Evaluation of Effective Dose on Tritium (HTO) Intake for CANDU' s Worker

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ABSTRACT

An evaluation of effective dose on tritium intake for CANDU nuclear power plants' worker was analytically conducted. The mathematical methods to calculate internal dose using the results of tritium bioassay with unknown intake time are derived and compared with the changes of variables such as sampling period, effective half-life of tritium, and relative concentration of tritium in urine.

An individual effective dose due to intake of tritiated water is, in general, evaluated by the results of successive bioassay using the linear interpolation method when the time of the exposure occurred is unknown. In the meanwhile, the acceptable criteria for determining the adequate evaluation model to estimate internal dose are practically applied on the basis of the upper limit of actual dose that could be received. However, the uncertainty in assessing the upper limits to the estimated dose shall not exceed 50% at the upper bound of the 95% confidence interval in accordance with *the Guidelines for Tritium Bioassay[3]*.

In this study, a couple of mathematical methods to evaluate internal dose from the tritium bioassay with unknown time of intake are derived and the comparative evaluation of effective dose on tritium intake for CANDU nuclear power plants' worker using those methods is conducted for sampling period, effective half-life of tritium, and relative concentration of tritium in urine.

As the results of this study, it is concluded that the exponential interpolation is more accurate than the linear interpolation and the mid-point intake assumption, which is generally used in the internal dosimetry, is well adopted in the exponential interpolation method. The applied methods for evaluating internal dose from the results of tritium bioassay under the assumption of both maximum single intake and minimum single intake could overestimate or underestimate the actual dose as the case may be.

1. Introduction

The dose assessment results of nuclear power plants' workers are essential for performing and establishing the radiation protection program or ALARA program. The nuclear power plant employer should guarantee the credibility of method and result of internal dosimetry for reporting to the government. And also, the regulatory agency should suggest the minimum requirements for the internal dosimetry.

In Korea, the Wolsong Unit 1, which is CANDU type Reactor with 678.7 MWe of capacity, has been operated since 1983. And also, the Wolsong units 2, 3 and 4 with 700 MWe capacity were constructed and began commercial operation in 1997, 1998, and 1999, respectively [1]. Since tritium (HTO) contributes the internal radiation exposure for Wolsong Plants' worker, it is obvious that internal dose of workers will be increased year by year in the future [2].

This study was intended to provide the information for establishing the regulatory requirement or guidelines for the tritium dosimetry. A variety of mathematical dose calculation methods used in Canada and USA were analyzed. The calculated doses and their relative errors by different methods for dose assessment were compared mutually.

2. Effective Dose Calculation from Bioassay Measurements

Individuals for dose assessment on intake of tritium are mainly CANDU workers, and their main intake pattern and type of tritium is chronic intake of tritiated water (HTO) [3]. Since the effective half-life of tritium is relatively short, the worker's urine should be sampled and measured periodically and the exposed dose should be evaluated. That is, the periodic assessment of exposed dose is applied as a routine monitoring method rather than the committed dose.

Therefore an annual effective dose, H_A is defined as sum of dose periodically evaluated, as follows [4]:

$$H_A = \sum_{i=1}^{n} H_i \,, \tag{1}$$

Where, H_i is effective dose evaluated during i period, and n is annual frequency of assessment.

(1) Acute Intake of Tritium

Acute intake or a single intake of tritium means that no intake of tritium takes place between successive bioassay or during the sampling period.

The concentration of tritium in urine (assumed here to be equal to that of any body fluid) sample at the time of T will be expressed as follows [4]:

$$C_T = C_0 e^{-\lambda T}, \tag{2}$$

Where, C_0 is the concentration of tritium in urine at time 0, and λ is the effective removal constant for that period. And the effective dose (H_a) will be written as follows [4]:

$$H_a = C_0 R \int_0^T e^{-\lambda t} dt = \left(\frac{C_0 R}{\lambda} \right) \left(1 - e^{-\lambda T} \right), \tag{3}$$

Where, R is the dose conversion factor.

(2) Chronic Intake of Tritium

The chronic intake of tritium means that a single or more intake of tritium occur(s) between successive bioassay.

When a single intake occurs between successive bioassay and the time of intake is known, the dose calculation equation at time t within the sampling period T will be described as follows [4]:

$$H_{ex} = H_1 + H_2 = \left(\frac{RC_0}{l_1}\right)\left(1 - e^{-l_1 t}\right) + \left(\frac{RC_T}{l_2}\right)\left(e^{-l_2(T-t)} - 1\right) \tag{4}$$

Assumed that $\lambda_1 = \lambda_2 = \lambda_{avg}$ = (ln 2)/(10 days) = 0.0693/day, the Eq. (4) can be formulated, so called the 'exponential model:

$$H_{ex} = \left(\frac{R}{l_{avg}}\right)\left[C_0\left(1 - e^{-l_{avg} t}\right) + C_T\left(e^{l_{avg}(T-t)} - 1\right)\right], \tag{5}$$

When a single or more intake(s) occur(s) between successive bioassay and the time of intake is unknown, tritium activity concentration varies in accordance with body fluid in Fig. 1.

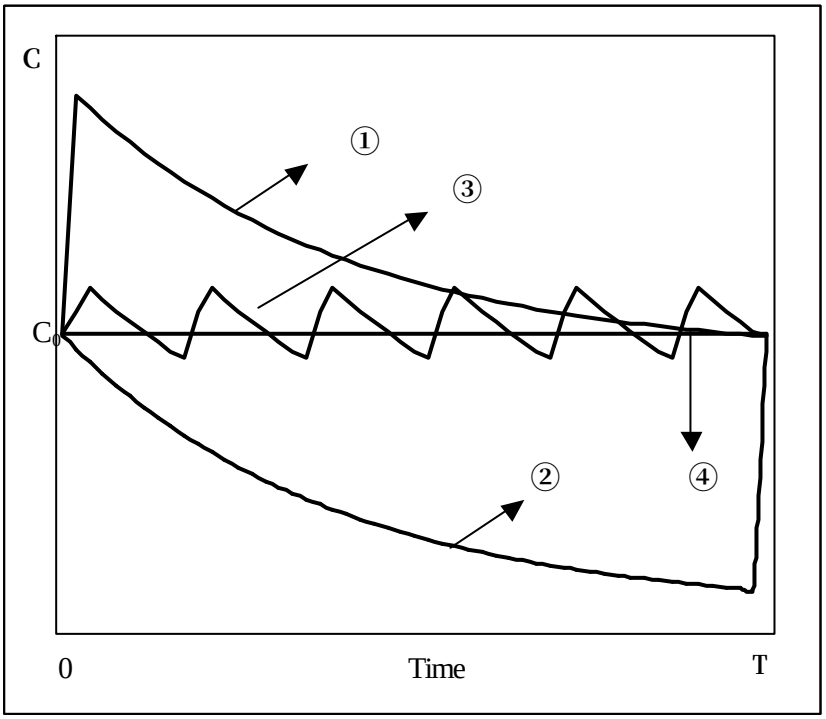

Figure 1. The variation of tritium concentration in body fluid

Where, numbers in Figure mean as follows;

① A single intake of tritium occurs just after sampling time, 0

② A single intake of tirtium occurs just before sampling time, T

③ Several or periodic intakes occur between 0 and T

④ Continuous intakes occur between 0 and T

If an initial concentration of tritium in urine sample C_0, the next concentration of tritium in urine sample C_T, and bioassay sampling time T are known, the following assumptions are possible; (i) the amount of tritium taken by an individual is a maximum, when an intake occurs just after sampling time, 0. Here, we are able to call this assumption a 'Maximum Intake Assumption' (curve ①), and (ii) the amount of tritium is a minimum, when an intake occurs just before sampling time, T. So we could call the assumption a 'Minimum Intake Assumption' (curve ②) and equations can be expressed [4].

$$H_{\max} = \left(\frac{RC_T}{l_{avg}}\right)\left(e^{l_{avg}T} - 1\right) \quad , \tag{6}$$

And,

$$H_{\min} = \left(\frac{RC_0}{l_{avg}}\right)\left(1 - e^{-l_{avg}T}\right), \tag{7}$$

But these equations are based on the very conservative or optimistic assumption. It will be more reasonable that a single intake has occurred within a whole period of sampling time has a uniform probability of occurrence. Then, dose calculation equation can be driven as follows. And we can call it as the *Uniform Distribution Assumption* [3]:

$$H_{uni.dist} = \frac{1}{T}\int_0^T H_{ex}(t)dt \, , \tag{8}$$

And from the Eq. (5)[3]:

$$H_{uni.dist} = RC_0\left[\frac{1}{l_{avg}} - \frac{\left(1 - e^{-l_{avg}T}\right)}{l_{avg}^2 T}\right] - RC_T\left[\frac{1}{l_{avg}} - \frac{\left(e^{l_{avg}T} - 1\right)}{l_{avg}^2 T}\right], \tag{9}$$

Several intakes of tritium are possible between successive bioassay, then a trend of tritium concentration in body fluid will be appeared as the curve 3. If intakes are more continuous for whole duration, the curve 3 will approach the curve 4, then the dose calculation equation will be Eq. (10) which linearly interpolates C_0 and C_T. It is known as the *linear interpolation method* [3]:

$$H_{lin} = \frac{RT\left(C_0 + C_T\right)}{2}, \tag{10}$$

Meanwhile, the U.S. NRC Regulatory Guide allows that a health physician could evaluate internal dose under the assumption of mid-point intake [5].

If an individual, who has taken some radioactive material, does not know the time of intake, then health physician could calculate internal dose of the person under the assumption of a single intake has taken a place at the mid-time (t=T/2) of sampling period. In this regard, plugging t = T/2 to Eq. (5), we can obtain the Eq. (11) and we can call it the *exponential interpolation method*:

$$H_{\exp} = \left(\frac{R}{l_{avg}}\right)\left[C_0\left(1-e^{-l_{avg}\frac{T}{2}}\right)+C_T\left(e^{l_{avg}\frac{T}{2}}-1\right)\right] \quad , \qquad (11)$$

A comparison of tritium activity concentration between linear interpolation method and exponential interpolation method is described in Fig. 2.

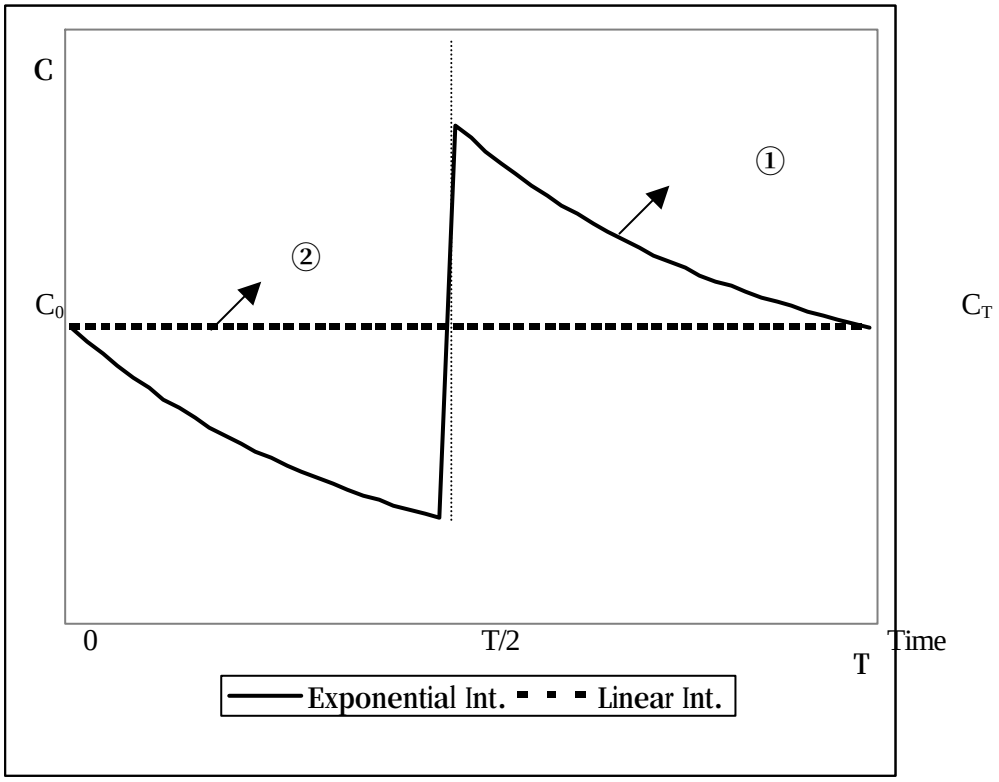

Figure 2. The comparison between exponential and linear interpolation methods

(3) Committed Effective Dose for Tritium Intake

When a worker completes his work or is dispatched, i.e. no more tritium intake, the committed dose could be assessed after the final bioassay measurement. The maximum value of the committed effective dose (H_C) may occur to a person who has the longest retention time [4]:

$$H_{C,\max} = \frac{RC_0}{l_{\min}}, \qquad (12)$$

The difference of accuracy between the average removal constant (λ_{avg} = 0.0693/day, when the $T_{1/2}$ of ^3H = 10 days) and the minimum removal constant (λ_{min} = 0.05/day, $T_{1/2}$ = 13.6 days) is less than 50%, the committed effective dose (H_C) can be expressed using the average removal constant as follows [4]:

$$H_C = \frac{RC_0}{l_{avg}}, \tag{13}$$

(4) Bioassay Measurements Frequency

The optimal sampling period for bioassay can be determined from the relative errors to the standard equation of dose calculation. The relative errors should be less than 50% with confidence level of 95%. According to the *Bioassay Guideline 2* and *HPS N13.14*, the uniform distribution assumption[3][4], Eq. (9) is selected as a standard method.

The effective half-life of tritium ranges 5.4 days < $T_{1/2}$ of ^3H < 13.6 days with 95% of confidence level, $\lambda = \lambda_{max}$ = (ln 2)/5.4 day^{-} could be applied. Using the linear interpolation method for calculating actual dose in Eq. (10), the sampling period of bioassay to satisfy relative errors R(lin) = $|$ [H(uni,dist) - H(lin)] / H(uni,dist) $| \leq$ 0.5 is 14 days [3]. Similarly, in order to acquire the maximum sampling period of exponential interpolation satisfying the 50% of accuracy condition, the relative errors, R(exp) = $|$ [H(uni,dist) - H(exp)] / H(uni,dist) $| \leq$ 0.5 can be used with same assumptions ($\lambda = \lambda_{max}$ = (ln 2)/5.4 day^{-1}, C_0 = 0, C_T = 5.4), sampling period is 32 days.

However, the average effective half life, 9.5 days is applied to H(exp) and 5.4 days to H(uni.dist), with another conditions are same (C_0 = 0, C_T = 5.4), the sampling period, T satisfying the R(exp) = $|$ [H(uni,dist) - H(exp)] / H(uni,dist) $| \leq$ 0.5 will be 20 days.

3. Evaluation of Dose Calculation Methods for Chronic Intake

(1) Sampling Periods

Assuming the effective half life of tritium is 9.5 days, the concentration of tritium in initial and last samples are all 1 μCi/L, the results from the dose calculation method for sampling period 1 to 36 days are shown in Figure 3. Relative errors to uniform distribution assumption with other methods are shown in Figure 4.

From Figures 3 and 4, the calculated doses from uniform distribution assumption, the linear interpolation and the exponential interpolation method show similar result within 50% of relative errors in whole range. But the relative error of exponential interpolation is lower than that of the linear interpolation. Minimum intake assumption shows more than 50% of relative errors after 17 days of sampling period and maximum intake assumption, the most conservative

method, tends to overestimate dose more than 50% of relative errors after 12 days.

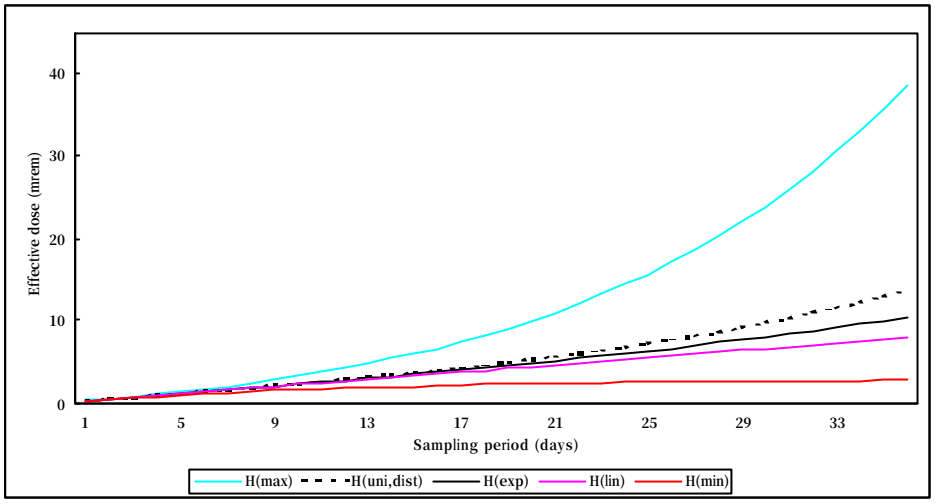

Figure 3. Comparison of dose calculation methods for various sampling period

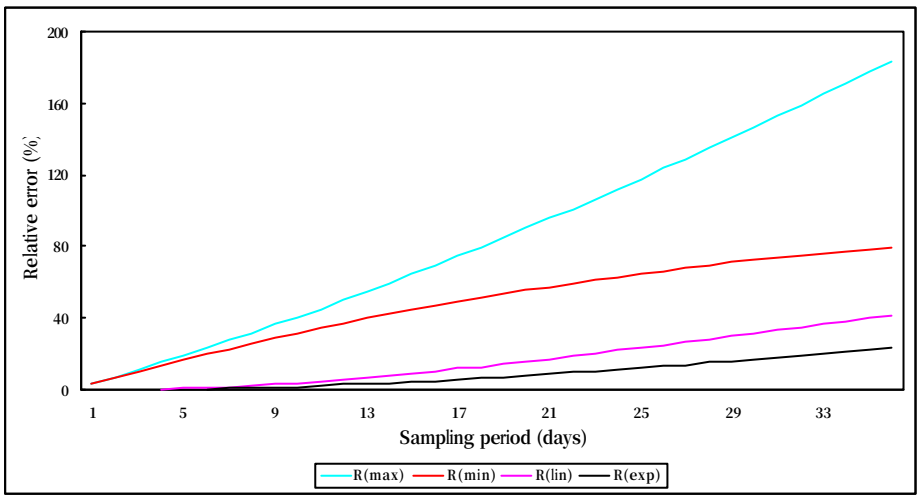

Figure 4. Comparison of relative errors to Uniform Distribution Assumption with other dose calculation methods for various sampling period

(2) Effective Half-life of Tritium

If a bioassay sampling period is 14 days, the concentration of tritium, initial and final sample are all 1 μCi/L, the results from the various dose calculation methods with changes of effective half- life are shown in Figures 5 and 6.

The calculated dose from maximum intake assumption results in highest value and Minimum Intake Assumption results in lowest value. The linear interpolation method shows the same value because it is not affected by effective half-life. The calculated doses from uniform distribution assumption, the linear interpolation method and the exponential interpolation method result in similar value within 50% of relative errors, but relative errors of the

exponential interpolation method are lower than those of the linear interpolation method. minimum intake assumption shows the relative errors more than 50% in range of the effective half-life less than 7.6 days and maximum intake assumption overestimates more than 50% of relative errors in range of effective half-life less than 10.9 days.

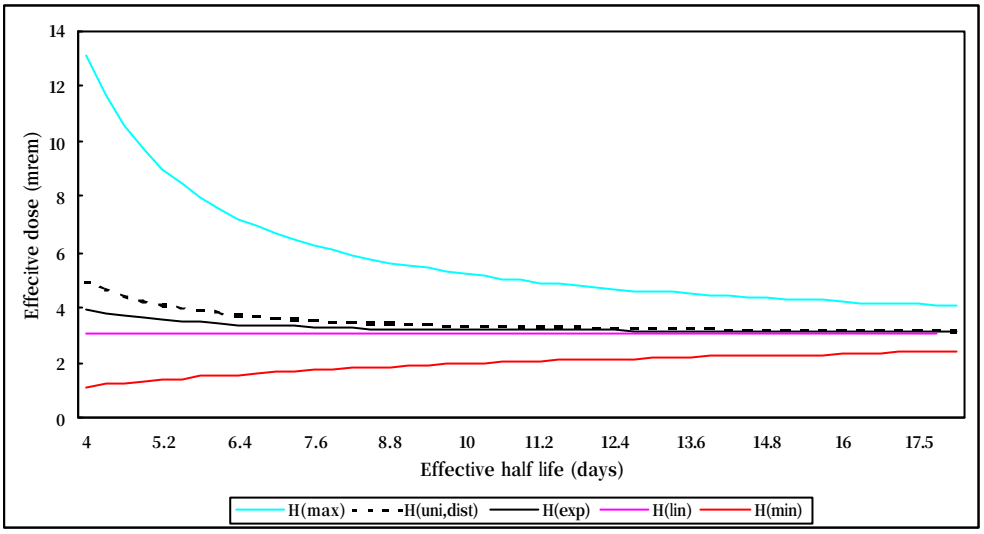

Figure 5. Comparison of dose calculation methods for various effective half-life of tritium

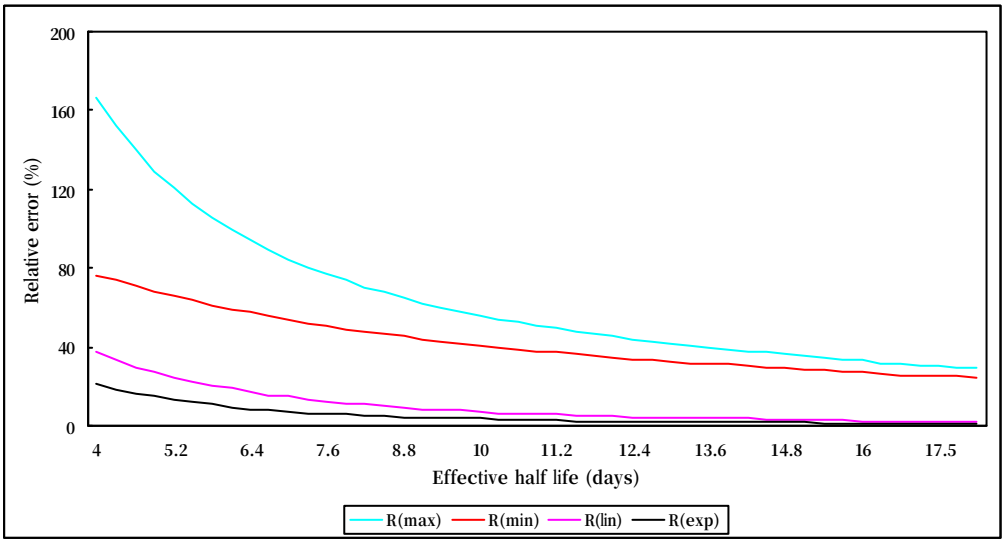

Figure 6. Comparison of relative errors to Uniform Distribution Assumption with other dose calculation methods for various effective half-life of tritium

(3) Tritium Concentration in Urine

If a bioassay sampling period is 14 days, C_0 is 1 μCi/L and the effective half life of tritium is 9.5 days, then dose calculation results and relative errors for changes of final urine sample, C_T (1 40 μCi/L) are shown in Figures 7 and 8.

Maximum/Minimum Intake Assumption results in more than 50% of relative errors in whole ranges and the result of the linear/exponential interpolation method shows less than 50% of relative errors in whole ranges. But relative errors of the exponential interpolation are less than that of the linear interpolation. The relative errors of each method saturate to the specific value in the range where the concentration of sample exceed 5 times of that of initial sample.

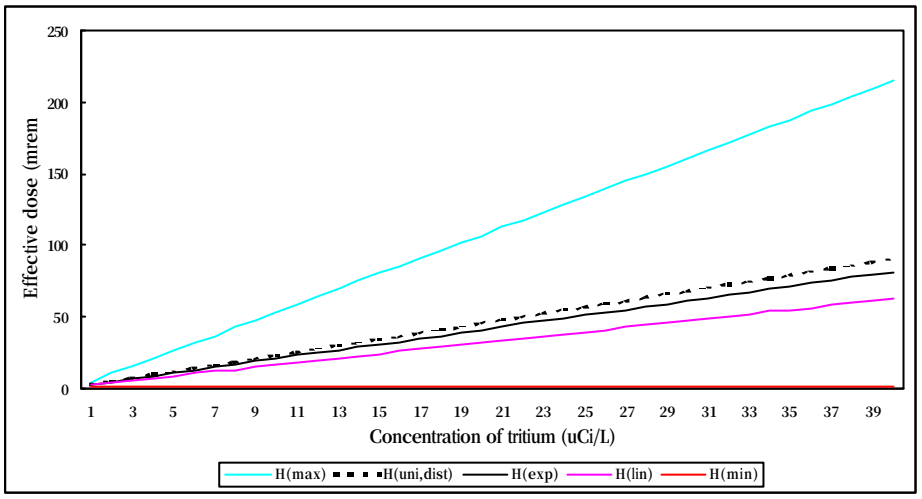

Figure 7. Comparison of dose calculation methods for various concentration of tritium in final urine sample (C_T)

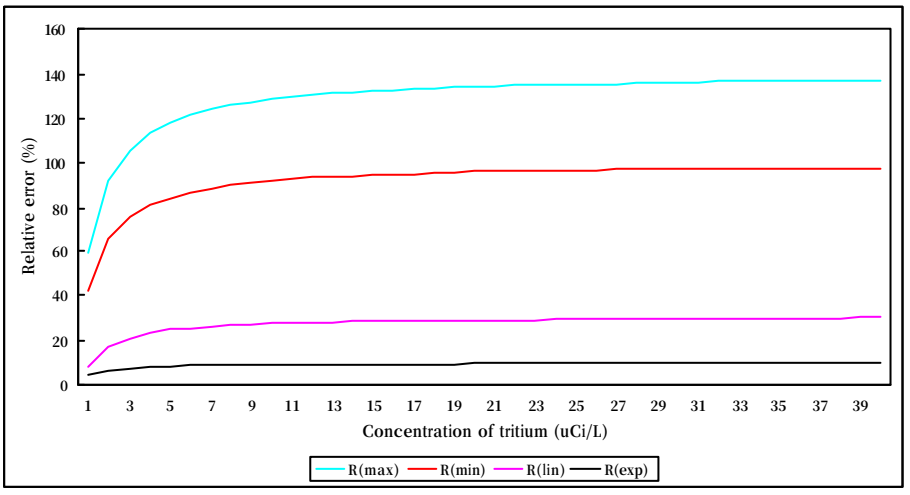

Figure 8. Comparison of relative errors to uniform distribution assumption with other dose calculation methods for various concentration of tritium in final urine sample (C_T)

4. CONCLUSION

The comparison of dose calculation methods between exponential interpolation with the linear interpolation, uniform distribution assumption, maximum and minimum intake assumption is carried out in accordance with various sampling period, effective half-life of tritium, and final urine sample concentration, respectively.

As for maximum and minimum intake assumption methods, the results of calculating actual dose are overestimate and underestimated respectively. The exponential interpolation method shows better results than those of linear interpolation, but both methods satisfy the accuracy requirements.

The exponential interpolation method, which is generally adopted internal dose assessment, can be applied in tritium dosimetry with low possibility of over- or under-estimation. In this study, it is concluded that the assumption of mid-point intake is reasonable for chronic intake of tritium.

The linear interpolation method for chronic intake does not consider the biological half-life of tritium, makes dose calculation simple but results in larger relative error than the exponential interpolation method.

In conclusion, the exponential interpolation method will be better to simulate effective dose calculation of tritium rather than the linear interpolation for CANDU workers entering two or three times in a week into high concentration areas.

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