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January 3, 2002
Account No. 20.OHD20.110

U.S. Nuclear Regulatory Commission
ATTN: Ms. Deborah A. DeMarco
Office of Nuclear Materials Safety and Safeguards
Program Management, Policy Development, and Staff
Office of the Director
Mail Stop 8D-37
Washington, DC 20555

Subject: Transmittal of Journal Paper

Dear Ms. DeMarco:

The purpose of this letter is to provide you a copy of a paper that will be submitted for publication in Nuclear Instruments & Methods in Physics Research, Section A. The research described in the attached paper, which is entitled, Age-specific Uncertainty of the $^{131}I$ Ingestion Dose Conversion Factor is derived from the Ph.D. work of Dr. Roland R. Benke. Because this work was not funded by the NRC you do not need to respond to this letter. However, if you have any questions regarding the content of the paper please contact me at (210) 522-5252 or Dr. Benke at (210) 522-5250.

Sincerely yours,

Budhi Sagar, Ph.D.
Technical Director

BS/cw

Enclosure

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# Age-specific Uncertainty of the $^{131}I$ Ingestion Dose Conversion Factor

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# Age-specific Uncertainty of the $^{131}I$ Ingestion Dose Conversion Factor

**ABSTRACT** – The production of weapons-grade nuclear materials and their by-products has resulted in a number of releases from United States Department of Energy (DOE) facilities. Iodine-131, a fission by-product, is one of the most common radionuclides generated and released to the environment. It is known that there are differences in various physiological parameters over all age groups when considering biokinetic modeling of iodine. The establishment of age-specific dose conversion factor uncertainty is necessary for accurate internal dose assessment. The $^{131}I$ dose conversion factor is log-normally distributed with varying age-specific distribution characteristics. The two most important parameters for determination of the dose conversion factor, in all age groups, are thyroid mass and iodine uptake fraction. These parameters are assumed to be highly correlated with a relationship that is quite important to dose conversion factor uncertainty. Dose estimates to individuals exposed to radioiodine can be determined more accurately with an increased understanding of the correlation between thyroid mass and uptake fraction. Improved dose estimates following oral intakes of $^{131}I$ can be made from the consideration of age-specific dose conversion factors and their input parameters.

# Age-specific Uncertainty of the $^{131}I$ Ingestion Dose Conversion Factor

## INTRODUCTION

Releases of radionuclides to the environment have occurred in the past and will likely continue to occur. The production of weapons grade nuclear materials and their by-products has resulted in a number of releases from United States Department of Energy (DOE) facilities (USDOE 1995). Iodine-131, a fission by-product nuclide, is one of the most common radionuclides generated and released to the environment. Early occupational practices, which included the processing of short-cooled fuel, resulted in significant releases of $^{131}I$ during the 1950s (Murphy et al. 1991; Kantelo et al. 1993; Shipler et al. 1996; Maharas 1998). These releases have been documented in a number of the dose reconstruction projects performed at various DOE complexes across the country (Shipler et al. 1996; Maharas 1998). These early atmospheric releases of radioiodine from the Savannah River Site (SRS) and the Hanford site contribute significantly to the total radiation dose received by members of the public from man-made sources (Ramsdell et al. 1996; Farris et al. 1996). Radioiodine is a potential hazard via atmospheric release from nuclear facilities throughout the world and was a major contributor to population doses in Europe after the Chernobyl accident (Makhon'ko et al. 1992; ; Nedveckaite et al. 1995; Kryshev 1996; Zvonova et al. 1998). These atmospheric releases of radiodine and the resulting ingestion dose estimates are an important consideration for current dose reconstruction projects and those continuing for Chernobyl.

Atmospheric releases of $^{131}I$ may result in the deposition of radioiodine on vegetation grown for human or animal consumption. Radiodine in the foodstuffs provided to livestock may result in significant accumulation of $^{131}I$ in these animals and eventual radiation dose to humans via ingestion. The milk consumption pathway is the most significant pathway for human ingestion of $^{131}I$ and results from an animal's intake of contaminated feed with subsequent milk production (Anderson et al. 1996). Previous sensitivity analyses have shown that the iodine dose conversion factor (DCF) is the most sensitive parameter in dosimetry models used for ingestion dose estimates (Hamby and Benke 1999). More careful consideration and research into this parameter and its variability is necessary to provide accurate probabilistic dose estimates.

Hamby and Benke (1999) have examined the ICRP 30 (1979) iodine biokinetic model and determined the uncertainty of the $^{131}I$ ingestion dose conversion factor for adults. The work developed herein is an extension of

those efforts to characterize the age-specific uncertainty of the dose conversion factor and determine the parameters to which the model is most sensitive. It is known that there are differences in modeling parameters for adults and younger age groups. Thyroid mass and uptake are age-specific; thus it is postulated that these parameters will have an influential effect on the $^{131}I$ ingestion dose conversion factor. The authors have determined the uncertainty of the $^{131}I$ ingestion dose conversion factor for fifteen-year-old males, fifteen-year-old females, ten-year-old children, five-year-old children, one-year-old children, and three-month-old infants.

## METHOD

A probabilistic assessment of age-specific $^{131}I$ ingestion dose conversion factors was generated by performing multiple calculations of thyroid dose, time-integrated activity, and S factor for each gender- and age-specific group. These estimates were determined from the simulated intake of 1 Bq of $^{131}I$ via ingestion using a commercially available software package for Latin hypercube sampling (Crystal Ball, Decisioneering, Inc., 1515 Arapahoe St., Suite 1311, Denver, CO 80202). The accumulation of multiple iterations of thyroid dose, time-integrated activity, and S factor allows uncertainty assessment and sensitivity analysis for the age-specific groups in this evaluation. The following sections will present the kinetic modeling parameters in more detail. The calculational steps can be found and referenced in the work of Hamby and Benke (1999).

Modeling iodine movement in biological systems is quite complex and simplifying assumptions have been made (Riggs 1952; ICRP 1979). The amount of iodine consumed in an individual's diet has a significant influence on thyroid function and metabolism. When evaluating specific samples or populations, it is necessary to take these factors into consideration because of their major role in iodine metabolism and kinetic modeling. Additionally, physiological parameters are age and gender specific. Thyroid mass and iodine uptake fractions are shown to be quite different for the various gender- and age-specific groups evaluated (Table 1).

The metabolism and transport of iodine in the body is simulated using a three-compartment, first-order kinetic model developed by Hamby and Benke (1999). The gender- and age-specific parameters have been used in the kinetic model to determine S factor distributions, time-integrated thyroid activity, and $^{131}I$ ingestion dose conversion factors. Multiple calculations of these output values have been determined via Monte Carlo techniques and Latin Hypercube sampling of input variables. One thousand estimates of the S factor with the thyroid as both

the source and the target, time-integrated activity, and $^{131}I$ ingestion dose conversion factor were made using the dose conversion factor model for each of the age and gender groups.

## PARAMETER DISTRIBUTIONS

There are a number of model parameters which are varied in the determination of the $^{131}I$ ingestion dose conversion factor and many are not known with a great deal of certainty. Parameters involved in the calculation of the S factor, such as radiation yield, energy per transition, and absorbed fraction are known very well, therefore, they are expected to have a minor effect on the uncertainty of the $^{131}I$ ingestion dose conversion factor. Physiological and anatomical parameters influencing calculation of the $^{131}I$ ingestion dose conversion factors have significantly larger variability and lack certainty, therefore, these parameters may have more influence on the uncertainty of a generalized $^{131}I$ ingestion dose conversion factor. A number of these physiological parameters have been assigned triangular or uniform distributions to reflect the amount of uncertainty and provide the least amount of bias in these parameters with the current information available. Much of the known information on iodine metabolism comes from the work of Riggs (1952) and from other cohort studies to assess the function of the thyroid gland (Riggs 1952; Dunning and Schwarz 1981). Only the parameters describing thyroid mass and uptake fraction have fitted distributions that reflect some degree of certainty. These parameters are also known to be directly and highly correlated, therefore, thyroid dose calculations in this work utilize a correlation coefficient of 0.9 between thyroid uptake fraction and mass (Hamby and Benke 1999).

***Radiation yield ($\Delta_i$).*** The fraction of the time a given radiation is emitted per transition of $^{131}I$ is taken from data provided by the NNDC (1994) and is reproduced in Table 2. These values are reported to three significant figures, and as such, each has been assigned a triangular distribution with a mode equal to the reported value and a range of ± 1%.

***Average energy per transition ($E_i$).*** Also given in Table 2 are the NNDC's values for the energy of each radiation emitted by $^{131}I$, average energies for beta particles (NNDC 1994). Radiation energies are reported to four significant digits, and as such, each has been assigned a triangular distribution with ranges of ± 1% and modes equal to the reported values. Although beta particle energies vary greatly, the average value of those beta energies has minimal variability.

***Absorbed fraction ($\phi_i$).*** The value of absorbed fraction is unity for beta particles and conversion electrons, but varies as a function of energy for photons. Variability of this parameter is not handled explicitly, but is linked to the variability established for $E_i$. The values of absorbed fraction are interpolated from the data of Fig. 1 (Eckerman 1998) for each iteration and each photon energy.

***Fractional absorption ($f_1$).*** Fractional absorption is the fraction of the initial intake that is absorbed to the bloodstream or transfer compartment from the gastrointestinal tract. Iodine fractional absorption has been assumed to be unity (ICRP 1979). Investigators have assumed that iodine absorption is extremely rapid and complete because very little iodine is removed from the body via elimination (Riggs 1952; Hetzel and Maberly 1986). The assumption seems valid, but it is very difficult to quantify; therefore, it is prudent to assign some variability to this parameter. The fractional absorption from the gastrointestinal tract to the transfer compartment is assumed to follow a uniform distribution ranging from 0.8 to 1.0 (Eckerman et al. 1999) for all age groups.

***Fractional transfer from body to blood ($f_{bbl}$).*** Thyroid hormones (iodinated proteins) produced and secreted from the thyroid gland circulate throughout the body while carrying out their physiological function. Thyroid hormones will eventually undergo degradation into their various structural components over time and free iodine present in the extracellular tissues of the body will be absorbed into the bloodstream. Fractional transfer from body to blood is more narrowly defined and there is little variation in this parameter with regard to thyroid condition, gender, or age. Iodine leaving the body compartment is recirculated to the transfer compartment where it may be taken up in the thyroid gland again or a small fraction of the iodine may be cleared from the body via elimination.

A ratio of rate constants was used to determine the fractional transfer to the blood. The transfer fraction is taken as the ratio of the rate constant for movement from the body to the blood, $k_{bbl}$, and the total body loss rate constant, i.e. the transfer to the blood plus the transfer to the feces, $k_{bf}$. This parameter, $f_{bbl}$, has been assigned a triangular distribution (Table 1) with a mode of 0.914 (Riggs 1952) and a range of 10% (yet, not to exceed 1.0) for all age groups. The range assigned to this distribution is rather large given the low variability in Riggs' data (Riggs 1952). This wide range will maximize the parameter's influence on model output; this influence can be quantified if it is shown to be significant.

***Blood-loss rate constant ($k_{blt}$).*** The ICRP 30 model (1979) makes no mention of gradual loss of iodine from the transfer compartment. Taken explicitly, the model suggests that the transfer of iodine from the blood to the

thyroid and out of the body via excretion is instantaneous. However, when examining the original model development and exercises by Killough and Eckerman (1983) and Eckerman (1994), it is evident that iodine is lost from the blood with a half-life of about 6 hours. Riggs (1952) estimates this value to be 5.8 hours, varying between 1 and 13.9 hours depending on dietary iodine deficiency and thyroid function. The blood-loss rate constant is assumed to follow a triangular distribution with a mode of 0.24 days and ranging from 0.042 and 0.58 days (Table 1). This parameter is assumed to be independent of age and gender, therefore, this distribution is used to describe all of the various age and gender groups.

***Radiological half-life ($T_{1/2}$).*** The estimate of the radiological half-life for $^{131}I$, and hence the decay constant, has varied over the years. Depending on the reference chosen, the literature value range spans only about 2%. The data chosen for radionuclide transformation was obtained from the National Nuclear Data Center, where the reported half-life is 8.0207 days (NNDC 1994). This value is known to be very precise as demonstrated by the five significant figures in the reported value. The radiological half-life is assumed to follow a triangular distribution with a mode of 8.0207 d and a range of ± 0.1% (Table 1). The relative certainty and limited variability of this value is expected to contribute very little to the total dose conversion factor uncertainty.

***Thyroid mass ($M_T$).*** The mass of the thyroid gland is directly related to its uptake fraction of iodine from the bloodstream, and diet has been shown to be an important influence on the fractional uptake and mass (Dolphin 1971). The values used to represent these two parameters must originate from comparable datasets to ensure accurate kinetic modeling and dose conversion factor estimation. Inaccuracies would be introduced into the model by combining data, for example, for thyroid uptake from a population deficient in dietary iodine (larger than normal uptake fractions) with the Standard Man data (normal thyroids) (ICRP 1974). Thyroid mass follows a lognormal distribution and age-specific values for geometric mean and geometric standard deviation can be found in Table 1 (Mochizuki et al. 1963).

***Fractional uptake from transfer compartment ($f_{blt}$).*** Iodine in the bloodstream circulates throughout the body and may be taken up by the thyroid gland. The healthy thyroid gland is approximately 20-45% efficient for extraction of iodine from the bloodstream. Fractional uptake is age- and gender specific, and is dependent on thyroid mass, metabolism, function, and the amount of dietary iodine intake. Multiple investigators have suggested thyroid uptake fractions corresponding to various size thyroid glands, thus supporting the thyroid uptake and mass dependency and high degree of correlation (Dolphin 1971). The ICRP estimate of fractional thyroid uptake is 0.3

for a 20 g thyroid gland (ICRP 1979). The data from Riggs (1952) has shown uptake fractions ranging from 0.1 to 0.9 with an approximate value of 0.33. This large variation in thyroid uptake demonstrated by Riggs comes from individuals with multiple thyroid conditions or chronic deficiencies. The approximate value of 0.33 determined by Riggs falls within the more typical range found in healthy thyroids of individuals. Age-specific thyroid uptake fractions are assumed to follow a lognormal distribution with the age-specific geometric means and geometric standard deviations available in Table 1 (Dunning and Schwarz 1981). As previously mentioned, thyroid uptake fraction and mass are directly correlated with an assumed correlation coefficient of 0.9.

***Thyroid-loss rate ($k_T$).*** Iodine is lost from the thyroid gland via the secretion of thyroid hormones containing iodine. This parameter is age-specific and there is significant variability between the thyroid-loss rates for various age groups. In adults, the iodine loss rate from the thyroid occurs with a half-life of 113 days (Riggs 1952). The ICRP (1979) uses Riggs' data to estimate the thyroid-loss rate and assigns a value of 120 days, but Riggs states that there is variation due to thyroid condition. The half-life in patients with with 'chronic iodine deficiency' increases to 156 days and drops as low as 20 days in patients with hyperthyroidism (Riggs 1952). Given this range of possible values in a large population, the variability assigned to this parameter is ± 40%. Thyroid-loss rate is assumed to follow a triangular distribution with age-specific modes (Table 1) and a range of ± 40% (Riggs 1952; ICRP 1989; ICRP 1993). Radioiodine is also lost from the thyroid compartment by radiological transformation, and in the case of short-lived iodines, radionuclide transformation dominates the removal from the thyroid.

***Body-loss rate constant ($k_b$).*** Clearance of iodine from extracellular tissues occurs by transfer to the blood, elimination, or radionuclide transformation. Riggs (1952) estimates a half-life of 11.9 days for adults in this compartment for both blood transfer and elimination. The body-loss rate is not affected by various thyroid conditions, but is age-specific. The lowest value for the half-life in the body is 3.9 days for adult patients with hyperthyroidism. Based on Riggs' data, the body-loss rate constant is assumed to follow a triangular distribution with various age-specific modes (Table 1) and a range of ± 75% (Riggs 1952; ICRP 1993).

## RESULTS

The sensitivity of the $^{131}I$ dose conversion factor model to its output parameters was determined using both rank correlation and contribution to variance methods (Hamby 1994; Hamby 1995). Estimates of several distributions have been made at a few intermediate steps through the calculation of dose conversion factor, i.e.

energy per transition, S factor, and time-integrated activity. No correlations between parameters were considered for the calculation of these distributions. However, since both uptake fraction and thyroid mass are used in calculation of dose conversion factor, these two input parameter distributions were assumed to be correlated with a coefficient of 0.9. The significance of choosing this value for correlation was investigated previously (Hamby and Benke 1999).

***Energy per transition.*** The energy per transition is calculated to assess the impact that radiation yield and radiation energy have on the parameter, $E_i\Delta_i\phi_i$, used in the calculation of the S factor. The resulting distribution is triangular in shape with a range of no more than 2% from the minimum to the maximum value (Hamby and Benke 1999). The variability in the distribution is almost entirely explained by the B4 beta yield parameter to a degree of 93% and the B4 beta energy by an additional 1%. Beyond that, no other single parameter of energy or yield contributes more than 1% to the variability of $E_i\Delta_i\phi_i$. Given that essentially one input parameter contributes to the uncertainty of this output parameter, the radiation energy and yield parameters are excluded from further consideration in the results that follow. Their slight contribution to the variability of the dose conversion factor, however, will be maintained throughout the estimation of total uncertainty in the dose conversion factor.

***S factor.*** The age-specific S factor distributions are best characterized by a lognormal distribution with geometric means and geometric standard deviations shown in Table 3. An as example, the characteristic distribution for ten-year-old children is shown in Fig. 2. The S factor geometric mean decreases with age as expected, due to the increase in thyroid mass as younger age groups undergo growth and development. The geometric standard deviation or amount of variability in the S factor tends to decrease with age and is dependent upon the uncertainty in thyroid mass.

***Time-integrated activity.*** After an intake of $^{131}I$, iodine accumulates in the thyroid gland and undergoes radionuclide transformation resulting in dose to the thyroid gland. The time-integrated activity describes the cumulated activity that results in radionuclide transformations within the thyroid over time. Time-integrated activity can be described by a lognormal distribution with an age-specific geometric mean and geometric standard deviation (Table 4). An as example, the characteristic distribution for three-month-old infants is shown in Fig. 3. The age-specific geometric mean of time-integrated activity increases with age due to the increase in uptake fraction and mass of the gland, which can accumulate more iodine as its size increases. The geometric standard deviation of time-integrated activity decreases as age increases. This is due to the decreased variability in the uptake fraction of

more mature age groups. As shown by results of the sensitivity analysis in Table 5, time-integrated activity is most influenced by thyroid uptake fraction and mass. The rank correlation coefficients and contribution to variance measures for thyroid mass and uptake fraction are of the greatest magnitude, therefore, they are the two most important parameters to the output of time-integrated activity for every age and gender group.

***Dose conversion factor.*** The characteristic distribution representing the dose conversion factor for fifteen-year-old females is shown in Fig. 4. Dose conversion factor distributions for other age/gender groups show similar results. The $^{131}I$ ingestion dose conversion factor is most sensitive to uptake fraction and thyroid mass (Table 6). This is due primarily to the high degree of correlation between these parameters, but also because thyroid mass drives the estimate of the S factor and the uptake fraction drives the estimate of the time-integrated activity. The dose conversion factor is best characterized by a lognormal distribution. Gender and age-specific geometric means and geometric standard deviations are shown in Table 7. The dose conversion factor decreases with increasing age because of the decrease in the S factor.

## DISCUSSION

Thyroid mass is extremely important in the S factor calculation and its influence has a significant effect on each of the age-specific S-factor distributions for self-irradiation of the thyroid. Time-integrated activity is driven by the uptake fraction of iodine, and thyroid mass is shown to be significant because of its direct correlation with uptake fraction. The calculation of $^{131}I$ ingestion dose conversion factor is completely dominated by uptake fraction and thyroid mass. Accurate information regarding these parameters play a significant role in probabilistic dose assessment for oral ingestion intakes of iodine and have a major influence dose conversion factor uncertainty.

In five- and one-year-old children, two different parameters are shown to have some influence on the $^{131}I$ ingestion dose factor. These are the fractional absorption of iodine from the gastrointestinal tract and the thyroid loss constant with fractional absorption being more important. The fractional absorption varied uniformly from 0.8 to 1.0 with no emphasis on unity or any specific value. This being the case, fractional absorption became more influential in younger age groups, although it was not shown to be important in three-month-old infants. The thyroid loss constant demonstrated a 2% contribution to variance, even though this parameter had a large variation of 40%. This variability in the thyroid loss constant has shown only a minor influence with a significant amount of

parameter uncertainty. Time-integrated activity also has shown a marginal response to the variability in fractional absorption, but the contribution to variance is less than 2%.

The emission yield of the B4 beta particle is very important in the calculation of the absorbed energy and only marginally for the S factor, but in light of the major influence of thyroid mass and uptake fraction, its influence on the total dose conversion factor uncertainty is vanishingly small. All other parameter variability related to the decay scheme of $^{131}I$ play an even smaller role than the B4 beta particle and their importance is essentially nil.

The correlation between thyroid mass and uptake fraction has a significant role in estimation of the $^{131}I$ ingestion dose conversion factor and its probability distribution. Hamby and Benke (1999) have determined that the correlation coefficient of 0.9 is a valid assumption and has minimal impact on the median value of dose conversion factor, but it significantly affects the shape of the probability distribution. Assuming this assumption to be valid, the age-specific $^{131}I$ ingestion dose conversion factors have been determined with this high degree of correlation between uptake fraction and thyroid mass. The overall uncertainty of the iodine dose conversion factor is actually decreased because of the correlation between thyroid mass and uptake fraction. The individual variability in the S factor and time-integrated activity distributions is greater than the uncertainty of the two combined. This is due to the uncertainties of thyroid mass and uptake fraction being driven by the uncertainties of the S factor and time-integrated activity, respectively, and that those two parameters are highly correlated.

Results of the sensitivity analysis demonstrate a strong relationship between uptake fraction and thyroid mass. The rank correlation coefficients show that these parameters are both either positively or negatively correlated with the $^{131}I$ dose conversion factor within a given each age group. This differs from what is anticipated, i.e., a dose factor that is positively correlated with uptake fraction and negatively correlated with thyroid mass. Our findings reveal that the anticipated results do not always hold true when a high degree of correlation between these two input parameters (cc=0.9) is present. The rank correlation data of Table 6 show that in some instances there is a positive correlation between the inputs (thyroid mass and uptake fraction) and the output (dose factor), and in other instances the inputs and output are negatively correlated. This is due to a combination of the high correlation between the two input parameters and the fact that the order of importance in the dose factor model for thyroid mass and uptake fraction is not the same between age groups.

Age-specific S factor variability increases with age due to the larger variation in adult thyroid masses; the most significant uncertainty is shown in fifteen-year-old females. The thyroid mass distribution chosen for this

assessment had a significantly large geometric standard deviation resulting in the increased uncertainty of the S factor for fifteen-year-old females. The geometric mean, or median value, decreased with increasing age because of the increased mass of the thyroid for absorption of dose delivered. The median value of the distribution describing time-integrated activity in the thyroid increased with age of the individual due to the longer residence time of iodine in thyroid. Thyroid loss constant values are larger in more mature age groups, thus resulting in decreased residence time of iodine in the thyroid gland. The uncertainty of the time-integrated activity distribution decreases with increasing age because of the decreased variability in the thyroid uptake fraction distribution. The smaller S factor values for more mature age groups results in lower values of $^{131}I$ ingestion dose conversion factors for older individuals. The dose conversion factors are significantly greater at younger ages due to their smaller thyroid mass and consistently greater uptake fractions as compared to those of adults (Hamby and Benke 1999). The largest $^{131}I$ ingestion dose conversion factors are those for infants and very young children.

## CONCLUSIONS

The $^{131}I$ dose conversion factor is log-normally distributed with varying age-specific geometric means and geometric standard deviations (Table 7). The two most important parameters for determination of the dose conversion factor, over all age groups, are thyroid mass and uptake fraction. These parameters are assumed to be highly correlated and this relationship is important to the characterization of dose conversion factor uncertainty. Dose estimates to individuals exposed to radioiodine can be determined more accurately with increased understanding of the correlation between thyroid mass and uptake fraction. Improved dose estimates from oral intakes of $^{131}I$ can be made from the consideration of age-specific dose conversion factors and their input parameters.

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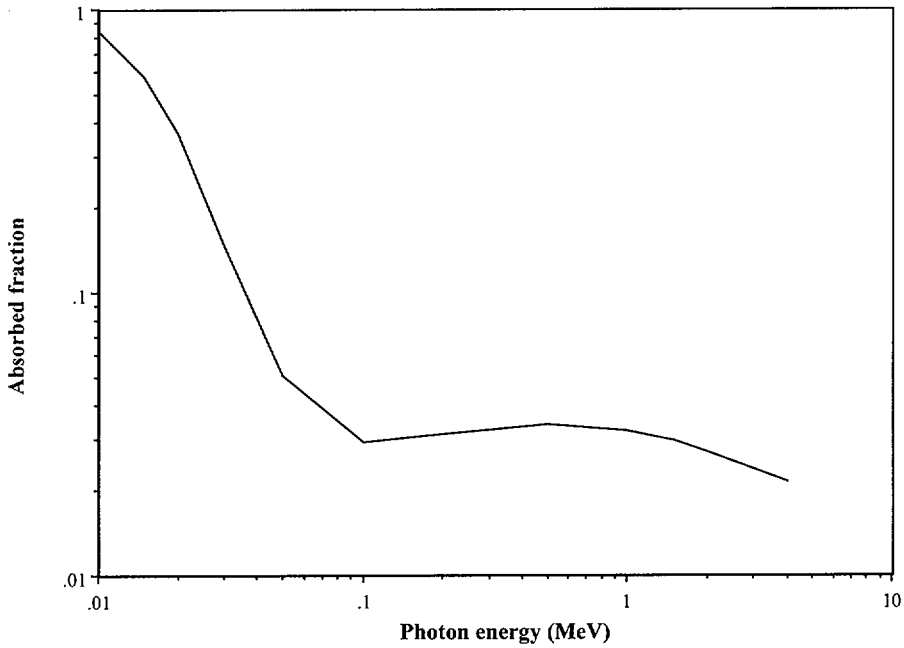
## FIGURE CAPTIONS

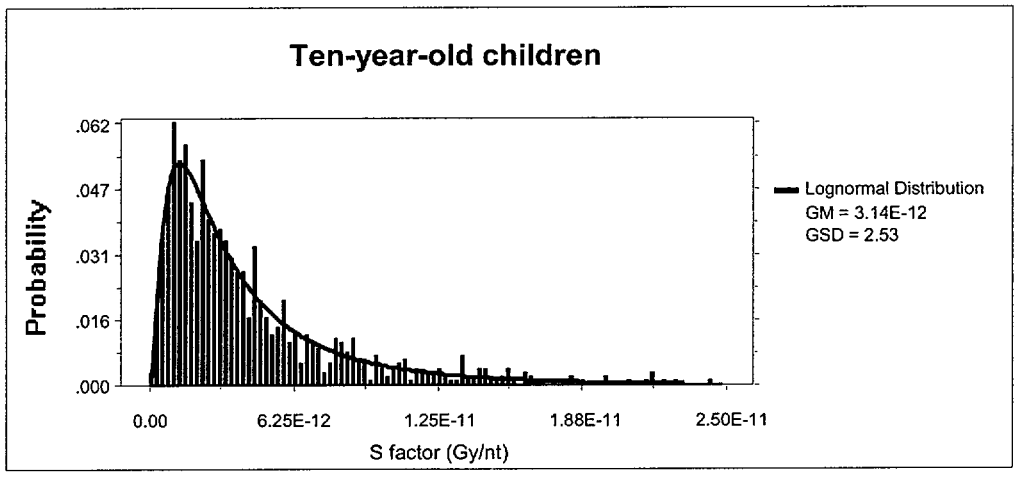
**Fig. 1.** Absorbed fraction as a function of energy with the thyroid as both source and target.

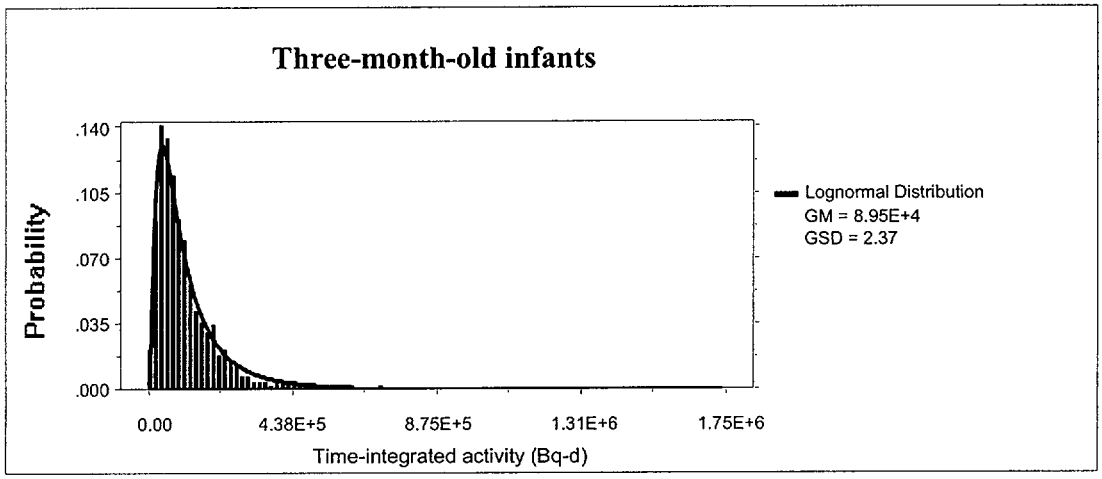
**Fig. 2.** Estimated probability distribution for the $^{131}$I S factor in ten-year-old children with the thyroid as both source and target (in units of Gy per nuclear transition).

**Fig. 3.** Estimated probability distribution for the $^{131}$I time-integrated activity in thyroid glands of three-month-old infants (in units of Bq-d).

**Fig. 4.** Estimated probability distribution for the $^{131}$I dose conversion factor in fifteen-year-old females (in units of Sv per Bq).


Absorbed fraction
1
.1
.01
.01
.1
1
10
Photon energy (MeV)


Ten-year-old children
Probability
.062
.047
.031
.016
.000
0.00
6.25E-12
1.25E-11
1.88E-11
2.50E-11
S factor (Gy/nt)
Lognormal Distribution
GM = 3.14E-12
GSD = 2.53


Three-month-old infants
Probability
.140
.105
.070
.035
.000
0.00
4.38E+5
8.75E+5
1.31E+6
1.75E+6
Time-integrated activity (Bq-d)
Lognormal Distribution
GM = 8.95E+4
GSD = 2.37

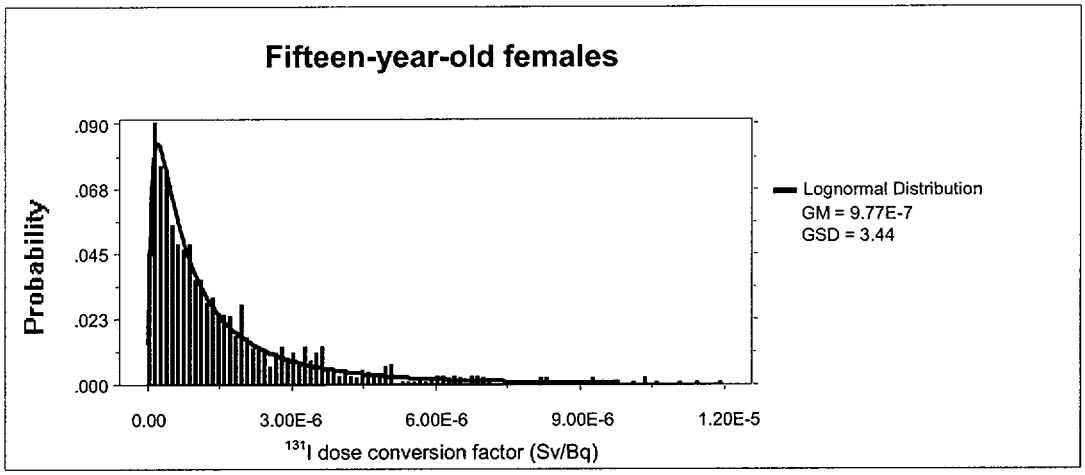

Fifteen-year-old females
Probability
.090
.068
.045
.023
.000
0.00
3.00E-6
6.00E-6
9.00E-6
1.20E-5
$^{131}$I dose conversion factor (Sv/Bq)
Lognormal Distribution
GM = 9.77E-7
GSD = 3.44

**Table 1.** Input parameter distribution assignments.[a]

| Symbol | Parameter (Units) | Distribution[b,c,d] |
|---|---|---|
| $\Delta_i$ | Radiation yield | see Table 2 |
| $E_i$ | Energy per transition | see Table 2 |
| $\phi_i$ | Absorbed fraction | see Figure 1 |
| $f_1$ | Fractional absorption (unitless) | U (0.8;1.0) |
| $f_{bbl}$ | Body-blood transfer (unitless) | T (0.82; 0.91; 1.0) |
| $k_{blt}$ | Blood loss constant ($d^{-1}$) | T (0.04; 0.24; 0.58) |
| $T_{1/2}$ | $^{131}I$ Radiological half-life (d) | T (8.0127; 8.0207; 8.0287) |
| **Fifteen-year-old males** | | |
| $M_T$ | Thyroid Mass (g) | LN (14.0; 3.0) |
| $f_{blt}$ | Uptake Fraction (unitless) | LN (0.43; 1.53) |
| $k_T$ | Thyroid Loss Constant ($d^{-1}$) | T (40.2; 67.0; 93.8) |
| $k_b$ | Body Loss Constant ($d^{-1}$) | T (1.68; 6.70; 11.73) |
| **Fifteen-year-old females** | | |
| $M_T$ | Thyroid Mass (g) | LN (12.4; 4.7) |
| $f_{blt}$ | Uptake Fraction (unitless) | LN (0.43; 1.53) |
| $k_T$ | Thyroid Loss Constant ($d^{-1}$) | T (40.2; 67.0; 93.8) |
| $k_b$ | Body Loss Constant ($d^{-1}$) | T (1.68; 6.70; 11.73) |
| **Ten-year-old children** | | |
| $M_T$ | Thyroid Mass (g) | LN (10.2; 2.5) |
| $f_{blt}$ | Uptake Fraction (unitless) | LN (0.43; 1.53) |
| $k_T$ | Thyroid Loss Constant ($d^{-1}$) | T (34.8; 58.0; 81.2) |
| $k_b$ | Body Loss Constant ($d^{-1}$) | T (1.45; 5.80; 10.15) |
| **Five-year-old children** | | |
| $M_T$ | Thyroid Mass (g) | LN (4.7; 1.4) |
| $f_{blt}$ | Uptake Fraction (unitless) | LN (0.43; 1.53) |
| $k_T$ | Thyroid Loss Constant ($d^{-1}$) | T (13.8; 23.0; 32.2) |
| $k_b$ | Body Loss Constant ($d^{-1}$) | T (0.58; 2.30; 4.03) |
| **One-year-old children** | | |
| $M_T$ | Thyroid Mass (g) | LN (1.9; 0.5) |
| $f_{blt}$ | Uptake Fraction (unitless) | LN (0.37; 1.38) |
| $k_T$ | Thyroid Loss Constant ($d^{-1}$) | T (9.0; 15.0; 21.0) |
| $k_b$ | Body Loss Constant ($d^{-1}$) | T (0.38; 1.50; 2.63) |
| **Three-month-old infants** | | |
| $M_T$ | Thyroid Mass (g) | LN (1.4; 0.5) |
| $f_{blt}$ | Uptake Fraction (unitless) | LN (0.37; 1.95) |
| $k_T$ | Thyroid Loss Constant ($d^{-1}$) | T (6.7; 11.2; 15.7) |
| $k_b$ | Body Loss Constant ($d^{-1}$) | T (0.28; 1.12; 1.96) |

[a] References are given in the text.
[b] Distributions: LN = lognormal; T = triangular; U = uniform.
[c] Geometric mean for lognormal distributions and the mode for triangular distributions.
[d] Geometric standard deviation for lognormal distributions, and minimum and maximum for triangular and uniform distributions.

**Table 2.** Nuclear data and absorbed fractions for the transition of $^{131}I$ with the thyroid as source and target.

| Radiations | Yield ($Bq^{-1}$ $s^{-1}$) | Energy, $E_i$ (MeV) | $E_i$ per transition (MeV $Bq^{-1}$ $s^{-1}$) | Absorbed fraction | Absorbed $E_i$ (MeV $Bq^{-1}$ $s^{-1}$) |
|---|---|---|---|---|---|
| $\beta^-$ 1 | 0.0210 | 0.06936 | 0.00146 | 1 | 0.00146 |
| $\beta^-$ 2 | 0.00651 | 0.08694 | 0.000566 | 1 | 0.000566 |
| $\beta^-$ 3 | 0.0727 | 0.09662 | 0.00702 | 1 | 0.00702 |
| $\beta^-$ 4 | 0.899 | 0.1916 | 0.172 | 1 | 0.172 |
| $\beta^-$ 6 | 0.00480 | 0.2832 | 0.00136 | 1 | 0.00136 |
| $\gamma$ 1 | 0.0262 | 0.08019 | 0.00210 | 0.0331 | 0.0000695 |
| ce-K, $\gamma$ 1 | 0.0354 | 0.04562 | 0.00161 | 1 | 0.00161 |
| ce-L, $\gamma$ 1 | 0.00464 | 0.07473 | 0.000347 | 1 | 0.000347 |
| $\gamma$ 3 | 0.00270 | 0.1772 | 0.000478 | 0.0283 | 0.0000135 |
| $\gamma$ 6 | 0.0614 | 0.2843 | 0.0175 | 0.0314 | 0.000548 |
| ce-K, $\gamma$ 6 | 0.00252 | 0.2497 | 0.000629 | 1 | 0.000629 |
| $\gamma$ 11 | 0.00274 | 0.3258 | 0.000893 | 0.0312 | 0.0000279 |
| $\gamma$ 13 | 0.817 | 0.3645 | 0.298 | 0.0310 | 0.00924 |
| ce-K, $\gamma$ 13 | 0.0155 | 0.3299 | 0.00511 | 1 | 0.00511 |
| ce-L, $\gamma$ 13 | 0.00246 | 0.3590 | 0.000883 | 1 | 0.000883 |
| $\gamma$ 16 | 0.00360 | 0.5030 | 0.00181 | 0.0319 | 0.0000577 |
| $\gamma$ 17 | 0.0717 | 0.6370 | 0.0457 | 0.0310 | 0.00142 |
| $\gamma$ 18 | 0.00217 | 0.6427 | 0.00139 | 0.0310 | 0.0000432 |
| $\gamma$ 19 | 0.0177 | 0.7229 | 0.0128 | 0.0306 | 0.000392 |
| $K\alpha_1$ X-ray | 0.0256 | 0.02978 | 0.000762 | 0.1515 | 0.000115 |
| $K\alpha_2$ X-ray | 0.0138 | 0.02946 | 0.000407 | 0.1551 | 0.0000631 |
| Omitted $\beta$, ce and Auger radiations | | | 0.00132 | 1 | 0.00132 |
| Omitted X-ray and $\gamma$ radiations | | | 0.00114 | <1 | <0.00114 |
| **SUM** | | | 0.574 | | 0.204 |

**Table 3.** Age-specific $^{131}$I S factor distributions with the thyroid as both source and target (units of Gy per nt)[a].

| Age and Gender Group | Geometric Mean | Geometric Standard Deviation |
|---|---|---|
| 15 Year Old Males | $2.35 \times 10^{-12}$ | 2.97 |
| 15 Year Old Females | $2.86 \times 10^{-12}$ | 5.02 |
| 10 Year Old Children | $3.14 \times 10^{-12}$ | 2.53 |
| 5 Year Old Children | $6.97 \times 10^{-12}$ | 1.39 |
| 1 Year Old Children | $1.73 \times 10^{-11}$ | 1.13 |
| 3 Month Old Infants | $2.35 \times 10^{-11}$ | 1.13 |

[a] All gender and age-specific $^{131}$I S factors are described by a lognormal distribution.

**Table 4.** Age-specific $^{131}I$ time-integrated activity distributions in the thyroid (units of Bq-d)[a].

| Age and Gender Group | Geometric Mean | Geometric Standard Deviation |
|---|---|---|
| 15 Year Old Males | $1.45 \times 10^5$ | 1.55 |
| 15 Year Old Females | $1.46 \times 10^5$ | 1.56 |
| 10 Year Old Children | $1.42 \times 10^5$ | 1.56 |
| 5 Year Old Children | $1.26 \times 10^5$ | 1.61 |
| 1 Year Old Children | $9.80 \times 10^4$ | 1.45 |
| 3 Month Old Infants | $8.95 \times 10^4$ | 2.37 |

[a] All gender and age-specific $^{131}I$ time-integrated activity distributions are described by a lognormal distribution.

**Table 5.** Age-specific sensitivity analysis for the time-integrated thyroid activity.

| Parameter | Symbol | Rank Correlation | Contribution to Variance (%)[a] |
|---|---|---|---|
| **Fifteen-year-old males** | | | |
| Uptake fraction | $f_{blt}$ | 0.99 | 52.9 |
| Thyroid mass | $M_T$ | 0.89 | 43.1 |
| Fractional absorption | $f_l$ | 0.13 | 0.9 |
| Thyroid loss constant | $k_T$ | 0.06 | 0.2 |
| Blood loss constant | $k_{bl}$ | -0.05 | 0.1 |
| Fraction body-blood | $f_{bbl}$ | 0.02 | 0.0 |
| Body loss constant | $k_b$ | 0.02 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.00 | 0.0 |
| **Fifteen-year-old females** | | | |
| Uptake fraction | $f_{blt}$ | 0.99 | 53.6 |
| Thyroid mass | $M_T$ | 0.88 | 42.5 |
| Fractional absorption | $f_l$ | 0.17 | 1.5 |
| Thyroid loss constant | $k_T$ | 0.08 | 0.4 |
| Blood loss constant | $k_{bl}$ | -0.02 | 0.0 |
| Fraction body-blood | $f_{bbl}$ | -0.03 | 0.1 |
| Body loss constant | $k_b$ | 0.00 | 0.0 |
| Radiological half-life | $T_{1/2}$ | -0.03 | 0.1 |
| **Ten-year-old children** | | | |
| Uptake fraction | $f_{blt}$ | 0.99 | 53.7 |
| Thyroid mass | $M_T$ | 0.89 | 43.3 |
| Fractional absorption | $f_l$ | 0.17 | 1.6 |
| Thyroid loss constant | $k_T$ | 0.03 | 0.0 |
| Blood loss constant | $k_{bl}$ | -0.02 | 0.0 |
| Fraction body-blood | $f_{bbl}$ | -0.01 | 0.0 |
| Body loss constant | $k_b$ | 0.01 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.00 | 0.0 |
| **Five-year-old children** | | | |
| Uptake fraction | $f_{blt}$ | 0.99 | 53.9 |
| Thyroid mass | $M_T$ | 0.88 | 42.7 |
| Fractional absorption | $f_l$ | 0.13 | 1.0 |
| Thyroid loss constant | $k_T$ | 0.07 | 0.3 |
| Blood loss constant | $k_{bl}$ | -0.01 | 0.0 |
| Fraction body-blood | $f_{bbl}$ | -0.01 | 0.0 |
| Body loss constant | $k_b$ | 0.02 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.01 | 0.0 |
| **One-year-old children** | | | |
| Uptake fraction | $f_{blt}$ | 0.97 | 51.4 |
| Thyroid mass | $M_T$ | 0.87 | 41.4 |
| Fractional absorption | $f_l$ | 0.18 | 1.9 |
| Thyroid loss constant | $k_T$ | 0.14 | 1.0 |
| Blood loss constant | $k_{bl}$ | -0.07 | 0.2 |
| Fraction body-blood | $f_{bbl}$ | 0.02 | 0.0 |
| Body loss constant | $k_b$ | 0.00 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.01 | 0.0 |

[a] The remainder of the variance corresponds to the correlations with radiation yield and average energy.

**Table 5 (cont.).** Age-specific sensitivity analysis for the time-integrated thyroid activity.

| Parameter | Symbol | Rank Correlation | Contribution to Variance (%)[a] |
|---|---|---|---|
| **Three-month-old infants** | | | |
| Uptake fraction | $f_{blt}$ | 0.97 | 54.2 |
| Thyroid mass | $M_T$ | 0.87 | 43.3 |
| Fractional absorption | $f_1$ | 0.04 | 0.1 |
| Thyroid loss constant | $k_T$ | 0.05 | 0.2 |
| Blood loss constant | $k_{bl}$ | -0.04 | 0.1 |
| Fraction body-blood | $f_{bbl}$ | 0.00 | 0.0 |
| Body loss constant | $k_b$ | 0.03 | 0.1 |
| Radiological half-life | $T_{1/2}$ | 0.01 | 0.0 |

[a] The remainder of the variance corresponds to the correlations with radiation yield and average energy.

**Table 6.** Age-specific sensitivity analysis for the $^{131}I$ dose conversion factor.

| Parameter | Symbol | Rank Correlation | Contribution to Variance (%)[a] |
|---|---|---|---|
| **Fifteen-year-old males** | | | |
| Uptake fraction | $f_{blt}$ | -0.96 | 59.7 |
| Thyroid mass | $M_T$ | -0.75 | 36.8 |
| Fractional absorption | $f_1$ | 0.08 | 0.4 |
| Thyroid loss constant | $k_T$ | 0.01 | 0.0 |
| Blood loss constant | $k_{bl}$ | -0.03 | 0.1 |
| Fraction body-blood | $f_{bbl}$ | 0.01 | 0.0 |
| Body loss constant | $k_b$ | -0.01 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.02 | 0.0 |
| **Fifteen-year-old females** | | | |
| Uptake fraction | $f_{blt}$ | -0.80 | 38.7 |
| Thyroid mass | $M_T$ | -0.98 | 58.5 |
| Fractional absorption | $f_1$ | 0.03 | 0.1 |
| Thyroid loss constant | $k_T$ | -0.03 | 0.0 |
| Blood loss constant | $k_{bl}$ | 0.02 | 0.0 |
| Fraction body-blood | $f_{bbl}$ | 0.02 | 0.0 |
| Body loss constant | $k_b$ | -0.04 | 0.1 |
| Radiological half-life | $T_{1/2}$ | 0.00 | 0.0 |
| **Ten-year-old children** | | | |
| Uptake fraction | $f_{blt}$ | -0.68 | 33.6 |
| Thyroid mass | $M_T$ | -0.92 | 62.1 |
| Fractional absorption | $f_1$ | 0.10 | 0.7 |
| Thyroid loss constant | $k_T$ | 0.05 | 0.2 |
| Blood loss constant | $k_{bl}$ | -0.05 | 0.2 |
| Fraction body-blood | $f_{bbl}$ | 0.03 | 0.1 |
| Body loss constant | $k_b$ | -0.03 | 0.1 |
| Radiological half-life | $T_{1/2}$ | -0.01 | 0.0 |
| **Five-year-old children** | | | |
| Uptake fraction | $f_{blt}$ | 0.68 | 67.0 |
| Thyroid mass | $M_T$ | 0.33 | 16.2 |
| Fractional absorption | $f_1$ | 0.27 | 10.3 |
| Thyroid loss constant | $k_T$ | 0.12 | 2.1 |
| Blood loss constant | $k_{bl}$ | 0.00 | 0.0 |
| Fraction body-blood | $f_{bbl}$ | 0.01 | 0.0 |
| Body loss constant | $k_b$ | -0.02 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.03 | 0.1 |
| **One-year-old children** | | | |
| Uptake fraction | $f_{blt}$ | 0.91 | 54.0 |
| Thyroid mass | $M_T$ | 0.73 | 34.4 |
| Fractional absorption | $f_1$ | 0.26 | 4.2 |
| Thyroid loss constant | $k_T$ | 0.19 | 2.2 |
| Blood loss constant | $k_{bl}$ | -0.07 | 0.4 |
| Fraction body-blood | $f_{bbl}$ | 0.03 | 0.1 |
| Body loss constant | $k_b$ | -0.02 | 0.0 |
| Radiological half-life | $T_{1/2}$ | 0.00 | 0.0 |

[a] The remainder of the variance corresponds to the correlations with radiation yield and average energy.

**Table 6 (cont.).** Age-specific sensitivity analysis for the $^{131}I$ dose conversion factor.

| Parameter | Symbol | Rank Correlation | Contribution to Variance (%)[a] |
|---|---|---|---|
| **Three-month-old infants** | | | |
| Uptake fraction | $f_{blt}$ | 0.96 | 55.9 |
| Thyroid mass | $M_T$ | 0.83 | 41.3 |
| Fractional absorption | $f_1$ | 0.05 | 0.2 |
| Thyroid loss constant | $k_T$ | 0.06 | 0.2 |
| Blood loss constant | $k_{bl}$ | -0.05 | 0.1 |
| Fraction body-blood | $f_{bbl}$ | 0.00 | 0.0 |
| Body loss constant | $k_b$ | 0.03 | 0.1 |
| Radiological half-life | $T_{1/2}$ | 0.01 | 0.0 |

[a] The remainder of the variance corresponds to the correlations with radiation yield and average energy.

**Table 7.** Age-specific $^{131}I$ dose conversion factor distributions (units of Sv per Bq)[a].

| Age and Gender Group | Geometric Mean | Geometric Standard Deviation |
|---|---|---|
| 15 Year Old Males | $7.93 \times 10^{-7}$ | 2.06 |
| 15 Year Old Females | $9.77 \times 10^{-7}$ | 3.44 |
| 10 Year Old Children | $1.04 \times 10^{-6}$ | 1.78 |
| 5 Year Old Children | $2.06 \times 10^{-6}$ | 1.27 |
| 1 Year Old Children | $3.95 \times 10^{-6}$ | 1.32 |
| 3 Month Old Infants | $4.91 \times 10^{-6}$ | 2.15 |

[a] All gender and age-specific $^{131}I$ dose conversion factors are described by a lognormal distribution.