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Health Sciences Research Division

Body Growth Considerations in Age-Specific Dosimetry

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ABSTRACT

This report describes the manner in which the age-specific dosimetric calculations of the International Commission on Radiological Protection (ICRP) addressed changes in organ size that occur with age. The approach involves an interpolation of dosimetric information derived for six reference individuals using the inverse of the total body mass as the interpolation variable. An alternative formulation is investigated that employs a functional representation of the organ mass as a function of age in conjunction with an explicit formulation of the dosimetric factors in terms of organ mass. Using an exponential-logistic growth function as suggested by Walker, this report demonstrates, through application to the dosimetry of radioiodines in the thyroid, that the alternative formulation can be formulated and implemented. Although either approach provides a workable basis for age-specific dosimetry, it is clear that the functional representation of organ growth has some attractive features. However, without question, the major difficulty is the quality and quantity of data available to address the age- and gender-specific parameters in the dosimetric formulations.

INTRODUCTION

Evaluation of the radiation dose following an intake of a radionuclide involves consideration of potential changes in anatomic and biokinetic parameters during the period the radionuclide resides within the body. Changes in anatomic and biokinetic parameters need to be considered in evaluating the dosimetric significance of intakes by children; however, similar changes can occur throughout life. Presently, changes in anatomic parameters are not reflected in dosimetric methodologies applied to adults; e.g., such changes are not considered in either the methodology of Committee 2 of the International Commission on Radiological Protection used in setting occupational radiation protection guidance (ICRP 1979) or the methodology of the Medical Internal Radiation Dose Committee of the Society of Nuclear Medicine (Loevinger and Berman 1976) for evaluation of the dose from administered radiopharmaceuticals. Development of age-specific dosimetric methods is an ongoing effort by researchers at the National Radiological Protection Board in the United Kingdom (Phipps et al. 1991), the Bundesamt für Strahlenschutz in Germany, and Oak Ridge National Laboratory (ORNL) in the United States (Cristy 1980; Leggett et al. 1984; Leggett and Warren 1987; Cristy and Eckerman 1987). The current state of the art in age-specific dosimetry is represented by the methodology used by the ICRP in its Publication 56 (ICRP 1989). That methodology, largely that of the ORNL group, considers six reference individuals of ages newborn, 1 year, 5 years, 10 years, 15 years, and adult. Dose estimates for the intake of a radionuclide by an individual of any age are derived by interpolation of the dosimetric data for the reference individuals.

This report discusses the ICRP age-specific methodology with particular emphasis on the manner in which anatomical information is reflected in the calculation of radiation dose. Limitations in the ICRP methodology are noted and their effects on dosimetric quantities are illustrated by consideration of the dosimetric quantities for the intake of iodine radioisotopes. The biokinetic and dosimetric aspects of radioiodine center around a single, rather small endocrine gland, the thyroid. The utility of an exponential-logistic function in representing the growth of the thyroid gland is examined.

The report begins with a presentation of the formulations of age-specific dosimetry. Next, the anatomic and physiologic characterization of the thyroid is briefly reviewed with particular emphasis on the changes in thyroid mass with age. The third section tabulates age-specific estimates of the energy deposition per unit mass of thyroid tissue per nuclear transformation of the radioiodines in

the thyroid. Values derived according to the methods of the ICRP are compared to those based on an exponential-logistic function. The final section presents the conclusions of this study.

DOSIMETRIC FORMULATION

Committee 2 of the International Commission on Radiological Protection has, in Publication 56 (ICRP 1989), begun an effort to address age-specific dosimetry. In particular, that publication presents a dosimetric framework, provides age-specific biokinetic data for selected nuclides, and includes tabulations of the dose per unit intake (dose coefficient) for oral intakes at selected ages. The material presented in this section is based on the presentation in ICRP Publication 56. The committed equivalent dose in target organ or tissue T per unit intake is referred to as a dose coefficient and denoted here as $h_T(t_0)$, where t_0 denotes the age at intake. The dose coefficient is defined in Publication 56 as

$$h_T(t_0) = \int_{t_0}^{70} \sum_S \sum_j q_{S,j}(t) SEE(T \leftarrow S; t)_j dt, \quad (1)$$

where $q_{S,j}(t)$ is the activity of radionuclide j present in source region S at age t following a unit intake at age t_0 and $SEE(T \leftarrow S; t)_j$ is the specific effective energy deposited in target tissue T per nuclear transformation of radionuclide j in source organ S . The dose coefficient represents the total dose in tissue T from the time of intake to age 70 years. The summation over source regions includes the contributions to the dose in the target region T from all source regions S of the body which contain the radioactivity. In a situation where the radionuclide taken into the body heads a decay chain, then the inner summation considers all members of the decay chain in source region S at age t resulting from the intake of the parent radionuclide. The SEE at age t for any radionuclide is

$$SEE(T \leftarrow S; t) = \frac{1}{m_T(t)} \sum_r E_r Y_r w_r AF(T \leftarrow S; E_r, t)_r, \quad (2)$$

where $m_T(t)$ is the mass of the target organ T at age t , E_r is the energy of the radiation r emitted with frequency Y_r per nuclear transformation, w_r is the radiation weighting factor for radiation r (previously called the radiation quality factor), and $AF(T \leftarrow S; E_r, t)_r$ is the fraction in energy of

radiation r emitted in source region S that is absorbed in tissue T for an individual of age t . The absorbed fraction AF depends on the anatomical variables characterizing the size, shape, composition, and density of the source and target regions and their spatial relationship. In addition, AF depends on the type and energy of the emitted radiation. The SEE is the principle dosimetric quantity directly reflecting the anatomical variables characterizing the individual.

The parameters of Eq. (2) which depend on the age of the individual are the masses of the target regions (organs or tissues) and the absorbed fractions. The emitted radiations (their energies and intensities) are characteristic of the radionuclide, and the radiation weighting factor is a radiobiological parameter that is age-invariant. Determination of the absorbed fractions for the source-target pairs of interest, as a function of radiation type and energy, is a complex computational problem due, in part, to the geometric shape of the body and its organs. Additional complexity is introduced by the manner in which radiation interacts with matter. Recourse must be made to Monte Carlo methods to solve the radiation transport equation under such complex geometries. Cristy (1980) has formulated age-specific mathematical representations of the body (referred to as phantoms), suitable for use in radiation transport calculations for photon radiation. The Cristy phantom series consists of six reference individuals of ages newborn, 1 year, 5 years, 10 years, 15 years, and adult. The photon absorbed fraction data derived by Cristy and Eckerman (1987) from a series of Monte Carlo radiation transport calculations (Ryman and Eckerman 1993) in the anatomical models for the six reference ages is currently being used by the ICRP. The complexity of the dosimetry problem is such that it can only be addressed by appropriate interpolation of dosimetric data for a finite set of reference individuals.

For non-penetrating radiations (alpha particles and electrons), the kinetic energy of emitted particles is assumed to be absorbed entirely within the source region, except when the source is mineral bone or the contents of a walled organ. For solid source-target regions, then

$$AF(T \leftarrow S; t) = \begin{cases} 1, & \text{if } T = S \\ 0, & \text{if } T \neq S \\ \frac{M_T(t)}{M_{TB}(t)}, & \text{if } S = TB \end{cases} \quad (3)$$

If the source is uniformly distributed throughout the body (i.e., S is the *total body* of mass M_{TB}), then

the fraction of the activity within target region T is $M_T(t)/M_{TB}(t)$; and since the energy is locally absorbed, the fraction of the energy emitted in the total body that is absorbed in T is $M_T(t)/M_{TB}(t)$. A separate tabulation of absorbed fraction data is used for the dosimetry of the skeletal tissues at risk (ICRP 1979).

The SEECAL code of Cristy and Eckerman (1993) is used to calculate the SEE values for the six reference ages using the specific absorbed fraction data of Cristy and Eckerman (1987). The nuclear decay data used in the calculations are from ICRP Publication 38 (ICRP 1983), as discussed by Eckerman et al. (1993).

The fundamental formulation for evaluation of the dose to organs and tissues of the body from a radionuclide distributed within the body is stated in Eq. (1). In evaluating the integral of Eq. (1), the SEE values at age t are obtained by linear interpolation of the SEE values for the six reference ages according to the inverse of the total body mass. The interpolation scheme, in effect, views SEE as a function of total body mass rather than age. The inverse of the total body mass was selected as the interpolation variable since SEE values are inversely proportional to mass, as seen in Eq. (2). However, for photon radiation the absorbed fraction is also dependent on the size of the body and, in this case, the SEE is inversely proportional to the total body mass raised to the 2/3 power (Adams 1981). The approach of the ICRP computes an SEE value at age a , $SEE(T-S; a)$ as

$$SEE(T-S; t_i) + \frac{SEE(T-S; t_{i+1}) - SEE(T-S; t_i)}{\frac{1}{M_{TB}(t_{i+1})} - \frac{1}{M_{TB}(t_i)}} \left[\frac{1}{M_{TB}(a)} - \frac{1}{M_{TB}(t_i)} \right], \quad (4)$$

where M_{TB} denotes the total body mass, the index i is such that $M_{TB}(t_i) \leq M_{TB}(a) < M_{TB}(t_{i+1})$, and $SEE(T-S; t_i)$ denotes the SEE value for the source-target pair of interest for the reference individual of age t_i . The above formulation applies for ages less than the adult (taken to be 20 years). For age 20 years and greater the $SEEs$ for the reference adult are used. As a practical matter, the above scheme is used only in the first five years of life; beyond age 5 year a linear interpolation by age is used.

Fig. 1 shows the SEE values for self-irradiation of the thyroid by I-131 as a continuous function of age based on the ICRP interpolation scheme. The FORTRAN code fragment of Appendix A is the interpolation routine used in the calculations of ICRP Publication 56. As can be seen from Fig. 1,

the interpolation scheme yields a continuous set of values. The procedure, however, does not ensure that the first and second derivatives are continuous in the region of the reference ages. A change in slope is evident in Fig. 1 in the neighborhood of the 10-year-old, and one has no assurance that similar or greater changes might not be observed for other combinations of nuclide, source-target pairs, and ages.

THYROID GLAND

Iodine is somewhat unusual among the essential trace elements in that the body's inventory is largely associated with a single gland, i.e., the thyroid. Radioiodines, when absorbed into blood, follow the same pathways inside the body as the stable iodine isotope, ^{127}I . Iodine is a component of hormones produced by, stored within, and released into blood by the thyroid gland. The thyroid hormones, thyroxine and triiodothyronine, are required for normal growth, development, and metabolism.

Iodine in a water-soluble form, usually iodide, is readily absorbed into blood from the gastrointestinal tract, respiratory tract, and skin. Iodide in the circulating blood is removed rapidly by both the thyroid and kidneys. Usually less than one-fourth of the iodide is taken up by the thyroid gland, with the remainder being removed from blood by the kidneys and excreted in the urine.

Iodine taken up by the thyroid is concentrated by the gland and incorporated into thyroid hormones, which may be stored in the colloid of the thyroid follicles until required by the body. A number of factors influence the production and utilization of the thyroid hormone, e.g., age and gender. Other factors, such as the quantity of stable iodine in the diet, also influence the gland's function, and can markedly alter the uptake and retention of iodine by the thyroid, as well as the size of the gland. The biokinetics of iodine, as considered in ICRP Publication 56, is shown schematically in Fig. 2 (see Table 1 for the numerical values of the parameters).

The size of the normal human thyroid gland is dependent upon the age — and, to a lesser extent, the gender — of an individual and on the functional status of the thyroid, as determined by a number of dietary and physiological influences.

Adult thyroid weight. Among the largest studies of clinically normal thyroid glands is a series of 821 thyroids obtained at routine autopsies of patients without clinical thyroid abnormalities at the Mayo Clinic during the period 1951 to 1953 (Mortenson et al. 1955). The arithmetic mean of the thyroid weights for individuals between 20 and 70 years of age has been reported to be about 29 g for men and 25 g for women. A more detailed report on thyroid weight is that of Mochizuki et al. (1963), who studied 762 normal thyroid glands. This data set is cited by the ICRP in its Report on Reference Man (1975) and is shown graphically in Fig. 3. The mean ($\pm$ S.D.) weight of the adult thyroid is 16.7 ± 6.9 g for males and females combined, 14.9 ± 6.7 for females, and 17.5 ± 6.8 g for males. In adults, no correlation was seen between thyroid weight and body weight, height, or body

surface area. In their review of the literature, Dunning and Schwartz (1981) estimated the adult thyroid weight to have a mean of 18.3 g (median of 16.5 g).

The data summarized above were from studies of U. S. subjects. Studies from other countries appear to indicate somewhat higher thyroid weights. A recent study performed in Copenhagen, Denmark (Hegedus 1983) reported an analysis of thyroid volume by ultrasound and validated the method by comparison to the volumes of the glands when surgically removed. That study showed a mean thyroid volume of 18.6 ± 4.5 ml (males, 19.6 ± 4.7 and females, 14.7 ± 4.2 ml). A density of about 1.04 g cm^{-3} is typical (ICRP, 1975). The influence of body weight on the thyroid volume was three times that of age, suggesting that gender difference in thyroid gland volume is solely attributable to difference in body weight. The values from the study of Hegedus were somewhat lower than those measured by Auerback (1974) in Jutland, Denmark, where the mean was 24.8 g (25.5 for males and 22.9 g for females).

The ICRP Report on Reference Man (1975) presents a reference adult male thyroid weight of 20 g and adult female value of 17 g. The 20-g weight was also used earlier by the ICRP in radiation protection (ICRP 1959).

Thyroid Weight in Children. The most detailed study of thyroid weight in children is that of Kay et al. (1966), who studied 537 histologically normal glands of children through the age of 19. These glands were obtained from six hospitals across the United States. Kay et al. did not indicate a significant difference in gland weight between male and female children. They suggested the following expression for estimating the thyroid weight for individuals up to age 19:

$$T = 1.48 + 0.054 A \quad , \quad (5)$$

where T is the thyroid weight in grams and A is the age of the individual in months. Fig. 4 shows the measurements reported by Kay et al. and the above regression equation. Their formula also fits the data of Wellman, as quoted by Kereiakes et al. (1972), and is in general agreement with the findings of Mochizuki et al. (1963) as summarized in Table 83 of ICRP Report on Reference Man (1975). Also shown in Fig. 4 are the mass values for 1236 thyroids in Japanese subjects as reported by Tanaka (1992). The Japanese data are in general agreement with the Kay et al. data at the younger ages, but at the later ages they tend to be higher. Note that the larger number of measurements in the Japanese study enables the data to be presented in narrower age groupings, which gives a better indication of the variability at the later ages than does the Kay et al. data.

The most striking characteristic of the data on thyroid weights appears to be the large variability in the individual measurements. There is a general tendency for the gland weight in adult men to be slightly greater than in women, which is consistent with the assumption that total body weight might be a controlling parameter. This also is consistent with the increase in thyroid weight with increasing age as well as the apparent lack of gender differences at earlier ages.

Thyroid growth function. Walker (1988, 1989, 1992) has fit various age-specific organ mass data to an exponential-logistic function of the form

$$m(t) = a_0 + a_1 [1 - e^{-k_0 t}] + \frac{a_2}{1 + e^{-k_1(t - b_0)}}, \quad (6)$$

where $m(t)$ is the organ mass at age t , and a , b , and k are fitted parameters. Walker, in describing the growth patterns, considers that two growth processes are involved. The primary process is represented by the first two terms of the above equation. Walker (1992) refers to the second process as "sexual maturation." This process is represented by the logistic function in the third term of Eq. (6) and is associated with the maximum growth rate and subsequent saturation in organ growth. Whatever the nature of the growth processes, Walker has shown that the exponential-logistic function can describe the postnatal change in mass of a number of organs, and thus has suggested that such functional representation of growth might be of utility in age-specific dosimetry.

The parameters of the thyroid growth of Eq. (6) are given in Table 2 (J. T. Walker, personal communication). These parameters were derived by regression analysis of the data in Table 83 of ICRP Publication 23 (ICRP 1975). The thyroid growth function, shown graphically in Fig. 5, indicates that gender is not a significant variable until about age 14 years. The thyroid mass values at the six reference ages of Publication 56 and the values predicted by the thyroid growth function are compared in Table 3. The tabulated values for the newborn and the adults exhibit the most significant differences. Walker's values at age 20 are probably too low for adults, since the thyroid appears to continue growing after this age (Fig. 3); and the adult reference values of ICRP Publication 23 may be too high, at least for the U.S. population. Walker's function predicts a smaller thyroid mass for the newborn than was assumed in ICRP Publication 56; however, by age one year the tabulated values are in reasonable agreement. The gender differences indicated in thyroid mass at ages less than 15 years do not seem to be supported by the data and may be an artifact of the method.

Walker's growth function was also shown in Figs. 3 and 4 with the data of Mochizuki et al. and Kay et al., respectively. The latter comparison is of particular interest since the Kay et al. data were apparently not used to determine the coefficients of the function. The growth function, including its parametric values, is in general agreement with the Kay et al. data set.

SEE (Thyroid - Thyroid) FOR RADIOIODINES

When the source and target regions are the same (referred to as self-irradiation), Eq. (2) can be written as

$$SEE(T \rightarrow T; t_i) = \frac{1}{m_T(t_i)} \left[\sum_{r=\beta} E_r Y_r w_r + \sum_{r=\gamma} E_r Y_r w_r AF(T \rightarrow T; t_i)_r \right], \quad (7)$$

where the first term represents the contributions from the non-penetrating radiations, and the second term is the contribution from penetrating radiations. For solid regions (regions other than the walls or targets in the skeleton), the non-penetrating radiations are assumed to be totally absorbed in the source region. Thus, the absorbed fraction for these radiations is one and the contribution of non-penetrating radiations to the *SEE* is inversely proportional to the mass of the target. The contribution of the penetrating radiations is directly proportional to the absorbed fraction and inversely proportional to the mass of the target region, m_T .

The *SEE* values used in ICRP Publication 56 are computed using the SEECAL code (Cristy and Eckerman 1993). The masses of the thyroid gland at the reference ages are tabulated in Table 3. *SEE* values at the reference ages for self-irradiation of the thyroid are given in Table 4 for the radioisotopes of iodine considered in ICRP Publication 30 (1979). These data were computed using the SEECAL code. Killough and Eckerman (1986) earlier had derived a closed-form expression for the thyroid *SEE* for radioiodines as a function of thyroid mass. That expression is of the form

$$SEE(Thyroid \rightarrow Thyroid) = \frac{A}{m_{Thyroid}} + B m_{Thyroid}^C, \quad (8)$$

where the parameter A is the total energy (joule) of the non-penetrating radiations, and B and C are regression parameters derived by fitting the photon contribution to *SEE* as a power function of thyroid mass. The coefficients of Eq. (8) for all the radioiodines are tabulated in Table 5.

Note that the value of C obtained from the regression is well approximated by -2/3, as noted above. Only for the radioiodines emitting very-low-energy photons (I-125 and I-129) does the value depart from the -2/3 power. In effect, Eq. (8) invokes a change in variable; that is, the *SEE* is expressed as a function of thyroid mass rather than age. The formulations of Eqs. (6) and (8) in conjunction with the data of Table 5 were used to derive age-specific *SEE* values as a function of age

for comparison with values based on the data of Table 4 and the ICRP interpolation scheme. These comparisons are given in Table 6.

RESULTS

We have outlined above two means to derive *SEE* for self-irradiation of the thyroid. *SEEs* calculated with the growth function are compared with values based on the mass data and interpolation method of ICRP Publication 56. To compare these two methods the *SEE* values were computed for ages 0 through 20 years. The maximum observed numerical differences in the *SEEs* were tabulated for various age groups as shown in Table 6. The results were expressed in terms of the percent difference computed as

$$100 \frac{|SEE_{ICRP} - SEE_{Growth\ function}|}{SEE_{ICRP}},$$

where SEE_{ICRP} and $SEE_{Growth\ function}$ denote the values derived following the mass values/interpolation scheme of ICRP Publication 56 and the thyroid growth functions, respectively. Fig. 6 shows the percent difference as a continuous function of age for I-131. In this figure a negative difference corresponds to the growth function method yielding a higher *SEE* value than that derived following the ICRP Publication 56 methods. Note also that, although the differences in childhood tend to be small (less than 6%), the difference curve exhibits considerable structure. This structure, although small in magnitude, is introduced by the ICRP Publication 56 method since the growth curve is mathematically well behaved.

For all the radioiodines the maximum differences in *SEE* values for an individual under 5 years of age occurred for the newborn. The percent difference (about 32% for males and 42% for females) reflects the difference between the reference value of ICRP Publication 56 (1989) and that of the growth function (see Table 3). That is, the difference is not a matter of the interpolation scheme. In a similar manner, the maximum difference seen in the oldest age group (age greater than 15 years), always occurred at age 20. Here again the numerical difference was about 30% for the male and almost 50% for the female. ICRP Publication 56 did not differentiate by gender. In the other age groups, the differences are on the order of 10%. Little dependence on radioisotope is evident in the data of Table 6.

Table 7 compares the committed equivalent dose in the thyroid gland per unit of activity ingested, as computed using the ICRP Publication 56 methods, with values derived using the thyroid growth function. Data are presented for ^{129}I , ^{130}I , and ^{131}I . In both sets of calculations the iodine biokinetics (see Table 1) were interpolated as a function of age in a linear manner as is the practice in ICRP Publication 56. The numerical difference between the two approaches is seen to be rather small.

The analysis indicates that the *SEE* values are primarily sensitive to the quality of the underlying organ mass data. Either a functional or an interpolation approach is capable of meeting the computational needs of age-specific dosimetry.

SUMMARY AND CONCLUSIONS

Considerable difficulties are encountered in attempting to establish reference weights for organs of the body. While it is beyond the scope of this study to address these issues, some comments are in order; particularly to place Table 3 in proper context. The ICRP Report on Reference Man (ICRP Publication 23, 1975) did not set reference values for non-adults. The age-dependent data on thyroid mass cited in Table 83 of that publication indicate a mass of about 1 g for newborns based on only 4 measurements. The data of Kay et al. (1966), which were cited but not tabulated in Publication 23, indicate a mean thyroid mass of 1.5 ± 0.7 g, based on 74 measurements. The Japanese data give similar results: males and females of average age 1 month had thyroid masses of 1.58 ± 0.56 g (n=62) and 1.57 ± 0.47 g (n=43), respectively (Tanaka 1992). It appears that both the value for the newborn in ICRP Publication 56 (1.29 g) and the value predicted by the thyroid growth function (0.9 g) underestimate the gland's weight at birth.

The adult thyroid mass in Table 3 predicted by the thyroid growth function (15.4 and 13.5 g for male and female, respectively) are lower than the mean values stated by the ICRP of 17.5 and 14.9 g for the male and female data of Table 83 (ICRP 1975). Furthermore, the reference values cited for the adult are 20 and 17 g for the male and female, respectively. The ICRP Task Group provides no discussion as to how they arrived at the reference values in light of the mean values cited. Without such information, it is difficult to fit a mathematical function to the observations and still remain consistent with the cited reference values. (It is noted that the autopsy weights in Table 83 of Publication 23 were based on the weights of thyroid glands drained of blood. Thus, the *in situ* weight, in the case of the adult, might be 3 to 4 g greater than the autopsy values.)

Some comments are also in order on the ICRP consideration of gender. While the Task Group on Reference Man in its 1975 publication did set reference values for the adult female, the ICRP Committees have been rather inconsistent in addressing gender. For example, in estimating the dose from inhaled and ingested radionuclides, the ICRP continues to use *SEE* values based on a hermaphrodite of a size corresponding to the adult male. Thus, the adult thyroid mass in ICRP Publication 56 is stated as 20 g (Table 3), which corresponds to the reference male. However, in Publication 51 (1987) on protection against external radiation, the ICRP derived the effective dose coefficients from the average organ dose for reference adult males and females. In light of the increasing number of females in the workplace and concerns regarding potential *in utero* exposure,

one would expect that future dosimetric methodologies would explicitly address the female.

Functional representation of the changes in organ mass with age offers some attractive features. In particular, the language of mathematics introduces an element of completeness and clarity in presentation that is presently missing in current tabulations. However, it should be clearly understood that the functions have no inherent validity in themselves and are only as good as the supportive data. The exponential-logistic function suggested by Walker has the desirable mathematical properties required of such a function.

The *SEEs* derived using a thyroid growth function were compared to values obtained using the interpolation scheme of ICRP Publication 56. The comparison was dominated by difference in the thyroid mass predicted by the growth function at the reference ages considered in ICRP Publication 56. While the two methods yield different *SEE* values, the differences were attributed to the underlying interpretation of the observations on thyroid mass rather than the computational procedures themselves. It is estimated that numerically the two procedures differ by less than 10%.

Because of the complexity of the radiation transport calculations in the body, it is necessary to use tabulations of absorbed fraction data based on anatomical characterization of individuals of specific ages. While Committee 2 elected in ICRP Publication 56 to interpolate the *SEE* values based on the total body mass, we have shown that for self-irradiation it is possible to derive the *SEE* value for a specific organ mass. Since the dosimetry of internal emitters is often dominated by self-irradiation of organs, the alternative formulation would appear to offer considerable advantages in the instances of an organ whose growth does not parallel that of the total body. The availability of functional representation of the organ growth would facilitate the development of such an approach to addressing age-specific changes in organ size.

It should be quite obvious from this report that the available data on organ growth and development are scattered, generally incomplete, and often not contemporary. There are glaring gaps in our knowledge which hamper the development of a comprehensive picture of growth. The need for additional measurements is quite clear; however, it appears unreasonable to expect that this need can be met by reliance on measurements at autopsy. Extraction of anatomical data from medical images appears to provide the best means of assembling such information in the near future.

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APPENDIX A

ICRP INTERPOLATION SCHEME: FORTRAN CODE FRAGMENT

ICRP Committee 2 Task Group on Dose Calculation uses an interpolation scheme to derive SEE values at any age. The interpolation is performed on SEE values for six reference ages (newborn, 1-, 5-, 10-, 15-year old and the adult) using the inverse of the total body mass as the interpolation variable. The scheme uses a piece-wise power function representation of the total body mass. Beyond age 5 years, the interpolation is by age. The following FORTRAN code fragment was extracted from the computer code used in the calculations for ICRP Publication 56.

```

C IAGE is the age at which SEEs are desired.
C MSEE is the array of reference ages (d) at which SEE values exist
C IPT is an index such that MSEE(IPT-1) < IAGE < MSEE(IPT)
C Element S(Jage, Ispec, Isou, Itarg) is the SEE value for the jage
C reference individual, the Ispec nuclide in the decay chain, the
C Isou source organ, and Itarg target organ. Element SX(Ispec, Isou, Itarg)
C is the SEE value at IAGE for the Ispec nuclide and the Isou, Itarg source-
C target pair as interpolated from the S array.
C

```

```

      REAL S, SX, SP
      INTEGER IAGE, MSEE, IPT, NSPEC, NSOU, NTARG
      DIMENSION MSEE(6), S(6, 12, 18, 21), SX(12, 18, 21)
      DATA MSEE/ 0, 365, 1825, 3650, 5475, 7300/
      :
      :
      IF (IAGE .LE. MSEE(2)) THEN
        IPT = 2
        SP = FLOAT((IAGE - MSEE(1))) / FLOAT(MSEE(2))
        SP = SP**(0.3 + 0.7 * ((1.0 - SP)**10.))
      ELSEIF (IAGE .LE. MSEE(3)) THEN
        IPT = 3
        SP = FLOAT((IAGE - MSEE(2))) / FLOAT((MSEE(3) - MSEE(2)))
        SP = SP**(0.5 + 0.5 * ((1.0 - SP)**5.))
      ELSEIF (IAGE .LE. MSEE(4)) THEN
        IPT = 4
        SP = FLOAT((IAGE - MSEE(3))) / FLOAT((MSEE(4) - MSEE(3)))
      ELSEIF (IAGE .LE. MSEE(5)) THEN
        IPT = 5
        SP = FLOAT((IAGE - MSEE(4))) / FLOAT((MSEE(5) - MSEE(4)))
      ELSEIF (IAGE .LE. MSEE(6)) THEN
        IPT = 6
        SP = FLOAT((IAGE - MSEE(5))) / FLOAT((MSEE(6) - MSEE(5)))
      ELSE
        IPT = 7
        SP = 1.
      END IF
      :
      :
C The SEE values for an individual of age IAGE, SX, for the chain are
      DO 40 ISPEC = 1, NSPEC
        DO 40 ISOU = 1, NSOU
          DO 40 ITARG = 1, NTARG
            IF(IPT .LT. 7) THEN
C              Interpolate for ages less than 20 years.
              SX(ISPEC, ISOU, ITARG) = S(IPT-1, ISPEC, ISOU, ITARG) +
                SP * (S(IPT, ISPEC, ISOU, ITARG) - S(IPT-1, ISPEC, ISOU, ITARG))
            ELSE
C              An adult, use IPT-1 or 6 values
              SX(ISPEC, ISOU, ITARG) = S(IPT-1, ISPEC, ISOU, ITARG)
            END IF
          END IF
        END IF
      40 CONTINUE

```

As an example, consider the computation of the SEE for self-irradiation of the thyroid by I-131 in an individual of age 100 d; this is the youngest age at intake considered in ICRP Publication 56. The age of interest, 100 d, is less than the age of the second reference individual and thus the interpolation variable SP is

$$\begin{aligned} SP &= \left[\frac{100}{365} \right]^{0.3 + 0.7 \left(1 - \frac{100}{365} \right)^{10}} \\ &= \left[\frac{100}{365} \right]^{0.3285} \\ &= 0.6536 \end{aligned}$$

The SEE at age 100 d is then

$$\begin{aligned} SEE(100 \text{ d}) &= SEE(0 \text{ d}) + SP [SEE(365 \text{ d}) - SEE(0 \text{ d})] \\ &= 2.44 \times 10^{-11} + 0.6536 [1.78 \times 10^{-11} - 2.44 \times 10^{-11}] \\ &= 2.00 \times 10^{-11} \end{aligned}$$

Table 1. Age-specific biokinetic parameters for ingestion iodine

Transfer		Transfer Rate Coefficient (d ⁻¹)					
From	To	3 months	1 years	5 years	10 years	15 years	Adult
ST Cont	SI Cont	24.	24.	24.	24.	24.	24.
SI Cont	Blood	594.	594.	594.	594.	594.	594.
SI Cont	ULI Cont	6.	6.	6.	6.	6.	6.
ULI Cont	LLI Cont	1.8	1.8	1.8	1.8	1.8	1.8
LLI Cont	Feces	1.0	1.0	1.0	1.0	1.0	1.0
Blood	Thyroid	0.8318	0.8318	0.8318	0.8318	0.8318	0.8318
Blood	U Bladder	1.941	1.941	1.941	1.941	1.941	1.941
Thyroid	Other	0.06189	0.04621	0.03014	0.01195	0.01034	0.008664
Other	ULI Cont	0.1238	0.09242	0.06027	0.02390	0.02069	0.01155
Other	Blood	0.4951	0.3697	0.2411	0.09561	0.08276	0.04621
U Bladder	Urine	40.	32.	12.	12.	12.	12.

Table 2. Thyroid growth function

Parameter	Numerical Value	
	Males	Females
a_0 (kg)	0.00032	0.00067
a_1 (kg)	0.00075	0.00096
a_2 (kg)	0.0152	0.012
k_0 (mo ⁻¹)	0.358	0.476
k_1 (mo ⁻¹)	0.02532	0.0346
b_0 (mo)	129.3	113.5

Table 3. Thyroid mass (g) as function of age

Age	ICRP-56	Growth Function	
	Reference	Males	Females
Newborn	1.29	0.874	0.902
1 y old	1.78	1.80	1.98
5 y old	3.45	3.31	3.26
10 y old	7.93	7.78	8.30
15 y old	12.4	13.0	12.5
Adult	20	15.4	13.5

Table 4. Age-specific SEE values for self-irradiation of the thyroid

Nuclide	SEE(Thyroid <- Thyroid) (Gy nt ⁻¹)					
	Newborn	1 y	5 y	10 y	15 y	Adult
I-120	1.808E-10	1.315E-10	6.833E-11	3.001E-11	1.933E-11	1.207E-11
I-120m	1.625E-10	1.187E-10	6.221E-11	2.763E-11	1.795E-11	1.129E-11
I-121	1.116E-11	8.162E-12	4.305E-12	1.930E-12	1.263E-12	8.005E-13
I-123	4.020E-12	2.941E-12	1.567E-12	7.128E-13	4.709E-13	3.017E-13
I-124	2.593E-11	1.900E-11	1.002E-11	4.486E-12	2.932E-12	1.855E-12
I-125	2.918E-12	2.129E-12	1.138E-12	5.213E-13	3.445E-13	2.218E-13
I-126	2.039E-11	1.487E-11	7.768E-12	3.437E-12	2.227E-12	1.398E-12
I-128	9.303E-11	6.744E-11	3.481E-11	1.516E-11	9.698E-12	6.016E-12
I-129	8.151E-12	5.913E-12	3.069E-12	1.348E-12	8.672E-13	5.416E-13
I-130	4.037E-11	2.967E-11	1.572E-11	7.082E-12	4.654E-12	2.955E-12
I-131	2.443E-11	1.777E-11	9.242E-12	4.065E-12	2.622E-12	1.639E-12
I-132	6.514E-11	4.762E-11	2.501E-11	1.113E-11	7.249E-12	4.568E-12
I-132m	2.040E-11	1.484E-11	7.729E-12	3.404E-12	2.198E-12	1.375E-12
I-133	5.198E-11	3.779E-11	1.962E-11	8.604E-12	5.538E-12	3.453E-12
I-134	8.140E-11	5.945E-11	3.118E-11	1.384E-11	9.001E-12	5.664E-12
I-135	4.793E-11	3.498E-11	1.834E-11	8.137E-12	5.285E-12	3.326E-12

Table 5. Regression coefficients for SEE (Thyroid <- Thyroid)¹

Nuclide	A (Gy g/nt)	B (Gy/g)	C
I-120	2.280E-11	4.945E-12	-0.6600
I-120m	1.992E-11	9.814E-12	-0.6597
I-121	1.326E-11	1.053E-12	-0.6759
I-123	4.512E-12	6.161E-13	-0.6984
I-124	3.104E-11	2.271E-12	-0.6658
I-125	3.106E-12	5.989E-13	-0.7365
I-126	2.521E-11	1.035E-12	-0.6685
I-128	1.198E-10	1.837E-13	-0.6632
I-129	1.022E-11	2.628E-13	-0.7232
I-130	4.762E-11	4.206E-13	-0.6576
I-131	3.072E-11	7.466E-13	-0.6561
I-132	7.936E-11	4.408E-12	-0.6588
I-132m	2.545E-11	8.096E-13	-0.6864
I-133	6.579E-11	1.200E-12	-0.6570
I-134	9.970E-11	5.002E-12	-0.6599
I-135	5.881E-11	2.841E-13	-0.6610

¹ $SEE = \frac{A}{m_{thy}} + B m_{thy}^C$ where m_{thy} is the thyroid mass (g).

Table 6. Maximum differences in age-specific SEEs derived according to mass values and interpolation scheme of Publication 56 with values based on thyroid growth function

Nuclide	Percent Difference Relative to ICRP Publication 56							
	Age < 5		5 < Age < 10		10 < Age < 15		15 < Age < 20	
	Male	Female	Male	Female	Male	Female	Male	Female
I-120	32.1	42.8	3.7	7.0	6.4	9.4	29.4	47.5
I-120m	31.9	42.4	3.6	6.9	6.4	9.2	28.9	46.5
I-121	31.6	41.9	3.6	6.7	6.2	9.0	28.3	45.5
I-123	31.1	40.9	3.7	6.4	6.1	8.8	27.3	44.1
I-124	31.7	42.1	3.5	6.8	6.3	9.1	28.5	45.8
I-125	30.7	40.2	3.9	6.3	6.0	8.7	27.0	43.6
I-126	31.9	42.5	3.7	6.9	6.4	9.3	29.0	46.7
I-128	32.2	43.0	3.9	7.2	6.6	9.5	29.8	48.3
I-129	32.0	42.5	3.9	7.0	6.5	9.4	29.3	47.4
I-130	31.6	42.0	3.4	6.7	6.2	9.0	28.2	45.3
I-131	32.0	42.7	3.7	7.0	6.4	9.4	29.3	47.3
I-132	31.8	42.3	3.5	6.9	6.3	9.2	28.7	46.3
I-132m	32.0	42.6	3.7	7.0	6.4	9.4	29.2	47.2
I-133	32.1	42.8	3.7	7.1	6.5	9.4	29.5	47.6
I-134	31.9	42.4	3.5	6.9	6.3	9.2	28.8	46.4
I-135	31.9	42.4	3.6	6.9	6.3	9.2	28.8	46.5

Table 7. Comparison of dose coefficients based on ICRP Publication 56 methods with values obtained using a thyroid growth function

Nuclide	Age at intake	Equivalent dose per unit ingested activity (Sv/Bq)	
		ICRP-56	This work
I-129 $T_{1/2} = 1.57\text{E}7$ y	3 month	3.7E-06	3.9E-06
	1 year	4.3E-06	4.2E-06
	5 year	3.4E-06	3.6E-06
	10 year	3.8E-06	3.7E-06
	15 year	2.8E-06	2.7E-06
	Adult	2.1E-06	2.7E-06
I-130 $T_{1/2} = 12.36$ h	3 month	3.9E-07	3.9E-07
	1 year	3.5E-07	3.1E-07
	5 year	1.9E-07	1.7E-07
	10 year	8.5E-08	7.5E-08
	15 year	5.6E-08	4.5E-08
	Adult	3.6E-08	3.8E-08
I-131 $T_{1/2} = 8.04$ d	3 month	3.7E-06	4.0E-06
	1 year	3.6E-06	3.5E-06
	5 year	2.1E-06	2.1E-06
	10 year	1.0E-06	1.1E-06
	15 year	6.8E-07	6.5E-07
	Adult	4.3E-07	5.6E-07

Age-Specific SEE (Thyroid)

Fig. 1. SEE values for self-irradiation of the thyroid gland by I-131 as a function of age. Graph was derived from the methodology of ICRP Publication 56.

Fig. 2. Schematic of iodine biokinetics. Note the explicit consideration of the routes of excretion. Fecal excretion of systemic iodine is via the upper large intestine (ULI) and urinary excretion is through the urinary bladder.

Thyroid Mass in ICRP 23

Fig. 3. Thyroid mass as a function of age. Data of Mochizuki et al. (1963), as given in ICRP Publication 23 (1975). Solid circles are males and open squares are females. The heavy curves correspond to the thyroid growth function of Walker.

Thyroid Mass in Children

Fig. 4. Thyroid mass in children. The solid circle are the data of Kay et al. (1966) for U. S. subjects. The Japanese data of Tanaka (1992) are the solid square. The dashed curve represents the thyroid weights for males as predicted by the growth function of Walker.

Fig. 5. The thyroid growth function of Walker for males and females.

Fig. 6. Difference between SEE values for the thyroid derived following the methods and mass values of ICRP Publication 56 and values based on the thyroid growth function of Walker. Positive difference corresponds to the ICRP Publication 56 SEE being greater than the value derived from the growth function.

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