drank approximately 1 μc radon plus daughters in 100 ml of water. Measurements on radon loss in expired air, whole body Radium C content, and radon in the blood permit the calculation of an $(MPC)_w$ of 2.0×10^{-4} μc/ml for occupational exposure. This is based on the stomach as the critical organ, but doses to the lung, kidney, and liver are estimated.

FOUR experiments were performed on man to explore the fate of radon ingested in water. They yield data from which a recommendation can be made for permissible chronic intake of this radioactive gas, namely the specification of a maximum "occupational" daily intake of 0.24 μc radon ($MPC_w = 2 \times 10^{-4}$ μc/ml) with 0.3 rem per week to the stomach as a criterion for the limitation. The data obtained and the argument used to develop the limit stated above are presented in this report.

It may be noted that the limit recommended is 100 times higher than the Handbook 52[1] listed limit of 2×10^{-6} μc/ml (2000 pc/l.) for radon in equilibrium with its daughters. Later reports by NCRP[2] and ICRP[3] do not list a recommended value. The Handbook 52 value is based on "submersion" of the gastro-intestinal tract in water of this concentration and is recognized as an ultra-conservative limit. The need for a current recommendation based on new data is highlighted by the discovery of drinking water sources (Table 1) containing natural levels of radon which may exceed the prior occupational limit by two orders of magnitude.†

Although no estimate was made by the authors[5] of the size of the population using the 280 separate water supplies measured in the Maine-New Hampshire study, a conservative guess would be 100,000 people. The authors suggest that there may be a "more or less continuous band of natural radioactivity along the Atlantic Coast . . . ." If so, more extensive exploration may reveal that a substantially larger number of water consumers are involved. The population of Cornwall, England, in the neighborhood of 300,000 people, consumes radon in water at or about the prior occupational limit. Since current practice is to specify limits to be applied to the population at about one-thirtieth of occupational limits, both the Maine-New Hampshire and the Cornwall supplies may be regarded as exceeding the conservative Handbook 52 recommendations.

EXPERIMENTAL METHOD

Two male subjects, Subject A (56 years old, 76 kg, 173 cm) and Subject B (36 years old, 78 kg, 184 cm) each on two occasions drank approximately 1 μc of radon (plus daughters in equilibrium) dissolved in 100 ml of water. For the first three experiments the ingestion time was two hours after a normal light breakfast. Subject A, for the fourth experiment, finished a breakfast of cereal garnished with one banana and including 225 ml heavy whipping cream (as liquid) 10 minutes before drinking the radon.

Dose administration

The preparation of the dose involved transfer of radon from a radon generator (0.8 mg Ra-226)

* This report is based on the work performed under contract with the U.S. Atomic Energy Commission at the University of Rochester, Atomic Energy Project, Rochester, New York.

† The comparison between the Hb. 52 limit specifying radon in equilibrium with its daughters and the radon activities listed in Table 1 is valid because the limit developed below depends only on the radon ingested and is unchanged by the presence of radon daughters in the equilibrium amounts.

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Table 1. Measurements of radon in natural waters

Source	pc Rn/l. average	pc Rn/l. maximum	pc ^{226}Ra/l. average	Reference
Springs near Rochester, N. Y.	363	1,110	0.44	(4)
Springs, Maine*	16,000	229,000	70	(5)
Springs, N. H.*	30,000	237,000	6.9	(5)
Cornish waters* England	1,100	3,330	0.45	(6)
Whole of Britain*	2.3	—	0.05	(6)
Spas—				
Hassia Sprudel	650	—	13	(7)
Kronthal (Taunus)	1,650	2,000	20	(7)
Bath, England	166	—	—	(8)
Springs—				
Beshtaugorsky, USSR*	228,000	—	—	(9)

* Converted by us from listed values to units suitable for entry in the table.

into a 250 ml gas collecting bottle which contained either 200 ml distilled water or 200 ml of 0.1% Na citrate solution. The transfer was effected in a closed circuit which contained a pump, glass-wool filter and a 2-stage sulfate-water scrubber. After standing 24 hours, the solution was assayed and after an additional 24 hours, an appropriate volume (2.5–5.0 ml) was withdrawn in a 5-ml syringe and carefully discharged into the bottom of a beaker containing 100 ml distilled water. The subject drank this forthwith. A second identical aliquot was withdrawn for assay of Rn and daughters. Counts on the empty syringe and on the beaker showed no appreciable Rn or Rn daughter residues. This method of radon introduction, although it closely resembled the mode in which natural radon in water would be ingested, resulted in radon gas losses estimated as high as twenty-five per cent. For this reason the total radon dose chosen for calculation was arrived at from the breath radon recovery data.

Radon collection

After drinking the radon solution, the subject held his breath while a valved face mask was slipped on. The masks had been previously fitted and found to be leak-free. The valving permitted the subject to inspire room air and expire through a M-11 charcoal cannister.† For the first three experiments the charcoal cannisters were cooled with solid CO_2. Prior to the fourth experiment, an additional series of recovery determinations established that, for the breathing intervals employed, better than 99 per cent recovery was obtained without cooling the cannister. Accordingly, the cannisters were not cooled for the last experiment.

Fresh cannisters were substituted at the end of specified collection periods which varied from 1 minute at early times to spot collections of 20 minutes several hours later. All of the expired radon was collected for the first 60–70 minutes. From then on the expired air was sampled at increasing intervals as will be indicated on the pertinent figures in the section on Results.

After removal of a used cannister it was immediately sealed and laid aside for future assay by gamma-counting using a NaI(Tl) crystal detector in an iron-cave shield. The crystal output was fed into a 256-channel spectrum analyzer and the net gamma count from 0.2–2.56 MeV was utilized. After equilibrium with the short-lived daughters had been established, the 4″ diameter, 4″ thick crystal

† The cannisters were obtained from the Army Chemical Warfare Service and contained 150 grams of 8–12 mesh activated coconut charcoal.

0000863

in our geometry yielded 0.32 cpm/pc Rn. The radon in the breath measurement at 1526 minutes for experiment 4 utilized a more sensitive method developed in this laboratory.[10]

Radium C measurement

At intervals throughout the experiment the subject entered an iron room (8″ thick walls) and was counted in the chair position[11] with an 8-inch diameter, 4-inch thick NaI(Tl) crystal detector fed into a 256-channel analyzer. The spectra were recorded on punch tape for future analysis. Counting periods were extended from an initial 2 minutes to 20 minutes as the experiment progressed. The initial net count (0.40–2.56 MeV) at about 2 minutes after time zero was equated to the known micro-curie dose of RaC ingested, and subsequent net counts were evaluated on this basis. The sensitivity is about 60,100 cpm per μc RaC and the clean subject plus background over the same energy range is 1050 cpm.

Radon-in-blood measurements

At specified intervals during the experiment 5 ml blood were withdrawn from the cubital vein of the subject and transferred immediately to a de-emanation tower containing 50 ml of 5 per cent HCl acid. A total of six blood samples were taken for each experiment. As soon as convenient the samples were swept with aged tank air, using a train which removed water vapor in a solid CO_2 trap and condensed radon in a liquid N_2 trap. When de-emanation was complete, the liquid N_2 trap was warmed and helium gas used to transfer the radon into Lucas chambers.[12] After a 4-hour interval, to permit the daughters to grow to near equilibrium, the chambers were set with the window on the face of a 2″ photomultiplier tube and counted. The background count is about 5 counts per hour and the sensitivity is about 4.6 cpm per pc radon.

Urine measurements

Complete urine collections were made up to 400 minutes post ingestion. The samples were collected in polyethylene bottles which were placed directly on the face of the 4-inch crystal for RaC assay.

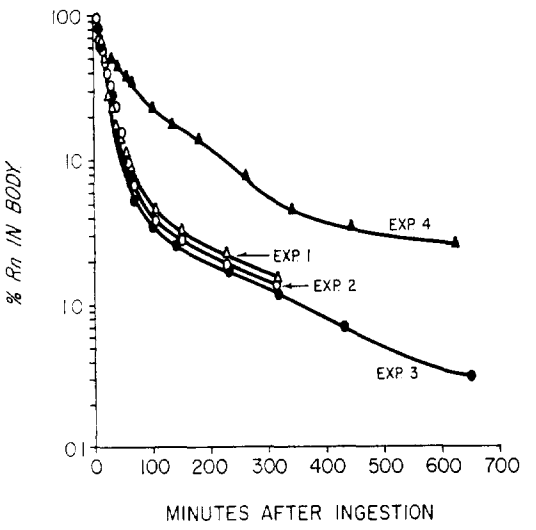

FIG. 1. The body radon content as a function of time after ingestion of about 1 μc radon plus daughters in 100 ml water. For Experiments 1, 2, and 3, the stomach was empty; for Experiment 4, food was taken just prior to the radon dose.

RESULTS

Radon loss from the body

Figure 1 plots radon body content as a function of time. The ingested dose of radon is taken equal to the sum of the losses in the breath (decay-corrected to zero time) including interpolated losses for the intervals between spot samples (after 60–70 minutes) and an extrapolation to include the small amount left in the body after the last spot sample. The points plotted in Fig. 1 mark the end of successive sampling periods and the decrease in body content includes the radon breath loss in the interval and a point-to-point allowance for physical decay. Because of crowding the graph does not include all of the experimental points for times less than 20 minutes.

The curves can be satisfactorily represented as equations incorporating three exponential terms. The values for the constants determined by graphical analysis are listed in Table 2. The amount of radon decaying in the body has been calculated and the last two columns list this value as per cent of the radon taken in, calculated both from the parameters of the equations and by the analytical method of Cornfield[13].

These results reaffirm earlier measurements

Table 2. Parameters of the radon loss curves derived from graphical analysis of data to fit the general equation $R = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t} + Ce^{-\lambda_3 t}$ *where "R" at time zero equals 1 and "t" is in minutes*

Exp.	Subj.	A	λ1 (min⁻¹)	B	λ2 (min⁻¹)	C	λ3 (min⁻¹)	% Radon dose decaying in body	
1.	A	0.644	0.063	0.300	0.033	0.056	0.00408	0.41*	0.426†
2.	B	0.586	0.0462	0.370	0.0385	0.044	0.00365	0.43	0.446
3.	B	0.606	0.0578	0.350	0.0385	0.044	0.00408	0.38	0.385
4.	A	0.392	0.0578	0.510	0.0116	0.098	0.00231	1.17	1.19

* Using the equation with constants as listed.
† Using the analytical method of estimation proposed by Cornfield[13].

by STEFAN MEYER[14] and in general conform to the measurements of others.[15,16] As reported by MEYER, the presence of food in the stomach, witness the results in Experiment 4, may cause a marked delay in the removal of radon from the body. It seems reasonable to assume that this delay is associated with an increased emptying time of the stomach and that a large fraction of the radon decay occurs in the gastro-intestinal tract.

The fate of RaC

Figure 2 charts the body content of RaC, transformed from gamma counting rate (0.40–2.55 MeV band) into per cent dose by setting the counting rate obtained a few minutes after ingestion equal to 100 per cent. No attempt was made to correct for a possible change in counting efficiency as the RaC moved through the gastro-intestinal tract or consequent to the new formation of RaC in body tissues. Some reliance is placed on 1) an appreciable delay in the stomach during which the levels of RaB and RaC are falling, 2) poor absorption of Pb(RaB) and Bi(RaC) from the gut and, 3) the inference that a large fraction of the RaC (both ingested and newly formed) decays in the gut, as factors which would reduce the disturbing effect of a major re-distribution of the RaC sources.

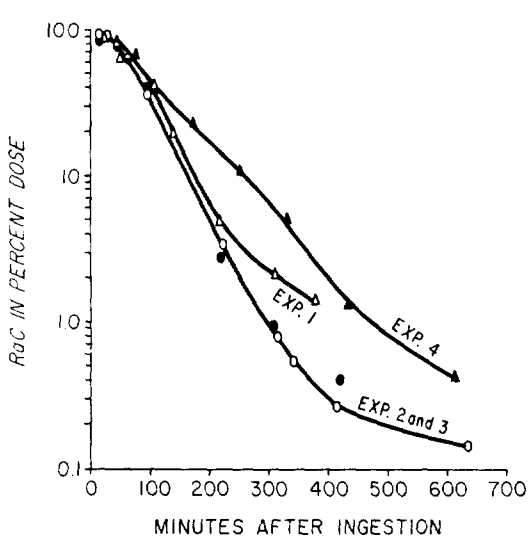

FIG. 2. The Radium C body content as measured by gamma-counting in a shielded room.

In reference to the curves themselves, the data points for experiments 1, 2 and 3 appear to fall on the same descending curve with some divergence when the body burden falls to a few per cent and the net counting rate approaches the background counting rate. Background, including counting rate of the "clean" subject, in our facility is approximately equal to the net count from 0.009 μc RaC.

The relatively slower rate of fall for the Experiment 4 data is associated with the longer body residence time of radon and the associated greater production of radon daughters in the body. This relationship is described in more detail by the curves in Figure 3. Because, at the time of ingestion, the daughter products were in equilibrium with a known radon activity, it is possible to calculate the RaC level at any later time, under conditions of separation of the daughters from the parent radon and no excretion, by use of the appropriate Bateman equations.[17] This calculation has been made and the results plotted as the dotted curve. The measured body content of RaC minus the value at the same time read from the "ingested RaC" curve gives a measure of the RaC level due to daughters newly

formed in the body. The dot-dash difference curve has been generated in this way. Inserting parameters from the body radon into a general formula such as listed in the ICRP Committee II Report (3), equation 9, will yield the activity of RaC formed from radon. The results of such calculations made for different times t are plotted as triangles on the figure and show a reasonable correspondence with the difference curve. Whether or not some loss of RaC by excretion occurred for times greater than 400 minutes is not known. Total urine collections up to 400 minutes yielded less than 0.2 per cent of the RaC ingested.

The significance of the newly formed radon daughters derives from their potential location in systemic tissues, whereas the ingested daughters are poorly absorbed (Pb and Bi respectively 8% and 1% from the intestine (3) and consequently may be neglected in the consideration of the dose to body tissues other than the gastro-intestinal tract. This is not to say that all of the newly formed daughters are available to the systemic tissues. The mobile component depends on the fraction of the radon

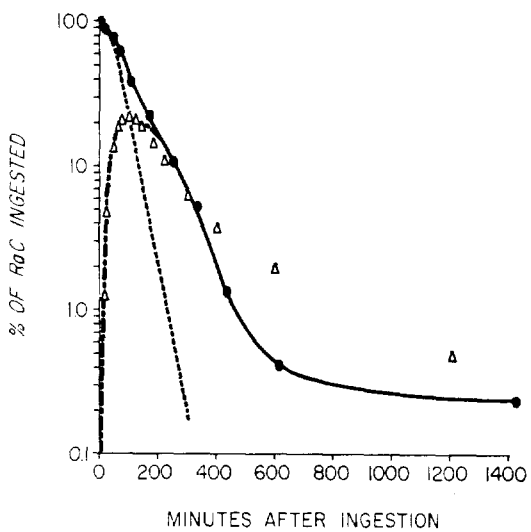

FIG. 3. The Radium C whole body counting data, Experiment 4, are plotted on the solid line. The dotted line is the calculated decay of the ingested Radium C (separated from radon) plus Radium C formed from ingested Radium B. The difference is plotted as the dot-dash curve and represents the amount of newly formed Radium C. The open triangles are calculated values of newly formed Radium C based on the radon loss equation for Experiment 4.

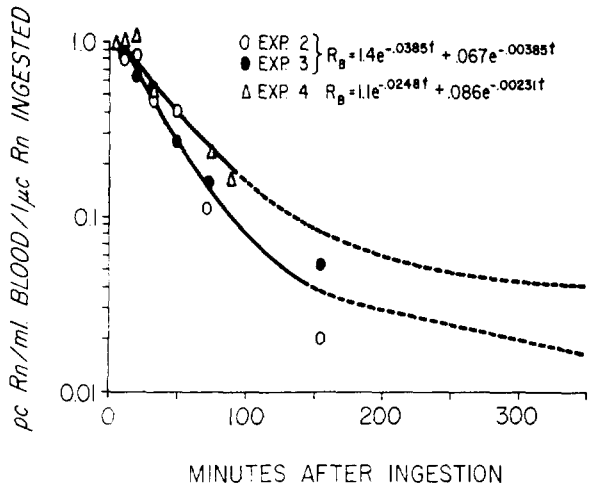

FIG. 4. Radon concentration in the systemic blood normalized to 1 μc radon ingested dose.

body content which decays outside of the gut. Estimations of the distribution of radon will be made after consideration of the measurements of radon in the blood.

Radon in the blood

As part of the plan for Experiment 1, a 3 ml aliquot of each of the blood samples was analyzed for RaC by gamma counting in a NaI crystal well counter. All samples measured less than 10 pc per ml, the detection limit of the measurement system. Accordingly this measurement was omitted in the later experiments. Due to accidental loss of the de-emanation tower samples for Experiment 1, the radon in-the-venous-blood measurements include data only from Experiments 2, 3 and 4. These results, normalized to 1 μc input, are presented in Figure 4. Lines have been drawn by eye through the points and extrapolated assuming a second component with a 180 minute half-life for the data of Experiments 2 and 3 and a 300 minute half-life for the data of Experiment 4. It is presumed that the late decrease in blood radon will follow the radon whole body loss. Equations containing two exponential terms are submitted on the figure.

DISCUSSION

Distribution of radon body content between the gut and other tissues

In the later consideration of radiation dose to the gastrointestinal tract and to other organs

0000866

of the body, the distribution of the radon body burden as a function of time becomes an important factor. The estimate which will be made considers three contributions to the systemic (i.e. non-gut) radon burden: 1) the liver, the only organ* perfused by the radon-rich portal blood 2) the fat, considered separately because of its high radon solubility coefficient 3) all other tissues assumed to be in equilibrium with the measured venous blood radon level.

For assignment of radon to the liver the concentration in portal blood is arrived at by dividing the whole body radon loss per minute by the splanchnic minute volume of blood flow assumed to be 1500 ml per minute.[18] Knowing the portal blood concentration and using the radon distribution factor (1:0.71) for blood and liver[19,20] the liver content can be calculated for the particular subject assuming that the liver is 2.4 per cent[3] of the total body weight.

The calculation of the fat component of the systemic radon burden employs the equation for radon level in the venous blood. It assumes that 11.5 kg of fat will take up radon with an exponential rate constant of 0.0006 min^{-1}.[21]

$$\frac{dR_F}{dt} = k(\mu R_B - R_F)$$

where (see Figure 4) $R_B = Ae^{-\alpha t} + Be^{-\beta t}$ and $\mu = \frac{5.38}{0.43} = 12.3$, the ratio of the equilibrium distribution coefficients between fat and blood,[19] and $k = 0.0006\ \text{min}^{-1}$.

Then:

$$R_F(t) = \frac{\mu k A}{\alpha - k}(e^{-kt} - e^{-\alpha t}) + \frac{\mu k B}{\beta - k}(e^{-kt} - e^{-\beta t})$$

where $R_F(t)$ is the pc/gram fat at any time "t" for a radon intake of 1 μc.

This equation has been solved for a number of times "t" and for the empty stomach when

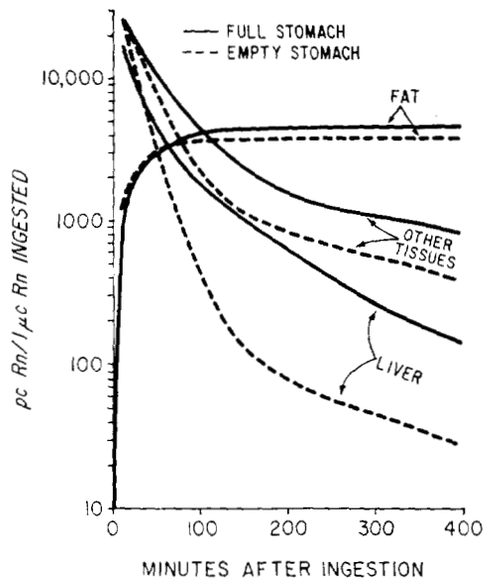

FIG. 5. Calculated activity partition of body radon outside of gastrointestinal tract as a function of time normalized to 1 μc ingested radon dose.

$\alpha = 0.0385\ \text{min}^{-1}$, $\beta = 0.00385\ \text{min}^{-1}$, A = 1.4 pc/gram, and $B = 0.06$ pc/gram and for the full stomach when $\alpha = 0.0248\ \text{min}^{-1}$, $\beta = 0.00231\ \text{min}^{-1}$, $A = 1.1$ pc/gram, and $B = 0.086$ pc/gram.

The other systemic tissues exclusive of the liver and fat are assumed to be in equilibrium with the venous blood and to attain radon concentrations in accordance with the radon distribution coefficients proposed by NUSSBAUM[19] based, in part, on human and, in part, on rat data.

The contributions from the three components are normalized to a radon water imput of 1 μc and are plotted as a function of time in Figure 5 and Figure 6. The calculations have been made for the two conditions of an "empty" and a "full" stomach. It would be unwise to attach much significance to the exact character of these curves. It is apparent that the model overestimates the radon in body tissues for early times since it neglects the build-up times of the "compartments" designated by HARLEY and others[21] as the extra and intracellular phases and associated with the respective half-times of 41 and 203 minutes. As a corollary one might expect that the lag of these components in the face of a dropping blood level

* The lung sees blood in which the radon has been diluted by admixture of other venous blood, and which suffers further loss to the air spaces. It is therefore included in category 3, resulting in a small underestimate of its radon tissue content.

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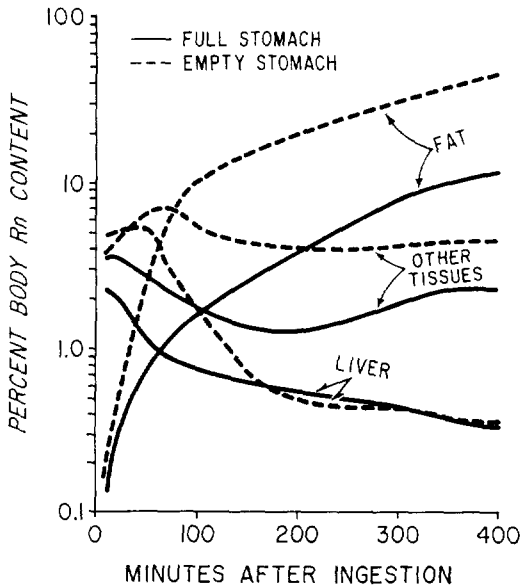

FIG. 6. Calculated radon located in extra-gut components in percent of the body radon content as a function of time.

causes the model to underestimate the radon outside the gut for later time periods. However, it may be noted that, in respect to the two later dose calculations which will involve this approximation, the model tends to overestimate the radon outside the gut in the first case and to be compensatory in the second. To be more specific, the calculation of the dose to the stomach, embracing the time period from 0 to 1 hour assumes that all the body radon burden is in the gut. The model therefore furnishes an estimate of the maximum error in this assumption. The dose calculation for the kidney concerns itself with the fraction of RaC formed outside the gut and compares the time integral of the radon burden outside the gut to the time integral of the radon burden in the total body over the period zero minutes to infinity in which case the errors are, to a degree compensatory.

Calculations of dose to stomach

The data are interpreted as indicating that ingested radon in water proceeds to the stomach where it mixes with the stomach contents, diffuses out through the stomach walls into the splanchnic venous blood system, passes through the liver and up into the right heart to the lung where it is rapidly lost in the expired air. During the first hour the radon body content is shown (Fig. 6) to be on the average 90 per cent or more in the gastro-intestinal tract The amount dissolved in body tissues and the amount enroute to the lungs will be neglected in the proposed model.

In addition the model assumes that the stomach wall contains radon at the same concentration as occurs in the stomach contents. Since the half-life of RaA is only 3 minutes. it seems reasonable to postulate that it exists in equilibrium with radon in the stomach wall. Calculation of dose is made for the empty stomach in which case it is assumed (1) that the volume of dilution has a mass of 200 grams added as water, 130 grams stomach mass, and 50 grams stomach residuum (digestive juices, etc.) and (2) that the appropriate equation giving the fractional amount of the ingested radon which is present in the body at any time "t" is:

$$\mathrm{Rn}_E = 0.612e^{-0.062t} + 0.340e^{-0.0371t} + 0.048e^{-0.00394t}$$

A second calculation is made for the "full" stomach, with 1) an assumed volume of dilution which has a mass of 200 grams as water, 130 grams stomach mass, 300 grams stomach contents (food), 50 grams stomach residuum, and (2) a radon retention equation:

$$\mathrm{Rn}_F = 0.392e^{-0.0578t} + 0.510e^{-0.0116t} + 0.098e^{-0.00231t}$$

For both calculations it is assumed that the radon is held in the stomach for 1 hour and then discharged into the small intestine.

The equation for the dose contribution from each phase of the radon loss equation for a single drinking episode becomes:

$$D_i = \frac{F_i A_0 (1 - e^{-\lambda_i t}) \times E}{\lambda_i \times m \times 6.24 \times 10^7}$$

where F_0 equals the fractional body content associated with the particular phase at zero time, A_0 = the zero time radon activity in disintegrations per minute, λ_i = the phase rate constant in reciprocal minutes, t = 60 minutes, E = the sum of the alpha energies of radon and RaA, m = the combined mass of dilution

0000868

and 6.24×10^7 is the MeV/gram rad conversion factor. The dose in rad for the sum of the three phases of the radon loss (empty stomach) for a single drinking episode becomes:

$$D_E = 9.9 \times 10^{-9} A_0$$

and for the "full" stomach becomes:

$$D_F = 9.3 \times 10^{-9} A_0$$

The conclusion may be reached that the dose to the stomach per drinking episode is in fact slightly less for the full versus the empty stomach if the assumptions above are valid. Otherwise, if, for example, a longer emptying time is selected for the stomach, the dose for a full stomach increases in relation to the dose for an empty stomach. Thus, for 3 hours emptying time the dose to the "empty" stomach increases about 1.2 times whereas the dose to the full stomach increases 1.7 times. One hour emptying time appears to be conservative and will be used in the $(MPC)_w$ calculation. An occupational $(MPC)_w$ can be arrived at if a total daily intake of 1200 ml or 6 drinking episodes and an RBE of 10 are assumed. Thus, 0.043 rem divided by 6 permits 0.0072 rem per drinking episode and stipulates an $(MPC)_w$ of 0.16 μc per liter or rounded off to 2×10^{-4} μc per ml.

Comments on the stomach model used

The NCRP[2] and ICRP[3] reports adopt a stomach model for ingested nuclides which differs in one important respect from the model used above. The reports assume that because the alpha particle penetrates only a few tens of microns into the gut wall, the effective dose delivered to the wall is only 1 per cent of the dose to the stomach contents. This approximation while acceptable for most nuclides which are not absorbed in the stomach, becomes quite untenable when the radioactive material is a gas. The rapid appearance in the expired air of substantial amounts of the radon ingested make it clear that the gas passes readily through the stomach wall. The above calculation is conservative and overestimates the average dose because it neglects the decreasing gradient of the radon concentration through the stomach wall to the blood capillary.

It will be noted that no account is taken of radiation to the stomach wall by radon daughters ingested as such. The total decay of ingested RaA, RaB and RaC in the stomach, assuming 250 grams stomach contents and assessing the alpha particle effectiveness at 1 per cent would yield an alpha particle dose of 2 mrem if 0.24 μc of each daughter were taken in. The contribution from this source is therefore neglected. The RaA produced in the stomach wall is included since the energy, E, used in the dose formulation includes the 6.0 MeV from RaA as well as the 5.5 MeV from radon alpha particles.

Two additional departures by the model from biological reality should be acknowledged. One has been already referred to, the circumstance that a small fraction of the radon placed in the gut, is in fact dissolved in body tissues. For the first 60 minutes after ingestion the average value of the extra-gut fraction is estimated at less than 10 per cent. The other biological circumstance not allowed for in the model is the presence of gas in the stomach prior to ingestion. BLAIR and others[22] find that normally the gastro-intestinal tract contains about 1 liter of gas. It is reasonable to suppose that 100–300 ml of gas will be present in the stomach. The effect of this dilution volume is amplified about five times due to the distribution coefficient of radon between the gas phase and water phase. Although it is difficult to make a general allowance for the effect on stomach dose it is apparent that presence of 100 ml of gas added to a distribution volume (food, water, stomach mass, etc.) of 500 ml would reduce the calculated dose by half.

Calculation of dose to the kidney

Because several experimental studies on animals report that the radon daughters Ra and RaC concentrate in the kidney[16,23,24] and that kidney lesions are found in animals exposed to high levels of radon and its daughters[25,26] it is necessary, in the present context, to examine the probable dose to the kidney in some detail. The first step is to estimate the amount of RaC which is available for distribution to systemic tissues. It will be assumed that RaB and RaC are not appreciably absorbed

0000869

from the gut and that, therefore, the distribution of radon between the gut and systemic tissues will cause an equivalent distribution of the radon daughters. Using the data presented in Figure 5, and other similarly calculated values not shown, a plot of radon activity versus time from 0 to 600 minutes was prepared using linear coordinates for (a) the total body radon content and (b) the radon in systemic tissues, that is, excluding the gastro-intestinal tract. It was assumed that these two curves decreased linearly from the values at 600 minutes to a common value equal to the experimentally determined 0.2 per cent of the dose at 1400 minutes. For the purpose of the calculation this 0.2 per cent was assumed to be contained entirely in the body fat and lost with a 1155 minute[21] effective half-life. The areas under these two curves extending from zero to infinity, were determined and it was found that 12 per cent of the total radon disintegrations occurred outside the gastro-intestinal tract. Because the objective of the calculation is to reject the kidney as a critical organ, the full stomach experimental data were used yielding a slightly higher final dose estimate.

If 1.17 per cent of the total intake of radon decays in the body and if 12 per cent of this amount decays in the systemic tissues, the total number of atoms of RaC available for distribution to body tissues other than the gastro-intestinal tract becomes:

$$\frac{0.0117 \times 2.22 \times 10^6 \times 0.12}{1.26 \times 10^{-4}} = 2.47 \times 10^7 \text{ atoms per } \mu c.$$

radon intake. This is equivalent to 1.9×10^8 MeV (RaC′ alpha).

In order to approximate the distribution of this energy between the kidneys and other tissues, reference is made to the experimental results of HOLLCROFT and LORENZ,[24] of MORKEN,[25] and of ANDREEV.[27]

HOLLCROFT and LORENZ injected intravenous doses of radon in equilibrium with its daughters into mice. They calculate that the dose to the kidney, due to preferential translocation of RaB and RaC was 14 times the average dose to other tissues, basing their calculation on sacrifice data covering times from 0 to 120 minutes. In their experiments radon decay constituted only 2 per cent of the dose. Because of the relatively small contribution of RaA and RaB, the value of 14 for the distribution ratio of kidney dose to average dose for the remainder of the body may be attributed to concentration of RaC.

MORKEN exposed rats for 210 minutes in an atmosphere containing 1.25×10^{-4} c radon per liter. The rats were sacrificed and tissues were measured for RaB plus RaC by gamma counting. He finds that the ratio of active deposit to radon in kidneys is 7.2 referred to the time of removal from the exposure chamber. Additional unpublished measurements by MORKEN indicate that RaB and RaC are found in approximately equal activity in the kidney. For purposes of comparison it may be assumed that after 210 minutes the rat's tissues are in radon equilibrium (fat component has climbed to about 90 per cent saturation) and that RaB and RaC are not excreted. Using NUSSBAUM's[19] radon solubility coefficients of 0.28 for the kidney and of 0.59 for the whole body (rat) average, it may be estimated that the kidney RaC′ alpha dose rate at time of sacrifice is:

$$\frac{0.28}{0.59} \times 7.2 = 3.4$$

times the average body dose rate from RaC′.

ANDREEV administered 200 μc radon in 5 ml water per orally to rats and sacrificed at times beginning at 5 minutes up to about 4 hours. He presents data for the concentration of Rn, RaA, and RaC in twelve organs as a function of time. These data show a total RaC′ kidney dose which is 5.7 times the average whole body dose from RaC with the gastro-intestinal tract excluded.

All three experiments demonstrate a translocation of RaC to the kidney. Since the intravenous injection of radon solution plus radon daughters creates conditions most favorable for concentration of RaC in the kidney, it is perhaps not surprising that this experiment yields the highest kidney dose relative to the average dose. It is apparent that the oral administration to rats forms the best analogy to the human study reported here, and therefore it will be assumed that RaC′ alpha dose to the kidney is 6 times the average dose to the body (from RaC′).

0000870

Using standard man data, the body mass of 70 kg minus the gastro-intestinal tract at 2 kg yields 68 kg. The average RaC′ dose would be:

$$\frac{1.9 \times 10^8}{6.8 \times 10^4 \times 6.24 \times 10^7} = 4.38 \times 10^{-5} \text{ rads}$$

and the kidney dose would be 0.26 mrad or 2.6 mrem per μc radon intake. This leaves the dose from radon and RaA to be accounted for. Figure 5 shows that an average value of 4 per cent of the body radon may be conservatively assigned to the other tissues which have an aggregate mass of 55 kg. Therefore the total radon dose to other tissues becomes:

$$\frac{0.0117 \times 0.04 \times 2.22 \times 10^6 \times 5.5}{1.26 \times 10^{-4} \times 5.5 \times 10^4 \times 6.24 \times 10^7}$$
$$= 1.35 \times 10^{-5} \text{ rads}$$
$$= 0.14 \text{ mrem}$$

per μc radon intake. Since the radon absorption coefficient for kidney does not differ appreciably from that of other tissues included in this average, the average dose determined is a satisfactory estimate of the kidney dose.

Examination of ANDREEV's data show that with the exception of the lung and the blood, the RaA total dose to the tissues is not more than 1.6 times the radon dose, indicating that in general the short half-life RaA tends to decay at the site where it is formed. Any error in the experimental determination would be likely to involve a loss of radon in the transfer of the tissue samples from the sacrificed rat, and therefore might contribute to the small differences detected. ANDREEV's Rn to RaA dose ratio for the kidney is 1.5. Summing the dose from radon (0.14 mrem) from RaA (0.21 mrem) and from RaC′ (2.6 mrem) gives a total estimated dose to the kidney of 3 mrem per μc radon taken in. If the intake is limited to 0.24 μc radon per day on the basis of the stomach as a critical organ the estimated kidney dose would be 0.7 mrem per day or 1.6 per cent of the maximum permissible occupational average daily exposure of 43 mrem.

Comments on the kidney dose assumptions

It is apparent that the calculation presented above is by no means rigorous in a biological sense. The blood experimental data extend out to about 150 minutes and are depended on for the partition of radon between the gut and other tissues. The rat experiments serving as a source of the estimate for the ratio of kidney to average dose include data carried out to only 240 minutes. It seems likely that for very long times when the bulk of the radon burden is in the fat the translocation of RaB and RaC to the kidney would be decreased. If this is the case, the assumptions used tend to overestimate the kidney dose. An effect in the same direction is caused by the assumption that 4 per cent of the radon is located in "other tissues" which is quite apparently an overestimate for late times. Since according to the model used more than half of the radon decay outside the gut occurs after 400 minutes, the calculated kidney dose may be 2 or 3 times the true dose. However, despite these uncertainties, the calculation is believed to serve its purpose of rejecting the kidney as a critical organ for radon ingestion.

Dose to other tissues and organs

The general agreement that the concentration of RaB and RaC in the kidney is higher than in other systemic tissues or organs, while the radon concentration would be nearly equivalent, serves to eliminate them from consideration as critical organs. This leaves the liver and lung doses from radon to be evaluated. The radon level in the liver (Figure 4 integrated from 0 to 400 minutes divided by radon level in the whole body integrated over the same time period indicates that 1.9 per cent of the total radon decay takes place in the liver. If it be assumed that one RaA and RaC′ alpha particle are emitted for 1 radon particle the total energy per radon disintegration is 19.2 MeV and:

$$\frac{0.019 \times 0.0117 \times 2.22 \times 10^6}{1.26 \times 10^{-4}} \times 19.2 = 7.5 \times 10^7 \text{ MeV/liver/}\mu\text{c intake}$$

$$\frac{7.5 \times 10^7}{1700 \times 6.24 \times 10^7} = 7.1 \times 10^{-4} \text{ rad/}\mu\text{c intake}$$
$$= 7 \text{ mrem/}\mu\text{c intake}$$

If the dose to the stomach limits the intake to

0000871

0.24 μc radon-in-water per day, the corresponding dose to the liver would be 1.7 mrem per day from radon plus daughters in equilibrium. MORKEN finds that the active deposit in the liver of rats[23] exceeds the radon supported daughter level by a factor of 2. This condition would increase the liver dose by 40 per cent to about 2.4 mrem per day or a factor of 19 times lower than the limiting stomach dose.

In order to calculate the lung dose a biological half-life of 0.4 minutes is assigned to radon atoms in the lung. This estimate depends on nitrogen washout measurements summarized by BARTELS and others[28]. The calculation is made conservative by postulating that all of the lung-produced daughters are retained in the lung. Since the human alveolus has a diameter of 250–300 micra, no allowance is made for alpha particle energy absorption in the air space. The dose from the beta particles from RaB and RaC is held to be negligible. The total amount of radon taken in by mouth is assumed to be lost through the lung. Thus for a daily input of 0.24 μc the dose would be:

$$\frac{5.33 \times 10^5 \times 1.44 \times 0.4 \times 19.2}{1000 \times 6.24 \times 10^7} = 0.95 \times 10^{-4} \text{ rad} = 0.95 \text{ mrem/day}$$

where 5.33×10^5 equals the disintegration rate of 0.24 μc, 1.44×0.4 equals the average residence time of a radon atom in the lung, 19.2 MeV equals the sum of the alpha particle energies of Rn, RaA, RaC′, 1000 equals the lung mass.

If half of the RaA daughters were lost before decaying, that is, were swept out with the air stream, the dose would be reduced to 0.62 mrem per day. The calculated dose with no daughters retained would be 0.3 mrem. The calculated maximal and minimal lung doses are therefore 2 per cent and 0.6 per cent respectively of the limiting dose to the stomach.

CONCLUSIONS

The data presented, interpreted in the light of what appear to be reasonable inferences about the fate of radon in water ingested by man, suggest an occupational $(MPC)_w$ equal to 2×10^{-4} μc radon per ml of water with the stomach designated as the critical organ. For reasons which are developed in the text, the presence of radon daughters in the ingested water does not cause a substantially higher dose and therefore the suggested limit is framed in terms of radon only.

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0000872

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0000873