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ANNUAL LIMITS ON INTAKE AND DERIVED AIR CONCENTRATIONS FOR THE RADIOIODINES WITH MASS NUMBERS FROM 123 TO 135

by

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Chalk River Nuclear Laboratories

Chalk River, Ontario

July 1977

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Limites annuelles d'apport et de concentration d'air dérivées pour les radioiodes ayant des nombres de masse allant de 123 à 135

par

J.R. Johnson

Résumé

Les limites annuelles de l'apport et des concentrations d'air dérivées sont calculées pour les radioiodes ayant des nombres de masse allant de 123 à 135, en utilisant un modèle couramment accepté de métabolisme de l'iode chez l'homme et des valeurs pour un homme de référence. Des résultats sont également donnés pour les charges de thyroïde et les taux d'excrétion urinaire en fonction du temps pour trois types d'exposition.

L'Energie Atomique du Canada, Limitée
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ABSTRACT

Annual Limits on Intake and Derived Air Concentrations are calculated for the radioiodines with mass numbers 123 to 135 using a currently accepted model of iodine metabolism in man and values for reference man. Results are also given for thyroid burdens and urinary excretion rates as functions of time for three exposure patterns.

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ANNUAL LIMITS ON INTAKE AND DERIVED AIR CONCENTRATIONS FOR THE RADIOIODINES WITH MASS NUMBER FROM 123 TO 135

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I. INTRODUCTION

The three compartment model for radioiodine in man previously described by the author[1)] has been used to calculate the thyroid burden and urinary excretion rates for the radioiodines with mass numbers 123 to 135 for both chronic and acute inhalation exposure patterns. The calculated thyroid burdens are used, in conjunction with values for reference man[2)], to calculate Annual Limits on Intake (ALI) and Derived Air Concentrations (DAC) for occupational inhalation exposure. Graphs of thyroid burdens and urinary excretion rates as functions of time for selected radioiodines are included.

A chronic exposure pattern is normally assumed to exist for persons occupationally exposed to chronic air contamination, even though the exposure is more likely to be five, eight-hour exposure periods per week. This assumption leads to mathematical simplicity compared to the true situation and will give the same results for the calculated Total Expected Dose (TED) provided the total uptake is identical. However, the results obtained with this simplifying procedure can be misleading, as is the case for urinary excretion rates during chronic exposure to radioiodine. Calculations have been performed for both ^{125}I and ^{133}I for the "chronic-acute" exposure of five, eight hour days per week and the results compared graphically to the chronic situation. This comparison illustrates that large errors can result in thyroid uptakes calculated from urinary excretion data unless the exposure pattern is known accurately.

II. MODEL CALCULATIONS

The three differential equations[1)] that describe the model (see figure 1)

$$\frac{dI(t)}{dt} = -(\lambda_1 + \lambda_2 + \lambda_r)I(t) + \lambda_4 O(t) + X(t) \qquad (1)$$

$$\frac{dT(t)}{dt} = \lambda_1 I(t) - (\lambda_3 + \lambda_r)T(t) \qquad (2)$$

$$\frac{dO(t)}{dt} = \lambda_3 T(t) - (\lambda_4 + \lambda_5 + \lambda_r)O(t) \qquad (3)$$

where I(t), T(t) and O(t) are the activities in the inorganic, thyroidal, and organic compartments respectively and X(t) is the rate of uptake of activity by the inorganic compartment. The rate constants $\lambda_1 \rightarrow \lambda_5$ are given in Table 1 and λ_r is the radioactive decay constant of the radioiodine being considered.

For the purposes of the model used here, it is assumed that any intake of radioiodine is transferred immediately to the inorganic compartment. This assumption can result in a slightly overestimated value for radioiodine uptake as Riggs[3)], and others [2,4)] find that approximately 95% of the activity is transferred, independent of whether the route of entry is inhalation or ingestion. It is also assumed here that the only loss of radioiodine is by urinary excretion. This assumption will result in a slightly overestimated urinary excretion rate as some iodine has been reported to be excreted with feces and perspiration[2,3)].

The urinary excretion rate is therefore given by

$$E_u(t) = -\lambda_2 I(t) - \lambda_5 O(t) \qquad (4)$$

and the rate of uptake will equal the rate of intake; that is

$$X(t) = C(t)B(t) \qquad (5)$$

for inhalation exposure, where C(t) is the air concentration and B(t) is the breathing rate for reference man[2)], and X(t) is equal to the ingestion rate for ingestion exposure.

Numerical solutions for equations 1) through 3) can be easily obtained with the computer program FORSIM[5)] once X(t) is specified. FORSIM can also be used to calculate

$$Q = \int_0^{18250\text{ days}} T(t)dt \qquad (6)$$

which is the thyroid activity integrated to 50 years.

The Total Expected Dose to 50 years (TED50)* resulting from an Annual Intake (AI) of

$$AI = \int_0^{365} X(t)dt \qquad (7)$$

is $\quad TED50 = FQ$ rem**

---

* *This quantity is sometimes called the Committed Dose Equivalent and assigned the symbol $\underline{H}_{50}$, or H50.*

** *1 rem = 0.01 Sv.*

where Q, calculated from (7) with X(t) put into (1), is in μCi*-day and F is the appropriate rem per μCi-day factor given by Snyder et al[6]. These factors are reproduced in table 2 for the radioiodines being considered.

The Annual Limit on Intake (ALI) is that value of AI which will result in a TED50 of 30 rem (0.3 Sv), the maximum allowable annual thyroid dose to atomic radiation workers[7]. Note that the ALI does not depend on the form of the function X(t) but only on the total annual intake (see Appendix). ALI's for the radioiodines listed above have been calculated and are given in table 2.

While the form of X(t) does not affect the TED50 it is, of course, the controlling factor in the growth of activity in the thyroid and the rate of excretion of radioiodine. Two limiting cases are often used to calculate limits that can be used for control purposes. They are acute exposure, where the intake is assumed to be instantaneous, and chronic exposure, where all exposures are averaged to give a constant rate of intake. These cases are treated separately below, and a third situation, that of "chronic-acute" exposure, is also examined.

(a) Acute Exposure

The results given in table 3 for acute exposure were obtained with FORSIM[5] by setting X(t) = 0 and using I(0) = I_0 as a boundary condition, where I_0 is the instantaneous uptake by the inorganic compartment. I_0 was chosen arbitrarily to be 2.5 μCi (9.25×10^4 Bq), which is also the AI that results from chronic exposure to an air concentration of 1 fCi/cm^3 (37 Bq/m^3) that is used below.

---

* *SI Equivalent: 1 Ci = 3.7×10^{10} Bq.*

In table 3, column (a) lists the times at which the maximum thyroid burden occurs, columns (b) and (c) the maximum thyroid burden and TED50 respectively for an uptake of 2.5 μCi (9.25×10^4 Bq), and columns (d) and (e) the intake and maximum thyroid burden that will result in 1.5 rem (0.015 Sv) TED50 to the thyroid. 1.5 rem (0.015 Sv) is 1/20 of the annual occupational limit on thyroid dose[7)] and is often used as an investigation level[8)].

Figures (2) and (3) give the urinary excretion rates and thyroid burdens respectively as functions of time following an acute exposure resulting in an uptake to the inorganic compartment of 2.5 μCi (9.25×10^4 Bq) of ^{125}I, ^{129}I*, ^{131}I or ^{133}I.

(b) Chronic Exposure

The results given in table 4 for chronic exposure were obtained with FORSIM[5)] by setting X(t) = constant. This constant was obtained in the usual manner[9)] by calculating the annual intake for reference man[2)] breathing air contaminated at 1.0 fCi/cm^3 (37 Bq/m^3) for five, eight-hour days per week, fifty weeks per year, and dividing by 364** to obtain the average daily rate of intake. Reference man breathes at a rate of 10^7 cm^3 (10 m^3) per 8 hour working day. The AI is therefore

$$\begin{aligned} \text{AI} &= 1.0 \times 10^7 \times 5 \times 50 \text{ fCi} \\ &= 2.50\ \mu\text{Ci}\ (9.25 \times 10^4 \text{ Bq}) \end{aligned}$$

---

* *An acute uptake of 2.5 μCi of ^{129}I would be equivalent to an uptake of 15.3 mg of iodine. This large amount would upset the iodine balance in the subject and the rate constants of table 1 could no longer be used. Uptakes of ^{129}I in the range of μCi's are unlikely. The results given here for ^{129}I can be reduced by a constant factor for uptakes of the range of ηCi's, which would not upset the iodine balance and which are more reasonable.*

** *ICRP Publication 2 uses 7 x 52 = 364 days/year[9)].*

and the average daily intake is

$$X_o = 2.50\ \mu\text{Ci}/364\ \text{days}$$
$$= 6.87\ \text{nCi/day}\ (254\ \text{Bq/day})$$

In table 4, column (a) lists the time required for the thyroid to reach 90% of its equilibrium burden, columns (b) and (c) the equilibrium thyroid burden and dose rate respectively for a constant intake rate of 6.87 nCi/day (254 Bq/day) and column (d) the Derived Air Concentration (DAC) that will result in a dose rate of 30 rem (0.3 Sv) per year to the thyroid of reference man at equilibrium.

Figures (4) and (5) give the urinary excretion rate and thyroid burden respectively as functions of time during chronic exposure to ^{125}I, ^{129}I, ^{131}I, or ^{133}I.

(c) Chronic-Acute Exposure

The results calculated using FORSIM[5)] for an exposure pattern of five, eight-hour days per week are compared to results obtained for chronic exposure for the same weekly intake in figures 6 through 9.

Figures 6 and 7 give urinary excretion rates for ^{125}I and ^{133}I respectively as functions of time during exposure and demonstrate that the excretion rate is essentially independent of the radioactive half-life for this range of half-lives. This result is due to the short time constant for urinary excretion from the inorganic compartment. They also demonstrate that any attempt to evaluate a "chronic" exposure from urinary excretion rates is futile unless the source of exposure is removed.

Figures 8 and 9 give the thyroid burdens as functions of time during exposure for ^{125}I and ^{133}I respectively. They demonstrate that the thyroid burdens calculated using the simplifying assumption for occupational chronic exposure improves as the half-life of the radioiodine increases.

III. SUMMARY

Annual Limits on Intake and Derived Air Concentrations have been calculated for all radioiodines of radiological significance. The models used as a basis for the calculations are those already recommended by the ICRP[2)] or which are expected to be recommended in forthcoming publications[10)]. Included in the report are tables and graphs of thyroid burdens and urinary excretion rates which should prove useful to persons working in the field of radiological protection.

FIGURE 1

THREE COMPARTMENT MODEL OF IODINE METABOLISM IN MAN

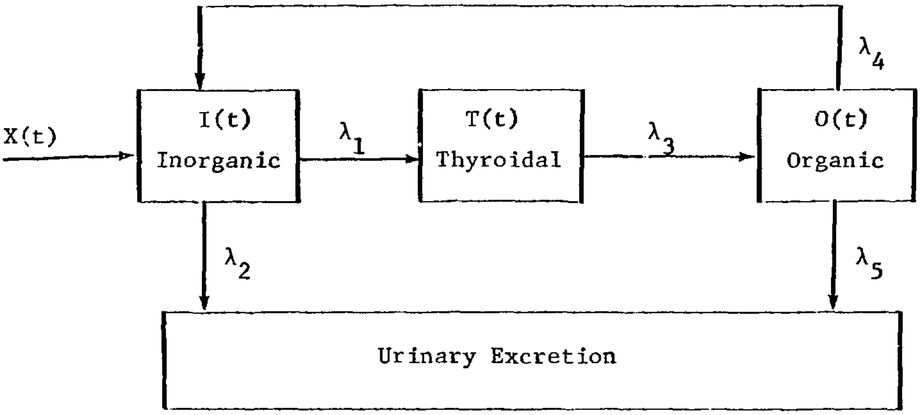


TABLE 1

RATE CONSTANTS CALCULATED FROM TABLE 3 OF REFERENCE 3

Route	Rate Constant λ_i in $(\text{Days})^{-1}$	Half-Life Days
1	0.93	0.74
2	1.92	0.36
3	0.0087	79
4	0.053	13
5	0.0050	139

TABLE 2

Radioiodine Parameters

Mass No.	Radioactive Half-life (days)	Effective Half-life[a] in Thyroid (days)	rem* / µCi•day	ALI[b]* (µCi)
123	0.543	0.541	0.0972	1740
124	4.02	3.89	0.656	25.7
125	60.25	39.91	0.0725	23.1
126	13.0	11.7	0.441	12.9
128	0.0174	0.0174	1.68[c]	32000
129	5.73×10^9	118	0.172	3.29
130	0.521	0.519	0.942	191
131	8.06	7.55	0.524	16.9
132	0.0992	0.0991	1.45	1530
133	0.867	0.861	1.10	86.4
134	0.0368	0.0368	1.92	6820.
135	0.279	0.278	1.12	383

a) *Time for the thyroid to obtain one-half its maximum burden during chronic exposure.*

b) *Annual Limit on Intake.*

c) *Calculated Value (not given in reference 6).*

* *Equivalents:*

$$\frac{\text{rem}}{\mu\text{Ci}\cdot\text{day}} = 2.703 \times 10^{-7} \frac{\text{Sv}}{\text{Bq}\cdot\text{d}}$$

$$\text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$$

TABLE 3

Acute Exposure to Radioiodine

Mass No.	(a) days	(b) μCi*	(c) rem*	(d) μCi*	(e) μCi*
123	0.42	0.335	0.043	87.2	11.7
124	1.00	0.643	2.92	1.28	0.329
125	1.76	0.785	3.25	1.15	0.361
126	1.36	0.738	5.82	0.640	0.189
128	0.03	0.021	0.002	1600	13.5
129	2.11	0.803	22.8	0.164	0.053
130	0.41	0.325	0.392	9.57	1.24
131	1.22	0.708	4.43	0.847	0.24
132	0.13	0.103	0.049	76.2	3.12
133	0.54	0.415	0.868	4.32	0.717
134	0.05	0.043	0.011	341	5.80
135	0.28	0.248	0.196	19.1	1.72

(a) *Time after an acute exposure at which the maximum thyroid burden occurs.*

(b) & (c) *Maximum thyroid burden (b) and the total expected dose (TED50) (c) from an intake of 2.5 μCi of radioiodine.*

(d) & (e) *Intake (d) and maximum thyroid burden (e) that will result in 1.5 rem TED to the thyroid.*

**Equivalents: rem = 0.01 Sv, Ci = 3.7 x* 10^{10} *Bq.*

TABLE 4

Chronic Exposure to Radioiodine

Mass No.	(a) days	(b) nCi*	(c) rem/year*	(d) DAC fCi/cm^3*
123	1.9	1.21	0.043	698.
124	14	12.2	2.92	10.3
125	140	123	3.25	9.23
126	38	36.2	5.82	5.15
128	0.09	0.004	0.002	13000
129	400	363	22.8	1.32
130	1.9	1.14	0.392	76.5
131	25	23.2	4.43	6.77
132	0.5	0.093	0.049	612
133	3.3	2.16	0.868	34.6
134	0.2	0.016	0.011	2730
135	1.2	0.480	0.196	153

(a) *Time required for the thyroid to reach 90% of its equilibrium burden.*

(b) & (c) *Thyroid burden (b) and thyroid dose rate (c) at equilibrium for chronic exposure to 1.0 fCi/cm^3.*

(d) *Air concentration that will result in a dose rate of 30 rem/year at equilibrium.*

**Equivalents: rem = 0.01 Sv, Ci = 3.7 x 10^{10} Bq.*

FIGURE 2

Urinary excretion rate following an acute exposure resulting in a radioiodine uptake to the inorganic compartment of 2.5 μCi (9.25×10^4 Bq).

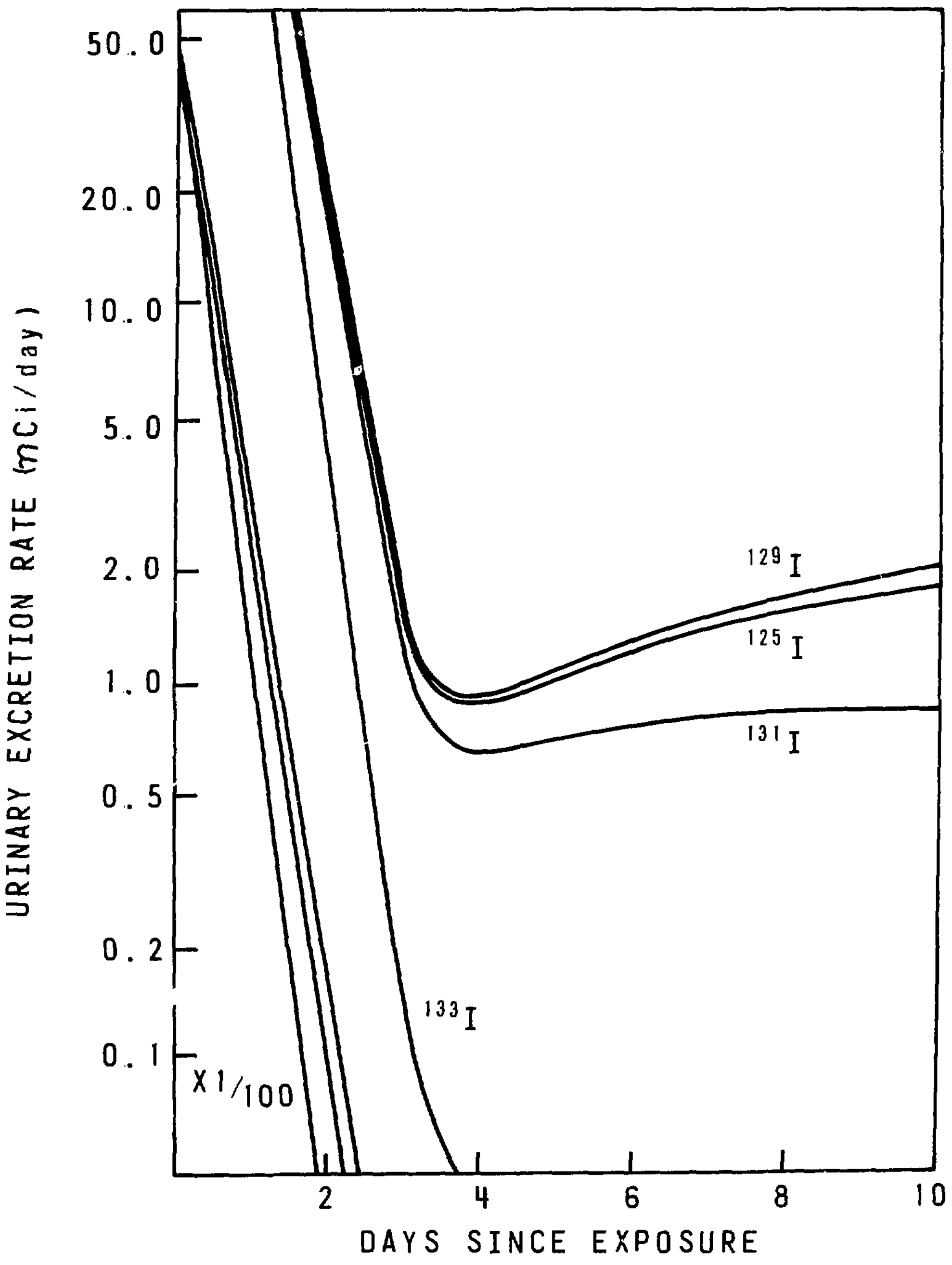


FIGURE 3

Thyroid burden following an acute exposure resulting in a radioiodine uptake to the inorganic compartment of 2.5 µCi (9.25 x 10^4 Bq).

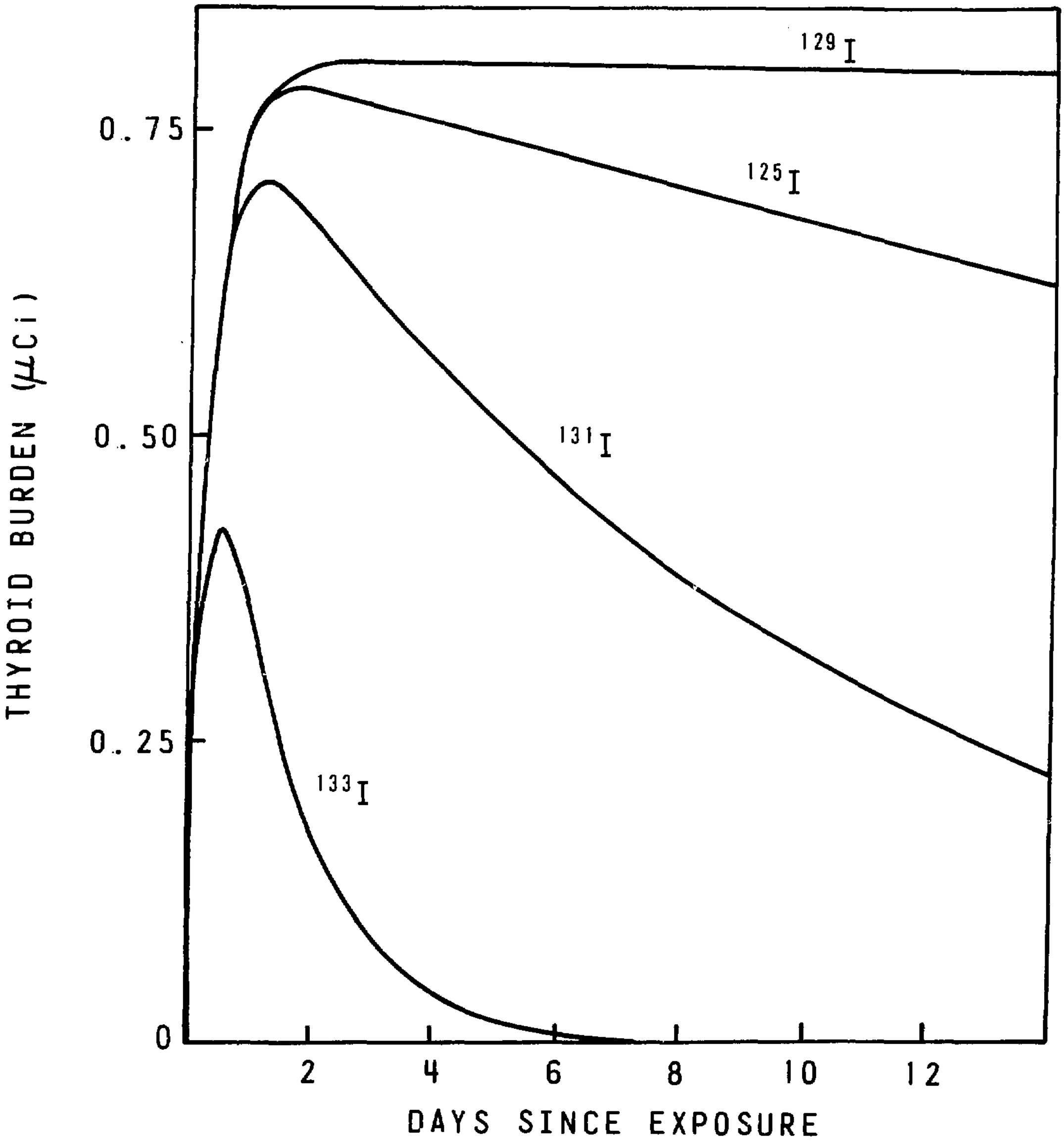


FIGURE 4

Urinary excretion during a chronic exposure to an air concentration of 1.0 fCi/cm^3 or any exposure giving a constant uptake to the inorganic compartment of 6.87 nCi/day (254 Bq/d) (see text).

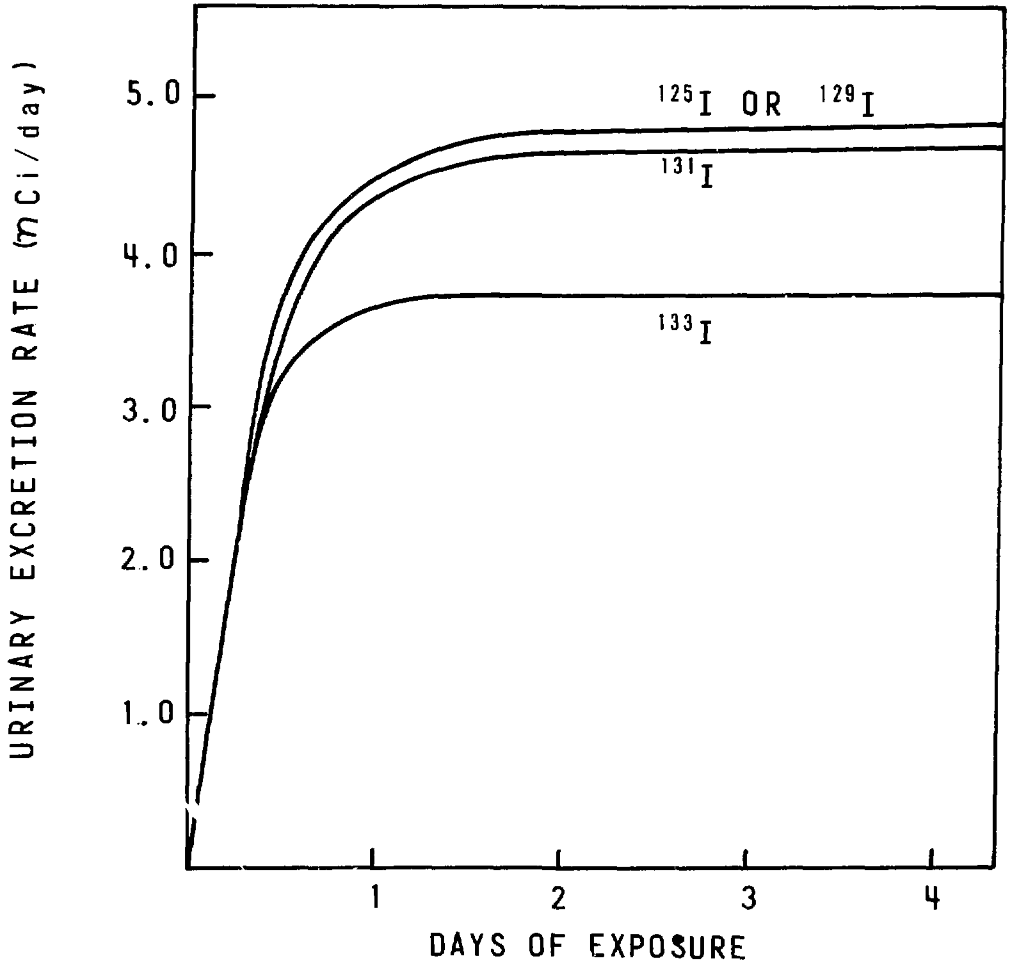
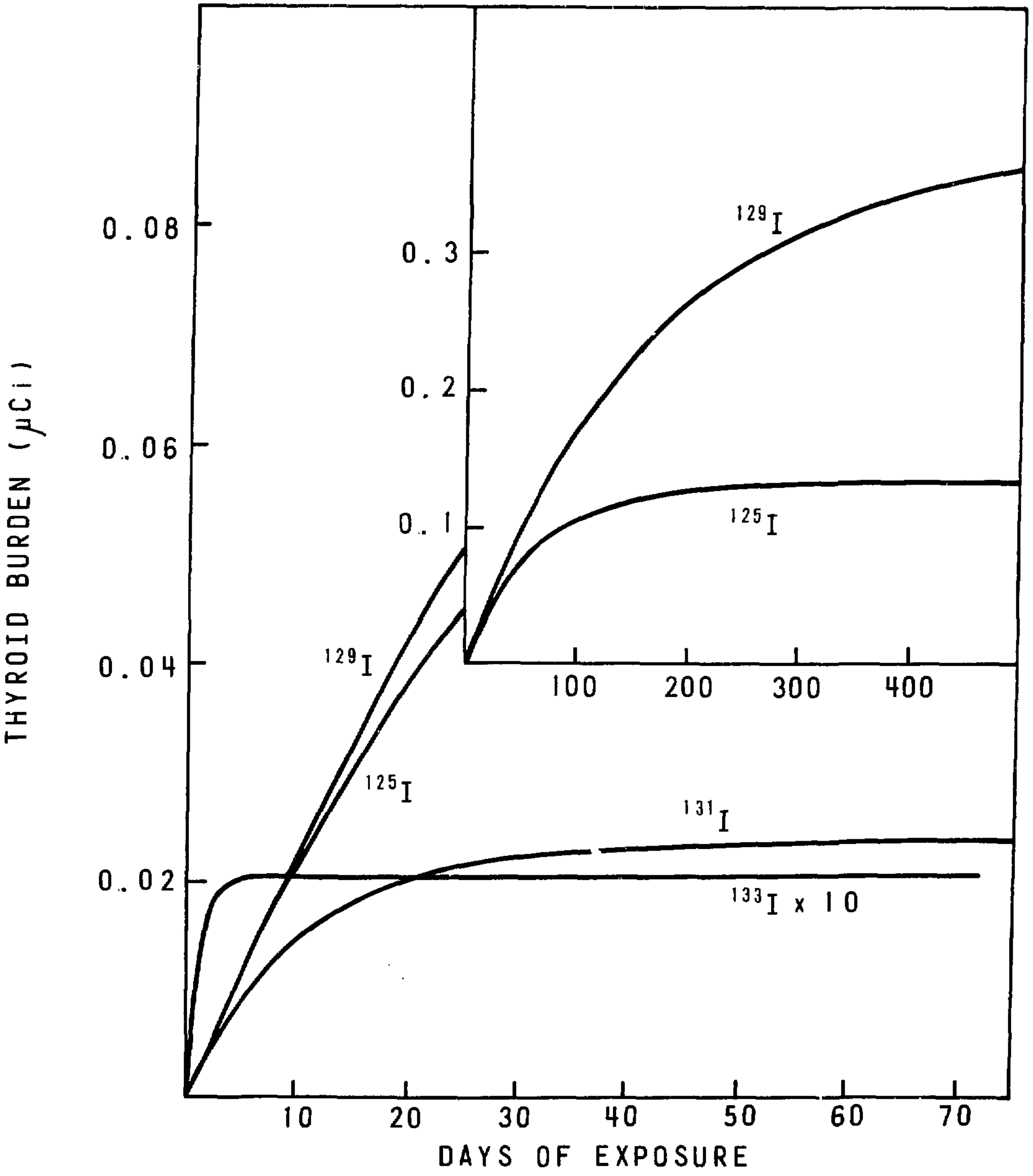


FIGURE 5

Thyroid burden during a chronic exposure to an air concentration of 1.0 fCi/cm^3 or any exposure giving a constant uptake to the inorganic compartment of 6.87 nCi/day (254 Bq/d) (see text).



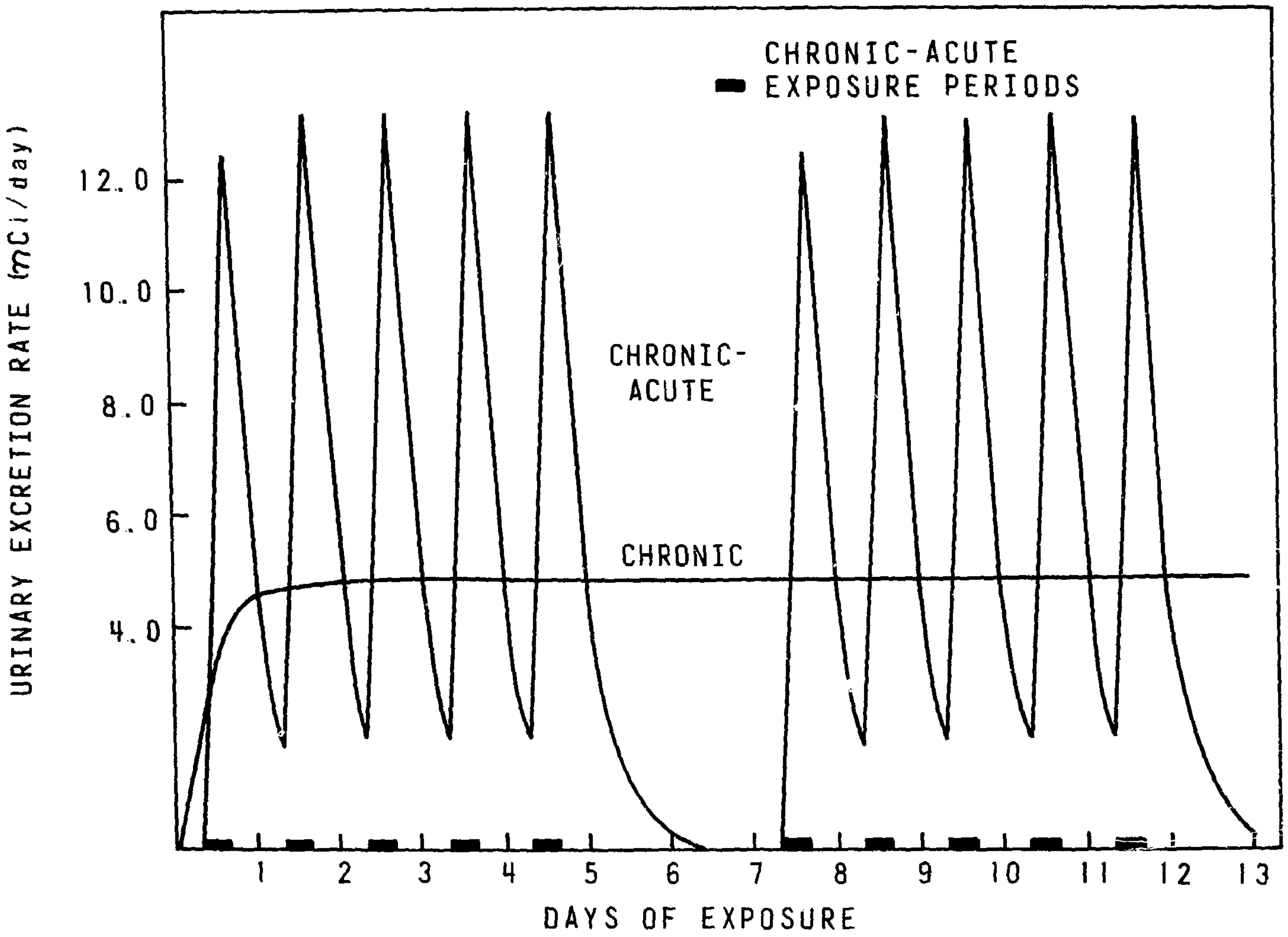


FIGURE 6

Comparison of urinary excretion rates as functions of time during chronic and chronic-acute exposure to 1.0 fCi/cm^3 (37 Bq/m^3) of ^{125}I in air.

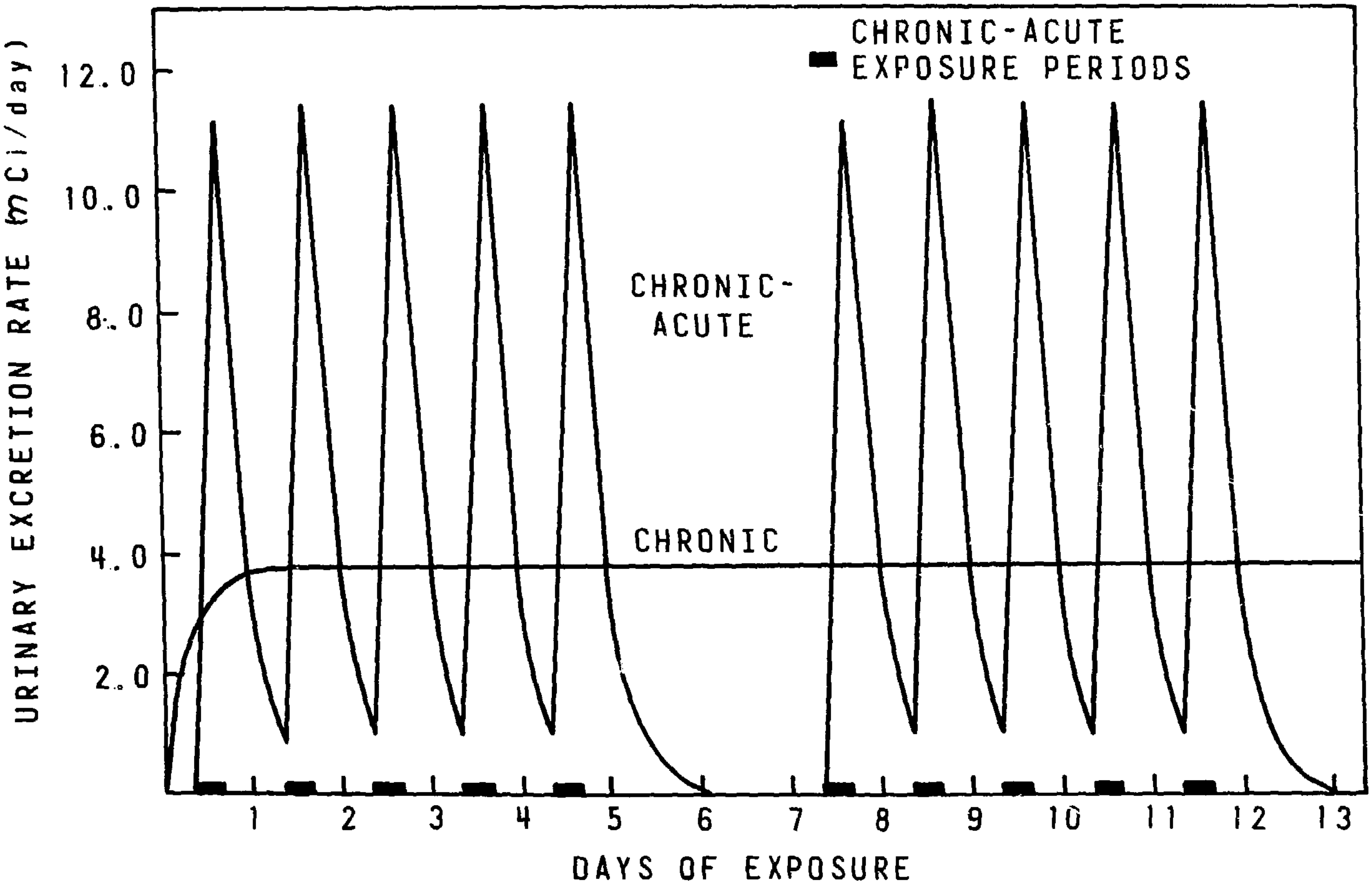


FIGURE 7

Comparison of urinary excretion rates as functions of time during chronic and chronic-acute exposure to 1.0 fCi/cm^3 (37 Bq/m^3) of ^{133}I in air.

FIGURE 8

Comparison of thyroid burdens as functions of time during chronic and chronic-acute exposure to 1.0 fCi/cm^3 (37 Bq/m^3) of ^{125}I in air.

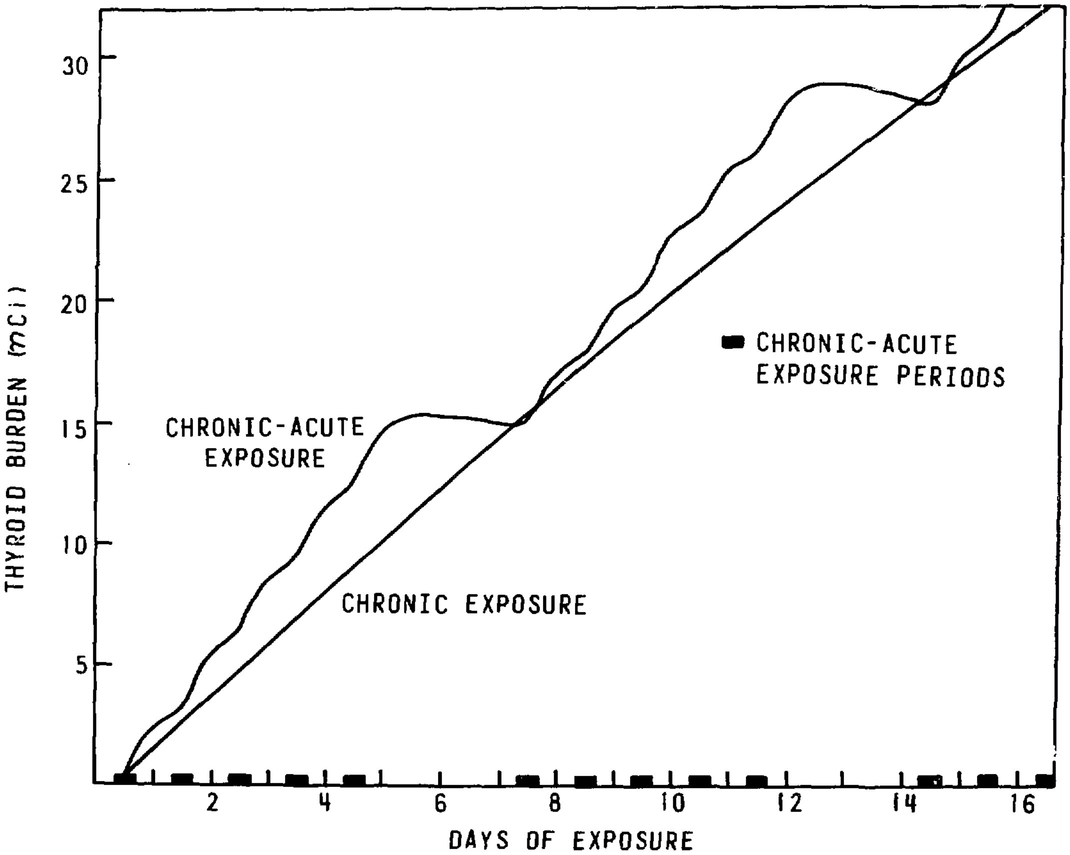
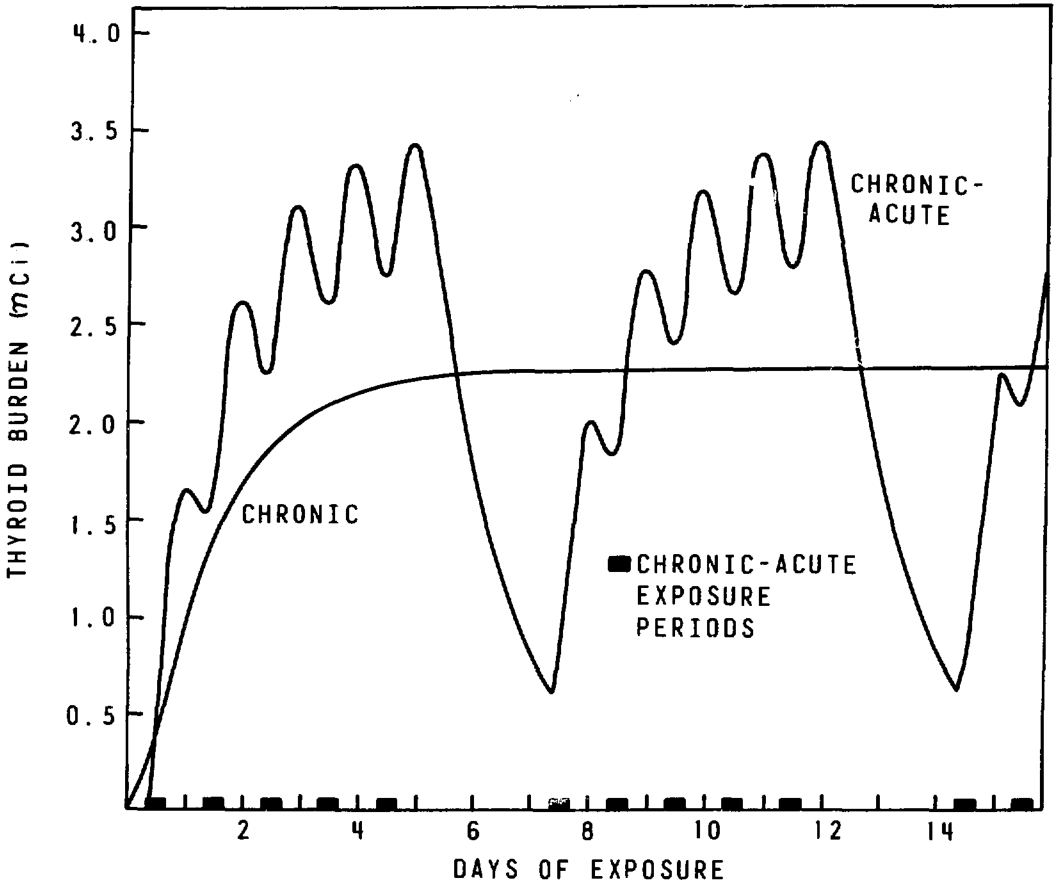


FIGURE 9

Comparison of thyroid burdens as functions of time during chronic and chronic-acute exposure to 1.0 fCi/cm^3 (37 Bq/m^3) of ^{133}I in air.



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* *References to AECL-XXXX are to reports of Atomic Energy of Canada Limited.*

APPENDIX

Annual Limit on Intake

The concept of an annual limit on intake (ALI) arises from the following consideration.

If the retention of a radionuclide in an organ can be written as the sum of exponential terms, then the total expected dose (TED) to that organ from an exposure to the radionuclide is independent of the time sequence of the exposure. That is, the TED only depends on the *amount of activity taken up by that organ. It does not depend on whether* the exposure was acute, chronic or something in between. This fact is demonstrated below. Therefore an individual limited to an intake of activity in one year of a particular radionuclide, such that the TED from that intake is less than the maximum allowed yearly dose, will never receive in any year a dose from that radionuclide exceeding the yearly maximum dose regardless of the number of years the individual may be exposed.

The retention function for the radionuclide in the organ is

$$R(t) = \sum_i a_i e^{-\lambda_i t} \qquad \text{(A-1)}$$

(a) Acute Exposure

The dose in μCi-days to time T to the organ from an acute exposure that results in a total intake of I_o μCi of the radionuclide at time T=0 is

$$Q_a(0\text{-}T) = I_o \int_0^T R(\tau)\, d\tau$$

$$= I_o \sum_i a_i/\lambda_i \left(1 - e^{-\lambda_i T}\right) \mu\text{Ci}\cdot\text{days} \qquad \text{(A-2)}$$

(b) Chronic Exposure

The organ burden at time t during a chronic exposure that results from a constant total intake of I_o/t_o μCi/day is

$$B(t) = I_o/t_o \int_0^t R(t-\tau)d\tau$$

$$= I_o/t_o \sum_i a_i/\lambda_i \left(1-e^{-\lambda_i t}\right) \qquad \text{(A-3)}$$

The intake from this exposure in t_o days is I_o μCi, and the accumulated dose to the organ in this time is

$$Q_c(0-t_o) = \int_0^{t_o} B(t)\, dt$$

$$= I_o/t_o \sum_i a_i/\lambda_i \left[t_o - \frac{1}{\lambda_i}\left(1-e^{-\lambda_i t_o}\right)\right] \qquad \text{(A-4)}$$

The dose from t_o to T is

$$Q_c(t_o-T) = \sum_i b_i \int_{t_o}^{T} e^{-\lambda_i (t-t_o)} dt$$

where the b_i's are given by equation A-3 with $t=t_o$, i.e.,

$$b_i = \frac{I_o a_i}{t_o \lambda_i}\left(1-e^{\lambda_i t_o}\right)$$

hence

$$Q_c(t_o-T) = \sum_i \frac{I_o a_i}{t_o \lambda_i^2}\left[1-e^{-\lambda_i t_o} + e^{-\lambda_i T}\left(1-e^{\lambda_i t_o}\right)\right] \qquad \text{(A-5)}$$

The dose from t=o to t=T is the sum of equation A-4 and A-5.

$$Q_c(0\text{-}T) = I_o \sum_i a_i/\lambda_i \left[1 - \frac{e^{-\lambda_i T}}{\lambda_i t_o}\left(e^{\lambda_i t_o} - 1\right)\right] \qquad \text{(A-6)}$$

$$0 < t_o < T$$

(c) Comparison of Acute and Chronic Exposure

The TED to time T from chronic exposure (equation A-6) is equal to that from acute exposure (equation A-2) provided that

$$1 - e^{-\lambda_i T} \approx 1 - \frac{e^{-\lambda_i T}}{\lambda_i t_o}\left(e^{\lambda_i t_o} - 1\right) \qquad \text{(A-7)}$$

for all i.

Conditions that will satisfy A-7 are

i) $$e^{\lambda_i t_o} - 1 \approx \lambda_i t_o$$

that is

$$\lambda_i t_o << 1 \qquad \text{(A-8)}$$

ii) Both $$e^{-\lambda_i T} << 1 \qquad \text{(A-9)}$$

and

$$\frac{e^{-\lambda_i T}}{\lambda_i t_o}\left(e^{\lambda_i t_o} - 1\right) << 1$$

iii) $$e^{-\lambda_i T} \simeq \frac{e^{-\lambda_i T}}{\lambda_i t_o} (e^{\lambda_i t_o} - 1)$$

Expanding the exponentials in the right-hand side of iii) in power series gives

$$\text{RHS} = \frac{1}{\lambda_i t_o} \sum_{k=0}^{\infty} \frac{(-\lambda_i T)^k [(1-t_o/T)^k - 1]}{k!}$$

Expanding $(1-t_o/T)^k$ and simplifying gives

$$\text{RHS} = \sum_{k=1}^{\infty} (-\lambda_i T)^{k-1} \Bigg[\frac{1}{1!\,(k-1)!} + \frac{1}{2!\,(k-2)!} (-t_o/T)$$

$$+ \,\ldots\ldots + \frac{1}{(m+1)!\,(k-m-1)!} \quad (-t_o/T)^m$$

$$+ \,\ldots\ldots + \frac{}{k!\,0!} \;(-t_o/T)^{k-1} \Bigg]$$

Then if

$$t_o/T << 1 \qquad \text{A-10}$$

$$\text{RHS} = e^{-\lambda_i T}$$

Note that for $Q_a(0\text{-}T) = Q_c(0\text{-}T)$ does not require that any one of conditions A-8 through A-10 be satisified for all i, only that at least one of them be satisfied for each i.

The essence of equations A-8 through 10 is that if t_o and $1/\lambda_i$ is small enough and/or T large enough the TED to time T from chronic exposure will equal the TED to time T from acute exposure for the same total uptake. Also, since any exposure pattern can be broken down into the sum of acute and/or short chronic exposures, the TED from any exposure pattern only depends on the total uptake and the retention function, provided that the duration of exposure is short compared to the time to which the TED is calculated.

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