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FATE OF THE IODINE RADIOISOTOPES IN THE HUMAN AND ESTIMATION OF THE RADIATION EXPOSURE

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Abstract—Fate of the iodine isotopes and resulting organ exposures have been studied using the four-compartment model proposed by BROWNELL to account for the metabolism of this element.

Mathematical equations have been established for this model from biological data accepted in the human. They have been used to calculate the amounts of iodine-131 in the thyroid and in the remaining body as a function of time in case of a single or a chronic contamination; in this latter case three phases have been considered: rise, equilibrium and decrease after removal of the contaminating source. The importance of the daily stable iodine intake from the food has been emphasized.

Some of these theoretical results have been checked by experiments on eight volunteers. Calculations have been extended to nine other iodine isotopes in order to determine the exposure doses of the thyroid and the remaining body for a single or a chronic contamination; maximum permissible concentrations in water and in air have also been computed.

It appears that some I.C.R.P. recommendations for maximum permissible body burden must be revised.

1. INTRODUCTION

THE study of the fate of the iodine isotopes in the human body and of the resulting radiation doses delivered to the thyroid gland, is of prime importance for nuclear health problems.

Indeed, one of the first consequences of a reactor accident can be the release of great amounts of ^{131}I in the atmosphere with the contamination of the neighbouring population by inhalation or by ingestion of contaminated food (in particular, the milk). This hazard has been illustrated by the Windscale incident of 10 October 1957.[1] The high volatility of molecular iodine is responsible for the easy dispersion of the compound and prevents its retention by ordinary filters.

During the numerous nuclear bomb tests performed in 1961 and 1962, one of us (J. C.) found ^{131}I in the atmospheric fall-out and in the milk by γ-spectrometry. Identical observations were made at several stations in Europe[2] and in U.S.A. Moreover several iodine radioisotopes (^{129}I, ^{131}I, . . .) are found during the reprocessing of irradiated nuclear fuels.[3]

The development of the diagnostic and therapeutic uses of several iodine radioisotopes (^{125}I, ^{131}I, ^{132}I, ^{133}I) must also be considered here; contamination may result in radioisotope laboratories and in production areas owing to the high volatility of many iodine compounds. Such contaminations have been frequently observed in several centres where radioiodines are produced.[4]

The high radiotoxicity of iodine is explained by the retention of a great fraction of the ingested or inhaled radionuclide in the thyroid, a small organ of about 20 g in the adult human. This local concentration makes the thyroid the critical organ.

In order to calculate the dose delivered to the thyroid in case of a single as well as of a chronic absorption of radioiodine, it is necessary to know the metabolism of the element iodine.

2. BIOLOGICAL DATA

It can be found in recent textbooks[5] that about 85 per cent of the body total iodine is

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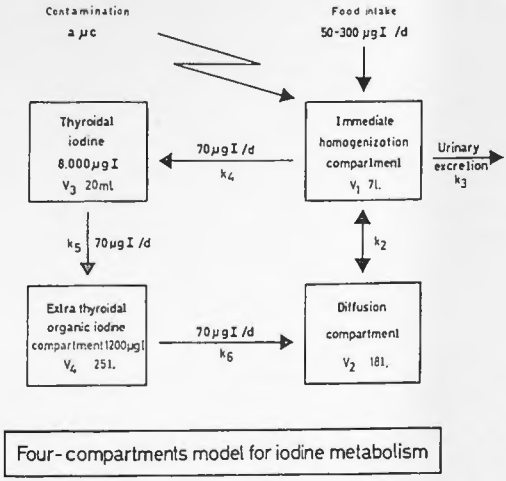


FIG. 1

localized in the thyroid, i.e. 8 mg for a normal thyroid and 9–9.5 mg for the whole body.

The body iodine is divided between several compounds, chemically different, forming distinct pools with particular turnover rates. When radioiodine finds its way into the organism, there is no global homogenization; the specific radioactivities remain different in the various pools and the ratios of these activities are dependent on the periods of the radionuclide and a few other parameters. A simple scheme of the iodine metabolism, which is sufficient for the discussion on the tissue exposure after contamination by the radioisotopes of this element, has been published by BROWNELL;[6] three distinct pools, also identified as "spaces", are considered: iodide, thyroid iodine and extra-thyroidal organic iodine (Fig. 1).

(A) The *iodide space* has 25 l.; it is divided into two compartments V_1 and V_2. Iodide from the food penetrates in V_1; it is also in this compartment that the thyroid and the kidneys take up iodine. The barrier between V_1 and V_2 can be demonstrated with radioactive iodide: the homogenization in V_1 is more rapid than the diffusion towards V_2.

Extrapolation at time 0 of experimental semi-logarithmic curves obtained after i.v. injection of ^{131}I and plotting of the plasma radioactivities vs. time, enabled BROWNELL to calculate for V_1 a mean volume of 7 l. This value, which exceeds the plasma volume, will be called "volume of immediate homogenization" hereafter.

The iodide biological half-life is very short so that the plasma concentration changes rapidly: relatively high after a meal, it falls quickly. In the calculations however, we shall use a mean concentration which is merely dependent on the daily iodine intake from the food.

(B) The *thyroidal iodine* is chemically polymorphous although it is mostly in the thyroglobulin. In the normal human, the decrease of the radioiodine (after correction for the radioactive decay) caught by the thyroid follows, after a few days, an exponential function and the hormone secreted by the gland has the same specific radioactivity as the thyroidal iodine.[7] It seems that, in normal adults, the 8 mg of thyroidal iodine behave as if they were in a single pool.*

* Many investigators think that the active thyroidal iodine pool is more restricted; this would not have great influence on our results except in the case of long-lived iodine radioisotopes such as ^{125}I.

(C) The 1200 μg of *extra-thyroidal organic iodine* (mostly thyroxine and triiodothyronine) are in a space of 25 l. These compounds are partially excreted in the feces; this pathway, which is quantitatively not very well known, will be ignored in this study. The catabolism of the thyroidal hormones yields iodide which is recycled.

(D) For our purpose the whole system can be supposed in a dynamic equilibrium. It is then obvious that:

The amount of iodide that enters the body (from the food) is equal to the amount excreted (mostly in the urine). This amount is not the same in different countries and depends on the diet; it is about 150 μg per day in Boston, U.S.A.[7] but seems to be lower in western Europe: about 75 μg per day[8,9] (see also later).

The daily iodide uptake of the thyroid from the "volume of immediate homogenization" is equal to the amount of hormonal iodine secreted; an equivalent quantity of the extra-thyroidal organic iodine is catabolized to iodide which diffuses back into the iodide space. The daily turnover is about 70 μg of iodine in the normal adult; the thyroid adapts the level of its plasma clearance in order to take this amount of iodide daily whatever the plasma concentration. However, when a huge dose of iodide is administered (100 mg for instance), it is likely that the absolute thyroidal intake is larger although it would never exceed a few mg, i.e. a very small percentage of the given dose;[10,11] afterwards, the saturated gland will not take anything from a new feeding of iodide which will be completely excreted by the kidneys.

3. MATHEMATICAL ANALYSIS OF THE METABOLISM

The metabolism, summarized in Fig. 1, can be analyzed mathematically in order to know the fate and distribution of radioactive iodine that would penetrate accidentally into the body.

To set the equations, the mechanisms of diffusion between V_1 and V_2, of transfers $V_1 \rightarrow V_3$, $V_3 \rightarrow V_4$, $V_4 \rightarrow V_2$, and of kidney excretion, will be measured by the "clearance" values: $k_2, \ldots, k_6$, whose dimensions are l l./hr; these coefficients are the volumes (fractions of $V_1 \ldots V_4$) whose iodine is cleared per unit time by the process involved.

3.1. *Acute contamination by an iodine isotope having a radioactivity constant* λ

The specific activities $A_1 \ldots A_4$ in the different spaces are given by the following system of differential equations:

$$\frac{dA_1}{dt} = -\left(\frac{k_2}{V_1} + \frac{k_3}{V_1} + \frac{k_4}{V_1} + \lambda\right) A_1 + \frac{k_2}{V_1} A_2$$

$$\frac{dA_2}{dt} = \frac{k_2}{V_2} A_1 - \left(\frac{k_2}{V_2} + \lambda\right) A_2 + \frac{k_6}{V_2} A_4$$

$$\frac{dA_3}{dt} = \frac{k_3}{V_3} A_1 - \left(\frac{k_5}{V_3} + \lambda\right) A_3$$

$$\frac{dA_4}{dt} = \frac{k_5}{V_4} A_3 - \left(\frac{k_6}{V_4} + \lambda\right) A_4 \qquad (1)$$

with the following initial conditions:

$$\text{for } t = 0: \quad A_1 = a/V_1$$
$$A_2 = A_3 = A_4 = 0$$

The solution was obtained by a digital computer using the following numerical data (BROWNELL[6] and RIGGS[7].)

V_1 Volume of the immediate homogenization compartment 7 l.

V_2 Volume of the diffusion compartment 18 l.

V_3 Thyroid gland volume $2 \cdot 10^{-2}$ l.

V_4 Extra-thyroidal organic iodine volume 25 l.

k_2 Diffusion constant between V_1 and V_2 from BROWNELL's data = 14 l./hr*

k_3 Kidney clearance = 2 l./hr

* BROWNELL has isolated the process of diffusion between V_1 and V_2 from the rest of the metabolism so that the specific radioactivity A_1 is governed by the following equation:

$$A_1(t) = C_1 + C_2 \exp\left(-\frac{0.693 \cdot t}{T}\right)$$

where $T = \dfrac{0.693}{k_2} \cdot \dfrac{V_1 V_2}{V_1 + V_2}$

Experimentally, BROWNELL got a mean value: $T = 0.25$ hr; hence $k_2 = 14$ l./hr.

k_4, k_5, k_6, when the metabolism is at equilibrium, $k = dV/dt = (dQ/dt) \cdot (1/C)$ where dQ is the amount of iodine transferred during the time dt, and C is the concentration of stable iodine in the compartment from which the iodine is taken.

The equilibrium implies that the kidney daily excretion is equal to the daily intake from the food (X µg) so that the concentration of stable iodine in the volume of immediate homogenization must be

$$C_1 = \frac{X}{2 \times 24} \text{ µg/l.}$$

With a daily transfer of 70 µg of iodine through the thyroid and the extra-thyroidal organic iodine space, one calculates:

k_4 = thyroidal intake $= \dfrac{140}{X}$ l./hr

k_5 = hormone secretion $= 7.3 \cdot 10^{-6}$ l./hr

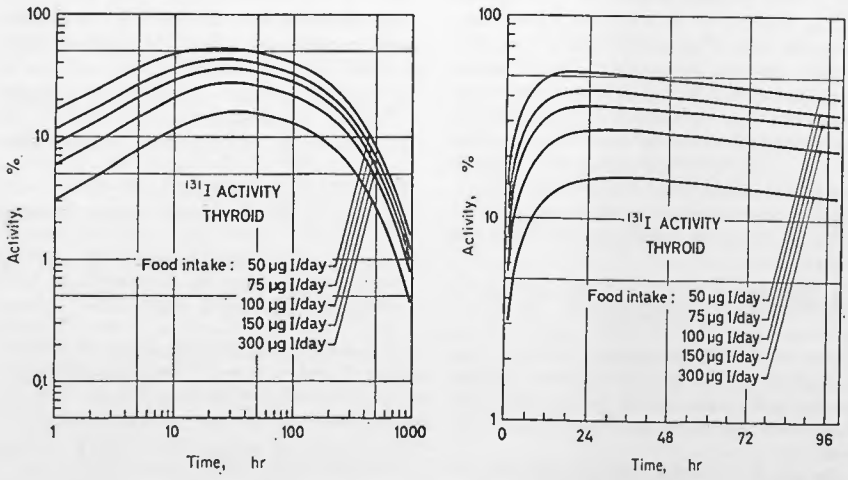
k_6 = hormone catabolism $= 6.1 \cdot 10^{-2}$ l./hr

The X µg intake of iodine from the food is likely to vary much with the diet and the geographical localization; that is the reason why we kept it as a parameter with values ranging from 50 to 300 µg/day.

The calculations were first done for ^{131}I which happens to be the most common contaminant and because its 8-day half-life ($\lambda = 3.587 \cdot 10^{-3}$ hr^{-1}) makes it more dangerous than its short-lived isotopes such as ^{128}I, ^{132}I, ^{133}I, . . .

The numerical data for the radioactivities obtained from equations (1) have been plotted on graphs. The activity in the thyroid, $Q_3(t) = A_3(t) \cdot V_3$ is given by Figs. 2 and 3. The curves clearly show that the fraction of the radioiodine caught by the thyroid is greater when the diet contains less iodine.

The thyroidal uptake (obtained after correction for the radioactive decay) is maximal between 24 and 48 hr, and reaches 50 per cent of this maximum within about 5 hr (Table 1); this is in agreement with experimental results known for a long time. The maximum of radioactivity in the thyroid is also found from 24 to 48 hr after the contamination; this is only because of the relatively long physical half-life



Figs. 2 and 3. Theoretical thyroidal activities in per cent of the absorbed quantity of iodine-131 after a single contamination (at time 0) for various intakes of stable iodine.

Table 1. *Thyroidal uptake as a function of the stable iodine intake (X) from food. Thyroidal activities* 5, 24 *and* 48 *hr after a single absorption of* 1 μc *of* ^{131}I

X (μg)	Uptake (%)	^{131}I (μc)	Uptake (%)	^{131}I (μc)	Uptake (%)	^{131}I (μc)
	After 5 hr		After 24 hr		After 48 hr	
50	36.6	0.36	56.9	0.52	57.3	0.48
75	27.0	0.26	46.3	0.42	47.5	0.40
100	21.3	0.21	38.9	0.36	40.5	0.34
150	14.8	0.14	29.3	0.27	31.2	0.26
300	7.9	0.078	16.8	0.15	18.4	0.16

of ^{131}I; with isotopes of shorter physical periods, the maxima are reached much earlier (see Table 5).

Afterwards, the radioactivity in the thyroid decreases with an effective period of about 7.5 days resulting from the 8-day physical period and an "apparent"* biological period which varies between 95 and 160 days depending on the magnitude of the recycling which is linked to the size of the iodine intake from the food. One calculates indeed, between the fourteenth and the fiftieth day, "apparent" biological half-lives of:

for $X = 50$ μg	$T_B = 158$ days
$= 75$ μg	$= 137$ days
$= 100$ μg	$= 124$ days
$= 150$ μg	$= 110$ days
$= 300$ μg	$= 95$ days

The radioactivity in the remaining body (i.e. body without thyroid) is given by the sum $A_1(t)V_1 + A_2(t)V_2 + A_4(t)V_4$ and represented in Fig. 4. There is a very rapid decrease due to the kidney excretion and the thyroid uptake so that, at the forty-eighth hr, only 1–2 per cent of the absorbed radioactivity remains in the iodide pool. After 4 days, a rise of the radioactivity is observed in the remaining body owing to the secretion, by the thyroid, of hormones labelled with ^{131}I; this phenomenon has a maximal amplitude at about the tenth day after the contamination. Afterwards that radioactivity decreases following the progressive decrease of the thyroid radioiodine.

3.2. *Chronic contamination*

This situation is considered for the calculation of the maximum permissible levels of contamination in the drinking water and in the air.

Let us assume a chronic contamination of "a" μc/hr. This case is mathematically described by the system of differential equations (1); it is only necessary to add the term $(+a/V_1)$ to the right hand side of the first equation.

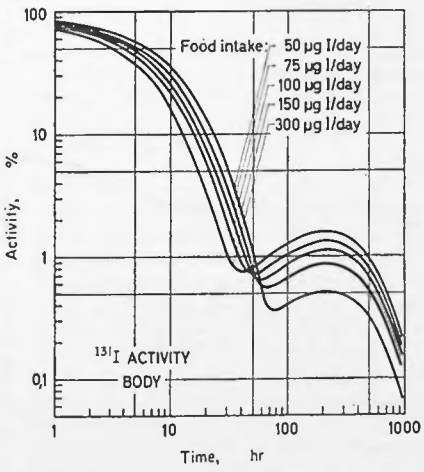


FIG. 4. Theoretical activities in the remaining body (body without thyroid) in per cent of the absorbed quantity of iodine-131 after a single contamination (at time 0) for various intakes of stable iodine.

* This biological half-life considered by the health physicist characterizes the decrease of radioactivity of the organ when the correction for the physical decay has been made. It is different from that studied by the physiologist who must correct also for any recycling.

Table 2. Amounts of ^{131}I *in the volume of immediate homogenization* (Q_1), *the diffusion volume* (Q_2), *the thyroid* (Q_3) *and the extra-thyroidal organic iodine* (Q_4) *for a chronic contamination of* 1 μc/hr

$X(\mu g)$ ⟶	50 μc	75 μc	100 μc	150 μc	300 μc	500 μc	1000 μc
Q_1	1.46	1.80	2.13	2.34	2.76	2.96	3.15
Q_2	3.77	4.63	5.24	6.01	7.07	7.55	8.01
Q_4	8.97	7.36	6.25	4.79	2.82	1.82	0.96
Total	14.2	13.8	13.6	13.1	12.6	12.3	12.1
Q_3	148	122	103	79.0	46.9	30.0	16.0

The study of the evolution of the body contamination by the isotope can be divided into three phases:

(a) the beginning of the contamination with a progressive approach to the equilibrium. The initial conditions are then

$$A_1 = A_2 = A_3 = A_4 = 0 \quad \text{for} \quad t = 0 \ ;$$

(b) the equilibrium is reached. The differentials are equal to zero. There remains a system of 4 equations with 4 unknowns which is easy to solve;

(c) the decrease of the contamination after the removal of its source. In this case, the initial conditions are the specific activities $A_1 \cdots$ which exist in equilibrium in the various spaces considered. The analysis of the latter situation enables one to calculate the irradiation dose that the person will still receive in spite of the suppression of the absorption of radioiodine.

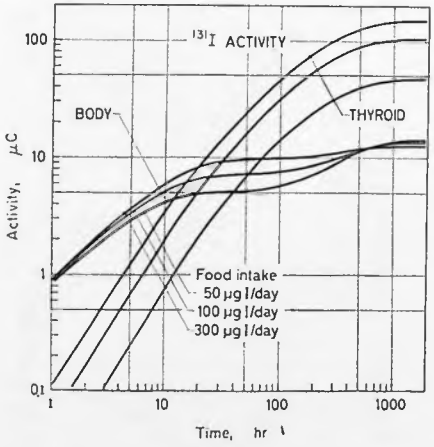


FIG. 5. Chronic contamination resulting from the absorption of 1 μc of iodine-131 per hour starting at time *O*. Theoretical activities in thyroid and remaining body for various intakes of stable iodine.

(a) *Beginning of the contamination.* A chronic contamination by the absorption of 1 μc/hr of ^{131}I has been considered. The results given by the digital computer are represented in Fig. 5.

The radioactivity concentrated by the thyroid increases with time to reach 50 and 90 per cent of the equilibrium value after 8 and 25 days respectively. The important correlation between this activity and the iodine daily intake from the food is particularly obvious.

On the other hand, the activity in the remaining body reaches its equilibrium much more quickly: 50 per cent of the maximum is attained in less than 1 day; the subsequent variations are due mostly to the secretion of radioactive thyroidal hormones.

(b) *Equilibrium.* The solution of the equation describing the situation can be found in Table 2.

It can be seen that the amount of ^{131}I in the thyroid is very dependent on the intake of stable iodine from the food; by contrast, the total activity in the remaining body is about constant in spite of the variations in the distribution of this radioiodine between the several compartments according to the amount of stable iodine in the diet. Consequently the ratio between the thyroidal activity and that of the remaining body, is variable: for a man receiving daily 150 μg of iodine from this diet, this ratio is 86/14, a result very similar to that given by the literature for the stable iodine: 85/15.[11]

(c) *Suppression of the source of contamination.* The results reported in Fig. 6 show that the activity in the thyroid diminishes with the

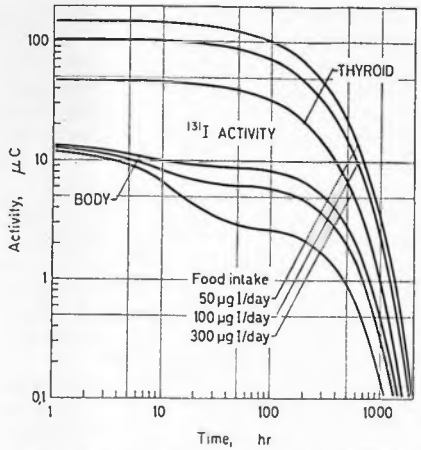


FIG. 6. Interruption at time O of a chronic contamination of 1 μc of iodine-131 per hour. Theoretical activities in thyroid and remaining body for various intakes of stable iodine.

previously found effective half-life of about 7.5 days; there are only slight variations depending on the stable iodine diet as in the case of the acute contamination.

The activity in the remaining body decreases in two phases: the first one is bound to the rapid elimination of the iodide fraction from the volumes V_1 and V_2; the second to the slower disappearance of the organic iodine that is being continually secreted by the thyroid.

4. EXPERIMENTAL

Experiments have been carried out on eight male adults in order to check the validity of the hypotheses used in the present work for the calculation of irradiation doses. These people, fasting for more than 12 hr, ingested 0.5 μc of carrier-free ^{131}I as NaI in a solution of 10^{-3} M · $Na_2S_2O_3$. The radioactivity assays on the thyroid and on the remaining body were started 1 hr later and pursued at intervals, during 40 days. The urines were collected during the first days in order to have a complete picture of the metabolism and to determine the efficiencies of counting for ^{131}I in the thyroid or the remaining body for each individual.*

* These data gave the opportunity to check the validity of the phantoms used afterwards.

4.1. *Apparatus and methods*

The determinations of ^{131}I in the thyroid were performed with a NaI crystal of 5 × 5 cm shielded with 2 cm of lead, and which was placed at 6 cm from the thyroid in a reproducible way by means of a lucite block in contact with the neck. The γ-spectrum was recorded with a 256-channel analyzer and the activity was obtained by the determination of the peak area at 364 keV and by comparison with a thyroid phantom; this phantom consists of two 10-ml flat vials containing a ^{131}I standard solution placed at 0.5 cm depth within a cylinder full of water simulating the neck.

The radioactivity of the remaining body was measured, also by γ-spectrometry, in a whole body counter.[12] The incidence of the thyroid radioactivity however was cancelled by a shield of 15-mm lead placed in front of the neck of the patient. The calculation of the activity in the body used the counting efficiency established previously by means of phantoms simulating the human body and filled with radioactive solution of known activity.

The urine assays were carried out with a NaI crystal of 5 × 5 cm surrounded by 10 cm of lead.[13]

The sums of the activities in the thyroid, the remaining body and the urine were compared with the amount of ^{131}I ingested in order to have a permanent check of the efficiencies utilized in the calculations.

4.2. *Results*

For each patient, the curves of ^{131}I activities in the thyroid and in the remaining body have been plotted as a function of time. In Fig. 7 are the examples of the graphs given by:

(a) an individual whose iodine metabolism appears to be normal; very similar results were obtained with six other people;

(b) a patient whose thyroidal uptake is accelerated; the ^{131}I also leaves the thyroid quicker. There is a remarkable increase of the remaining body radioactivity due to the secretion of the labelled thyroidal hormones.

The maximum radioactivity is reached in the thyroid after about 24 hr in normal people; it has a mean value of 0.21 μc in the seven cases considered for a single ingestion of

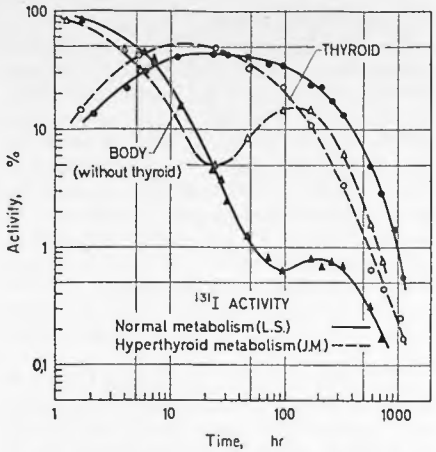


FIG. 7. Experimental data. Activities in thyroid and remaining body in per cent of the amount of iodine-131 given at time *0*.

0.5 μc of ^{131}I. The individual results are scattered between 0.16 and 0.26 μc.

5. DISCUSSION. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL DATA

The experimental curves are quite similar to those previously calculated (compare Figs. 2, 4 and 7). Table 1 however shows that the agreement is good for the uptake by the thyroid only if the stable iodine brought by the food is about 75 μg/day.

In order to know the daily intestinal absorption which, at equilibrium, is approximately equal to the daily excretion by the kidneys, an assay of the stable iodine in the urine has been carried out by activation analysis.[14]

Samples of 10 ml of urine in polyethylene bottles were irradiated for 15 min in a flux of 1.2×10^{12} neutrons/sec · cm^2 in the BR-1 nuclear reactor. A chemical separation was necessary because of the great amounts of other elements, particularly chlorine, which are highly activated. 0.5 g of iodide was added as a carrier to the irradiated solution; the iodide was oxidized by HNO_2 to iodine which was extracted with CCl_4. The organic solution was washed several times with an aqueous solution of NaCl, before the measurement of the ^{128}I radioactivity by γ-spectrometry on the 455-keV photoelectric peak. A chemical assay of I_2 in the CCl_4 solution gave the yield of extraction so that a suitable correction could be applied.

During the 24 hr following the ingestion of ^{131}I, the seven normal males used in this work excreted in the urine:

79, 51, 78, 140, 340, 60, 58 μg of iodine.

These persons had been asked not to eat anything known to contain much iodine (such as sea food) during the 3 days preceding the experiment. With the exception of the 340 μg value—which concerned an individual usually very fond of sea food—the mean value of the iodine intake was 78 μg/day.

Other runs were made at 10-day intervals over a period of 2 months on two subjects in order to see the possible variations of this iodine intake:

L: 53, 57, 48, 40, 42, 42, μg for 24 hr
S: 120, 84, 121, 37, 50, 79, μg for 24 hr

It is obvious that the iodine content of the urine of L is very constant around an average of 47 μg/day. For S, the two highest results were coincident with the ingestion of mussels during the experimental period.

It thus seems that, for people living around the Belgian Nuclear Centre at Mol, the daily iodine intake is between 50 and 100 μg. With this result, the agreement between experimental and theoretical curve is sufficient to validate Brownell's model of iodine metabolism for the purpose of this study.

6. EXPOSURE DOSES RESULTING FROM ABSORPTION OF AN IODINE RADIOISOTOPE

The equations used for ^{131}I have also been applied to other iodine isotopes in order to calculate the permissible burdens for workers contaminated with these radionuclides.

The solution of the system of equations (1) gives the activities in the thyroid A_3V_3, and in the remaining body $A_1V_1 + A_2V_2 + A_4V_4$. The exposure dose for an organ is given by

$$R = \int_0^T \frac{q f_2 \, dt \cdot 3.7 \cdot 10^4 \cdot 1.6 \cdot 10^{-6} \, \varepsilon}{100 \cdot m} \qquad (2)$$

where: q = total activity in the whole body;
f_2 = ratio of the activity in the organ to that in the whole body;

Table 3. Radioactivities in thyroid and remaining body for a chronic absorption of 1 μc/hr. In the case of ^{131}I *the stable iodine daily intake is considered at three levels— 50 μg (1), 100 μg (2) and 300 μg (3). For the other isotopes, it is fixed at 100 μg/day.*

Isotope	Burden (μc) in thyroid	Burden (μc) in body	Isotope	Burden (μc) in thyroid	Burden (μc) in body
^{131}I (1)	148	14	^{129}I	5710	896
(2)	103	14	^{130}I	5.3	5.1
(3)	47	13	^{132}I	0.50	2.1
^{125}I	570	80	^{133}I	9.4	5.9
^{126}I	165	21	^{134}I	0.33	3.0
^{128}I	0.034	0.52	^{135}I	7.0	12

ε = the energy effectively spent in the organ: $\varepsilon = \Sigma$ EF (RBE)n

m = mass of the organ;

T = integration time = 13 weeks in this case.

The maximal dose rate exposures adopted are those recommended by the ICRP Committee II:[15]

8 rem during a 13-week period for the thyroid,

1.3 rem during a 13-week period for the whole body.

The energies effectively absorbed by the organ have been taken in Table 5a of ICRP for ^{131}I; they have been computed for isotopes 125, 128 and 130 following equations (25)–(30) of ICRP. The following figures were obtained:

^{125}I: Σ EF(RBE)n = 0.085 MeV (body)
0.031 MeV (thyroid)

^{128}I: Σ EF(RBE)n = 0.86 MeV (body)
0.81 MeV (thyroid)

^{130}I: Σ EF(RBE)n = 1.68 MeV (body)
0.49 MeV (thyroid)

6.1. *Chronic contamination*

This case is considered by ICRP to establish the maximal permissible burdens. We have recalculated these levels for the thyroid which is always the critical organ, and also for the remaining body.

It appears useful to distinguish between the remaining body (without thyroid) and the whole body because the radioactivity localized in the thyroid does not irradiate the remaining body to any appreciable extent. Moreover, at the equilibrium, the amount of radio-iodine in the thyroid is usually much greater than the amount in the remaining body which is then only exposed to this latter small part of the total radioactivity (Table 3).

From the maximal burdens admitted in the organ* and calculated with equation (2), the maximal permissible concentrations in water and air for 40 or 168 hr exposure per week can be computed.

Indeed

$$\mathrm{MPC_{water}} = \frac{\mathrm{MPB}^x}{Q^x_{\mathrm{acc}} \cdot C_m}$$

where MPB^x = the maximal permissible burden in organ x (μc),

Q^x_{acc} = activity accumulated in the organ resulting from a chronic contamination of 1 μc/hr,

C_m = mean water intake in l./hr.

When the contamination comes from the air, it is assumed that only 75 per cent of the inhaled activity is transferred to the blood, so that

$$\mathrm{MPC_{air}} = \frac{\mathrm{MPB}^x}{Q^x_{\mathrm{acc}} \cdot 0.75\, C_m}$$

The calculated data are shown in Table 4.

6.2. *Acute contamination*

In the not infrequent event of a unique accidental contamination, the maximal permissible burden of the radionuclide in the body is usually much higher than what is allowed in

* It might be that the thyroid is not the critical organ for the very short-lived iodine isotope.

Table 4. Maximum permissible burden in critical organ and in total body and maximum permissible concentrations in water and air. In the case of iodine-131 the stable iodine daily intake is considered at three levels: 50 μg (1), 100 μg (2) and 300 μg (3). For the other isotopes, it is fixed at 100 μg/day

	Critical organ	MPB in organ (μc)	MPB in total body (μc)	$(MPC)_{water}$ for 40 hr week (μc/cm³)	$(MPC)_{air}$ for 40 hr week (μc/cm³)	$(MPC)_{water}$ for 168 hr week (μc/cm³)	$(MPC)_{air}$ for 168 hr week (μc/cm³)
^{131}I (1)	Thyroid	0.15	0.16	$3 \cdot 10^{-5}$	$5 \cdot 10^{-9}$	$1 \cdot 10^{-5}$	$2 \cdot 10^{-9}$
	Body	44	500	$1 \cdot 10^{-1}$	$1 \cdot 10^{-5}$	$3 \cdot 10^{-2}$	$5 \cdot 10^{-6}$
(2)	Thyroid	0.15	0.17	$4 \cdot 10^{-5}$	$6 \cdot 10^{-9}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-9}$
	Body	44	370	$1 \cdot 10^{-1}$	$2 \cdot 10^{-5}$	$4 \cdot 10^{-2}$	$5 \cdot 10^{-6}$
(3)	Thyroid	0.15	0.19	$1 \cdot 10^{-4}$	$1 \cdot 10^{-8}$	$4 \cdot 10^{-5}$	$5 \cdot 10^{-9}$
	Body	44	210	$1 \cdot 10^{-1}$	$2 \cdot 10^{-5}$	$4 \cdot 10^{-2}$	$6 \cdot 10^{-6}$
^{125}I	Thyroid	1.1	1.3	$6 \cdot 10^{-5}$	$9 \cdot 10^{-9}$	$2 \cdot 10^{-5}$	$3 \cdot 10^{-9}$
	Body	230	1900	$9 \cdot 10^{-2}$	$1 \cdot 10^{-5}$	$3 \cdot 10^{-2}$	$4 \cdot 10^{-6}$
^{126}I	Thyroid	0.21	0.24	$4 \cdot 10^{-5}$	$6 \cdot 10^{-9}$	$1 \cdot 10^{-5}$	$2 \cdot 10^{-9}$
	Body	85	770	$1 \cdot 10^{-1}$	$2 \cdot 10^{-5}$	$4 \cdot 10^{-2}$	$7 \cdot 10^{-6}$
^{128}I	Thyroid	0.042	0.68	$4 \cdot 10^{-2}$	$6 \cdot 10^{-6}$	$1 \cdot 10^{-2}$	$2 \cdot 10^{-6}$
	Body	23	24	1	$2 \cdot 10^{-4}$	$5 \cdot 10^{-1}$	$7 \cdot 10^{-5}$
^{129}I	Thyroid	0.50	0.59	$3 \cdot 10^{-6}$	$4 \cdot 10^{-10}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-10}$
	Body	220	1600	$8 \cdot 10^{-3}$	$1 \cdot 10^{-6}$	$3 \cdot 10^{-3}$	$4 \cdot 10^{-7}$
^{130}I	Thyroid	0.14	0.27	$8 \cdot 10^{-4}$	$1 \cdot 10^{-7}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-8}$
	Body	12	24	$7 \cdot 10^{-2}$	$1 \cdot 10^{-5}$	$2 \cdot 10^{-2}$	$4 \cdot 10^{-6}$
^{132}I	Thyroid	0.053	0.28	$3 \cdot 10^{-3}$	$5 \cdot 10^{-7}$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-7}$
	Body	13	16	$2 \cdot 10^{-1}$	$3 \cdot 10^{-5}$	$6 \cdot 10^{-2}$	$9 \cdot 10^{-6}$
^{133}I	Thyroid	0.064	0.10	$2 \cdot 10^{-3}$	$3 \cdot 10^{-7}$	$7 \cdot 10^{-4}$	$1 \cdot 10^{-7}$
	Body	23	60	$1 \cdot 10^{-1}$	$2 \cdot 10^{-5}$	$4 \cdot 10^{-2}$	$6 \cdot 10^{-6}$
^{134}I	Thyroid	0.042	0.42	$4 \cdot 10^{-3}$	$6 \cdot 10^{-7}$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-7}$
	Body	13	14	$1 \cdot 10^{-1}$	$2 \cdot 10^{-5}$	$5 \cdot 10^{-2}$	$7 \cdot 10^{-6}$
^{135}I	Thyroid	0.066	0.18	$3 \cdot 10^{-4}$	$4 \cdot 10^{-8}$	$1 \cdot 10^{-4}$	$2 \cdot 10^{-8}$
	Body	15	24	$4 \cdot 10^{-2}$	$6 \cdot 10^{-6}$	$1 \cdot 10^{-2}$	$2 \cdot 10^{-6}$

the case of a chronic contamination at equilibrium, because of a progressive decrease of the radioactivity due to the biological metabolism and the physical decay: the exposure dose must indeed be integrated over a period of 13 weeks.[16] The maximal permissible quantities computed from equation (2) for the radioiodines can be found in Table 5.

COMPARISON OF THE RESULTS OF THIS STUDY AND THE DATA USED BY IRCP TO SPECIFY THE MAXIMUM PERMISSIBLE LEVELS

According to ICRP, the human body contains 40 mg of iodine, one-fifth of which is concentrated in the thyroid. This iodine forms a single pool in the thyroid and the remaining body, which is not divided by any chemical or physical barrier and which has a half-life of 138 days.

When a contamination with radioactive iodine is considered, the effective half-life takes the place of the biological half-life in order to account for the radioactive decay. But as, for ICRP, iodine is in a single pool, the homogenization is instantaneous and the distribution of the contaminating radioisotope between the thyroid and the remaining body must be precisely the same as that of the stable iodine: f_2 = thyroidal iodine/total iodine = 0.2. The repartition of the radionuclide between the thyroid and the remaining body and the exposure doses for the tissues, in case of a single absorption, are computed in the following way:

thyroidal activity: $q^{th} = q f_1 f_2' \cdot \exp - \lambda^{th} t$

where q = absorbed radioactivity,

$f_1 = 1$ = fraction of absorbed quantity passing in the blood,

$f_2' = 0.3$ = fraction from blood to organ,

λ = effective time constant,

Table 5. Acute contamination. Maximal permissible absorption: resulting maximum burdens in thyroid, and time necessary to reach these maxima

Isotope of iodine	Maximum permissible intake (μc)	Maximum permissible burden in thyroid (μc)	Delay to reach burden (hr)
^{131}I (1)	2.2	1.2	30
(2)	3.2	1.1	36
(3)	7.0	1.1	48
^{125}I	5.3	2.1	48
^{126}I	2.9	1.1	36
^{128}I	2700	73	0.4
^{129}I	1.6	0.67	50
^{130}I	29	5.0	8
^{132}I	230	16	2
^{133}I	14	3.0	12
^{134}I	810	32	0.8
^{135}I	620	78	5

In the calculations, a dose rate of 8 rem/13 weeks has been admitted. In the case of ^{131}I the stable iodine daily intake is considered at three levels: 50 μg (1), 100 μg (2) and 300 μg (3). For the other isotopes, it is fixed at 100 μg per day.

total body activity:

$$q^{TB} = q(f_1 - f_1 f^U) \exp -\lambda^{TB} t$$

where: f^U = fraction rapidly excreted in urine. But as ICRP supposes an instantaneous homogenization, even in the thyroid, and that there is no immediate urinary excretion $qf_1 f^U$ (equations (41) and (42) of ICRP):

$$q^{TB} = qf_1 \exp -\lambda^{TB} t$$

Moreover, for ICRP, $\lambda^{th} = \lambda^{TB}$ so that, at any moment:

$$f_2 = \frac{q^{th}}{q} = \frac{qf_1 f_2'}{qf_1} = f_2'$$

Thus a contradiction appears when ICRP uses different values for f_2 and f_2' (0.2 and 0.3).

In the case of a chronic contamination, the ratio of the body and thyroid radioactivities is obviously the same as for an acute contamination, i.e. the ratio of the amounts of stable iodine. Accepting a rate of exposure of 8 rem/13 weeks for the thyroid, ICRP calculates a maximum burden of 0.15 μc ^{131}I in the thyroid and 0.7 μc ^{131}I for the whole body.

In contradiction with the above data used by ICRP, recent textbooks[6] put 85 per cent of the body iodine in the thyroid, i.e. 8 mg out of a total of 9–9.5 mg. Moreover this iodine forms several pools. The iodide in the plasma and in the diffusion volume is quickly removed by the kidneys and the thyroid; its biological half-life is only about 6 hr. The organic iodine secreted by the thyroid has a longer half-life of 12 days[7] that is still much shorter than the 80-day half-life of the thyroidal iodine. A complete analysis of this metabolic sequence led us to propose 0.17 μc as the maximal constant burden permissible for the whole body; this level of contamination corresponds to the presence of 0.15 μc in the thyroid (this latter figure is obviously identical with that of ICRP).

The MPC for water and air that we have computed are in better agreement with those of ICRP which utilizes in the calculation only $f_2' = 0.3$ referring directly to the critical organ—thyroid. This value, likely derived from clinical studies, would be consistent with a daily stable iodine intake of 160 μg (adopting the other data of the present paper). With the mean intake of 75 μg found in our small sample of the Belgian population

$$f_2' = \frac{70}{70 + 78} = 0.47$$

CONCLUSIONS

The concentration of the radioiodine in an organ of small size makes it an important hazard for health as demonstrated by the values of the maximal permissible body burdens.

Because the activity ratio between thyroid and body changes rapidly, it is necessary to measure directly the radioactivity of the critical organ. For this purpose, we use at the C.E.N. a cylindrical NaI crystal of 5 × 5 cm shielded with 2 cm of lead; when it is localized at 6 cm from the thyroid, it is possible to detect less than 0.002 μc of ^{131}I in the organ. Another set-up with two NaI crystals of 7.5 cm diam. × 5 cm ht. placed on each side of the neck enables to reach an even higher sensitivity: 3×10^{-5} μc.[17]

The radioiodine in the remaining body can be assessed with a total body counter. The ratio of the activities in thyroid and remaining

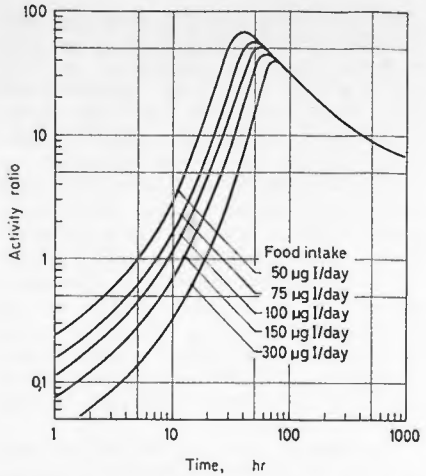


FIG. 8. Thyroid and remaining body activities ratios after a single absorption of iodine-131 at time *O* for various intakes of stable iodine.

body enables one to determine the time of contamination in Fig. 8 for ^{131}I.

Workers liable to be contaminated with the radioisotopes of iodine must be frequently checked. When the physician thinks that it is important to prevent the accumulation of radioiodine in the thyroid by the administration of a carrier (NaI, lugol . . .), this medication must be given in the very first hours following the accident. We believe however that a regular preventive administration of these drugs to workers frequently in contact with radioiodines is not to be recommended; it could give a false impression of security and be responsible for a relaxing of the necessary precautions in the working and near-by areas. Moreover it is not impossible that the frequent intake of important doses of stable iodine for years can finally deteriorate the health of these people. However workers with a diet rich in iodine are better protected than others.[18]

In the case of a chronic contamination (or a situation that can be considered as such), when the worker is removed from the contaminated zone, it is important in the computation of the cumulated dose to take into account what the tissues will get before the radioisotope is completely eliminated. For 1 μc of radioiodine in the thyroid, this complementary dose for the organ will be:

for ^{125}I: 3.6 rem
for ^{126}I: 7.1 rem
for ^{129}I: 12.7 rem
for ^{131}I: 6.5 rem

It is worth mentioning that, for Euratom, the thyroid must not be considered apart from the other internal organs, and the permissible dose rate ought not to exceed 4 rem/13 weeks. If this point of view is adopted (as it is by the Belgian regulations), all the data in the Tables 4 and 5 must be divided by 2. Some authors think however that the thyroid has a rather good radioresistance.[19]

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