THYROID DOSE ESTIMATION WITH POTASSIUM IODIDE (KI) ADMINISTRATION IN A NUCLEAR EMERGENCY

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In a breach-of-containment nuclear reactor accident, the near-field exposure is primarily through inhalation of radioiodine. Thyroid blockade by oral potassium iodide (KI) is a practical and effective protective measure for the general public in such an emergency. The retention functions incorporating the thyroid blocking effects by KI have been derived using a standard three-compartment model of iodine metabolism. This allows more accurate estimation of the thyroid dose by calculating the blocking factor.

INTRODUCTION

Radioiodines are produced in abundance in a nuclear reactor and could be released into the environment during a nuclear accident. As the dominant contribution to the inhalation dose comes from radioiodines, such as $^{131}$I and $^{133}$I, potassium iodide (KI) is administered to the public to reduce irradiation of the thyroid by uptake of radioiodines. Administration of KI at the appropriate times can block most of the thyroidal uptake of radioiodine$^{(1)}$. Therefore, the assessment of thyroid dose by inhaled radioiodine should take into account the associated effect of thyroid blocking. The blocking effect of KI can be expressed by incorporating a ‘blocking factor’ into radioiodine retention functions (i.e. time–activity functions) in the thyroid. In this study, the retention functions incorporating the thyroid blocking effects by KI were derived to calculate the blocking factor, and thyroid doses were then evaluated by accounting the effects of thyroid blockade.

MATERIALS AND METHODS

Respiratory tract model

Exposure to airborne radioiodine occurs in different chemical forms such as elemental iodide, methyl iodide and particulate aerosol. These different chemical species play an important role in the uptake of iodine in the respiratory tract$^{(2)}$. For radioiodines inhaled in a particulate form, it is assumed that entry and regional deposition in the respiratory tract depend on the size distribution of the aerosol particles. However, their chemical form determines deposition fractions of gases$^{(3)}$. ICRP 66$^{(4)}$ has assumed that the typical particle size distribution inhaled by members of the public is 1 µm activity median aerodynamic diameter (AMAD). In the case of particulate aerosols, default Type F is recommended for use in the absence of specific information. Type F means that deposited materials are rapidly absorbed into body fluids from the respiratory tract.

Iodine metabolism modelling

Radioiodines taken up in the gas-exchange tissues are absorbed into blood and transferred to other organs. The thyroid then takes up radioiodines in the circulatory system. The radioiodine kinetics was estimated using the standard three-compartment model, as shown in Figure 1$^{(5)}$. The rate constants shown in Figure 1 indicate exchange rates between compartments.

The differential equations for the three compartments are as follows, where $\lambda_k$ is the physical decay constant of the $k$th radiiodine:

\[
\frac{dX(t)}{dt} = dZ(t) - (a + b + \lambda_k)X(t)
\]

\[
\frac{dY(t)}{dt} = aX(t) - (c + \lambda_k)Y(t)
\]

\[
\frac{dZ(t)}{dt} = cY(t) - (d + e + \lambda_k)Z(t)
\]

When KI is administered, the blood-to-thyroid exchange rate of radioiodines, $a$, becomes a time-dependent parameter$^{(6)}$. The WinSAAM computer program$^{(7)}$ was used to calculate the blood-to-
The equations (1)–(3) can be solved by the creation of a single third-order linear homogeneous differential equation. Solving Equation (2) for \( X(t) \) and differentiating yields:

\[
X(t) = \frac{1}{a} \left[ \frac{dY(t)}{dt} + (c + \lambda_k)Y(t) \right] \tag{4}
\]

\[
\frac{dX(t)}{dt} = \frac{1}{a} \left[ \frac{d^2Y(t)}{dt^2} + (c + \lambda_k) \frac{dY(t)}{dt} \right] \tag{5}
\]

Substituting Equations (4) and (5) into Equation (1) results in

\[
Z(t) = \frac{1}{ad} \left[ \frac{d^3Y(t)}{dt^3} + (a + b + c + 2\lambda_k) \frac{d^2Y(t)}{dt^2} \right.
\]

\[
+ (a + b + \lambda_k)(c + \lambda_k) \frac{dY(t)}{dt} \tag{6}
\]

Differentiating Equation (6) and then substituting Equations (6) and (7) into Equation (3) result in the third-order linear homogeneous differential equation.

\[
\frac{d^3Y(t)}{dt^3} + A \frac{d^2Y(t)}{dt^2} + B \frac{dY(t)}{dt} = CY(t) \tag{8}
\]

where \( A = a + b + c + d + e + 3\lambda_k \), \( B = (a + b + \lambda_k)(c + \lambda_k) + (a + b + c + 2\lambda_k)(d + e + 2\lambda_k) \), and \( C = acd - (c + \lambda_k)(a + b + \lambda_k)(d + e + \lambda_k) \).

The solution of Equation (8) has the following form:

\[
Y(t) = c_1 e^{r_1 t} + c_2 e^{r_2 t} + c_3 e^{r_3 t} \tag{9}
\]

Retention functions

Three linear homogeneous first-order differential equations (1)–(3) can be solved by the creation of a

<table>
<thead>
<tr>
<th>Age</th>
<th>Exchange rates (h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 months</td>
<td>0.035 0.08 0.026 0.021 0.0052</td>
</tr>
<tr>
<td>1 y</td>
<td>0.035 0.08 0.0019 0.015 0.0039</td>
</tr>
<tr>
<td>5 y</td>
<td>0.035 0.08 0.0013 0.010 0.0025</td>
</tr>
<tr>
<td>2 y</td>
<td>0.035 0.08 0.0005 0.040 0.001</td>
</tr>
<tr>
<td>15 y</td>
<td>0.035 0.08 0.0043 0.0035 0.00086</td>
</tr>
<tr>
<td>Adult</td>
<td>0.035 0.08 0.00036 0.0019 0.00048</td>
</tr>
</tbody>
</table>

Table 1. Age-dependent exchange rates.

Figure 1. A compartment model of whole-body iodine metabolism, where \( X(t) \), \( Y(t) \) and \( Z(t) \) are the activities in the blood, thyroid and extrathyroidal organified iodine, respectively, at time \( t \) after inhalation.

Figure 2. Blood-to-thyroid exchange rate after KI administration for a euthyroid adult.

thyroid exchange rate, \( a \), over the 24-h period following administration of KI (Figure 2). This exchange rate is dependent on the concentration of iodide in the blood and therefore the time following KI administration. Because administration of KI is recommended once a day in the event of environmental dispersion of radioiodine, the blood-to-thyroid exchange rate would vary widely, from \( 10^{-5} \) to \( 10^{-4} \) h⁻¹, over the 24-h period following each KI administration. However, over each such 24-h period, this exchange rate remains well below the unblocked value recommended by the ICRP (8) (Table 1) and may therefore be reasonably assumed to be equal to the mean value over each such period.

Retention functions

The blood-to-thyroid exchange rate, \( a \), may therefore be reasonably assumed to be equal to the mean value over each such period.

Single third-order linear homogeneous differential equation. Solving Equation (2) for \( X(t) \) and differentiating yields:

\[
X(t) = \frac{1}{a} \left[ \frac{dY(t)}{dt} + (c + \lambda_k)Y(t) \right] \tag{4}
\]

\[
\frac{dX(t)}{dt} = \frac{1}{a} \left[ \frac{d^2Y(t)}{dt^2} + (c + \lambda_k) \frac{dY(t)}{dt} \right] \tag{5}
\]
The initial conditions are $X(0) = f_1 S$, $Y(0) = 0$ and $Z(0) = 0$ for solving $c_1$, $c_2$ and $c_3$, where $f_1$ is the fraction of inhaled radioiodine absorbed by the blood and $S$ is the initial iodine activity inhaled. From Equations (4) and (6),

$$Y'(0) = af_1 S$$

$$Y''(0) = -a(a + b + c + 2\lambda_k)f_1 S$$

The age-dependent exchange rates without KI blocking are listed in Table 1. Substituting initial conditions and constants into Equation (9), the third-order equation and three linear equations can be solved. Assuming that $f_1$ is 1 and $S$ is equal to 1 Bq, for the adult, the retention function for $^{131}$I in the thyroid is obtained as follows:

$$Y^{131}$$(t) = $-0.307e^{-0.118t} + 0.0607e^{-0.00611t}$

$$+ 0.246e^{-0.00384t}$$

When the effect of KI is considered and $a$ is assumed to be $3.0 \times 10^{-2}$ h$^{-1}$, the mean value over the 24-h period (Figure 2) for the adult and the retention function for $^{131}$I in the thyroid are obtained as follows.

$$Y^{131}$$(t) = $(-2.605 \times 10^{-4})e^{-0.119t}$

$$+ (9.862 \times 10^{-9})e^{-0.00611t}$

$$+ (2.605 \times 10^{-4})e^{-0.00384t}$$

The age-dependent retention functions for $k$th radioiodine with or without blocking effect by KI can be solved by the same manner.

RESULTS AND DISCUSSION

Verification of the retention functions

There is no retention or excretion data provided for the members of the public in the ICRP publications. To verify the retention functions, the calculated results for $^{131}$I are compared with the values of retention for the public suggested by Ishigure et al.$^{(9)}$ The following chemical forms of $^{131}$I were reviewed: elemental, methyl iodide and Type F. As shown in Figure 3, for the adult, derived retention functions agree with reference values within relative errors 10% for 100 d. The relative errors of the retention within 7 d are <3%.

Thyroid dose estimation

When the KI is administered to the public in a nuclear emergency, committed dose equivalent $H_{\text{Thyroid},k}$ (Sv) of the inhaled radioiodine incorporating the effect of thyroid blocking is obtained by the following formula.$^{(10)}$

$$H_{\text{Thyroid},k}(A) = h_{\text{Thyroid},k}(A)$$

$$\times \int_0^{t_e} i_k(t, A)b_k(t - t_b)dt$$

where $h_{\text{Thyroid},k}(A)$ (Sv Bq$^{-1}$) is ICRP dose coefficient for inhalation of the $k$th radioiodine by a person of age $A$ (y)$^{(3)}$. $i_k(t, A)$ (Bq h$^{-1}$) is the intake rate for the $k$th radioiodine by a person of age $A$ and $b_k(t)$ (dimensionless) is the thyroid blocking factor of the $k$th radioiodine. The blocking factor can be calculated by the ratio of the retention in the thyroid with KI administration to that without KI administration. $t_e$ (h) and $t_b$ (h) are the time of evacuation and KI administration, respectively.

When the measured activity of the $k$th radioiodine using thyroid monitoring system is equal to $G_k(t_m)$, its uptake can be calculated using its respective
retention function.

\[
\int_{t_0}^{t_e} i_k(t, A) \eta_{inh} R_k(t_m - t, A) dt \\
= \eta_{inh} \int_0^{t_b} i_k(t, A) R_{k,1}(t_m - t, A) dt \\
+ \int_{t_b}^{t_e} i_k(t, A) R_{k,2}(t_m - t, A) dt \\
= G_k(t_m)
\]  

(15)

where \( R_k(t, A) \) is the retention function of the \( k \)th radioiodine by a person of age \( A \); \( R_{k,1}(t, A) \) and \( R_{k,2}(t, A) \) are retention functions of the \( k \)th radioiodine without and with KI administration, respectively; \( \eta_{inh} \) is the fraction of the radioiodine absorbed in the blood by inhalation and \( G_k(t_m) \) is the measured activity of the \( k \)th radioiodine at \( t_m \).

If the intake rate \( i_k(t, A) \) is constant from 0 to \( t_e \), it can be written by as follows:

\[
i_k(A) = \frac{G_k(t_m)}{\eta_{inh} \int_0^{t_b} R_{k,1}(t_m - t, A) dt + \int_{t_b}^{t_e} R_{k,2}(t_m - t, A) dt}
\]  

(16)

For example, for the adult, when \( G_k(t_m = 40 \text{ h}) \) is \( 1 \times 10^3 \text{ Bq} \) of \( ^{131}\text{I} \), and \( t_b \) and \( t_e \) are 2 and 36 h, respectively, the intake rate will be \( 5.690 \times 10^3 \text{ Bq h}^{-1} \) for a particulate aerosol of \( 1 \mu \text{m AMAD} \) (Type F). If the blocking effect is not considered even though KI is administered, the intake rate will be \( 3.507 \times 10^2 \text{ Bq h}^{-1} \).

After the determination of intake rate, the committed equivalent dose for thyroid can be calculated according to Equation (14) for inhalation of the \( k \)th radioiodine.

\[
H_{\text{Thyroid},k}(A) = h_{\text{Thyroid},k}(A) i_k(A) \int_{t_0}^{t_e} b_k(t - t_b) dt \\
= h_{\text{Thyroid},k}(A) i_k(A) \left[ \int_0^{t_b} b_k(t - t_b) dt + \int_{t_b}^{t_e} b_k(t - t_b) dt \right] \\
= h_{\text{Thyroid},k}(A) i_k(A) \left[ l_b + \int_{t_b}^{t_e} R_{k,2}(t - t_b) dt + \int_0^{t_b} R_{k,1}(t - t_b) dt \right]
\]  

(17)

Inhalation dose coefficients of committed equivalent dose per unit intake are determined according to the chemical form of radioiodide. In the case of particulate aerosol of \( 1 \mu \text{m AMAD} \) (Type F), for the adult, the committed equivalent dose for thyroid is \( 3.0 \times 10^{-7} \text{ Sv} \) for the intake rate of \( 1 \text{ Bq h}^{-1} \) of \( ^{131}\text{I} \) with KI administration. If the thyroid blocking effect by KI administration is neglected, the committed equivalent dose for thyroid is \( 5.4 \times 10^{-6} \text{ Sv} \) for the same intake rate of \( ^{131}\text{I} \).

### Table 2. Committed equivalent dose for thyroid per unit intake rate (1 Bq h\(^{-1}\)) of \( ^{131}\text{I} \).

<table>
<thead>
<tr>
<th>Age</th>
<th>Without KI administration</th>
<th>With KI administration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( H_{\text{Thyroid}} ) (Sv)</td>
<td>( H_{\text{Thyroid}} ) (Sv)</td>
</tr>
<tr>
<td>3 months</td>
<td>( 5.0 \times 10^{-5} )</td>
<td>( 2.8 \times 10^{-6} )</td>
</tr>
<tr>
<td>1 y</td>
<td>( 5.0 \times 10^{-5} )</td>
<td>( 2.8 \times 10^{-6} )</td>
</tr>
<tr>
<td>5 y</td>
<td>( 2.6 \times 10^{-5} )</td>
<td>( 1.5 \times 10^{-6} )</td>
</tr>
<tr>
<td>10 y</td>
<td>( 1.3 \times 10^{-5} )</td>
<td>( 7.4 \times 10^{-7} )</td>
</tr>
<tr>
<td>15 y</td>
<td>( 7.9 \times 10^{-6} )</td>
<td>( 4.4 \times 10^{-7} )</td>
</tr>
<tr>
<td>Adult</td>
<td>( 5.4 \times 10^{-6} )</td>
<td>( 3 \times 10^{-7} )</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

It is necessary, of course, to accurately evaluate the dose to the thyroids (e.g. absorbed dose or the committed equivalent dose) of members of the general public when KI administration is employed in a nuclear emergency such as a breach-of-containment reactor accident. The algorithm for thyroid dose assessment developed in this study is presented in Figure 4. If the blocking effect of KI is not considered, it can be shown that the committed equivalent dose for thyroid is overestimated considerably. The
algorithm presented allows reliable estimation of the thyroid dose in such an emergency and can therefore be applied to the decision-making process for medical treatment and radiation protection of the public.

REFERENCES