20. METABOLIC MODELS FOR ESTIMATION OF INTERNAL RADIATION EXPOSURE RECEIVED BY HUMAN SUBJECTS FROM THE INHALATION OF NOBLE GASES

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The purpose of this paper is to present and develop metabolic models needed for estimation of dose equivalent from exposure to noble gases. Human subjects may inhale low levels of radioactive noble gases released to the atmosphere by nuclear reactors or fuel reprocessing plants either on a regular basis or after an accidental release. Also, medical studies using radioactive noble gases are employed to obtain data on ventilation and perfusion of the lungs.[2] Estimates of radiation dose to human tissue are sometimes based on the equilibrium levels predicted from the Ostwald absorption coefficient (ratio of concentration (mass per unit volume) of gas in the tissue or fluid to the concentration in air)[3]. This amounts to assuming an equilibrium between the gas present in the atmosphere and that present in tissue. Such an estimate may be valid for long-lived radioactive gases, but does not appear adequate for short-lived radioactive gases. It is for this reason that a metabolic model is needed.

In 1950, Harley et al.[4] published data on the exhalation of ^{222}Rn by a human subject (actually more than one, but adequate data are available on only one subject) who inhaled ^{222}Rn at a concentration of 7×10^{-10} Ci/ℓ for 8½ hours. Data on the rate of exhalation in pCi/min were measured out to 76 hours after the exposure ceased (see

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Fig. 20.1). The authors fit a five-term exponential equation to these data:

$$\text{Rate of exhalation} = 3210e^{-1.818t} + 328e^{-0.155t} + 71e^{-0.0168t} + 25e^{-0.00342t} + 4.8e^{-0.00063t} \text{ pCi/min}, \quad (1)$$

t in minutes. This equation is not corrected for radioactive decay but the value of the decay constant is $\lambda_r = 0.00013 \text{ min}^{-1}$.

This equation has been converted to the equation for a single intake via inhalation by the following procedure. Let $R_S(t)$ denote the fractional retention in the body at time t (min) following a single intake by inhalation and assume

$$R_S(t) = \sum_{i=1}^{5} b_i e^{-\mu_i t} \quad (2)$$

where

$$\sum_i b_i = 1$$

and

$$\mu_i = \lambda_r + \lambda_i \quad \text{min}^{-1},$$

i.e., the μ_i is the ith effective elimination constant and the λ_i is the constant for removal or transfer from the compartment. For an intake rate of IpCi/min, the intake in a period $d\tau$ is $Id\tau$ pCi. In the case of continuous exposure at a constant level, the retention is

$$\int_0^t d\tau \; I \, R_S(t - \tau) = I \sum_{i=1}^{5} \frac{b_i}{\mu_i} \left(1 - e^{-\mu_i t}\right) \text{pCi}. \quad (3)$$

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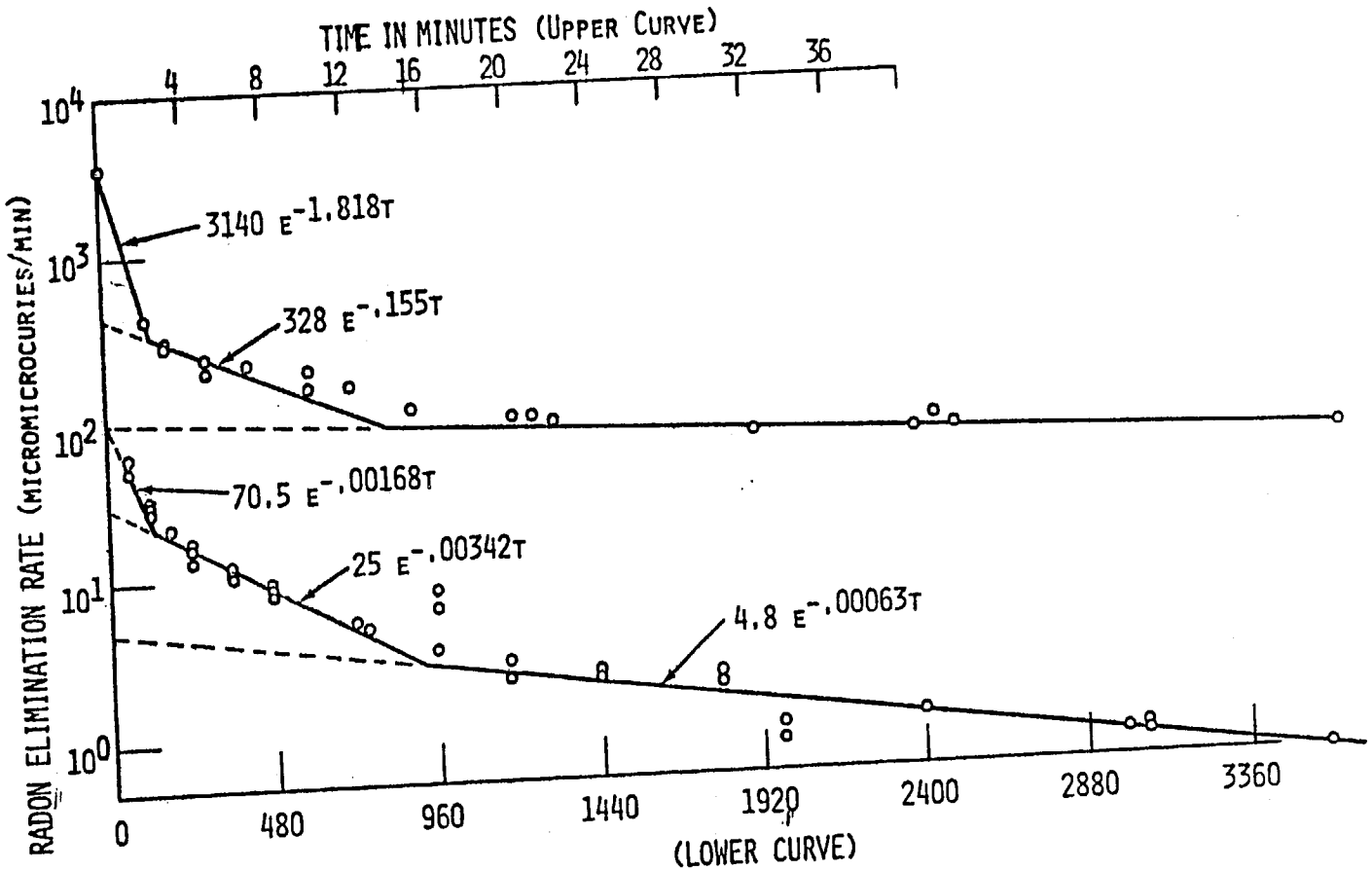

Fig. 20.1 Rn ELIMINATION RATE BY A HUMAN VOLUNTEER WHO HAD INHALED Rn FOR 8½ HOURS. (DATA OF HARLEY, ET. AL)

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If exposure of the tissue to the gas continues for a period of E (min) and then ceases, the retention at a time t (min) following the cessation of exposure is given by

$$R(t) = I \sum_{i=1}^{5} \frac{b_i}{\mu_i} \left(1 - e^{-\mu_i E}\right) e^{-\mu_i t} \quad \text{(pCi)}, \qquad t \geqq 0. \tag{4}$$

The derivative with respect to t, assuming $t > 0$, is

$$I \sum_{i=1}^{5} \frac{b_i(\lambda_i + \lambda_r)}{\mu_i} \left(1 - e^{-\mu_i E}\right) e^{-\mu_i t}, \quad \text{(pCi/min)}. \tag{5}$$

The term involving λ_r corresponds to radioactive decay. Thus the biological elimination which is here assumed equal to the exhalation is given by

Rate of exhalation =

$$I \sum_{i=1}^{5} \left[\frac{b_i \lambda_i}{\mu_i} \left(1 - e^{-\mu_i E}\right)\right] e^{-\mu_i t} \quad \text{(pCi/min)}. \tag{6}$$

This equation can be compared to the experimental equation of Harley et al. and the values of each λ_i can be identified by inspection. The expression $(1 - e^{-\mu_i E})$ can be computed and the values of each b_i can then be obtained. The retention equation for the total body for the case of a single intake via inhalation is found to be

$$R_S(t) = 0.874e^{-1.818t} + 0.0913e^{-0.155t} + 0.0198e^{-0.01686t} + 0.00863e^{-0.00342t} + 0.00612e^{-0.00063t} \tag{7}$$

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(t in min), without correction for radiological decay (λ_r = 0.00013 min^{-1} for ^{222}Rn).

This equation, corrected for radioactive decay, for retention was then analyzed with the MAMX code described by Bernard[5] to obtain rate transfer constants λ_{ij} for a five-compartment mammillary model taken to represent the distribution of Rn in the body. In this last reference the following equations were solved for λ_{ij} and λ_{ji} using the MAMX code:

$$g\ (\lambda_{ij}) = \sum_{i=1}^{5} \frac{b_i \lambda_i}{\lambda_{1j} - \lambda_i} = 0 \qquad (8)$$

$$\sum_{j=1}^{5} \frac{\lambda_{j1}\ \lambda_{1j}\ b_i}{\lambda_{1j} - \lambda_i} = \lambda_{11} - \lambda_i, \quad \begin{matrix} i=1, \ldots .5, \\ j=2, \ldots .5. \end{matrix} \qquad (9)$$

$$C_{ji} = \frac{\lambda_{j1}(b_i\ \lambda_i)/(\sum_i b_i\ \lambda_i)}{\lambda_{1j} - \lambda_i} \ . \qquad (10)$$

The biological elimination constants (λ_i) in units of min^{-1} are obtained from Equation (7). This model together with the symbol for the rate transfer constants between compartments appears in Fig. 20.2. The values of b_i, λ_i, λ_{ij}, and C_{ji} are listed in Table 20.1 and 20.1a. The time integrals of the activities in the various compartments, r_i, appear in Table 20.1b.

This equation, when converted back to the case of continuous intake of 7 x 10^{-10} Ci/ℓ for a period of 8½ hours exposure and for an inhalation rate of 5 ℓ/min, will recover the equation of Harley et al. within ∿4% for exhalation after cessation of exposure.

For dosimetry, the compartments must be identified with the tissues of the body. The data of Nussbaum[6] on the distribution of

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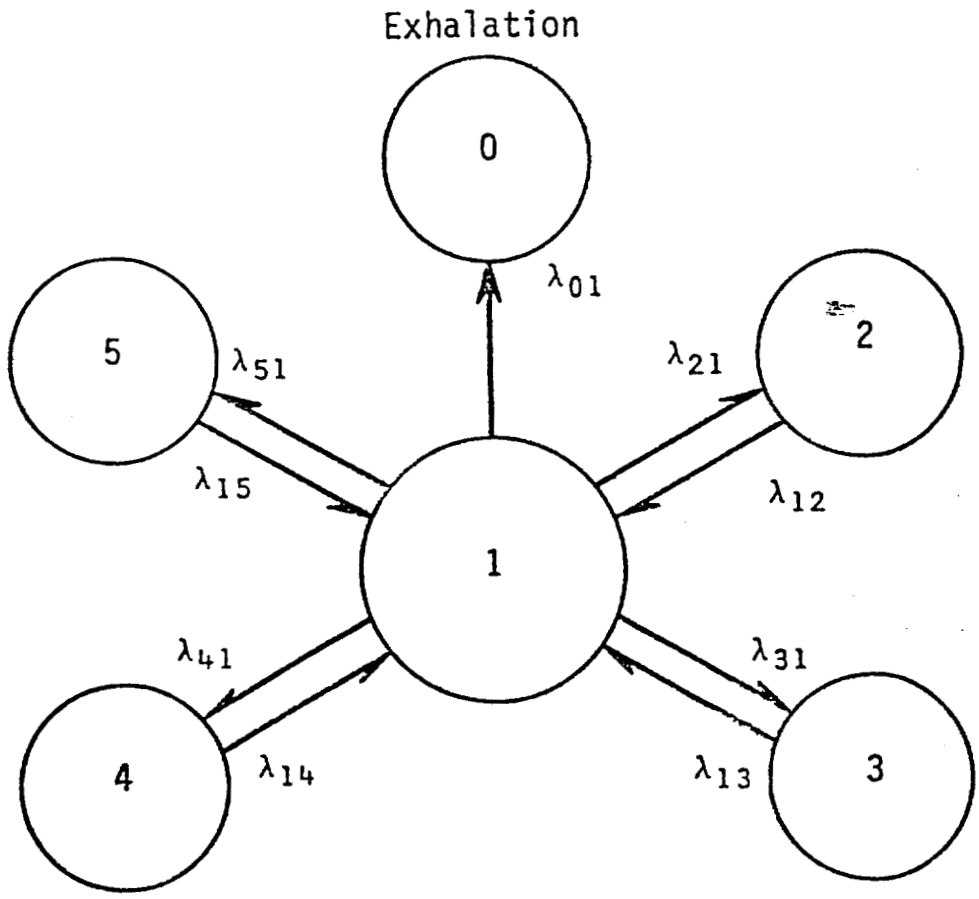

Fig. 20.2 | MAMMILLARY MODEL FOR RADON

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TABLE 20.1 CONSTANTS FOR THE MAMMILLARY MODEL OF HUMAN RETENTION OF Rn FOLLOWING A SINGLE INHALATION BY MAN*

b_1	b_2	b_3	b_4	b_5
6.12D-03	8.63D-03	1.98D-02	9.13D-02	8.74D-01
λ_1	λ_2	λ_3	λ_4	λ_5
5.00D-04	3.29D-03	1.67D-02	1.55D-01	1.82D 00
λ_{11}	λ_{12}	λ_{13}	λ_{14}	λ_{15}
1.80D 00	5.03D-04	3.32D-03	1.71D-02	1.70D-01
λ_{11}	λ_{21}	λ_{31}	λ_{41}	λ_{51}
1.80D 00	9.82D-03	1.39D-02	3.22D-02	1.43D-01

*Units on λ's are min^{-1}.

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TABLE 20.1a. C_{ji} Matrix for Rn Retention in Man

j \ i	1	2	3	4	5
1	1.91D-06	1.77D-05	2.06D-04	8.83D-03	9.91D-01
2	6.10D-03	-6.24D-05	-1.25D-04	-5.61D-04	-5.36D-03
3	9.43D-06	8.62D-03	-2.14D-04	-8.10D-04	-7.60D-03
4	3.70D-06	4.13D-05	1.97D-02	-2.06D-03	-1.77D-02
5	1.62D-06	1.52D-05	1.93D-04	8.59D-02	-8.61D-02

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TABLE 20.1b. TIME INTEGRALS (r_i) OF RETENTION IN THE ith COMPARTMENT OUT TO 50 YEARS

$r_1 = 0.622$ $r_2 = 9.65$ $r_3 = 2.51$ $r_4 = 1.16$ $r_5 = 0.523$

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activity in rats are used here. The rats were permitted to inhale ^{222}Rn for periods ranging from thirty minutes up to 48 hours. Samples of tissues and organs were obtained and analyzed for Rn concentrations. (We defer discussion of the loss of Rn from the tissue sample by diffusion and escape to the atmosphere until later in this report.) In general, it was found that fats (such as omental fat) contained ~ 5 μCi/cc if the inhaled air was at a level of 1 μCi/cc air, while for other non fatty tissues the Ostwald coefficient concentrated ^{222}Rn at values down to $\sim 1/30$ of this value. Nussbaum lists the data for rats and also some in vitro data on fat and blood and extrapolates these to organs and total body on the basis of the percentages of organs and tissues which are fat and non-fat. These data are shown in Tables 20.2 and 20.3.

By the single intake model for retention of ^{222}Rn, one obtains by integration the time integrals of activity for each compartment. These are indicated by r_i for compartment i and are listed in Table 20.1b. These values indicate the equilibrium levels which would be reached if a person were continuously breathing atmospheric ^{222}Rn at a level of 1 μCi/cc. It will be recalled that the basic data on which Equation 7 is based are for an individual breathing 5 ℓ of air per minute and thus the levels would be in terms of pCi/kg, taking the density of the total body as essentially 1.

The activity in the compartments must now be assigned to various tissues and organs of the body to make a dose calculation possible. The data on distribution of activity at equilibrium are taken from Nussbaum[6] and, ignoring minor differences, may be grouped into three

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Table 20.2 Calculation of the Whole Body Solubility Coefficient of Radon in the Rat.

Tissue	% of Whole Body Wt. (90)	Radon Solubility Coefficient α'	Product $\alpha' \times$ % Body Wt.
Depot Fat	7.08	4.83	34.20
Muscle	45.50	0.154	7.01
Liver	4.15	0.306	1.27
Heart	0.289	0.221	0.064
Kidney	0.76	0.285	0.22
Testis	0.94	0.184	0.17
Brain	0.550	0.309	0.18
Blood	4.95	0.405	2.01
Skin			
Non-fat	16.88	0.15*	2.53
Fat	1.22	4.83	5.41
Supportive			
Non-fat	7.38	0.15*	1.11
Fat	0.30	4.83	1.45
Balance	10.1	0.30**	3.03
	100		58.65

Whole Body Solubility Coefficient: 0.59

*Solubility estimated to be approximately equivalent to that in physiological saline.

**Solubility estimated to be equal to or lower than the weighted mean value in heart, kidney, brain and liver; i.e. 0.303.

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Table 20.3 Nussbaum's Calculation of the Whole Body Solubility Coefficient of Radon in Man

Tissue	% of Whole Body Wt. (9)	Radon Solubility Coefficient α'	Product $\alpha' \times$ % Body Wt.
Muscle	43	0.154	6.62
Skin (2000gm) and Subcutaneous Tissue	8.7	0.154	1.30
Fat	14	4.83	67.62
Skeleton (less Marrow)	10	0.154	1.50
Red Marrow	2.1	0.43	0.90
Yellow Marrow	2.1	4.83	10.14
Blood	7.7	0.43	3.31
G.I. Tract	2.9	0.303*	0.88
Liver	2.4	0.306	0.73
Brain	2.1	0.309	0.65
Lungs (2)	1.4	0.303*	0.42
Lymphoid Tissue	1.0	0.303*	0.30
Kidneys (2)	0.43	0.285	0.12
Heart	0.43	0.221	0.10
Spleen	0.21	0.303*	0.06
Urinary Bladder	0.21	0.154	0.03
Testes (2)	0.057	0.184	0.01
Balance	1.263	0.303*	0.38
Total Body	100.0		95.07

*Solubility is assumed to be approximately equal to the weighted mean of the values in heart, kidney, and brain.

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groups: separable fat, comprising ~ 12.5 kg; bone, heart, muscle, skin, testes, and urinary bladder which together comprise ~ 40 kg; and the other organs which comprise the remaining 17.5 kg of Reference Man. On the basis of Nussbaum's data,[6] Ostwald coefficients of ~ 5 for fat, ~ 0.15 for the group containing bone, muscle, etc., and ~ 0.4 for the remaining organs is suggested.

On this basis, the assignments to the compartments of these three groups of tissues are

$$5 \sum_{i=1}^{5} r_i \, \ell_{ij} = L_j \times W_j \qquad j = 1,2,3 \tag{11}$$

where L_j is ~ 5, ~ 0.4, ~ 0.15 for the three groups of tissues. It will quickly become apparent that the equations cannot be rigorously solved since

$$\sum_{j=1}^{3} \ell_{ij} = 1 \qquad i = 1,2,3,4,5, \tag{12}$$

and this requires by addition of all the equations that

$$5 \times \sum_{i=1}^{5} \sum_{j=1}^{3} r_i \, \ell_{ij} = 72.275 \cong \sum_{j=1}^{3} L_j W_j = 75.5. \tag{13}$$

The discrepancy is only of the order of 4% and this seems acceptable in view of the widely different sources of the data. To avoid accumulation of errors, we reduce the right members by a factor of 1/1.044. Thus, the equations to be solved are the following:

$$0.622\ell_{11} + 9.65\ell_{12} + 2.5\ell_{13} + 1.16\ell_{14} + 0.523\ell_{15} = 12 \tag{14}$$

$$0.622\ell_{12} + 9.65\ell_{22} + 2.5\ell_{23} + 1.16\ell_{24} + 0.523\ell_{25} = 1.34 \, . \tag{15}$$

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If the equations can be solved, the third equation is automatically met since

$$\sum_{j=1}^{3} \ell_{ij} = 1.$$

One cannot hope for a unique solution since there are far too many unknowns. However, there is some guidance in the choice of values which reflect some facts concerning the distribution. For example, fat is known to have a high Ostwald coefficient and it is apparent from inspection that ℓ_{12} must be fairly close to 1. This suggests $\ell_{12} = 1$, $\ell_{22} = \ell_{32} = 0$. Similarly, a few trials suggest that ℓ_{13} is fairly large and consequently a suggested set of values $\ell_{13} = 0.6$, $\ell_{23} = \ell_{33} = 0.2$ seem acceptable. The remaining values are found by trial and error but are by no means unique. The completed set of values for the ℓ_{ij} are given in Table 20.7.

The above is only one choice for the ℓ_{ij} values. There are probably others which can be obtained by iteratively seeking other sets of values. In this report, use will be made of the values derived above. How closely does this model determine the activity in the body at equilibrium?

For the case of equilibrium for inhalation of 1 μCi/cc air, the total activity is given by

$$\int_0^\infty \frac{1\mu Ci}{cc} \times \frac{2 \times 10^7 \text{ cc/da}}{1440 \text{ min/da}} \times \frac{R_S(\tau)\, d\tau}{7 \times 10^4 \text{ gms}} \cong 2.8 \ \mu Ci/gm. \quad (16)$$

In Equation 9 we are assuming 1 μCi/cm^3 as the concentration in air, 2×10^7 cc of air breathed per day, and 7×10^4 grams in the total

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TABLE 20.7 FRACTIONS OF COMPARTMENTS ASSIGNED

TO THE TISSUE GROUPS

	1	2	3	4	5
1	.225	1	.6	.5	.25
2	.225	0	.2	.5	.25
3	.55	0	.2	0	.5

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mass of the body. The value obtained from Equation (16) is ~ 3 times higher than Nussbaum predicts for man (Table 20.3). Reasons for the overestimates were sought, and it is believed the minute volume of air breathed by Reference Man

$$\left(\frac{2 \times 10^7 \text{ cc}}{1.44 \times 10^3 \text{ min}} \simeq 14 \times 10^3 \text{ cc/min}\right)$$

and used in obtaining Equation 9 may be partly responsible for the increase. The breathing rate of the human subject in the experiment of Harley et al. was 5×10^3 cc/min. In addition, there may be some individual variation and possibly some species differences between the Ostwald coefficients of a tissue in a rat and in man. This discrepancy by a factor of 2.8 is well within the range of variation usually found in biological experiments. This possible overestimate of uptake and retention is accepted here because no biological data are known to the authors which might resolve the question and also because the model will be used principally to estimate retention of short-lived radionuclides and this may introduce another uncertainty in that not only the activities in the various tissues, but also the time scale for their rate of build-up and removal are involved. This model using the breathing rate for reference man will now be extended to other inert gases, namely, Xe, Kr, and Ar.

In the case of Xe, there are human data on concentration in fat and blood and plasma, but experimental data on tissue distribution have not been found (Snyder et al.[7]). The same is true of data on Kr;

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Ostwald coefficients for blood and oils and fats are available (Snyder et al.). In the case of Ar, the only data seems to be those obtained in lab studies by the chemists on uptake by water and olive oil (Lawrence et al.[8]). Lawrence has chosen, from the reference cited, values of the Ostwald coefficients and plotted them versus the molecular weight of the gas atoms and a version of this graph is seen in Fig. 20.3. As can be noted, the Ostwald coefficient for fat decreases more steeply with decrease in atomic weight than do the values for water or plasma. This has been known by chemists for many years, and they expressed it in terms of the ratio of Ostwald coefficients in oil to that in water which they called the oil to water partition coefficients (Lawrence et al.). How should the mammillary model be modified to incorporate this effect?

Integration of Equation 6 indicates the equilibrium level of the gas in the total compartment system will decrease (in that the equilibrium level is given by the time integral out to 50 years) in inverse proportion to the elimination rate constants. Thus, if all the elimination constants are increased by a factor of 10, the concentration in the total body will decrease by a factor of 10. Actually the elimination rate constants of all exponentials will be multiplied by the factor $(L_{Xe}/L_{Rn})_{non\text{-}fat}$, necessary to account for the value for non-fat tissues. The coefficients of the two longer-termed exponentials (which largely represent fat) are multiplied by the factor

$$\left(\frac{L_{Rn}}{L_{Xe}}\right)_{NF} \Big/ \left(\frac{L_{Rn}}{L_{Xe}}\right)_{F} .$$

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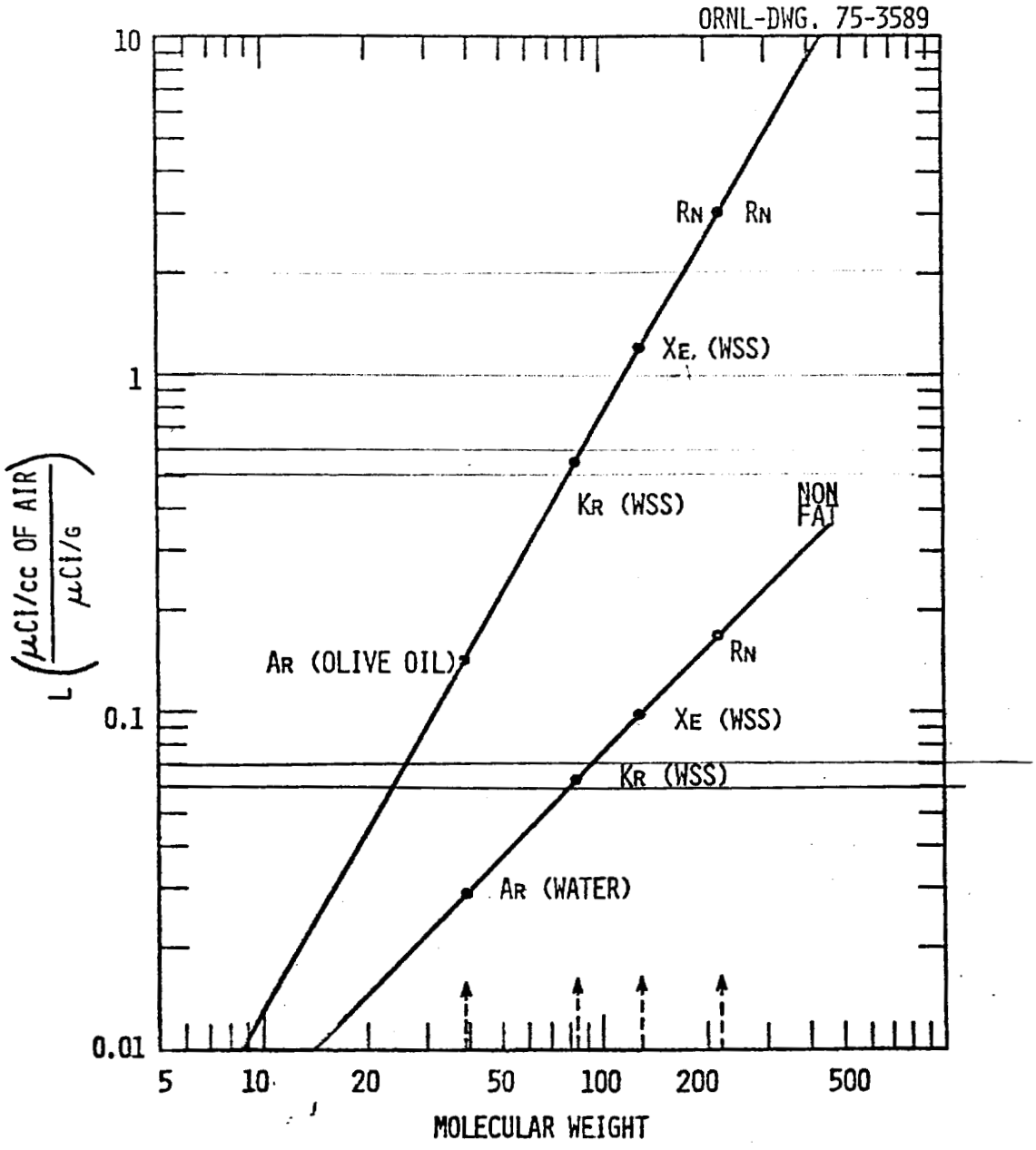

Fig. 20.3 Plot of L (the Ostwald solubility coefficient) for fatty tissues and oil and non-fat tissues versus molecular weight of the noble gas.

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The differences between these old and new coefficients is added to the coefficient of the shortest term exponential. This is necessary in order that the sum of the coefficients adds to unity. For example, the ratio of L for Xe in non-fat tissue to that for Rn in non-fat tissue is $\sim \frac{0.15}{0.08} \simeq 2$. So the elimination rate constants for Rn are multiplied by a factor of 2. For the fatty tissue, the value of L for Rn is ~ 5 while for Xe it is ~ 2 or a decrease by a factor of $\sim 2.5 = 5/2$. Thus, to decrease the coefficients of the two long-term exponentials in the Rn retention equation, the factor is $2/2.5 = 0.8$. So, the two coefficients of the long-term exponentials of 0.005 and 0.009 are multiplied by 0.8 to obtain 0.004 and 0.0072 and the difference (.005 - .004 and .009 - .0072) and these are added to the coefficient of the shortest term exponential whose value is 0.874, thus producing ~ 0.877. The general procedure is to get the ratio of the Ostwald coefficient for the fatty tissues, divide that ratio by the ratio of the Ostwald coefficient for the non-fatty tissues, decrease the coefficients of the two long term exponentials by this latter factor and place the difference in the coefficient of the shortest term exponential. The above procedure is used to obtain retention equations for the other noble gases, Xe, Kr, and Ar.

Tables 20.4, 20.5, and 20.6 present the parameters of the total body retention equations and the λ_{ij} for the mammillary model for Xe, Kr, and Ar, respectively, as obtained from the Rn equation for total body retention. Tables 20.4a, 20.5a, and 20.6a present the coefficients of the exponential terms C_{ji} for the compartments of the mammillary model for Xe, Kr, and Ar as obtained from the MAMX code.

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TABLE 20.4. MAMMILLARY MODEL FOR RETENTION OF Xe FOLLOWING A SINGLE INHALATION BY MAN*

b_1	b_2	b_3	b_4	b_5
3.00D-03	5.40D-03	2.00D-02	9.20D-02	8.80D-01
λ_1	λ_2	λ_3	λ_4	λ_5
7.50D-04	4.94D-03	2.53D-02	2.33D-01	2.70D 00
λ_{11}	λ_{12}	λ_{13}	λ_{14}	λ_{15}
2.68D 00	7.52D-04	4.97D-03	2.58D-02	2.55D-01
λ_{11}	λ_{21}	λ_{31}	λ_{41}	λ_{51}
2.68D 00	7.18D-03	1.29D-02	4.79D-02	2.13D-01

*Units on λ's are min^{-1}.

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TABLE 20.5. MAMMILLARY MODEL FOR RETENTION OF Kr FOLLOWING A SINGLE INHALATION BY MAN*

b_1	b_2	b_3	b_4	b_5
1.50D-03	2.70D-03	2.00D-02	9.20D-02	8.63D-01
λ_1	λ_2	λ_3	λ_4	λ_5
1.50D-03	9.87D-03	5.06D-02	4.65D-01	5.46D 00
λ_{11}	λ_{12}	λ_{13}	λ_{14}	λ_{15}
5.41D 00	1.50D-03	9.90D-03	5.16D-02	5.09D-01
λ_{11}	λ_{21}	λ_{31}	λ_{41}	λ_{51}
5.41D 00	7.29D-03	1.30D-02	9.64D-02	4.29D-01

*Units on λ's are min^{-1}.

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TABLE 20.6. MAMMILLARY MODEL FOR RETENTION OF Ar FOLLOWING A SINGLE INHALATION BY MAN*

b_1	b_2	b_3	b_4	b_5
8.00D-04	1.50D-03	2.05D-02	9.20D-02	8.86D-01
λ_1	λ_2	λ_3	λ_4	λ_5
2.50D-03	1.65D-02	8.43D-02	7.75D-1	9.10D 00
λ_{11}	λ_{12}	λ_{13}	λ_{14}	λ_{15}
1.81D-01	5.00D-03	3.29D-02	1.72D-01	1.70D 00
λ_{11}	λ_{21}	λ_{31}	λ_{41}	λ_{51}
1.81D-01	1.38D-02	2.40D-02	3.28D-01	1.43D 00

*Units on λ's are min^{-1}.

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TABLE 20.4a. C_{ji} MATRIX FOR Xe RETENTION IN MAN

9.31D-07	1.11D-05	2.11D-04	8.92D-03	9.91D-01
2.96D-03	-1.91D-05	-6.18D-05	-2.77D-04	-2.64D-03
2.87D-06	5.37D-03	-1.34D-04	-5.05D-04	-4.74D-04
1.79D-06	2.56D-05	1.98D-02	-2.07D-03	-1.77D-02
7.88D-07	9.48D-06	1.96D-02	8.59D-02	-8.61D-02

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TABLE 20.5a. C_{ji} MATRIX FOR Kr RETENTION IN MAN

4.62D-07	5.47D-06	2.08D-04	8.79D-03	9.91D-01
1.50D-03	-4.76D-06	-3.09D-05	-1.38D-04	-1.33D-03
7.16D-07	2.88D-03	-6.64D-05	-2.51D-04	-2.37D-03
8.89D-07	1.26D-05	1.99D-02	-2.05D-03	-1.77D-02
3.91D-07	4.70D-06	1.94D-04	8.56D-02	-8.59D-02

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TABLE 20.6a. C_{ji} MATRIX FOR Ar RETENTION IN MAN

2.46D-07	3.03D-06	2.12D-04	8.77D-03	9.91D-01
7.98D-04	-1.41D-06	-1.68D-05	-7.36D-05	-7.07D-04
2.12D-07	1.49D-03	-3.77D-05	-1.39D-04	-1.31D-03
4.83D-07	7.16D-06	2.01D-02	-2.09D-03	-1.81D-02
2.07D-07	2.60D-06	1.98D-04	8.55D-02	-8.57D-02

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The values of ℓ_{ij} in the three groups of tissues mentioned in the preceding are shown for Rn in Table 20.7. The equations for Xe, Kr, and Ar in the three groups of tissues are not given but may be estimated similarly to the procedure which can be used to obtain the equations for Rn in the three tissue groups. Thus, a metabolic model is now available for internal dose estimation for a single intake, via inhalation of the radionuclides of Rn, Xe, Kr, and Ar. Needless to say, it must be remembered, only a limited amount of data has been found to generate these models. They need to be tested against experimental data on man. No use of the diffusion coefficient for each of the noble gases has been made and this might be a drawback for the above models. Further theoretical studies need to be carried out coupled with an experimental program to provide better metabolic models for internal dose estimation.

The errors in the experimental data of Nussbaum and the effect of the breathing rate on clearance of inert gas from the body need to be discussed. As regards the Rn data on rats, Nussbaum did perform an experiment to estimate loss of Rn from the tissues. He estimates that on standing in the atmosphere for a period of 4½ hours, not more than ~3% of the Rn was lost from the dissected tissues. He is careful to point out that his estimates of L are probably underestimates rather than overestimates for various reasons (Nussbaum).[6] As regards the effect of breathing rate on Rn clearance and buildup in the human body, the equilibrium level is probably not affected. But the rate of attainment of equilibrium and loss probably is slower for a slow breathing rate and higher for a high breathing rate. How the

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exhalation rate curve given by Harley et al.[4] for a breathing rate of 5 ℓ/min would be shifted to a different rate needs to be tested on man and the effect on the deconvolution process needs to be checked.

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