放射線 防禦學會誌
第8卷 第2號 1983

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Calculation of Internal Exposure Dose in Korean Man Resulting from Single and Chronic Intake of Tritium

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Abstract

The doses to Korean adult by a single and chronic intake of tritiated water are determined using a three compartment model, which describes the retention of tritium radionuclide in body water and in bound organic form in the body. The results show that the total dose of a single intake, using retention half-time for the three-compartment of 9, 30, and 450 days, is 17.64 mrads (176.4 μGy) per 1mCi/kg (3.7×10^7Bq/kg) intake, 97% of which is due to tritium in body water and 3% to bound tritium in tissue. In the chronic intake of 1mCi/day(3.7×10^7Bq/day) tritiated water, the total dose is 85.5 mrad/day(0.855mGy/day).

Furthermore, in this study (MPC) a and (MPC)w values of tritium for Korean man are calculated by using the modified formula originated from ICRP Publication-2. From the results, we found that the (MPC) a,w values of ICRP underestimated approximately 50%, the (MPC)a,w values of Korean man must be elevated as high as approximately 50% than that of ICRP.

I. INTRODUCTION

Tritium (H-3), the heaviest and only one radioactive isotope in hydrogen nuclide, has been considered one of the least harzardous radioactive isotope[1], primarily because of its very low beta energy(Eavg= 5.7 keV) and the short initial biological half-life in man (8-10 days). But the increasing amounts of tritium in the environment from the expanding nuclear power industry and the corresponding increases in the numbers of workers at risk from high level intakes, and of the general population at risk from low level chronic exposure, require continual evaluation of the exposure dose to man and the biological effects of tritium. So far as the world's nuclear power program expands, it may even need to be controlled in order to keep doses by "As Low As Reasonably Achievable (ALARA)" principle.[2] It means that the integrity of the data used to derive maximum permissible dose (MPD) and maximum permissible concentration (MPC) values from estimated concentration in the environment should be carefully examined.

Woodard[3] already reported the information available on the incorporation of tritium into body components and discussed the nature of the biological effects. He showed that small amounts of tritium acquired as water by men are incorporated into tissue compounds and retained with half-times considerably longer than that associated with body water ratention. Based on the above consideration, Bennet[4] calculated the tissue dose from a single intake of 70mCi HTO by a 70kg standard man. And from the same consideration, calculation of a chronic intake was performed by NCRP[5] in the case of 1mCi/d intake. Also ICRP-2[6] has been evaluated MPC values of tritium in air and water for standard man in 1959, later replaced as reference man[7] in 1975 upon addition of supplementary data.

But their habitat, customs, body weight and each organ weight so on are different from those of Korean man. Therefore internal exposure dose and (MPC) a,w values for reference man can no longer be applicable to Korean man. So it need to determine the radiation exposure level for Korean man.

In this study, using reference Korean[8] and reference Japanese[9], analogous to Korean man, internal exposure doses were calculated by 3-compartment theory in the case of a single and chronic intake of tritium and (MPC)a,w values of tritium were calculated by the present method used in ICRP-2.

II. CALCULATION OF BODY BURDEN DOSE FOR TRITIUM.

II-1. N-Compartment Theory

Many of the complexities, associated with the involved pattern of distribution, fixation and elimination of radioisotopes within a living organism, can be eliminated if the so called n-compartment mathematical model of the living organism is employed.

This model visualizes the organism[10] as being composed of a number (n) of compartments that are interconnected by so called "first order reactions". First order reactions are term used to describe reactions in which the amount of radioisotope leaving a given compartment per unit time is proportional to the amount present in that compartment at that time. The differencial equation governing the time rate of change of q_i is

$$\frac{dq_i}{dt}=-\lambda_p q_i-k_{i0}q_j+\sum_{j=1}^{n}(k_{ji}q_j-k_{ij}q_i)$$

Where q_i=total radioactivity in the i-th compartment

k_{ij}=partial-turnover rate of compartment i to compartment j

k_{i0}=partial-turnover rate of compartment i to the out side

λ_p=physical decay constant of the radioisotopic species under consideration

n=number of compartment

The first term on the right represents the loss from compartment i because of radioactive decay. The second term represents elimination loss because of excretion out of the compartment system. The first term within the summation sign refers to gain of activity in compartment i because of transfer from all other compartments in turn. The second term within the summation sign refers to loss of activity from compartment i because of transfer to all other compartment in turn.

II-2. Calculation of a Single Intake.

The dose to tissue following an intake of tritium arises from tritium in body water, the tissue free-water tritium (TFWT), and from tritium combined in tissue (TCT). The model used for the calculation is represented by the following diagram.

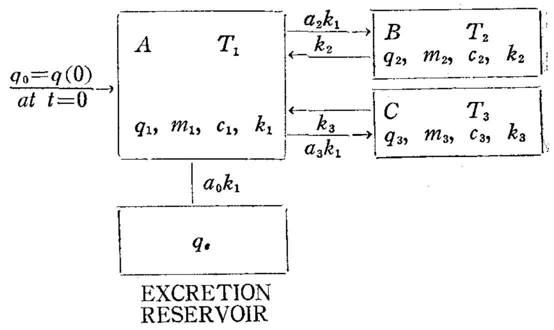

Fig. 1. Three-Compartment Model of Hydrogen in Body

A is the body water compartment, B and C are bound compartment. q_e represents tritium elimination from the body. The transfer coefficients(k_1, k_2, k_3) represent constant fractional exchange of tritium in the compartment. Body water (36 kg), compartment A, is assumed to be 60% of the body mass (60kg). Approximately 9kg of actively metabolizing tissue solids contain in the body. The dry tissue solids contain 7~8% hydrogen(8% assumed here), and this amount of organically bound hydrogen is distributed between compartment B and C, where the ratio of B to C is 1 to 5. So B and C compartment sizes are 120g of *H* and 600g of *H*, respectively. Also wet tissue is assumed to be consist of 75% water and 25% tissue solid.

The integral exposures from TFWT and TCT in 2000 days following an intake of 60 mCi HTO is calculated by the formula.

TFWT;

$$\frac{60\text{mCi}}{36\text{kgH}_2\text{O}}\times\frac{0.75\text{kg H}_2\text{O}}{1\text{kg wet tissue}}\times\int_0^{2000} q_1 dt \quad \cdots\cdots(1)$$

TCT;

$$\frac{60\text{mCi}}{9\text{kg tissue solids}}\times\frac{0.25\text{kg tissue solids}}{1\text{kg wet tissue}}\times\int_0^{2000} q_{2,3} dt \quad \cdots\cdots(2)$$

To calculate q_1, q_2, q_3, we use the following differential equations and initial conditions.

$$\frac{dq_1}{dt}=-\lambda_p q_1-a_e k_1 q_1-a_2 k_1 q_1-a_3 k_1 q_1+k_2 q_2+k_3 q_3$$

$$=-(\lambda_p+k_1)q_1+k_2 q_2+k_3 q_3 \quad \cdots\cdots(3)$$

$$\frac{dq_2}{dt}=-\lambda_p q_2-k_2 q_2+a_2 k_1 q_1$$

$$=-(\lambda_p+k_2)q_2+a_2 k_1 q_1 \quad \cdots\cdots(4)$$

$$\frac{dq_3}{dt}=-\lambda_p q_3-k_3 q_3+a_3 k_1 q_1$$

$$=-(\lambda_p+k_3)q_3+a_3 k_1 q_1 \quad \cdots\cdots(5)$$

$$\frac{dq_e}{dt}=-\lambda_p q_e+a_e k_1 q_1 \quad \cdots\cdots(6)$$

where at $t=0$, $q_1(0)=q_0$ and $q_2(0)=q_3(0)=0$

In these formula, retention quantity of radioisotope $q(0)=q_0$(microcuries) is introduced into compartment *A* at $t=0$. The turn-over rate of compartment *A*, *B*, and *C* are k_1, k_2, k_3 respectively. This turn-over rate is divided into three part, $a_e k_1$, the fraction given off per unit time to the excretion reservoir, $a_2 k_1$ and $a_3 k_1$ are the fraction given off per unit time to the compartment 2 and 3 respectively.(obviously, $a_e+a_2+a_3=1$)

To solve the above differential equation, we use the Laplace transform to each formula, so

$$SQ_1(s)-q_0=-(\lambda_p+k_1)Q_1(s)+k_2Q_2(s)+k_3Q_3(s) \quad \cdots\cdots(7)$$

$$SQ_2(s)=-(\lambda_p+k_2)Q_2(s)+a_2k_1Q_1(s) \quad \cdots\cdots(8)$$

$$SQ_3(s)=-(\lambda_p+k_3)Q_3(s)+a_3k_1Q_1(s) \quad \cdots\cdots(9)$$

$$SQ_e(s)=-\lambda_p Q_e(s)+a_e k_1 Q_1(s) \quad \cdots\cdots(10)$$

In formula (7), the last term of right side is canceled for very small value. Then using the formula (7), (8), and (9), we obtain following formula.

$$Q_1(s)=\frac{(S+\lambda_p+k_2)q_0}{(S+\lambda_p+\mu_1)(S+\lambda_p+\mu_2)} \quad \cdots\cdots(11)$$

Therefore,

$$q_1(t)=\frac{q_0}{\mu_2-\mu_1}e^{-\lambda_p t}[(\mu_2-k_1)e^{-\mu_1 t}+(k_1-\mu_1)e^{-\mu_2 t}] \quad \cdots\cdots(12)$$

Where $\mu_1=[(k_1+k_2)-\sqrt{(k_1-k_2)^2+4k_1k_2a_2}]/2$

$\mu_2=[(k_1+k_2)+\sqrt{(k_1-k_2)^2+4k_1k_2a_2}]/2$

Substituting (12) for (4), (5), and (6), we obtain the following solutions.

$$q_2(t)=\frac{a_2k_1q_0}{\mu_2-\mu_1}e^{-\lambda_p t}[e^{-\mu_1 t}-e^{\mu_2 t}] \quad \cdots\cdots(13)$$

$$q_3(t)=\frac{a_3k_1q_0}{\mu_2-\mu_1}e^{-\lambda_p t}\left[\frac{(\mu_2-\mu_1)}{(k_3-\mu_2)}e^{-\mu_1 t}+\frac{(k_1-\mu_1)}{(k_3-\mu_2)}e^{-\mu_1 t}+\frac{(k_2-k_3)(\mu_2-\mu_1)}{(k_3-\mu_1)(k_3-\mu_2)}e^{-k_3 t}\right] \quad \cdots\cdots(14)$$

II-3. Calculation of a Chronic Intake

The three compartment model can be also used for chronic intake by computing the compartment contents on a daily intake basis.

This model assums that the tritium becomes uniformly combined in actively metabolizing tissue and that all of the hydrogen of active tissue solids exchangeable. This assumption leads to equilibrium is state in the body.

In the calculation, a water balance of 3.08*l*/d has been assumed, based on the 36kg body water compartment size and the 9, 30, and 450 days retention half times. For an HTO intake of 1mCi/d(3.7×10⁷ Bq/d), the equilibrium specific activity is

$$1\text{mCi/d}\div\left[3.08\frac{\text{kg H}_2\text{O}}{\text{d}}\times\frac{1\text{kg H}}{9\text{kg H}_2\text{O}}\right]$$

$$=2.92\text{mCi/kgH}(1.08\times10^8\ \text{Bq/kg H})$$

The tritium content of each compartment, the hydrogen content times the specific activity, at equilibrium is 13.6, 0.35, and 1.75mCi for *A*, *B*, *C*, respectively.

Thus, the equilibrium dose rate to wet tissue is

$$A=\frac{13.6\text{mCi}}{36\text{kg H}_2\text{O}}\times\frac{0.75\text{kg H}_2\text{O}}{\text{kg wet tissue}}\times\frac{0.29\text{rad/d}}{\text{mCi/kg}}$$

$$=70\frac{\text{mrad}}{\text{d}}$$

$$B=\frac{0.35\text{mCi}}{9\text{kg H}_2\text{O}}\times\frac{0.25\text{kg H}_2\text{O}}{\text{kg wet tissue}}\times\frac{0.29\text{rad/d}}{\text{mCi/kg}}$$

$$=2.8\frac{\text{mrad}}{\text{d}}$$

$$C=\frac{1.75\text{mCi}}{9\text{kg H}_2\text{O}}\times\frac{0.25\text{kg H}_2\text{O}}{\text{kg wet tissue}}\times\frac{0.29\text{rad/d}}{\text{mCi/kg}}$$

$$=12.7\frac{\text{mrad}}{\text{d}}$$

The total dose is therefore 85.5 mrad/d(0.855mGy/d).

III. CALCULATION OF $(\text{MPC})_{\text{H-3}}$ FOR REFERENCE MAN AND KOREAN MAN

In the establishment of maximum permissible concentration values for internal exposure, it is assumed that elimination of radioactivity from a critical organ is an exponential function of time. Therefore if rate of P microcuries per day is to be intaked, the differential equation governing the critical organ of radioactivity is

$$\frac{d}{dt}(qf_2)=-\lambda_{eff}tqf_2+P$$

Where q and λ_{eff} are the total activity and effective decay constant, respectively and f_2 is the fraction of this body burden in the critical organ, so qf_2 is the burden of radionuclide in the critical body burden (μCi).

Solving with $qf_2=0$, when $t=0$, gives

$$qf_2=P[1-\exp(-\lambda_{eff}t)]/\lambda_{eff}$$

i.e. $C=qf_2\lambda_{eff}/S[1-\exp(-\lambda_{eff}t)]$

where $P=CS$ and C is the concentration (μCi/cm^3) of the radionuclides taken into the body and S is the product of the average rate of intake(cm^3/day) and the fraction of the microcuries arriving in the critical body organ.

It is assumed[11] that a reference man breathes 2×10^7cm^3 of air per day and consumes 2200cm^3 of water per day and that breathes and consumes half of his daily intake of air and water during the working time. For the reference man, an occupational exposure of 8hr/day, 5 days/week, 50 weeks/yr, it is

$Sw=1100\times5/7\times50/52\ fw$ cm^3 of water/day

and $Sa=10^7\times5/7\times50/52\ fa$ cm^3 of air/day

Also, it is assumed that a Korean man breathes and consumes the same amount of air and water as an reference man, but an occupational exposure of 8hr/day, 5.5 days/week, 50 weeks/years is to be taken, it is following that

$Sw=1100\times5.5/7\times50/52\ fw$ cm^3 of air/day

and $Sa=10^7\times5.5/7\times50/52\ fa$ cm^2 of air/day

where fw is the product of the fraction of the radionuclide reaching the blood (f_1), and the fraction of the nuclide in the blood reaching the reference organ(f_2'), fa is the fraction of inhaled radionuclide reaching the reference organ.

So $$(\text{MPC})a=\frac{10^{-7}qf_2}{T_{eff}f_a(1-e^{\lambda_{eff}t})}\mu\text{Ci/cm}^3$$

$$(\text{MPC})w=\frac{9.2\times10^{-4}qf_2}{T_{eff}f_w(1-e^{\lambda_{eff}t})}\mu\text{Ci/cm}^3$$

for reference man, and

$$(\text{MPC})a=\frac{9.2\times10^{-8}qf_2}{T_{eff}f_w(1-e^{\lambda_{eff}t})}\mu\text{Ci/cm}^3$$

$$(\text{MPC})w=\frac{8.3\times10^{-4}qf_2}{T_{eff}f_w(1-e^{\lambda_{eff}t})}\mu\text{Ci/cm}^3$$

for Korean man.

Where $T_{eff}=0.693\ \lambda^{-1}{}_{eff}=0.639\ (\lambda_p+\lambda_b)^{-1}$ is the effective half-life and t is the period of exposure in days.

IV. RESULTS AND DISCUSSION

Solution of equation (1) and (2) substituted by (12), (13), (14) for the tissue dose following an single intake of trititum have been obtained by computer calculation. The results of calculation are given in Table 1 in which summarized bellow, and in Fig. 2 and Fig. 3.

In Fig. 2 and Fig. 3, the dashed line shows Bennet results from application of the three compartment model of reference man, and solid line shows the presently calculated results for Korean man. The TFWT is approximately, consistent with the above two calculation, but TCT is small in Korean man compared to reference man because body mass and actively metabolizing tissue solid of Korean man (60kg and 9kg respectively) are different from those of reference man(70kg, 10kg respectively). Therefore, the total dose estimate of Korean man are slightly small than that of reference man(approximately 87%).

Fig. 4 shows the total retention in the body and also the retention in the body water (A) and bound compartments (B+C) in respect to average elimination half-times of Korean man.

The tissue dose is due 97% to tritium in body

Table 1. Tissue Dose (1 mCi/kg intake) in K.M.* and R.M.** which have a elimination half-times of 9-30 -450 days

Tissue Dose(1 mCi/kg intake)							
TFWT		TCT		Total		unit	K.M./R.M.
K.M.	R.M.	K.M.	R.M.	K.M.	R.M.		In Total(%)
17.21	17.0	0.52	3.3	17.64	20.3	mCi days/kg	87
5	4.9	0.15	1.0	5.1	5.9	rads	87

* Korean Man
** Reference Man

Table 2 Comparison of (MPC) a and (MPC) w Value of Reference Man and Korean Man with ICRP Results.

Radionuclide and Type of Decay	Organ of Reference	MPBB in Total Body $q(\mu Ci)$	MPC For 40h. week (MPC)w ($\mu Ci/cm^3$)	MPC For 40h. week (MPC)a ($\mu Ci/cm^3$)	MPC For 168h. week (MPC)w ($\mu Ci/cm^3$)	MPC For 168h. week (MPC)a ($\mu Ci/cm^3$)
	Body Tissue	10^3	0.1	5×10^{-6}	0.03	2×10^{-6}
	(Body Water)	(1.88×10^3)	(0.144)	(5×10^{-5})	(0.05)	(5.4×10^{-6})
$^3_1$H(HTO or ^3H_2O)		$[1.62\times10^3]$	[0.146]	$[1.59\times10^{-5}]$	[0.06]	$[6\times10^{-6}]$
β^-(Soluble)	Total body	2×10^3	0.2	8×10^{-6}	0.95	3×10^{-6}
		(3.14×10^3)	(0.24)	(1.3×10^{-5})	(0.08)	(4.5×10^{-6})
		$[2.69\times10^3]$	[0.24]	$[1.3\times10^{-5}]$	[0.09]	$[5\times10^{-6}]$

water; 3% is from combined tritium in tissue. A maximum of 0.7% of the tritium intake becomes combined (B+C), this maximum being reached in about 30 days. Fifty percent of the total tissue dose is excreted within 10 days, and over 100 days it may be thought that the total tissue dose is excreted almost all of them.

For dose of chronic intake of 1mCi/day tritiated water, the tissue dose of TFWT is 70 mrad/day and the dose of TCT is 15.5 mrad/day. So that the tissue dose is due 82% to tritium in body water, 18% is from combined tritium. This shows that the dose of chronic intake is larger than that of a single intake in combined tritium, because of equilibrium states between body water and combined tritium at all times.

A summary of all the (MPC) *a,w* values for Korean man and referenc man is given in Table 2. Three values are given for each situation. The first of these are quoted directly from ICRP-2 Tables. The values in rounded brackets thus ( ) are the

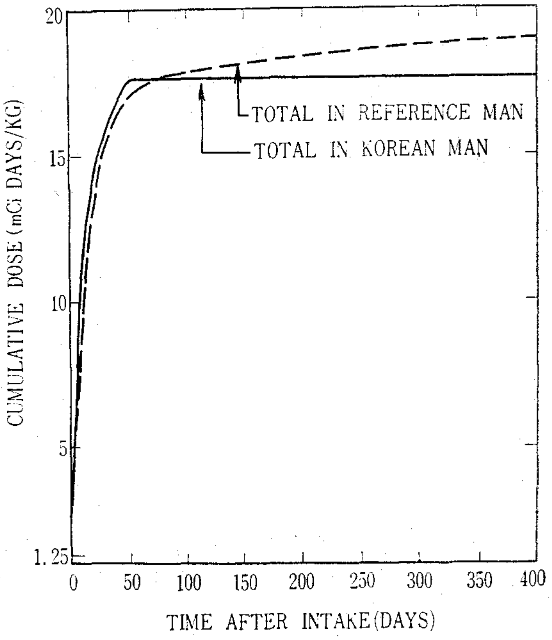

Fig. 2. Cumulative Dose of Tritium in Korean Man and Reference Man.

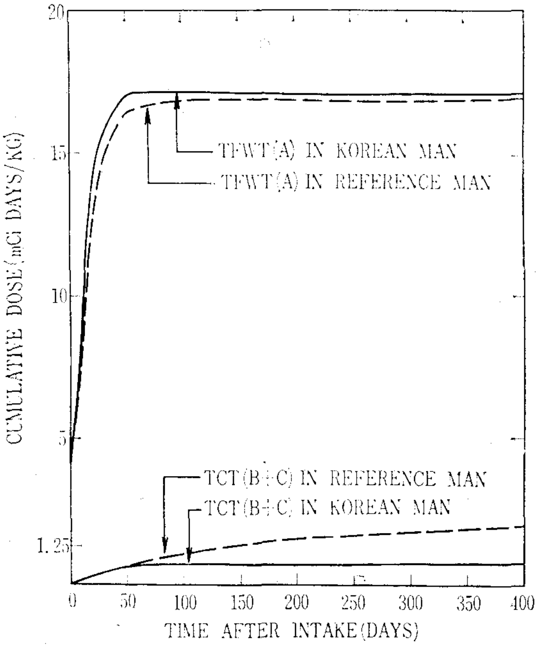

Fig. 3. Cumulative Dose ofTritium in Korean Man and Reference Man

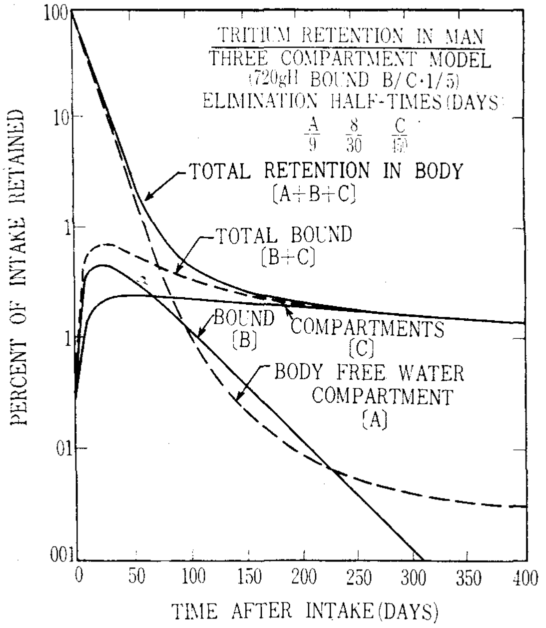

Fig. 4. Tritium retention in total body and in bound free water compartments-a three-component model with average elimination half-times.

(MPC) a,w values which have been calculated for the reference man. The final values in square brackets [ ] are the (MPC) *a,w* values for Korean man. From Table 2, the ICRP results were underestimated because the calculations were performed as quality factor of 1.7. The calculations in this study is as high as approximately 1.5 times than ICRP results by using the quality factor of 1. Reference man and Korean man are different from the body mass, but because the biological half-life is proportional to the body mass, the (MPC) *a,w* values are analogous each other.

V. CONCLUSSION

The calculation of body burden dose by a single intake in Korean man represents that 97% of the dose due to tritium in body water and 3% is from combined tritium in tissue. It is different from that of reference man, which is 87% of body water and 13% of combined tritium. In viewing totally, the ratio of Korean man to reference man in total dose is approximately 87%. The discripancy is due to the difference of body mass and actively metabolizing tissue solid. And in chronic intake, 82% of equilibrium dose rate is due to tritium in body water and 18% to bound tritium in tissue. From the above results, tritium combined in tissue is thus not the major contributor to the total dose to tissue following a single intake of HTO, but its contribution must not be ignored in chronic intake of HTO.

The MPC values of ICRP must be corrected by using of a quality factor of 1 for tritium. Hence, from the previous consideration it is likely that ICRP calculation have underestimated doses of approximately 50%. Therefore the (MPC) *a,w* values for Korean man must be elevated as high as approximately 50% than that of ICRP. This study used directly to various parameters of reference man such as elimination half-times, transfer coefficients, and water balance. Therefore further study will be required to establish the combined amounts, the retention half-times and the exact distribution pattern in the various critical components after internal deposition of trituim.

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트리튬(^{3}H)의 單一 및 晩性攝取에 대한 韓國人의 內部被曝 線量 計算

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요지

삼중수소의 단일 피폭과 만성피폭에 의한 한국인의 내부피복 선량을 삼단계형모델을 이용하여 계산하였다. 이 모델은 체내수분과 조직체 사이의 삼중 수소의 축적량을 잘 나타내 주는 것이다. 그 결과 삼단계형의 축적 반감기 9, 30과 450일을 사용한 단일 피폭의 총 선량은 1mCi/kg 섭취당 17.64 mrad였고 이것의 97%는 체내수분에 있는 삼중수소에 의한 선량이고 나머지 3%는 조직내 삼중수소에 의한 것이다. 그리고 1 mCi/day의 삼중 수소를 섭취하는 만성 피폭의 경우, 총 선량은 85.5 mrad/day이었다.

또한 본 연구에서는 한국인에 대한 최대허용 농도값을 선질계수 1을 사용하여 계산하였다. 그 결과, ICRP의 최대허용 농도값은 약 50%가량 낮게 평가되었으므로 한국인의 최대허용 농도값은 ICRP의 결과보다 약 50%높게 책정되어야만 한다.