RELIABILITY OF THE ICRP'S DOSE COEFFICIENTS

CASE STUDIES OF POTENTIAL ERRORS IN CURRENT BIOKINETIC MODELS AND DOSE COEFFICIENTS

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ABSTRACT

A pilot study was conducted for the U.S. Nuclear Regulatory Agency (NRC) to examine the feasibility of characterizing and improving the reliability of current dose coefficients for a comprehensive set of radionuclides of concern to the NRC. The dose coefficients considered for inhalation and ingestion were those currently recommended by the International Commission on Radiological Protection (ICRP) for members of the public and workers. The pilot study consisted largely of a set of case studies, i.e., detailed assessments of selected radionuclides and exposure situations, representing different sources and quality of biokinetic and dosimetric information. An assessment of a case study included critical evaluation of the database and current models for the radionuclide and comparison of model predictions with those of alternate models considered to be at least as strongly founded. This paper summarizes results and conclusions of eight case studies regarding the reliability of ICRP models and dose coefficients as central estimators for adult males. The focus of this paper is on potential errors in biokinetic models, which were judged to be the dominant sources of error in dose per unit intake in most instances, and the reflection of those errors in derived dose coefficients. It is concluded that potential errors in current models and dose coefficients often arise in large part from discrepancies between the models and database and thus are reducible errors rather than genuine uncertainties. The combination of reducible errors and uncertainties can result in large errors in applications of current dose coefficients, even for frequently studied radionuclides.

INTRODUCTION

A pilot study was conducted for the U.S. Nuclear Regulatory Agency (NRC) to examine the feasibility of characterizing and improving the predictive accuracy of current dose coefficients for a comprehensive set of radionuclides of concern to the NRC. Dose coefficients considered for inhalation and ingestion were those currently recommended by the International Commission on Radiological Protection (ICRP) for members of the public and workers. Dose coefficients for external exposure were those tabulated in U.S. Federal Guidance Report 12 (USEPA, 1993).

The pilot study consisted mainly of a collection of case studies, i.e., detailed assessments of models and dose coefficients for selected radionuclides and exposure situations. The cases were selected to represent different sources and quality of biokinetic and dosimetric information. Each assessment included critical evaluation of the database and current models for the radionuclide, and comparison of model predictions with those of alternate models judged to be at least as strongly founded as the current models.

This paper summarizes results and conclusions of eight case studies regarding the reliability of ICRP models and dose coefficients as central estimators for adult males. Attention is restricted to the adult male for ease of exposition and uniformity across case studies, and to keep the paper to a reasonable length. The paper focuses on potential errors in biokinetic models, which were judged to be the dominant sources of error in dose per unit intake in most instances, and the reflection of those errors in derived dose coefficients for inhalation or ingestion of radionuclides.

Other aspects of the reliability of current dose coefficients addressed in the NRC pilot study will be addressed in future publications. These include variability in dose with age and gender, variability in dose between two persons of the same age and gender, uncertainties in nuclear decay data, and uncertainties associated with current external dose coefficients.

CASE STUDIES

Case 1. Ingestion of cesium-137

Cesium is one of the most extensively studied and best understood elements with regard to its biological behavior in the human body. Dose coefficients for ingestion of ^{137}Cs are generally regarded as being among the most accurate of the ICRP's dose coefficients. The results of this case study are consistent with that view to some extent but indicate that these dose coefficients can result in large errors in dose estimates in some situations.

Case 1a. ^{137}Cs as a soluble inorganic compound or biologically incorporated in food

The structure of the ICRP's current systemic model for absorbed cesium (ICRP, 1989, 1993, 1994b) is shown in Figure 1. Absorbed activity is assumed to leave blood with a

half-time of 0.25 d and to be uniformly distributed throughout the body. Whole-body retention at t days after injection is described by a sum of two exponential terms:

$$R(t) = a \exp(-0.693t/T_1) + (1 - a) \exp(-0.693t/T_2). \quad \text{(Eq. 1)}$$

The parameters a, T_1, and T_2 vary with age, reflecting more rapid turnover of cesium in children than in adults (ICRP, 1989). Values for ages up to 15 y are related to total-body potassium (Leggett, 1986). Values for the adult (a = 0.1, T_1 = 2 d, and T_2 = 110 d) are carried over from the cesium model for workers used in ICRP Publication 30 (1979). Barium-137m produced in the body is assigned the biokinetics of cesium.

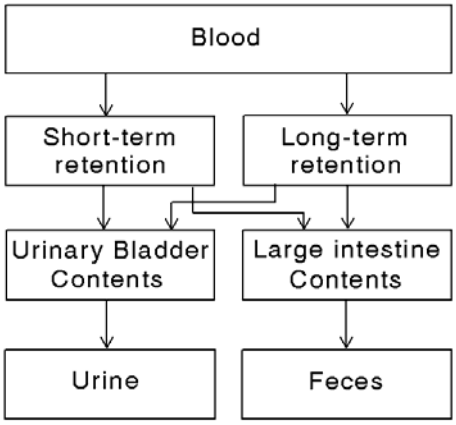

Figure 1. Structure of ICRP's current systemic biokinetic model for cesium (ICRP, 1989, 1993, 1994b).

The ICRP's current dose coefficients for ingested ^{137}Cs are based on this model and the assumption of complete absorption of ^{137}Cs to blood. These dose coefficients generally are thought to involve relatively small predictive errors. The reasoning is that: (1) most inorganic forms of cesium are highly soluble; (2) the ICRP's assumption of complete absorption of ingested cesium from the gut is reasonably accurate in view of human and animal studies indicating virtually complete absorption (~0.99) of cesium ingested in soluble inorganic form (e.g., as ^{137}CsCl) and high absorption (typically 0.7-0.99) of cesium ingested in food (Harrison et al., 2001); (3) the systemic biokinetics of cesium has been extensively studied in man, shows only modest variability for a given gender and age group, and for practical purposes seems to be adequately described by the two-exponential model used by the ICRP (Leggett, 1986; ICRP, 1989; Leggett et al., 2003); (4) data for man and laboratory animals indicate somewhat uniform distribution in the body, as assumed by the ICRP (Leggett et al., 2003); and (5) a separate model for ^{137m}Ba produced in vivo is unnecessary because its half-life (2.6 min) seems too short to permit significant migration from ^{137}Cs. Results of parameter uncertainty analyses based on the assumption of uniform distribution of ^{137}Cs and ^{137m}Ba suggest that the ICRP's dose coefficients for ingested ^{137}Cs may overestimate true central values slightly but still involve fairly small errors (<50%) in most cases, even when applied to individuals (Schwarz and Dunning, 1982; Apostaoaei and Miller, 2004).

While it is agreed that errors in dose estimates for ingested ^{137}Cs are modest compared with most radionuclides and exposure modes, the ICRP's systemic model and dose coefficients for this radionuclide may have lower accuracy, either as a central estimator or for individuals, than commonly assumed. The problem lies in the simplistic formulation of the ICRP model, specifically in the assumption that ^{137}Cs and ^{137m}Ba are uniformly distributed in the body.

Potential errors associated with dose coefficients for ^{137}Cs are revealed by comparison with predictions based on a more detailed model (Leggett et al., 2003). The alternate model structure is shown in Figure 2; parameter values are given by Leggett et al. (2003). The model is constructed around a blood flow model and depicts a non-homogeneous distribution of cesium in the body, particularly soon after entry into blood. For derivation of parameter values, information on the biokinetics of cesium in the human body or laboratory animals was supplemented with data on potassium and rubidium and information on patterns of discrimination between these elements by tissues.

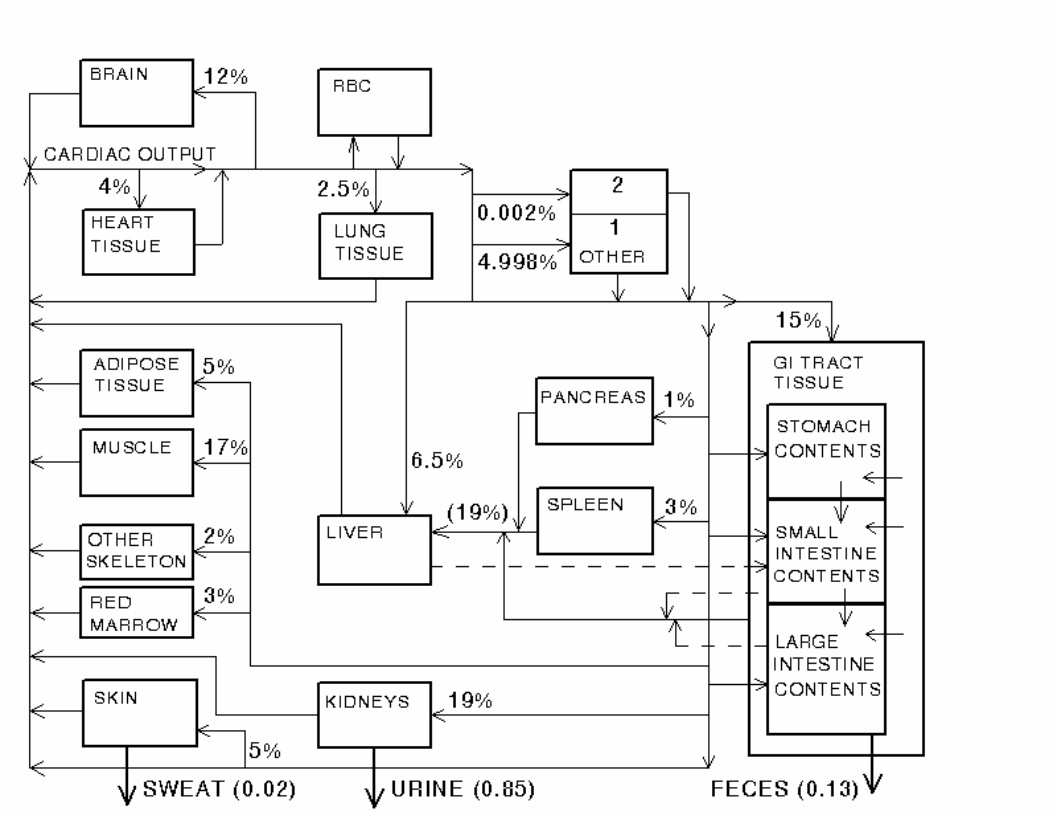

Figure 2. Structure of a physiologically based biokinetic model for Cs in the human body (Leggett et al., 2003). Solid arrows represent plasma flow and broken arrows represent flow not involving plasma. Percentages indicate distribution of cardiac output. Numbers beside SWEAT, URINE, and FECES are fractions of cumulative excretion.

Equivalent doses to tissues of an adult male were estimated for the case of ingestion of ^{137}Cs using a number of variations of the model shown in Figure 2, two of which are

described below. The published model (Leggett et al., 2003) does not specify the site of deposition or retention of cesium in "Other skeleton" nor the fate of radioactive progeny produced in vivo. A baseline gastrointestinal absorption fraction of 0.99 is assigned, but that value may be changed by the user, and separate values may be specified for absorption from food and from secretions into the alimentary tract (e.g., saliva or bile). In one variation of this model (Model A): (1) fractional uptake from the small intestine is assumed to be 0.8 for cesium in food and 0.99 for cesium that has been absorbed to blood but is later secreted into the stomach or small intestines; (2) ^{137}Cs depositing in "Other skeleton" is assigned to bone volume and is assumed to be equally divided between trabecular and cortical bone; and (3) ^{137m}Ba produced in the body is assumed to decay at the site of production. In another variation (Model B): (1) fractional uptake from the small intestine is assumed to be 0.99 both for ^{137}Cs in food and secretions into the stomach and small intestine; (2) half of ^{137}Cs depositing in "Other skeleton" is assigned to bone surface and half to bone volume, with activity entering bone equally divided between trabecular and cortical bone; (3) ^{137m}Ba produced at sites other than bone volume is assumed to move to plasma with a half-time of 10 min, to leave plasma with a half-time of 1 min, and to be redistributed as described by the ICRP's current model for barium (ICRP, 1993).

The treatment of ^{137m}Ba in Model B is based on data for rats (Wasserman et al., 1959) that show considerable migration of ^{137m}Ba from ^{137}Cs despite the extremely short half-life of ^{137m}Ba. It is assumed, however, that redistribution of ^{137m}Ba to tissues is slower in humans than rats due to slower blood circulation. Wasserman and coworkers determined activity ratios ^{137m}Ba:^{137}Cs of 0.8, 3.3, 3.9, and 14 times equilibrium values in liver, bone, whole blood, and plasma, respectively, at 4-7 days after intraperitoneal injection of ^{137}Cs into rats. Model B predicts activity ratios in these tissues and fluids of 0.9, 1.5, 2.7, and 22, respectively, at 4 d after injection of ^{137}Cs.

Ingestion dose coefficients for selected tissues of an adult based on the ICRP model and on Models A and B are compared in Figure 3. Coefficients based on Model A do not differ appreciably from ICRP values except that values for testes (and some other tissues not shown such as skin and breast) are about threefold lower than ICRP values. Values based on Model A are about threefold greater for bone and twofold greater for the upper large intestine wall than ICRP values. The difference in estimates for bone surface arises mainly from assignment of a portion of deposited ^{137}Cs to bone surface in Model B. The difference in predictions of the ICRP model and Model B for ULI arises mainly from the assumed relocation of ^{137m}Ba in Model B; radiobarium was found to transfer rapidly to the large intestine after its intravenous injection into human subjects (Korsunskii et al., 1981), and this is depicted in the model for barium used here. As suggested in Figure 3, estimates of effective dose are not highly sensitive to assumptions concerning the distribution of ^{137}Cs and ^{137m}Ba.

Comparison of predictions of Models A and B shown in Figure 3 suggests that ingestion dose coefficients for ^{137}Cs are not narrowly determined for some tissues, even as a central estimate for a large group of males. Thus, the relatively detailed model for cesium shown in Figure 2 points to larger uncertainties in dose estimates for internally deposited ^{137}Cs

than indicated by uncertainty analyses based on the simpler structure shown in Figure 1. Although only two non-ICRP models are addressed here, the original analysis considered several other plausible variations of the model shown in Figure 2. The full range of dose coefficients generated for bone surface and ULI indicate somewhat larger potential errors in dose coefficients for these tissues than suggested by the examples addressed in Figure 3.

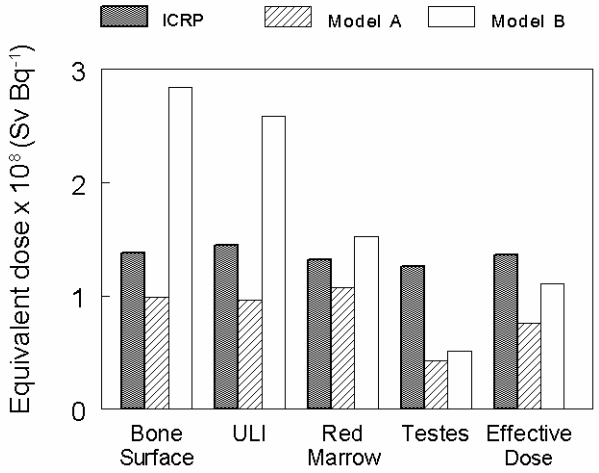

Figure 3. Comparison of the ICRP's dose coefficients for ingestion of ^{137}Cs by an adult male with values based on plausible variations of the model shown in Figure 2.

Case 1b. ^{137}Cs in fallout or irradiated reactor fuel particles

The above comparisons are for ingestion of forms of ^{137}Cs that consistently show high fractional absorption to blood. Some forms of ^{137}Cs present in the environment or occupational settings show relatively low or highly variable absorption to blood (Harrison et al., 2001). For example, studies on rats indicate that fractional absorption of ^{137}Cs from irradiated reactor fuel particles may be less than 0.1. Reported fractional absorption of ^{137}Cs ingested in real or simulated fallout by human volunteers has varied from less than 0.1 to 1.

Another set of dose coefficients for ingestion of ^{137}Cs by an adult male were based on a variation of Model B in which fractional absorption was reduced to 0.1 for the initially swallowed ^{137}Cs (e.g., in fallout on raw fruit and vegetables) but was left at 0.99 for ^{137}Cs that has been absorbed and later reaches the small intestines in secretions. Dose coefficients for adults based on this variation, called Model B*, are compared in Figure 4 with the ICRP's dose coefficients and values based on Model B. The large differences in the three sets of values suggest that applications of the ICRP's ingestion dose coefficients for ^{137}Cs involve particularly large uncertainties in situations where ^{137}Cs is present in moderately soluble or relatively insoluble form or when the form of ingested ^{137}Cs is not known.

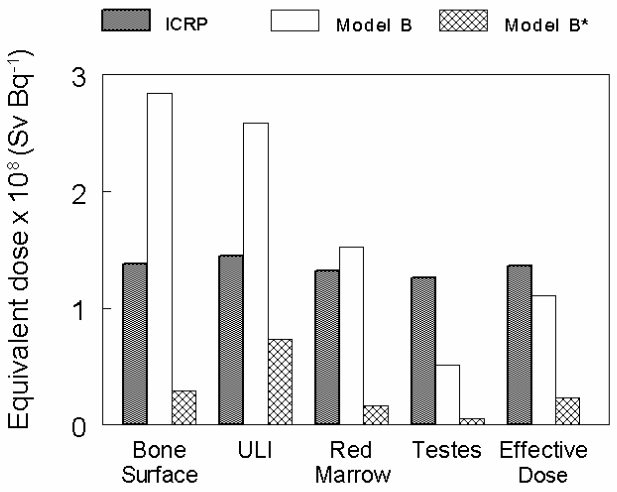

Figure 4. Comparison of the ICRP's dose coefficients for ingestion of ^{137}Cs by an adult male with values based on Model B (see text) or a modification of Model B that accounts for reduced absorption of cesium ingested in some forms (Model B).

One implication of this case study and others that follow is that the level of confidence that can be placed in a dose coefficient may depend strongly on the form of the radionuclide and the extent to which the form can be identified in a given application. Thus, the commonly used term "uncertainty in a dose coefficient" is not well defined for ingestion or inhalation of a radionuclide in the absence of specifications regarding the form of the radionuclide and the extent to which the form of the radionuclide is assumed to be identifiable by the user.

Case 2. Inhalation of $^{14}CO_2$

Carbon-14 represents a significant portion of the estimated dose to the public from nuclear reactor emissions and is considered a particular hazard to workers at heavy water moderated reactors (Killough and Rohwer, 1978; UNSCEAR, 2000; Whillans, 2003). An important pathway of exposure to ^{14}C released from reactors is inhalation of $^{14}CO_2$.

The ICRP's systemic biokinetic model for carbon inhaled as carbon dioxide was introduced in ICRP Publication 30 (1981). Retention, R(t), of absorbed carbon is described by the sum of three terms:

$$R(t) = 0.18 \exp(-0.693t/5) + 0.81 \exp(-0693t/60) + 0.01 \exp(-0.693t/T), \quad \text{(Eq. 2)}$$

where t is in minutes and T is a long-term half-time. T was originally given as 60,000 min but was later rounded to 40 d (ICRP, 1994b, 1995). The first two terms of Eq. 2 are based on a two-exponential curve fit to data of Winchell et al. (1970) on exhalation of ^{14}C by 13 normal human subjects over 120 min after intravenous injection with ^{14}C-labeled bicarbonate:

$$R(t) = 0.175 \exp(-0.693t/5) + 0.825 \exp(-0693t/60) \quad \text{(Eq. 3)}$$

As shown in Figure 5, this curve fit closely approximates predictions of a recycling model of Winchell and coworkers (Figure 6, Compartments 1-4) based on the same data set. The third term in Eq. 2 represents a small component of relatively long-term retention observed in laboratory animals after inhalation of $^{14}CO_2$. The long-term half-time, T ~ 40 d, was derived from balance data for dietary carbon; the assumption was made that long-term retention of carbon inhaled as carbon dioxide is similar to that of carbon entering the systemic circulation following dietary intake. The coefficient of the third term, 0.01, is based on the interpretation that any long-term component must be of this order, or smaller, since the two-exponential curve fit (Eq. 3) accounted for virtually all of the retained carbon.

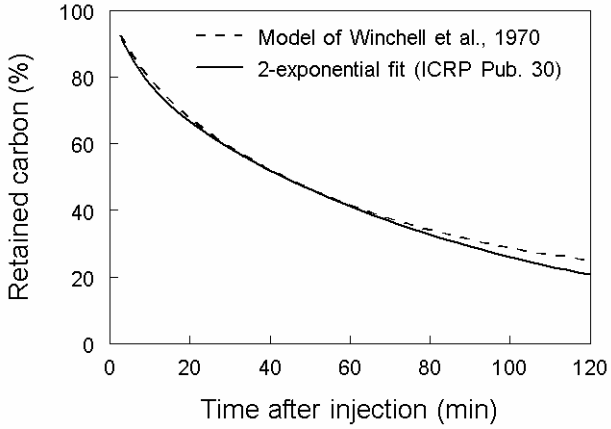

Figure 5. Comparison of model fits by authors of ICRP Pub. 30 (Part 3, 1981) and original investigators (Winchell et al., 1970) to data for whole-body retention of ^{14}C in 13 subjects receiving ^{14}C-labeled bicarbonate by intravenous injection.

Stubbs and Marshall (1993) used the same information as the authors of ICRP Publication 30 but a considerably different model structure to build a model of the systemic biokinetics of carbon dioxide or bicarbonate. They started with the recycling model of Winchell and coworkers and assigned a removal half-time of 60,000 min to Winchell's "relatively fixed" carbon compartment based on the long-term half-time used in ICRP Publication 30 (Eq. 1).

Despite their common foundations, the CO_2 model of ICRP Pub. 30 and that of Stubbs and Marshall yield substantially different predictions of retention from a few hours to several months after intake (Figure 7). The two models agree reasonably well over the two-hour period of observation of the subjects of Winchell and coworkers, but large differences between these two methods of fitting arise when they are used to extrapolate to longer times after exposure. In fact, the model of Winchell et al. (1970) predicts that relatively fixed ^{14}C represents about 15% of the injected activity. Thus, the half-time of

60,000 min was applied in ICRP Publication 30 to 1% and in ICRP Publication 80 to about 15% of absorbed activity; moreover, the effective half-time is even greater than 60,000 min in the model of Stubbs and Marshall due to depiction of recycling of ^{14}C. This illustrates the importance of the model structure in interpreting and fitting the data.

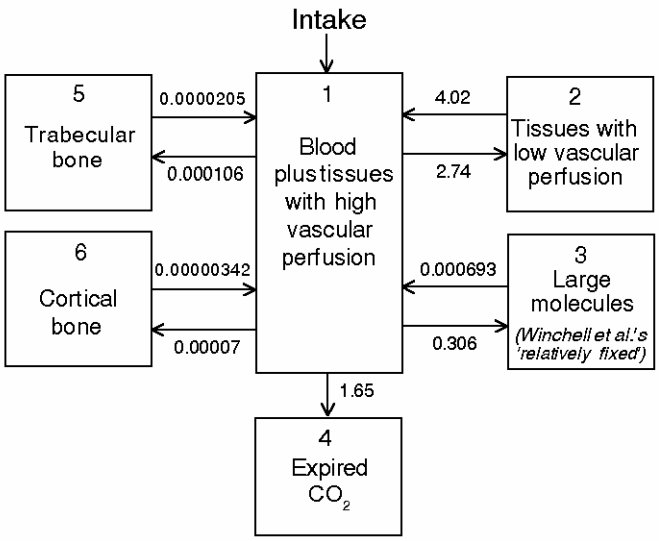

Figure 6. Biokinetic model for $^{14}CO_2$ described in ICRP Publication 80 (1998). The underlying model of Winchell et al. consists of Compartments 1-4 and the indicated transfers between these compartments, excluding return from 3 to 1. Transfer rates are in units of h^{-1}.

A recent publication (Leggett, 2004) describes a critical review of the biokinetic database for CO_2 and bicarbonate and presents a new biokinetic model for intake of carbon in these forms that is reasonably consistent with current information. The structure of the updated model, referred to here as the ORNL model, is shown in Figure 8, and parameter values are given in an earlier paper (Leggett, 2004). The ORNL model predictions of total-body retention of ^{14}C following inhalation of $^{14}CO_2$ are compared in Figure 7 with predictions of the two ICRP models that address the fate of carbon absorbed to blood as CO_2. The curve labeled 'ICRP Pub. 68' represents the ICRP's model for CO_2 inhaled by workers or adult members of the public. The curve labeled 'ICRP Pub. 80' represents the ICRP's model for CO_2 or bicarbonate absorbed to blood following the breakdown of administered ^{14}C-urea in the gut. Calculations are based on the assumption that inhaled CO_2 is immediately and completely absorbed to blood. Compared with the ICRP's model for inhaled CO_2, the ORNL model predicts greater retention at all times beyond a few hours after exposure. Compared with the model for CO_2 or bicarbonate formed from ^{14}C-urea, the ORNL model predicts much lower retention from a few hours to a few hundred days after exposure, but slightly greater retention at longer times.

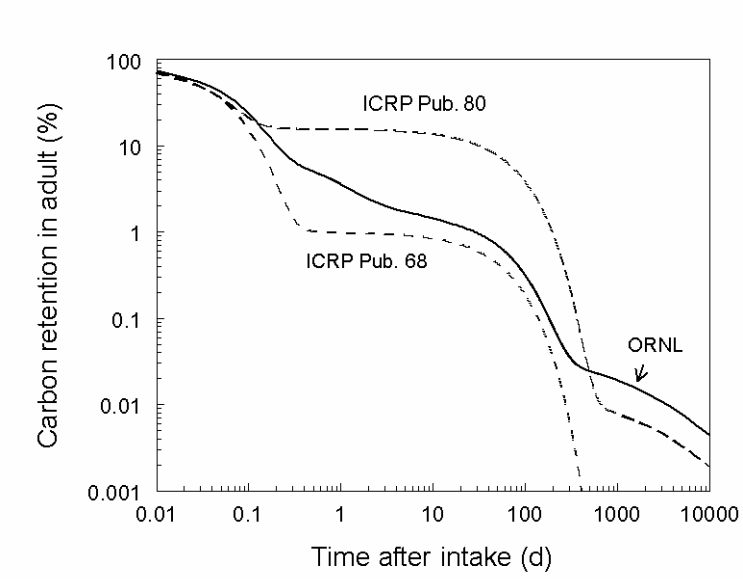

Figure 7. Comparison of predictions of total-body retention of ^{14}C over 10,000 d following inhalation of $^{14}CO_2$ by an adult, based on two current models of the ICRP (1994b, 1998) and a model based on updated information (ORNL) (Leggett, 2004).

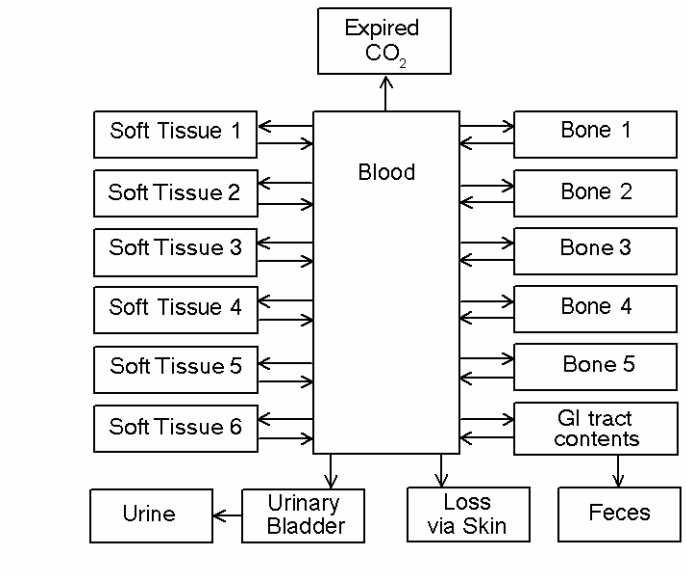

Figure 8. Structure of a recently published systemic model for $^{14}CO_2$ (Leggett, 2004).

Dose coefficients for inhalation of $^{14}CO_2$ based on the three models addressed in Figure 7 are given in Table 1. Compared with the ICRP's model for CO_2 inhaled by a worker or adult member of the public (ICRP, 1994b), the ORNL model yields substantially higher coefficients for skeletal tissues and a threefold higher effective dose coefficient. Compared with the ICRP model for CO_2 formed in the body (ICRP, 1998), the ORNL

model yields a similar estimate of dose to skeletal tissues and a six-fold lower estimate of effective dose.

Table 1. Comparison of dose coefficients (Sv Bq^{-1}) for inhalation of $^{14}CO_2$ derived from three different biokinetic models. Instantaneous absorption of inhaled CO_2 to blood is assumed.

Tissue	ICRP Pub. 68, 1994b	ICRP Pub. 80, 1998	ORNL (Leggett 2004)
Bone surface	6.2E-12	1.7E-10	1.8E-10
Red marrow	6.2E-12	1.4E-10	8.1E-11
Effective dose	6.2E-12	1.2E-10	2.0E-11
Normalized effective dose[a]	0.31	6.0	1.0

[a]Normalized to value derived from ORNL model

To summarize, the ICRP has two much different models for inhaled $^{14}CO_2$ based on essentially the same information but yielding widely divergent dose coefficients. The discrepancies arise in large part from differences in the model structures used to fit the early data. A model based on updated information and a more detailed modeling scheme gives much different estimates of effective dose from either of those models. It appears that the current ICRP tools for assessing dose from inhalation or ingestion of ^{14}C involve potentially large errors. For the most part, these errors can be reduced using current information and thus should not be equated with uncertainties. Of course, the updated model also involves uncertainties, but their magnitude may be less than that of the correctable problems within the ICRP models.

Case 3. Inhalation of $^{106}RuO_4$ (ruthenium tetroxide vapor)

The biokinetic database for ruthenium is considerably smaller than that for cesium or CO_2, particularly the database on human subjects. The biokinetics of ruthenium has been studied in some animal species, but the fate of inhaled, ingested, or absorbed ruthenium still cannot be estimated with much confidence.

The fate of internally deposited ruthenium has been studied in a few accidentally exposed workers, but the only easily interpreted data on systemic biokinetics of ruthenium in humans comes from a controlled study on a healthy adult male who ingested different chemical forms of ^{103}Ru ($T_{1/2}$ = 39.3 d) or ^{106}Ru ($T_{1/2}$ = 373.6 d) on different occasions (Yamagata et al. 1969, 1971). Results of the ^{103}Ru study suggest the possibility of two retention components for absorbed activity, one with a biological half-life of 2.3 d and one with a half-time of about 30 d. The estimate for the early component is not particularly useful for modeling purposes because it could reflect mainly unabsorbed activity. The long-term behavior of ruthenium in the body cannot be determined from data for ^{103}Ru due to its short half-life. Results from a later study on the same subject using ^{106}Ru suggested a retention component with half-time of about 9 d and a second component with half-life 32 d. At longer times, estimates of a biological half-time lengthened with the period of observation: 81 d based on observations in the period 40-

80 d after intake, 122 d at 80-150 d after intake, 158 d at 150-350 d after intake, and 385 d at 350-660 d after intake.

Due to the sparsity of data for humans, the ICRP based its systemic biokinetic model on data for laboratory animals, primarily results of an interspecies comparison involving mice, rats, monkeys, and dogs (Furchner et al. 1971). Those data were interpreted as indicating that the systemic biokinetics of ruthenium is reasonably independent of species and that absorbed ruthenium is somewhat uniformly distributed in the body. The ICRP's systemic model derived from that data (ICRP, 1981, 1989, 1993) depicts one-directional movement of activity from blood to tissues to excretion pathways. Activity is assumed to be removed from blood with a half-time of 0.3 d, with 15% going to excretion pathways. The remainder is assumed to be uniformly distributed throughout all organs and tissues of the body and is divided into three retention components: 35% is removed to excretion pathways with a biological half-time of 8 d, 30% with a half-time of 35 d, and 20% with a half-time of 1000 d. Activity assigned to excretion pathways is divided between the urinary bladder contents and the upper large intestine contents in the ratio 4:1. The long-term half-time of 1000 d is a rounded central estimate based on a wide range of values (200-1600 d) estimated from data for laboratory animals and for the human subject of Yamagata et al. 1969, 1971).

In the ICRP's model, radioactive progeny of ruthenium isotopes are assigned the biokinetics of ruthenium. Ruthenium-106 decays to ^{106}Rh ($T_{1/2}$ = 29.9 s). In addition to having a short half-life, ^{106}Rh is chemically similar to its parent ^{106}Ru, in contrast to the situation for ^{137}Cs and its daughter ^{137m}Ba. Thus, it seems unlikely that ^{106}Rh migrates to any appreciable extent from ^{106}Ru before decaying, although there is no direct information on the fate of ^{106}Rh produced in vivo.

A comparison was made of dose per unit uptake of ^{106}Ru to blood generated by the ICRP model and two substantially different but equally plausible systemic models for ruthenium called Model A and Model B. Model A, shown in Figure 9, was developed by Runkle et al. (1980) as a fit to their measurements of ^{106}Ru in tissues and excreta of rats exposed to $^{106}RuO_4$ by inhalation or ingestion. In selection of a biokinetic model for ruthenium, the authors of ICRP Publication 30 assumed in effect that the biokinetics of ruthenium is not species dependent. If this assumption is correct, the model of Runkle et al. is just as plausible as the ICRP's model. Model B, developed by the present author, has the same structure as that of Model A but differs substantially from Model A with regard to rates of movement of activity between compartments. Transfer rates for Model B were based on retention data for dogs (Furchner et al., 1971) and the broadly similar data for a human subject (Yamagata et al., 1971), together with relatively detailed information on the distribution of systemic ruthenium in guinea pigs (Burykina, 1962). In Model B, activity is assumed to be removed from blood with a half-time of 0.25 d, with 20% depositing in the urinary bladder contents, 5% in the small intestine contents, 20% in liver (in a compartment called Liver 1), 10% in the kidneys (Kidney 1), 35% in other soft tissues (Other 1), and 10% on bone surface (Skeleton 1). Activity leaves Liver 1, Kidney 1, Other 1, and bone surface with a half-time of 5 d. Of activity leaving Liver 1 or Other 1, 90% returns to blood and 10% moves to a long-term compartment of

the same tissue (Liver 2 or Other 2, respectively). Of activity leaving Kidney 1, 98% returns to blood and 2% moves to a long-term compartment in the kidneys (Kidney 2). Of activity leaving bone surface, 75% returns to blood and 25% moves to bone volume (Skeleton 2). Activity moves from Liver 2 to small intestine contents with a half-time of 100 d, from Kidney 2 to Kidney 1 with a half-time of 100 d, from Other 2 to Other 1 with a half-time of 500 d, and from bone volume to bone surface with a half-time of 1000 d.

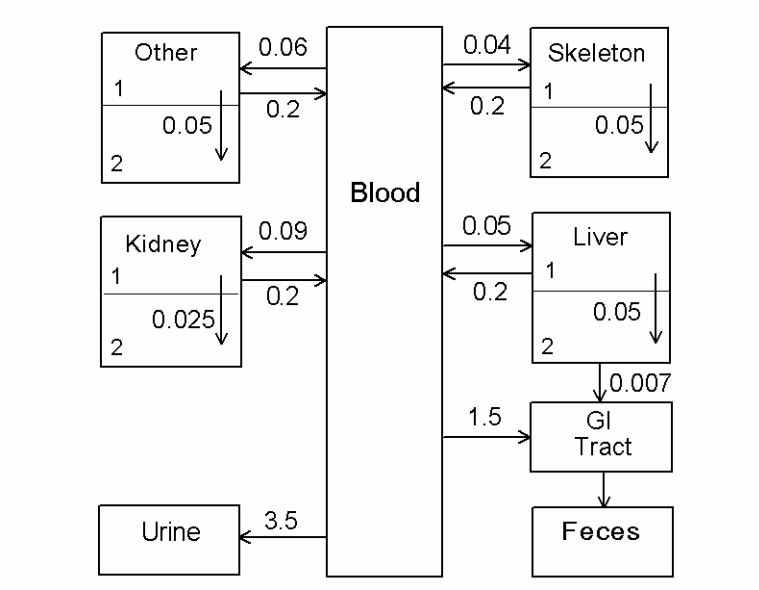

Figure 9. Systemic biokinetic for ruthenium (Model A) developed by Runkle et al. (1980) based on data for rats exposed to $^{106}RuO_4$ by inhalation or ingestion.

Dose per unit uptake of ^{106}Ru to blood based on the three different models are compared in Table 2. Relative to the ICRP's model for ruthenium, Model B yields substantially higher estimates of dose equivalent to liver, kidneys, and skeletal tissues, generally lower estimates for other tissues, and a reasonably similar (30% greater) effective dose. Compared with the ICRP's model for ruthenium, Model A yields lower estimates of dose equivalent to all tissues except the kidneys, and estimates of the effective dose are reduced by a factor of 6.

Next, the ICRP's dose coefficients for the case of inhalation of ^{106}Ru as ruthenium tetroxide vapor ($^{106}RuO_4$) by an adult male were compared with coefficients based on alternate models. Each of the alternate models involved a modification of the ICRP's respiratory model for RuO_4, coupled with either systemic Model A or systemic Model B for ruthenium (described above).

The ICRP's respiratory model for RuO_4 is built within the structure of the ICRP's Human Respiratory Tract Model (HRTM) shown in Figure 10. Complete deposition of inhaled activity in the upper respiratory tract is assumed. Removal of activity is described by

parameter values for Type F material, which implies that roughly half of the deposited activity is absorbed to blood. While the assumed sites of deposition seem consistent with data for laboratory animals and accidentally exposed workers (Webber and Harvey, 1975; Runkle et al., 1980; Snipes, 1981), animal studies suggest that use of Type F parameter values may overestimate absorption to blood by an order of magnitude (Runkle et al., 1980; Snipes, 1981). Also, gastrointestinal absorption of ruthenium was estimated in the animal studies as about 0.3%, compared with the value 5% used by the ICRP.

Table 2. Comparison of equivalent dose per unit uptake of ^{106}Ru to blood, based on the ICRP's systemic model for ruthenium and Models A and B described in the text.

Tissue	*Dose based on ICRP model (Sv Bq^{-1})*	*Ratio Model A : ICRP*	*Ratio Model B : ICRP*
Bone surfaces	**2.9E-08**	**0.13**	**4.5**
Stomach wall	**2.9E-08**	**0.020**	**0.54**
Lower large intestine wall	**4.1E-08**	**0.53**	**0.73**
Kidneys	**2.9E-08**	**2.5**	**6.7**
Liver	**2.9E-08**	**0.11**	**4.5**
Red marrow	**2.9E-08**	**0.12**	**3.4**
Effective dose	**3.0E-08**	**0.16**	**1.3**

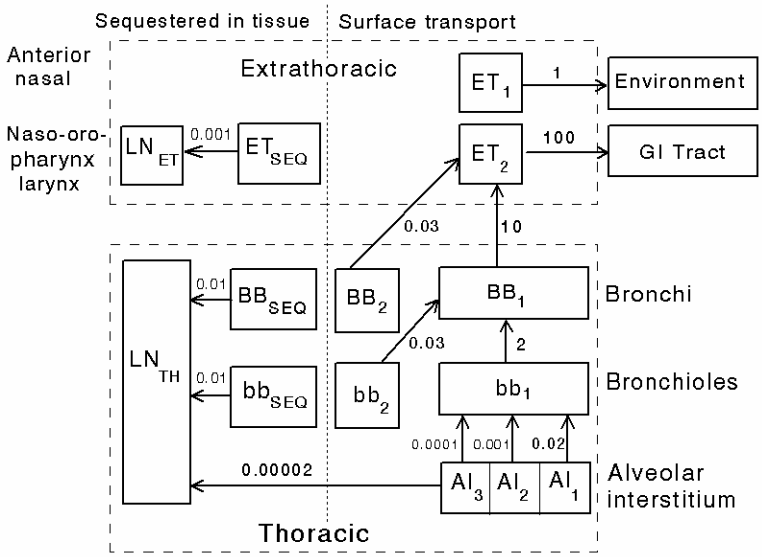

Figure 10. Structure of the ICRP's Human Respiratory Tract Model (HRTM) (ICRP, 1994a). The numbers beside or above the arrows indicate particle transport rates (d^{-1}). Abbreviations: AI = alveolar interstitium, BB = bronchi, bb = bronchioles, ET = extrathoracic, LN = lymph nodes, SEQ = sequestered, and TH = thoracic.

A variation of the ICRP's respiratory model for RuO_4 that seems more consistent with the animal data was developed by decreasing the transfer rate from the primary extrathoracic repository (ET_2) and the gastrointestinal absorption fraction to lower estimated absorption

to blood from about 50% to about 10% of the deposited amount. The gastrointestinal absorption fraction was lowered from 5% to 0.3% for consistency with the animal data. The ICRP's dose coefficients for inhaled $^{106}RuO_4$ are compared in Table 3 with coefficients based this modified respiratory model, coupled wither with systemic Model A or systemic Model B described earlier. Estimates involving Model A are much lower than the ICRP values for most tissues. Estimates involving Model B generally do not differ radically from the ICRP values; in this case, the higher doses per unit absorbed ^{106}Ru based on Model B (Table 2) are largely offset by the lower absorption assumed in the alternate respiratory model. The effective dose estimates do not differ greatly in the three sets of estimates. This is because the dose to the large intestine wall is an important contributor to the estimated effective dose for all three sets of models, and the three sets of models predict fairly similar cumulative activity in the colon.

Table 3. Comparison of the ICRP's inhalation dose coefficients for $^{106}RuO_4$ for an adult with values based on Models A and B and the modified respiratory model described in the text.

Tissue	*Dose based on ICRP model (Sv Bq^{-1})*	*Ratio Model A : ICRP*	*Ratio Model B : ICRP*
Bone surfaces	**1.5E-08**	**0.29**	**0.46**
Stomach wall	**1.6E-08**	**0.10**	**0.19**
Lower large intestine wall	**5.7E-08**	**1.2**	**1.2**
Kidneys	**1.5E-08**	**0.38**	**1.3**
Liver	**1.5E-08**	**0.22**	**0.87**
Red marrow	**1.5E-08**	**0.02**	**0.67**
Effective dose	**1.9E-08**	**0.29**	**0.46**

Model B seems preferable to the ICRP's systemic model on a logical basis, and the modified version of the ICRP's respiratory model for $^{106}RuO_4$ seems likely to reduce predictive errors of the ICRP model because it eliminates some discrepancies between the ICRP's model and the database. It is not evident, however, that the ICRP's dose coefficients for inhaled $^{106}RuO_4$ given in Table 3 are any less accurate than those based on the alternate respiratory model and Model B, because suspected overestimates of the ICRP respiratory model tend to offset suspected underestimates of the ICRP's systemic model.

Case 4. Inhalation of mercury isotopes as vapor

The ICRP's model for inhaled mercury vapor was introduced in ICRP Publication 30, Part 2 (1980) but later recast in the context of the HRTM (Figure 10). According to the original and updated versions of the model for mercury vapor, 70% of inhaled vapor is deposited in the lungs, and all of the deposited mercury is absorbed to blood with a half-time of 1.7 d. In the original version, mercury is assumed, in effect, to be distributed uniformly in the lungs. In the updated version applied in ICRP Publication 68 (ICRP, 1994b), 10% is assigned to the bound compartment of the large bronchi (BB), 20% to the bound compartment of the small bronchi (bb), and 40% to the bound compartment of the alveolar-interstitial region (AI). The bound compartments represent deeply penetrated material assumed to be removed only by absorption to blood.

A critical review of the literature on the biokinetics of inhaled mercury vapor was performed recently as part of an accident analysis for the Spallation Neutron Source (SNS) at ORNL (Leggett et al., 2001). The SNS uses stable mercury as a target. Radioisotopes of mercury build up during irradiation of the target by neutrons and high energy protons and could be released as vapor during an accident, particularly a fire. It was concluded from the review that the ICRP's model for mercury vapor does not accurately represent the database. The evidence indicates that inhaled mercury vapor deposits largely in the AI region, most of the deposited mercury is rapidly absorbed to blood, and the remainder may have multiple components of retention in the lungs

Parameter values of the HRTM were modified for agreement with reevaluated and updated bioassay data (Leggett et al., 2001). In the modified version:

1. Total retention in the respiratory tract is increased from 70% to 80%.
2. 2% of inhaled activity is assigned to the extrathoracic region (ET_2) 1% to the large bronchi (BB), 2% to small bronchi (bb), 75% to AI, and 20% is exhaled. As in the ICRP model, mercury atoms are assumed to be instantaneously transferred to the "bound" compartments in each region.
3. A portion of activity deposited in AI, equivalent to 70% of the deposition in the respiratory tract (that is, $0.7 \times 80\% = 56\%$ of inhaled activity), is absorbed to blood with a half-time of 1 min; 80% of the remaining activity in all regions is absorbed with a half-time of 8 h; and 20% is absorbed with a half-time of 5 d.

Dose estimates based on the ICRP model are compared in Table 4 with values based on this alternate model. In each case, the ICRP's current systemic biokinetic model for mercury was used. The revised model reduces the effective dose coefficients for ^{203}Hg and ^{197}Hg by factors of 4 and 10, respectively, due to the decreased mean residence time of these short-lived isotopes in the lungs. The effective dose coefficient is increased slightly for the longer-lived isotope ^{194}Hg, for which a small, long-term component of retention in the updated model becomes a more important factor.

Table 4. Comparison of dose coefficients for inhalation of mercury vapor by a worker, based on the HRTM with current ICRP parameter values for mercury vapor (ICRP, 1994b) and parameter values proposed by Leggett et al. (2001).

Mercury isotope	Half-life	Ratio of dose coefficients B:A based on HRTM with (A) current and (B) proposed parameter values		
		Lung	Kidneys	Effective dose
Hg-203	46.6 d	0.09	1.2	0.26
Hg-197	64.1 h	0.06	1.7	0.10
Hg-194	260 y	0.74	1.1	1.1

Case 5. Inhalation of Actinium-227

The International Atomic Energy Agency's (IAEA's) guidelines for exemption of slightly radioactive materials from transport regulations (IAEA, TS-R-1, 1996 Revised) are radionuclide specific but include a default exemption activity concentration of 0.1 Bq g^{-1} for radioactive material containing undetermined radionuclides. This limit was chosen because 0.1 Bq g^{-1} is the lowest exemption value calculated for any of the radionuclides addressed in the IAEA transport regulations. The value was derived for ^{227}Ac and is a factor of 10 lower than the next lowest value of 1.0 Bq g^{-1}, which was derived for a number of radionuclides. The low exemption value for ^{227}Ac can be traced to the relatively high dose coefficients for ^{227}Ac given in ICRP documents, together with the rounding convention used for exemption values (derived exemption values falling between 3x10n^{-1} and 3x10n Bg g^{-1} are rounded to 10n Bq g^{-1}). The ICRP's dose coefficients for ^{227}Ac are several times higher than values for physiologically related radionuclides such as ^{239}Pu and ^{241}Am. Actinium-227 is the parent of a long chain of radionuclides including several alpha emitters, and dose estimates for ^{227}Ac depend strongly on the biokinetics assigned to these chain members. As discussed below, elimination of reducible errors in the ICRP's biokinetic model for ^{227}Ac and its radioactive progeny would bring dose coefficients for ^{227}Ac in line with those for ^{239}Pu and ^{241}Am.

The biokinetics of actinium has been studied in rats administered ^{227}Ac and in human subjects accidentally exposed to ^{227}Ac by inhalation or puncture wound (ICRP, 1993; EPA, 1999; Leggett, 2001). The data indicate that the biokinetics of actinium is consistent with the general pattern found for most other actinide elements, in that actinium deposits mainly in the skeleton and liver, is a bone surface seeker with tenacious retention in the skeleton, and is only slowly removed from the human body. Among the frequently studied actinides, the behavior of actinium may be closest to that of americium (EPA, 1999; Leggett, 2001). It has been found that decay products produced in the body after intake of ^{227}Ac, particularly ^{223}Ra and its daughters, migrate extensively from ^{227}Ac and are excreted at much higher rates than ^{227}Ac (Campbell et al., 1956; Newton and Brown, 1974).

The ICRP's current systemic biokinetic model for actinium was introduced in ICRP Publication 30, Part 3 (1981) and carried over to ICRP Publication 68 (1994b) on occupational exposure and ICRP Publication 72 (1996) on environmental exposure. That model was based on the standard ICRP approaches at the time of assigning the model for plutonium to the infrequently studied actinides, and assigning the parent's kinetics to all chain members produced in the body. The model depicts one-directional movement of activity from blood to tissues to excretion pathways. It is assumed that activity leaves blood with a half-time of 0.25 d, with 45% depositing in the skeleton, 45% in the liver, 0.011% in ovaries, and 0.035% in testes. The rest is promptly excreted. The removal half-time is 100 y for skeleton, 40 y for liver, and infinite for gonads. Activity lost by prompt excretion or through biological removal from tissues is equally divided between the urinary bladder contents for removal in urine and the upper large intestine contents for removal in feces. Even though the ICRP's systemic model for plutonium has been

revised several times since the appearance of Publication 30, the systemic model for actinium has not been updated. The gastrointestinal absorption fraction has been changed from 0.001 to 0.0005, however, for consistency with plutonium, americium, and some other actinide elements.

A systemic model for actinium that seems more consistent with the biokinetic database for this element than the current ICRP model was used in U.S. Federal Guidance Report No. 13 (FGR 13) (EPA, 1999). That is, the ICRP's recycling model for americium was applied to actinium, and radioactive progeny of ^{227}Ac or other actinium isotopes produced in the body other than in bone volume were treated independently of the parent. Dose coefficients for inhalation of ^{227}Ac based on this model generally are much lower than corresponding values based on the current ICRP models. This is illustrated in Table 5 for the case of inhalation of moderately soluble form of ^{227}Ac (Type M, 1 μm AMAD) by an adult. In this example, the assumption of independent kinetics of radioactive progeny was not applied to material deposited in the respiratory tract, with the result that the dose to the lungs was virtually unchanged. The extent of migration of radioactive progeny from parents in the respiratory tract seems likely to depend on the properties of the inhaled particles.

Table 5. ICRP's dose coefficients for inhalation of ^{227}Ac (Type M, 1 μm) by an adult male, compared with values based on a model that seems more consistent with the database (FGR 13, EPA, 1999).

Tissue	ICRP	FGR 13 (EPA 1999)
Lung	1.0E-04	1.1E-04
Bone	6.3E-03	1.8E-03
Red	5.1E-04	9.3E-05
Liver	1.5E-03	3.8E-04
Effective	2.3E-04	7.3E-05

As seen in Table 5, application of the revised systemic model decreases the inhalation dose coefficients for ^{227}Ac substantially below the current ICRP values. It appears that if the ICRP's systemic model for actinium were revised for consistency with the biokinetic database, the estimated effective dose from intake of ^{227}Ac would be only slightly higher than values for most other actinide elements. For example, for the case of inhalation of Type M material, the FGR 13 effective dose values shown in Table 5 are about 1.4 times the ICRP's value for ^{239}Pu inhaled as Type M material. Thus, assuming the transport exemption values for other actinides are reasonable, it may be appropriate to raise the transport exemption activity concentration for ^{227}Ac, and thus the concentration for undetermined radionuclides, from 0.1 Bq g^{-1} to 1.0 Bq g^{-1}.

Case 6. Wound contaminated with ^{252}Cf

The previous case studies addressed potential errors in ICRP models as tools for deriving estimates of dose per unit intake. The present case study is concerned primarily with potential errors in the models as bioassay tools used to back calculate intake and dose on the basis of urinary excretion data.

Californium-252 is a good source of neutrons and has been routinely encapsulated into compact, portable neutron sources that have a number of commercial uses. Interest in ^{252}Cf has increased in recent years due to the potential for its use in a radiological dispersal device.

The ICRP's current systemic biokinetic model for californium was introduced in ICRP Publication 30 (1979) and extended to a bioassay model in Publication 68 (1994b). The model depicts one-directional movement of activity from blood to tissues to excretion pathways. It is assumed that californium leaves blood with a half-time of 0.25 d, with 65% depositing in the skeleton, 25% in the liver, 0.011% in ovaries, and 0.035% in testes. The rest (9.954%) is promptly excreted. The removal half-time is 50 y for skeleton, 30 y for liver, and infinite for gonads. Activity lost by prompt excretion or through biological removal from tissues is equally divided between the urinary bladder contents for removal in urine and the upper large intestine contents for removal in feces.

A critical review of the literature revealed that the ICRP's model for californium does not closely reflect the database, particularly with regard to the rate of excretion of systemic activity (Leggett, 2001). The biokinetic database for californium consists of limited data on workers accidentally exposed to airborne californium isotopes, and several studies of the behavior of californium in laboratory animals, including dogs, mice, rats, and Chinese and Syrian hamsters. Animal studies indicate that its behavior is qualitatively similar to that of other transuranium elements such as plutonium, americium, and curium, although quantitative differences from each of these elements are evident. Species differences in the biokinetics of californium have been observed, particularly regarding the retention time in the liver. This is consistent with a pattern seen for other transuranic elements. That is, certain mammalian species show rapid removal of transuranics from the liver, while others show extremely slow removal. For example, rats, tree shrews, macaque monkeys, and baboons show rapid loss of plutonium from the liver, with half-times of 4-200 d, while another set of adult animals with an overlapping range of body weights, including hamsters, dogs, pigs, and humans, show tenacious retention of plutonium in the liver, with half-times measured in years or decades (Taylor, 1984).

The beagle is expected to be a reasonable laboratory model for the biokinetics of californium in humans due to qualitative similarities in the biokinetics of other transuranics (plutonium, americium, and curium) in dogs and humans, particularly for the liver and skeleton. In extrapolating biokinetic data for californium from beagles to humans, species differences in rates of apparently pertinent physiological processes must be taken into account. For example, the residence time of californium in bone may be substantially greater in adult humans than in adult beagles due to a slower rate of bone turnover in humans.

The decay chain beginning with ^{252}Cf includes 17 radionuclides, but the radioactive progeny of ^{252}Cf can be neglected in dose estimates from intake of pure ^{252}Cf due to the extremely long half-life of the next chain member, ^{248}Cm ($T_{1/2} = 3.5 \times 10^5$ y).

An updated model based on current data for californium has been proposed (Leggett, 2001). The ICRP's generic model for bone-surface-seeking radionuclides is applied (Figure 11). Parameter values are based on the relatively detailed information on californium biokinetics in laboratory animals, particularly dogs, and the comparative biological behavior of californium and americium. The rationale is that there is relatively good information on the behavior of americium in human subjects and comparative data on americium and californium in animals. It seems reasonable to use the ICRP's model for americium as a starting point for modeling the biokinetics of californium and adjust the parameter values for americium as indicated by comparative data on americium and californium in beagles.

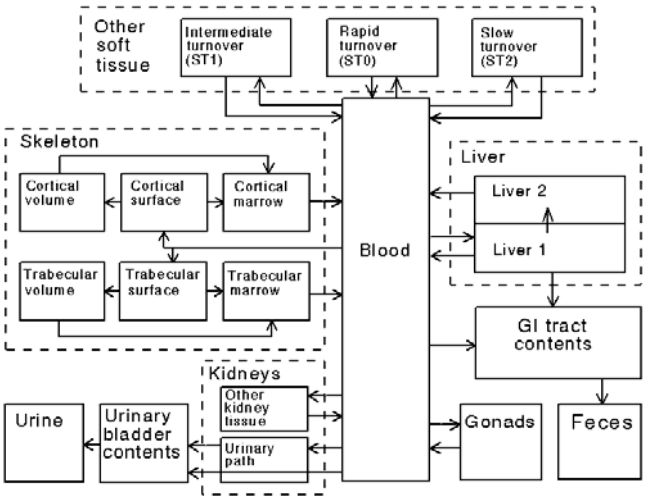

Figure 11. Structure of the proposed model for californium. This is the ICRP's generic model structure for bone-surface-seeking radionuclides (ICRP, 1993).

The following adjustments to the ICRP's systemic biokinetic model for americium were made for application to californium (Leggett, 2001): the removal half-time from blood is 1 h, compared with 30 min for americium; deposition in liver plus skeleton is 70% (i.e., 70% of activity leaving the circulation), compared with 80% for americium; the division between liver and skeleton is 20%-50%, compared with 50%-30% for americium; deposition in urinary bladder contents is 11%, compared with 7% for americium; deposition in the contents of the GI tract is 6%, compared with 1.3% for americium; deposition in the urinary path (Kidneys 1) is 2% and in other kidney tissues (Kidneys 2) is 1%, compared with 2% and 0.5%, respectively, for americium; the removal half-time from Kidneys 2 to blood is 5 y, compared with 500 d for americium; the removal half-time from the intermediate-term soft-tissue compartment to blood is 100 d, compared with 50 d for americium. Otherwise, the biokinetics of californium is assumed to be the same as that of americium.

The proposed model for californium was applied to estimate the rate of urinary excretion of californium and dose per unit intake of californium isotopes. Predicted urinary excretion rates following introduction of californium to blood are compared in Figure 12 with predictions of the current ICRP model. Predictions of the ICRP model are 1-2

orders of magnitude lower than those of the proposed model from a few days to a few weeks after uptake of californium to blood.

The proposed systemic model for californium was compared with the ICRP's current model as a bioassay model for ^{252}Cf, i.e., as a tool for back calculating dose from intake of ^{252}Cf based on urinary excretion data. The comparison was based on a simple exposure scenario in which an adult male receives a puncture wound from a piece of metal contaminated with ^{252}Cf. It is assumed that the metal is removed within hours after the incident and the wound is cleaned of residual radioactivity. A 24-hour urine sample is collected on Day 5 and is found to contain 1 Bq of ^{252}Cf. According to the ICRP's current model for californium, 0.0025% of acutely injected ^{252}Cf is excreted in urine on Day 5 (Table A.15.6 of ICRP Publication 78, 1997). The estimated intake based on the ICRP model is 1 Bq/0.000025 = 40,000 Bq. Forward calculation of dose based on this acute input to would yields an effective dose of about 3 Sv and a dose to bone marrow of about 9 Sv.

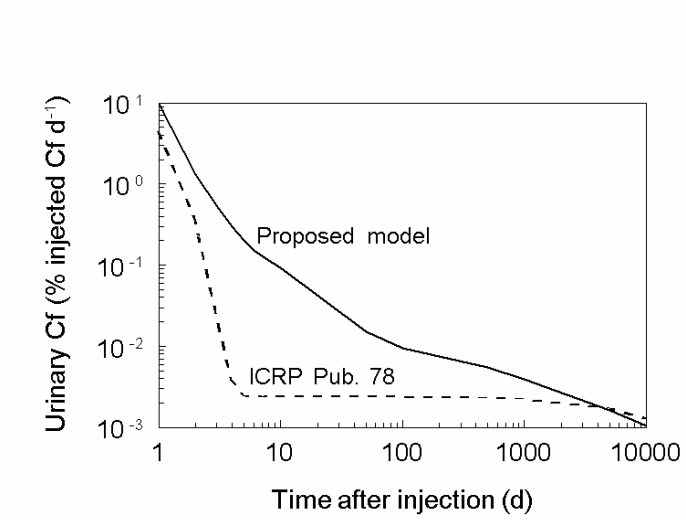

Figure 12. Comparison of predictions of urinary californium based on the systemic given in ICRP Publication 68 and Publication 78 (1997) and a proposed model (Leggett, 2001), assuming intravenous injection of californium at time 0.

The proposed model indicated in Figure 11 predicts that 0.2% of the injected amount would be excreted on Day 5 and thus predicts that 1 Bq/0.002 = 500 Bq reached blood. Forward calculation of dose based on this acute input to blood gives an effective dose of about 0.06 Sv and a dose to red marrow of about 0.15 Sv. In this hypothetical situation the two models would lead to much different conclusions concerning the urgency of medical intervention.

Clearly, predictions of the proposed model for californium involve uncertainty because the model is based primarily on animal data and comparisons with americium. However, the logical basis for the proposed model is considerably stronger than that of the ICRP's

model, and much of the difference in predictions of the two models appears to represent reducible error.

Case 7. Inhalation of ^{238}Pu oxide

As illustrated by this case study and the case study for uranium aluminide that follows, the time-dependent pattern of dissolution of some materials in the respiratory tract is not accurately represented by default parameter values of the ICRP's Human Respiratory Tract Model (HRTM). This can lead to sizable errors in estimates of dose that are back calculated from urinary excretion data. Thus, where feasible, it is important to develop material-specific parameter values describing time-dependent dissolution of inhaled material in the respiratory tract for purposes of bioassay interpretation.

The structure of the HRTM is shown in Figure 10. The HRTM depicts clearance of inhaled particles as competitive between absorption to blood and particle transport to the gastrointestinal tract and lymph nodes. Absorption is viewed as a two-stage process: dissociation of the particles into absorbable material (dissolution), and uptake of dissociated material to blood. A time-dependent dissolution rate is modeled by using one set of compartments representing an initial dissolution rate and a second set representing a final dissolution rate. As indicated in Figure 13, material deposited in a compartment representing the initial state dissolves and is absorbed to blood at a constant rate s_p but is simultaneously transferred at a rate s_{pt} to a corresponding compartment representing a transformed physical or chemical state. Particles in the transformed state have a dissolution rate s_t. With this system, the initial dissolution rate is approximately s_p and the final dissolution rate is approximately s_t. It is assumed that transformed particles are mechanically cleared from a compartment at the same rate as the particles in initial state. More generally, all of the particle transport rates indicated in Figure 10 (e.g., 0.0001 d^{-1} from AI_3 to bb_1) are assumed in standard applications of the HRTM to be independent of the material, although the structure of the model enables particle transport rates to be modified when information is available.

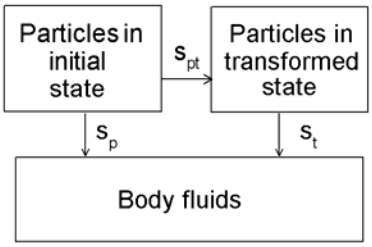

Figure 13. Schematic of treatment of time-dependent dissolution of inhaled particles in the HRTM. Material deposited in a compartment is absorbed to blood at a rate s_p and simultaneously transferred at a rate s_{pt} to a parallel compartment representing a transformed state. Transformed particles are absorbed to blood at a rate s_t.

This system can be used to depict an increasing rate of dissolution but generally has been used to describe a decreasing dissolution rate with a rapid phase of dissolution immediately after intake. The latter pattern is predicted by the ICRP's default parameter values representing fast dissolution and relatively high absorption to blood (Type F), a moderate, or intermediate, rate of dissolution and absorption to blood (Type M), and slow dissolution with low absorption to blood (Type S). When combined with the ICRP's systemic biokinetic models for specific elements, the modeled pattern of dissolution and absorption is reflected in the urinary excretion rate over time. That is, the ICRP models with default parameter values predict a decreasing rate of urinary excretion as a function of time following intake.

In contrast to predictions of the baseline ICRP models, a non-monotonic pattern of excretion been observed in a number of occupational exposures to relatively insoluble forms of radionuclides. That is, the rate of urinary increased over a period of weeks or months, leveled out briefly, and declined thereafter. Such a pattern has been reported most often for inhalation of ^{238}Pu but has also been seen for other transuranic radionuclides including ^{241}Am, ^{249}Cf, and ^{249}Bk and for different forms of uranium (Healy, 1957; Wood and Sheehan, 1971; Rundo and Sedlet, 1973;King, 1980; Zhao and Zhao, 1990; Hickman et al., 1995; Leggett et al., 2005a).

As indicated above, the system shown in Figure 13 can be used to depict an increasing rate of dissolution in the respiratory tract. This was done recently by James et al. (2003) in a retrospective study of a case of accidental inhalation of $^{239}PuO_2$ ceramic particles. The subject was one of eleven workers exposed to airborne ^{238}Pu during disassembly of a ^{238}Pu heat source in a shielded hot cell (Hickman et al., 1995). Initial urinary ^{238}Pu measurements were near the limit of detection. Measurements made on two of the workers over the next month showed increasing levels of ^{238}Pu in urine, a trend opposite to that predicted by ICRP models. During a seven-month period following the accident, five other workers present during the incident were found to have increasing levels of ^{238}Pu in urine.

Urinary excretion data for the worker addressed by James et al. (2003) are shown in Figure 14. The exposure was 17.9 y before the subject's death. The subject was a U.S. Transuranium and Uranium Registries (USTUR) whole body donor, and extensive postmortem measurements of ^{238}Pu in tissues were made. James and coworkers used fitting methods to find parameter values of the dissolution model (Figure 13) and of the ICRP's current systemic model for plutonium (ICRP, 1993) that were consistent with the subject's urinary data and the contents of ^{238}Pu in his tissues at death. Fractional absorption from the gut was arbitrarily set at 10^{-7} to represent the extremely low level of absorption of ^{238}Pu from the gut that evidently occurred in this case. Assuming a particle size of 5 μm (AMAD), James and coworkers used the fitted models to back calculate an intake of about 56,000 Bq of ^{238}Pu by the subject.

The parameter values of the HRTM dissolution model (Figure 13) determined by the fitting process are $s_p = 10^{-6}$ d^{-1}, $s_{pt} = 0.00189$ d^{-1}, and $s_t = 0.000257$ $^{d-1}$; the HRTM with this dissolution model is referred to in the following as the HRTM*. The HRTM*

together with the ICRP's current systemic model for plutonium (ICRP, 1993) with baseline parameter values (i.e., parameter values of the systemic model were not fit to the subject's data, in contrast to the analysis by James and coworkers) to predict tissue contents at 17.9 y after intake of 56,000 Bq of ^{238}Pu. As in the analysis by James and coworkers, a particle size of 5 μm (AMAD) and a gastrointestinal absorption fraction of 10^{-7} were assumed. Predictions of urinary excretion are compared in Figure 14 with the subject's urinary data, and predicted tissue contents are compared with measured values in Table 6. The same exercise was carried out by replacing the ICRP's systemic biokinetic model with an updated version (Leggett, 2003; Leggett et al., 2005b). The updated systemic model depicts a somewhat different systemic distribution of Pu in the early months or years after exposure but is consistent with the current ICRP model with regard to the long-term distribution, and it is predicts virtually the same urinary excretion rate as the current model at all times after exposure (Leggett et al., 2005b). Thus, it is not surprising that the updated model made virtually no difference in predictions of urinary excretion in this case, and only modest differences in predictions of the content of systemic tissues at 17.9 years after intake (Table 6).

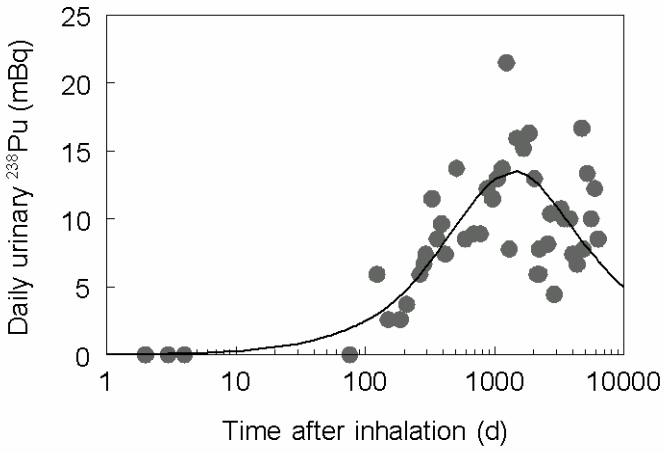

Figure 14. Predictions of the HRTM* (see text) together with the ICRP's current systemic model for plutonium with baseline parameter values (ICRP, 1993), compared with observations of urinary excretion of ^{238}Pu by a worker after acute inhalation of $^{238}PuO_2$ ceramic particles.

In contrast to the case discussed above, urinary data from some reported cases of $^{238}PuO_2$ inhalation are reasonably consistent with predictions based on one of the ICRP's default absorption types, either Type M or Type S, together with the ICRP's current systemic model. For example, data of Newton et al. (1983) for a subject accidentally exposed to $^{238}PuO_2$ are broadly consistent with Type S solubility. The different potential patterns of dissolution and excretion of $^{238}PuO_2$ lead to considerable uncertainty in interpretation of early urinary excretion data following inhalation of $^{238}PuO_2$, because there will generally be little basis for choosing between the Type M, Type S, or a model similar to that of James and coworkers at early times after exposure. As indicated in Table 7, estimated

dose per unit intake of ^{238}Pu does not differ greatly between Type S and the dissolution parameter values derived by James et al. (2003). As seen in Table 8, however, predicted 24-h urinary excretion of ^{238}Pu varies by orders of magnitude between the two situations during the first few weeks after exposure. This means, for example, that interpretation of early urinary excretion data based on Type S could underestimate intake and dose by orders of magnitude if the inhaled material actually behaved in the non-monotonic manner observed in some studies of $^{238}PuO_2$ exposure.

Table 6. Model predictions and observations of ^{238}Pu contents in tissues 17.9 y after acute intake. Based on the HRTM with modified parameter values describing time-dependent dissolution, together with indicated systemic model for Pu.

Tissue	Measured at autopsy	Systemic model	
		ICRP, 1993	Leggett et al., 2005b
Total body	287	327	328
Lung[a]	29.4	35.2	35.2
Liver	137	108	118
Skeleton	104	160	151
Red marrow	5.0	3.3	3.1
Kidneys	0.32	0.31	0.42
Testes	0.084	0.13	0.12
Remainder	15.8	23.3	23.6

[a]Including thoracic lymph nodes

Table 7. Estimated dose per unit intake for inhaled ^{238}Pu based on the ICRP's current systemic biokinetic for plutonium (ICRP, 1993) and the HRTM with alternate dissolution parameter values; AMAD = 5 µm.

Tissue	Equivalent dose (Sv Bq^{-1})	
	Type S	James et al. 2003
Lung	5.1E-05	4.7E-05
Liver	1.7E-05	2.3E-05
Bone surface	8.0E-05	1.1E-04
Red marrow	4.1E-06	5.6E-06
Kidneys	3.6E-07	4.9E-07
Testes	1.1E-06	1.5E-06
Most other tissues	~1.4E-07	~1.9E-07
Effective dose	1.1E-05	9.0E-06

Table 8. Estimated rate of urinary excretion of ^{238}Pu following inhalation, based on the ICRP's current systemic biokinetic for plutonium (ICRP, 1993) and the HRTM with alternate dissolution parameter values; AMAD = 5 µm.

Day after intake	24-h urinary ^{238}Pu (% of intake)	
	Type S	James et al. 2003
1	2.3E-04	6.5E-08
2	1.4E-04	1.2E-07
5	4.5E-05	2.8E-07
10	2.3E-05	5.6E-07
20	1.8E-05	1.1E-06
50	1.7E-05	2.5E-06
100	1.6E-05	4.7E-06
200	1.6E-05	8.6E-06
500	1.7E-05	1.7E-05
1000	1.7E-05	2.4E-05

Case 8. Inhalation of uranium aluminide

This case study resembles Case 7 in that the inhaled material showed a non-monotonic rate of dissolution and excretion. It differs from Case 7 in that the bioassay data, which included fecal as well as urinary data in the present case, could not be closely fit by adjusting only the system of parameter values shown in Figure 13.

In the late 1960s a group of workers was exposed over several months to high concentrations of airborne uranium aluminide (UAl_x), a material used in fuels for research and test reactors. Exposure to UAl_x occurred mainly in a work area where UAl_x powder was formed and pressed into a compact to be used in the core of a fuel plate. Monitoring of urinary data over the first few months of the program did not indicate unusually high exposures to uranium. Several months after the start of the UAl_x fuel fabrication program, however, it became evident that urinary uranium lagged far behind UAl_x intake. For example, in workers who had been removed from exposure, the rate of urinary excretion of uranium continued to rise over a period of months, reached a peak, and then decreased sharply. Relatively high lung burdens in several workers had resulted before the problem was recognized.

As illustrated in Figure 15 for Type M and Type S aerosols, the urinary data are inconsistent with the ICRP's default absorption types for inhaled particulates. The model predictions shown in the figure are based on repeated exposures during the first few months of 1967, as indicated by air monitoring data for the work room.

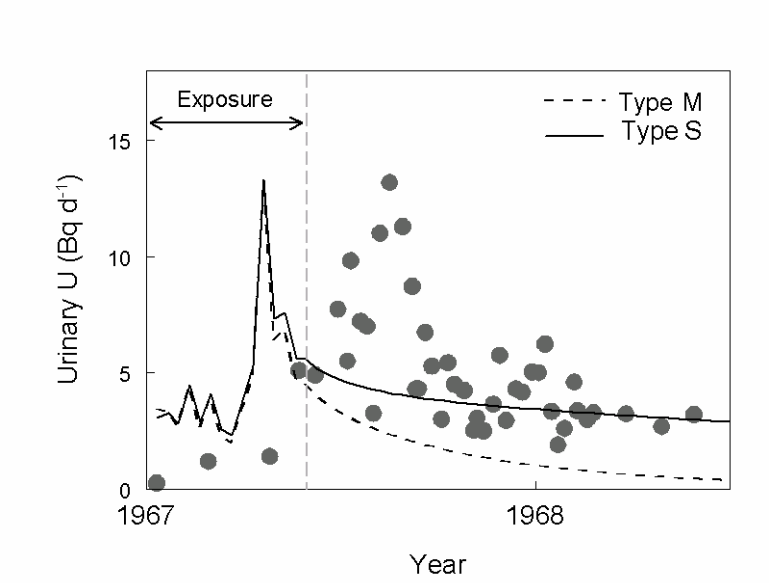

Figure 15. Urinary excretion data for a worker exposed to airborne UAl_x, compared with predictions of the HRTM based on Type M or Type S aerosols. The rise and fall of the model predictions during the exposure period reflect the change in measured air concentrations of UAl_x during that period.

Material-specific parameter values for the HRTM were developed to describe the behavior of UAl_x seen in these workers, using parameter values for Type S as a starting point (Leggett et al., 2005a). The parameter values that were adjusted included those representing the dissolution rate as well as those representing mechanical clearance rates from the AI region. While it was the intention of the HRTM Task Group that the parameters s_p, s_{pt}, and s_t (Figure 13) be modified to fit material-specific information, they considered the particle clearance rates to be fixed. The fit of the HRTM with parameter values adjusted by the present authors to account for a different dissolution kinetics model is illustrated in Figure 16 for one of the most heavily exposed workers.

As illustrated in Table 9, dose coefficients for inhalation of ^{234}U based on the UAl_x-specific parameter values differ substantially from those assuming Type M or Type S for some tissues. However, the effective dose for all three cases is largely determined by the lung dose, which does not differ greatly for these cases. The effective dose for "Type UAl_x" is slightly less than that for Type S and about 2.5 times that for Type M.

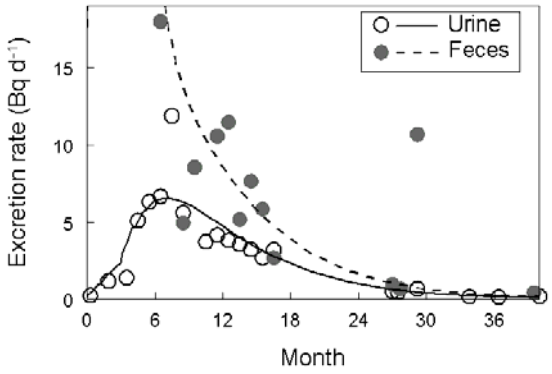

Figure 16. Comparison of the predictions of the modified HRTM with urinary U data for a worker who was heavily exposed to UAl_x.

Table 9. Comparison of 50-y committed equivalent dose coefficients (Sv Bq^{-1}) for inhalation of ^{234}U based on models for Type M and Type S and the UAl_x model described in this paper.

Tissue	Type M	Type S	This model
Bone surface	2.7E-6	2.7E-7	1.1E-6
Red marrow	2.8E-7	2.8E-8	1.2E-7
Liver	3.8E-7	3.8E-8	1.6E-7
Lung	1.6E-5	4.1E-5	3.6E-5
Effective dose	2.1E-6	6.8E-6	5.4E-6

As indicated earlier in the discussion of Case 7, relatively large uncertainties in predictions of the HRTM with default parameter values arise in dose reconstructions based on urinary data. Table 10 compares back calculations of effective dose based on parameter values for Type M or Type S with calculations based on the UAl_x specific parameter values developed by the authors (labeled as ORNL estimates). The comparisons are made for acute inhalation of UAl_x, assuming that a single urinary U measurement is available at 7 d, 15 d, 30 d, or 90 d after intake. Of course, there are uncertainties in the dose estimates based on the material-specific parameter values developed for UAl_x. Nevertheless, the material-specific parameter values are consistent with a large amount of urinary and fecal data for these workers.

Table 10. Comparison of effective dose estimates derived with Type M or Type S parameter values with estimates derived from UAl_x - specific parameter values developed by ORNL, based on a single urinary U measurement made on the indicated day after acute inhalation of UAl_x by a worker.

Day of urine measurement	Ratio of estimates of effective dose	
	Type M : ORNL	Type S : ORNL
7	0.014	1.5
15	0.027	2.9
30	0.059	6.6
90	0.20	19

CONCLUSIONS

A pilot study was conducted for the NRC to examine the feasibility of characterizing and improving the reliability of current dose coefficients for a comprehensive set of radionuclides of concern to the NRC. The dose coefficients considered for inhalation and ingestion were those currently recommended by the ICRP for members of the public and workers. The pilot study consisted largely of a set of case studies, i.e., detailed assessments of selected radionuclides and exposure situations, representing different sources and levels of biokinetic and dosimetric information.

The present paper summarizes results and conclusions from eight of those case studies. The focus in this paper is on the reliability of the ICRP's current biokinetic models, which were judged to be the dominant source of error in most estimates of dose per unit intake of radionuclides. The specific effective energies used to convert from activity to dose can occasionally introduce sizable errors into dose estimates (see the accompany paper on the ICRP's new alimentary tract model), but this was judged not to be the situation for the case studies addressed in this paper.

The author's judgments of total potential errors associated with the ICRP's dose coefficients considered in the present case studies are summarized in Table 11. Conclusions are given in terms of relatively broad "error categories" identified by letters A-E, indicating increasing levels of potential error associated with the dose coefficients as central estimators for adult males. Specifically, Categories A, B, C, and D indicate potential errors thought to be less than a factor of 2, 3, 5, and 10, and Category E represents potential errors greater than an order of magnitude. All of the conclusions summarized in Table 11 are based on more extensive analyses than might be suggested by the limited illustrative comparisons discussed in this paper.

In the case studies addressed in this paper, the potential error was found to arise not only from limitations in the database such as a limited quantity or questionable reliability of biokinetic data but also from the problem that the current models do not fully or accurately reflect available information. The latter contribution to the potential error is referred to here as a reducible error, because it is generally possible to reduce and sometimes virtually eliminate this contribution to the total potential error by improving the model on the basis of some combination of the following:

(1) consideration of additional data, including data that may have been overlooked by the modeler and data developed since completion of the model; this was done in all eight case studies;

(2) use of a more detailed and realistic model structure (e.g., Case Study 1, systemic model for $^{137}Cs/^{137m}Ba$; Case Study 2, systemic model for $^{14}CO_2$; Case Study 5, systemic model for ^{227}Ac and daughters; Case Study 6, systemic model for ^{252}Cf); (3) critical reevaluation of the database (e.g., Case Studies 1-6, particularly: Case Study 3 regarding absorption of RuO_4 from the respiratory tract to blood; Case Study 4 regarding deposition and retention of inhaled Hg vapor in the respiratory tract; Case Study 5 regarding the systemic behavior of Ac and the fate of radioactive progeny of ^{227}Ac; and Case Study 6 regarding the systemic biokinetics of Cf; (4) incorporation of site- or material-specific data (e.g., Case 7, inhalation of $^{238}PuO_2$; Case 8, inhalation of UAl_x).

Table 11. The author's judgments of potential errors in current ICRP dose coefficients as central estimators for adult male.

Case	Tissue	Potential error in dose estimate	
		Intake known	Based on urine data for Day 2
Ingestion of ^{137}Cs	Systemic tissues		
Soluble inorganic compound		A[a]	A[a]
Biologically incorporated in food		A[a]	A[a]
In reactor fuel fragment particle		C	A[a]
Unknown form		D	A[a]
Inhalation of $^{14}CO_2$	Systemic tissues	C	C
Inhalation of $^{106}RuO_4$	Systemic tissues	D	D
Inhalation of Hg vapor			
^{194}Hg	Lung	B	B
^{197}Hg	Lung	D	D
^{203}Hg	Lung	D	D
Inhalation of moderately soluble ^{227}Ac	Bone surface	C	E
^{252}Cf absorbed to blood from wound	Bone surface	C	E
Inhalation of $^{238}PuO_2$	Bone surface	B	E
Inhalation of UAl_x	Bone surface	C	E

[a]Category B assigned to bone surface and colon

These case studies suggest that an important byproduct of an uncertainty analysis involving critical evaluation of the database and models for a radionuclide may often be the improvement of the models and the reduction of potential errors in dose estimates derived from those models. Also, modification of models in view of reducible errors, particularly errors intimately connected with the model structure, would seem to be essential for a meaningful characterization of uncertainties associated with predictions of current dose coefficients.

As demonstrated in the case study of ingestion of ^{137}Cs, the level of confidence that can be placed in a dose coefficient may depend strongly on the form of the radionuclide as well as the level of knowledge concerning that form in a given exposure situation. This is also an important issue for inhalation of radionuclides. Suppose, for example, that an inhalation dose coefficient for ^{90}Sr, Type F, is used to estimate tissue doses to a worker

exposed for a known period to a known concentration of ^{90}Sr in air. Uncertainties in the derived doses would be relatively small if the physical and chemical form of airborne ^{90}Sr are known and indicated by the literature to be consistent with the ICRP's model for Type F. The uncertainties would be larger if available information is weak but suggestive of Type F material and still larger if Type F is applied as a typical absorption type for ^{90}Sr in the absence of any specific information on the form of inhaled material.

These examples show that the commonly used term "uncertainty in a dose coefficient" is not well defined for ingestion or inhalation of a radionuclide until the form of the radionuclide and the user's knowledge of that form are specified. Hence it would not be feasible to assign meaningful uncertainty bounds to each dose coefficient given in ICRP documents, because uncertainty bounds that may be appropriate for one application of a dose coefficient may be meaningless in other situations. On the other hand, it seems feasible to derive meaningful measures of uncertainty associated with dose coefficients for a radionuclide if attention is restricted to a few important forms of the radionuclide and a few specified levels of knowledge of the form at the time of application of the coefficients. For example, an uncertainty statement could be provided for an ingestion dose coefficient for ^{137}Cs under the assumption that the radionuclide is incorporated in food or ingested in soluble inorganic form, and an alternate uncertainty statement could be derived for arbitrary use of the dose coefficient, i.e., in the absence of knowledge of the form of ^{137}Cs ingested.

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