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Dose coefficients for intakes of radionuclides

by members of the public: Part 2

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|  | ICRP Publication XXX |  |

**Dose coefficients for intakes of radionuclides**

**by members of the public: Part 2**

ICRP PUBLICATION XXX

Approved by the Commission in 202Y

**Abstract**– This report is the second in a series of documents giving age-dependent dose coefficients for members of the public for environmental intakes of radionuclides (EIR) by inhalation and ingestion. This series replaces the *Publication 56* series of documents. The revised dose coefficients have been calculated using the *Publication 100* human alimentary tract model (HATM) and the *Publication 130* revision of the human respiratory tract model (HRTM). Revisions have also been made to many of the models that describe the systemic biokinetics of radionuclides absorbed to blood, making them more physiologically realistic representations of uptake and retention in organs and tissues and of excretion. Changes have been implemented that were introduced in *Publication 103* to: the radiation weighting factors used in the calculation of equivalent doses to tissues; the tissue weighting factors used in the calculation of effective dose; and the separate calculation of equivalent doses to males and females with sex-averaging in the calculation of effective dose. Reference voxel anatomical computational phantoms (i.e. models of the human body based on medical imaging data), have replaced the composite mathematical models used for previous calculations of organ doses. Dose calculations were also improved by using *Publication 107* updated radionuclide decay data and implementing the *Publication 116* treatment of radiation transport, using the *Publication 110* reference anatomical phantoms of the human body and the *Publication 143* paediatric reference computational phantoms.

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*Keywords:* Environmental exposure; Internal dose assessment; Biokinetic and dosimetric models;

# MAIN POINTS

* This report is the second in a series of documents giving age-dependent dose coefficients for members of the public for environmental intakes of radionuclides by inhalation and ingestion. This series replaces the Publication 56 series of documents.
* The data provided are age-dependent dose coefficients for members of the public for environmental intakes of radionuclides by inhalation and ingestion. As in the Publication 56 series, dose coefficients are presented in this series of reports for intakes by 3-mo-old infants, 1-, 5-, 10-, and 15-y-old children, and adults.
* The data provided in the printed reports are restricted to tables of committed effective dose per intake (Sv Bq–1) for inhalation and ingestion. Data are provided for all absorption Types and for the most common isotope(s) of each element. The electronic annex that accompanies this series of reports contains a comprehensive set of committed effective and equivalent dose coefficients per intake.
* This current report provides the above data for the following elements : Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu), Actinium (Ac), Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einsteinium (Es) and Fermium (Fm).

# INTRODUCTION

1. The present report is Part 2 of a report series aimed at providing revised dose coefficients for intakes of radionuclides by members of the public. This report series replaces the *Publication 56, 67, 69, 71*, *72*, *88* and *95* (ICRP, 1990, 1993, 1995a, 1995b, 1995c, 2001, 2004) that gave dose coefficients for members of the public, for intakes of radionuclides by inhalation and ingestion. The revised dose coefficients provided in this new series have been calculated using the Publication 100 (ICRP, 2006) Human Alimentary Tract Model (HATM) and a revision of the Human Respiratory Tract Model (HRTM) (ICRP, 2015), which takes account of more recent data. Revisions have also been made to many models for the systemic biokinetics of radionuclides, making them more physiologically realistic representations of uptake and retention in organs and tissues and of excretion.
2. Dose coefficients have been calculated for radioisotopes of the elements which are expected to be released into the environment as a result of human activities, such as uranium mining and milling, conversion, enrichment and fabrication, power station operations, fuel reprocessing, waste storage and disposal, and considered to be of significance for environmental radiation protection purposes. In addition, naturally occurring radionuclides are present in the environment and their concentrations may be modified by human activities. Consequently, the range of radionuclides to be addressed includes those of natural origin, fission products, actinides, and activation products.

## Methodology used in this report series

1. The general methodology for producing the biokinetic and dosimetric models is described in Part 1 of this report series (ICRP, 2024). For each element, detailed reviews of the literature were carried out to identify experimental studies and human contamination cases that provide information to quantify absorption to blood from the respiratory and alimentary tracts, and the biokinetics following systemic uptake. These reviews, and the analyses of the data obtained from them, are summarised in each element section. Uncertainties are treated as described previously in *ICRP Publication* 130 (ICRP, 2015).
2. The chemical forms considered in this report series are those found in workplaces and already described in the OIR series (ICRP, 2015, 2016, 2017, 2019, 2022). Since most of the radionuclides released in the environment may be gradually internalised in the food chain, an additional organic chemical form is taken into consideration for ingestion by humans.
3. To provide dose coefficients for members of the public, it is necessary to take into account the effect of age on the biokinetics of radionuclides and on anatomical and physiological data. The biokinetic data used for the adults in this series of report are taken from the OIR series (ICRP, 2015, 2016, 2017, 2019, 2022). Age-specific biokinetic data are given in this series of reports for intakes by 3-mo-old infants, 1-, 5, 10-, and 15-y-old children, in addition to the adults. Contamination of embryo and foetus from intakes of radionuclides by mothers and from ingestion of radionuclides in mothers’ milk will be treated in separate reports.
4. Dose coefficients are presented in this series of reports for intakes by 3-mo-old infants, 1-, 5-, 10-, and 15-y-old children, in addition to the adults. In most cases the adult is taken to be aged 20 y. Exceptions are made for the alkaline earth elements, lead, thorium, uranium, neptunium, plutonium, americium and curium (ICRP, 1993, 1995b). For these elements, the transfer rates for the adult apply to ages 25 y, because some of the transfer rates in the biokinetic models are equated with bone formation rates, which are expected to remain elevated up to about age 25 y. In the calculations of the activity in source regions of the body, following intakes at these ages, continuous changes with age in the transfer rates governing its distribution and retention are obtained by linear interpolation according to age. This also applies to the transfer of activity from the small intestine to body fluids. For application to other ages and protracted intakes, it is considered here, as in the *Publication 56* series (e.g. ICRP, 1989) that tissue doses can be estimated by applying the age-specific dose coefficients to the age ranges given below:

3 mo: from 0 to 12 mo of age

1 y: from 1 y to 2 y

5 y: more than 2 y to 7 y

10 y: more than 7 y to 12 y

15 y: more than 12 y to 17 y

adult: more than 17 y.

1. As in the *Publication 56* series, a single Reference Person is used to represent each age-group. Generally, parameter values for males have been adopted because of the availability of biokinetic data. Where there are known differences between sexes in the biokinetics of an element, this is noted in the relevant section of the biokinetic data.

## Data presented in this report series

1. Each element section of this reports series includes reviews of data on inhalation, ingestion and systemic biokinetics and the structure and parameter values of the reference systemic biokinetic model.
2. The data provided are age-dependent dose coefficients for members of the public for environmental intakes of radionuclides by inhalation and ingestion. As in the *Publication 56* series, dose coefficients are presented in this series of reports for intakes by 3-mo-old infants, 1-, 5-, 10-, and 15-y-old children, and adults.
3. The data provided in the printed reports are restricted to tables of committed effective dose per intake (Sv Bq–1) for inhalation and ingestion. Data are provided for all absorption types F, M and S and for the most common isotope(s) of each element. In cases for which sufficient information is available (principally for actinide elements), lung absorption is specified for certain chemical forms, and dose coefficients are calculated accordingly. The sizes of particles inhaled by the Reference Individuals are assumed to be log-normally distributed with an AMAD of 1 μm and geometric standard deviation σg of approximately 2.5 (ICRP, 2024*,*). They are assumed to have a density of 3.00 g cm–3, and a shape factor of 1.5. An exception is made for the short-lived progeny of radon, described in the previous report of this series (ICRP, 2024).
4. The electronic annex that accompanies this series of reports contains a comprehensive set of committed effective and equivalent dose coefficients per intake. Data are presented for almost all radionuclides included in *Publication 107* that have half-lives equal to or greater than 10 min, and for other selected radionuclides. Data are provided for a range of physico-chemical forms and for aerosols with median sizes ranging from an AMTD of 0.001 µm to an AMAD of 20 µm. Data for intake by ingestion (for specified values of *f*A) are also provided.
5. This current report provides the above data for the following elements : Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu), Actinium (Ac), Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einsteinium (Es) and Fermium (Fm).

# Lanthanum (Z = 57)

1. The fifteen elements from lanthanum (Z=57) to lutetium (Z=71) form the lanthanide series. The term 'rare earths' has also been used for this group of elements, and at times to a larger group, including yttrium (Z=39) and scandium (Z=21). The International Union of Pure and Applied Chemistry (IUPAC) prefers the term lanthanoid to lanthanide (IUPAC, 2005) but that terminology is not adopted in this series of documents.

## Routes of Intake

1. In *Publication 141*, ICRP (2019) recognised that information on the biokinetics of several lanthanide elements is too limited to develop well-supported biokinetic models based on element-specific data. However, the lanthanides show a regular gradation in chemical properties across the series, and animal studies indicate that this is reflected in reasonably predictable changes across the lanthanide family in their deposition in the liver and skeleton as well as in their excretion patterns. These regular differences in chemical and biological behaviour have been used to construct a generic lanthanide biokinetic model and, where specific information is not available, to assign element-specific parameter values for each of the lanthanides.
2. Section 2 of *Publication 141* describes the basis for the generic modeling scheme, the common model structure applied, and the generic and element-specific parameter values assigned to each element in the series. Subsequent element sections in *Publication 141* expand on specific data or assumptions for each of the lanthanides.

### Inhalation

1. In Section 2 of *Publication 141* (ICRP, 2019) (A Generic Biokinetic Modelling Scheme for the Lanthanides) information relating to the biokinetics following deposition in the respiratory tract of different lanthanide elements was compared. There is extensive information on the behaviour of cerium, but relatively little for other lanthanides, and for several of them there are no experimental studies at all. Because of the lack of information on the lung clearance characteristics of most lanthanides other than cerium, and the similarities in the chemical behaviour and biokinetics of the lanthanides, the behaviour of cerium was used in *Publication 141* and this document as a model for other lanthanide elements.
2. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including lanthanum, are given in Table 2.1 and Table 2.2 (taken from Section 2 of *Publication 141*).
3. For most elements, under the heading 'Default parameter values', the corresponding table includes a list of materials for which there is in-vivo information which is sufficient to assign the chemical form to a default absorption Type, but specific parameter values for that form are not adopted. This could be because there is insufficient information to derive parameter values, or for another reason, for example, exposure to it is unlikely. For the lanthanides, these materials are instead listed in Table 2.2. However, the behaviour of ionic (soluble) lanthanides following deposition in the respiratory tract is difficult to determine because ionic solutions (e.g. chloride) are unstable at neutral pH and in humansy biological media, resulting in colloid formation.
4. In the case of lanthanum, information on absorption from the respiratory tract is available from experimental studies, mainly as chloride. The radiotracer studies reported were of short duration because they used 140La, which has a half-life of only 1.7 d. For details see Section 3 of *Publication 141*.

Table 2.1. Absorption parameter values for inhaled and ingested lanthanides.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | | Absorption parameter values\* | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | *s*r (d–1) | | *s*s (d–1) | |
| Specific parameter values‡ | | | | |  | |  | |  | |  | |
| Water soluble forms, including chloride and citrate§ | | | | | 0.5 | | 1 | | 0.0015 | | 3 × 10–4 | |
| Dioxide | | | | | 0.001 | | 1 | | 0.001 | | 5 × 10–7 | |
| Default parameter values§ | | | | |  | |  | |  | |  | |
| Absorption Type | | | Assigned forms | |  | |  | |  | |  | |
| F | | | NB: Type F should not be assumed without evidence | | 1 | | 1 | | – | | 5 × 10–4 | |
| M¶ | | |  | | 0.2 | | 1 | | 0.005 | | 1 × 10–4 | |
| S | | |  | | 0.01 | | 1 | | 1 × 10–4 | | 5 × 10–6 | |
|  |  | | | |  | |  | |  | |  | |
| Ingested material\*\* | | | | |  | |  | |  | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | |
| 3 mo | | 1 y | | 5 y | | 10 y | | 15 y | | adult |
| All compounds | | 5 × 10–3 | | 5 × 10–4 | | 5 × 10–4 | | 5 × 10–4 | | 5 × 10–4 | | 5 × 10–4 |

\* It is assumed that for all lanthanides a bound fraction *fb* = 0.07 with an uptake rate *sb* = 0.02 d–1 is applied to material in the ET and AI regions, and associated lymph nodes LNET and LNTH. It is assumed that *fb* = 0.0 for material deposited in the BB and bb regions. The values of *sr* for Type F, M and S forms of all lanthanides (1 d–1) are element-specific.

† For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *fA* values for inhaled materials are applied: i.e., the (rounded) product of fr for the absorption Type (or specific value where given) and the *fA* value for ingested soluble forms of the lanthanide applicable to the age-group of interest (e.g. 5 × 10–4 for adults).

‡ See cerium section (Section 4 of Publication 141, ICRP, 2019) for summary of information on which parameter values are based, and on ranges of parameter values observed in different studies. For both water soluble forms, and dioxide, specific parameter values are used for dissolution in the lungs, but a default value of *fA* (footnote †). Note that oxides forms of lanthanides other than cerium will probably not be dioxides, and so will be assigned to Type M.

§ Materials are listed in Table 2.2 where there is sufficient information in the individual element section to assign to a default absorption Type. If specific parameter values are derived, they are not adopted here.

¶ Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

\*\*Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *fA* for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (e.g. 5 × 10–4 for adults).

Table 2.2. Summary of information from in-vivo studies to enable assignment of chemical forms to default absorption Types *fA*.

|  |  |  |  |
| --- | --- | --- | --- |
| Element | Type F | Type M | Type S |
| La | La-DTPA | Chloride |  |
| Ce |  | Chloride, citrate, fluoride, hydroxide | Irradiated fuel fragments |
| Pr |  | Chloride |  |
| Pm |  | Chloride, oxide (Pm2O3) |  |
| Sm |  | Chloride, oxide (Sm2O3) |  |
| Eu |  | Nitrate, oxide (Eu2O3) |  |
| Gd | Chloride, citrate | Oxide (Gd2O3) |  |
| Tb |  | Oxide (Tb4O7) |  |
| Tm |  | Oxide (Tm2O3) |  |

\*See text of individual element section in *Publication 141* (ICRP, 2019).

### Ingestion

1. *Adults.* In Section 2 of *Publication 141* (ICRP, 2019) (A Generic Biokinetic Modelling Scheme for the Lanthanides) information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For lanthanum, Section 3 of *Publication 141* reported results of animal studies showing fractional absorption from less than 7 × 10-6 to about 2 × 10-3. In one human study, the fractional absorption was around 10–5 (Pennick et al., 2006). The value of *f*A = 5 ×10–4 is adopted here for intakes of lanthanum by adult members of the public.
2. *Children*. The age-dependency of lanthanum absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for lanthanum.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. Data for human subjects indicate slow removal of systemic lanthanium from the body. After intravenous administration of 140LaCl3 to human subjects, urinary excretion ranged from 0.5% to 2% of the dose in 24 h (Spencer, 1968). Faecal excretion accounted for approximately 0.5% of the dose during the first four days (Spencer, 1968). In another human study, renal clearance amounted to 1.7% of total plasma clearance over the first 7 d (Pennick et al., 2006).
2. Cuddihy and Boecker (1970) studied the biokinetics of 140La in beagle dogs following administration of 140LaCl3 by inhalation, gavage, and intravenous injection. The division of 140La between liver and skeleton depended on the route of administration, with lower relative uptake by liver for inhaled lanthanum than for injected lanthanum. The tissue distribution patterns were greatly influenced by the chemical form administered. The investigators concluded that results of injection studies involving 140La may not be representative of the systemic behaviour of lanthanum absorbed to blood following inhalation. They developed a biokinetic model for lanthanum as a fit to the inhalation data for dogs. The model assigns 45% of outflow from blood to liver, 32% to skeleton, 3.8% to kidneys, 0.0048% to spleen, 9.6% to urine, and 9.6% to the intestinal contents. The model depicts slow return from tissues to blood.
3. In rats, bone and liver generally were the dominant systemic repositories for the lighter lanthanide elements (Durbin, 1959, 1962; Moskalev et al., 1974). The ratio of deposition in bone to that in liver increased with the ionic radius and atomic mass of the lanthanides, from much less than 1.0 for relatively light lanthanides such as La and Ce to 20 or more for the relatively heavy lanthanides such as Ho, Tm, and Lu. The lighter lanthanides were excreted primarily in faeces, and the heavier lanthanides were excreted primarily in urine.
4. No information was found regarding age dependence in the biokinetics of systemic lanthanum.
   * + 1. Systemic model
5. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
6. A common set of transfer coefficients is applied to the “cerium group”, which includes the lanthanide elements lanthanum, cerium, and praseodymium. The basis for the parameter values underlying those transfer coefficients is described is the section on cerium. Transfer coefficients for the cerium group are listed in Table 3.2 and Table 3.3 of that section.
   * + 1. Treatment of radioactive progeny
7. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of lanthanum is described in Section 3.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for lanthanum

Table 2.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 140La compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 3.2E-09 | 2.5E-09 | 1.3E-09 | 8.8E-10 | 6.0E-10 | 5.8E-10 |
| Dioxide | 3.6E-09 | 2.7E-09 | 1.4E-09 | 1.0E-09 | 6.9E-10 | 6.7E-10 |
| Type F, — NB: Type F should not be assumed without evidence | 2.9E-09 | 2.2E-09 | 1.1E-09 | 7.6E-10 | 5.1E-10 | 4.8E-10 |
| Type M | 3.4E-09 | 2.6E-09 | 1.3E-09 | 9.5E-10 | 6.5E-10 | 6.3E-10 |
| Type S, Irradiated fuel fragments | 3.5E-09 | 2.7E-09 | 1.4E-09 | 1.0E-09 | 6.9E-10 | 6.7E-10 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 3.5E-09 | 3.0E-09 | 1.8E-09 | 1.3E-09 | 8.5E-10 | 7.9E-10 |

# Cerium (Z = 58)

## Routes of Intake

### Inhalation

1. Studies have been reported of the behaviour of cerium (Ce) radioisotopes in humans following accidental inhalation. Information on absorption from the respiratory tract is available from experimental studies of cerium in various chemical forms, including chloride, citrate, dioxide, irradiated fuel fragments, and in fused aluminosilicate particles (FAP). For details, see Section 4 of *Publication 141* (ICRP, 2019). The behaviour of ionic (soluble) cerium following deposition in the respiratory tract is complex and difficult to quantify because ionic solutions (e.g. chloride) are unstable at neutral pH and in humansy biological media, resulting in colloid formation (see Section 2 of *Publication 141*, ICRP 2019). Absorption parameter values and Types, and associated *f*A values for particulate forms of cerium are given in Table 2.1 and Table 2.2 of the lanthanum section.

### Ingestion

1. *Adults*. The gastrointestinal absorption of cerium in humans is similar to that of trivalent actinides (for more details, see section 4 of *Publication 141*, ICRP, 2019). Human biokinetics of cerium citrate was investigated with stable isotopes (Höllriegl et al., 2017): comparing urinary excretions of oral and intravenous tracers with corresponding model predictions based on the structure presented by Taylor and Leggett (2003) indicated that the intestinal absorption was about 5 × 10-3 or lower. In *Publication 141* (ICRP, 2019) an *f*A value 5 × 10-4 was adopted for workers. The same *f*A = 5 × 10-4 is adopted here for intakes of cerium by adult members of the public.
2. *Children*. The uptake of cerium is influenced by age and diet (Inaba and Lengemann, 1972). The chemical form in which the cerium is administered appears to affect absorption only during the early period of life (Eisele et al., 1980). Administration of 141Ce as cerium chloride, cerium nitrate or cerium citrate to newborn or suckling animals (mice, rats) resulted in an absorbed fraction of up to 0.03, whereas the absorption of radioactive cerium salts from the GI tract of adult rats ranged from 5 × 10-4 to less than 1 × 10-3 of the administered dose (Inaba and Lengemann, 1972; Kistner et al., 1987; Kostial et al., 1987; Kostial, Kargacin and Landeka, 1989; Kostial, Kargacin, Blanusa, et al., 1989; Naharin et al., 1974; Shiraishi and Ichikawa, 1972). Mraz and Eisele (1977) observed that the absorption of cerium chloride was threefold greater in piglets treated at 1 day of age versus those treated at 4 days of age. All studies indicate that the retention of cerium in the gut is longer for the younger animals. In *Publication 67* (ICRP, 1993) a fractional absorption of 5×10-4 was considered for intakes by adult members of the public and children of 1 year and older, and a value of 5 × 10-3 was appliedfor 3-month-old-infants. In this report, the same *f*A values of 5 × 10-4 for intakes by children of 1 year and older, and 5 × 10-3 for 3-month-old-infants are adopted.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The systemic behaviour of cerium has been studied in a variety of laboratory animals including rodents (Durbin, 1959, 1962; Ewaldsson and Magnusson, 1964; Inaba and Lengemann, 1972), sheep (Buldakov and Burov, 1967), swine (McClellan et al., 1965; Mraz and Eisele, 1977), and dogs (Cuddihy et al., 1975, 1976; Cuddihy and Boecker, 1975; Guilmette et al., 1987; Hahn et al., 1997; Richmond and London, 1966; Stuart, 1967; Stuart et al., 1964). Results of these studies indicate that a sizable portion of the activity reaching blood is tenaciously retained in systemic tissues, with bone and liver being the dominant repositories. Following intravenous administration of 144CeCl3 to dogs, activity was retained with a biological half-time of about 10 y (Richmond and London, 1966). At 10 d after intravenous administration of 144Ce as chloride to miniature swine, the skeleton, liver, and kidneys contained about 40%, 35%, and 0.4%, respectively, of the administered amount. In rats, cerium that deposited in bone accumulated in the periosteum and endosteum but not in the cortex (Durbin, 1962).
2. Durbin (1959, 1962) compared the behaviour of lanthanide elements in rats following their intramuscular administration. The main sites of deposition of all lanthanides were the liver and skeleton. The initial division between liver and skeleton and the early excretion pattern appeared to be related to the ionic radius, which for the lanthanide family declines monotonically with increasing atomic number (Table 3.1). For elements with ionic radii between 92 pm and 106 pm, a decrease in ionic radius was associated overall with a decrease in uptake by liver, an increase in uptake by bone, and an increase in the early urinary excretion rate. Little difference in the distribution or excretion through 4 d was seen for lanthanide elements with ionic radius of 92 pm or less (Tb, Dy, Ho, Er, Tm, Yb, and Lu): the content of bone and liver ranged from 58–68% and 1–7%, respectively, and cumulative urinary excretion was 16–27% of the injected amount. Elements that deposited primarily in the liver were eventually excreted largely in faeces.
3. Moskalev et al. (1974) reached conclusions similar to those of Durbin from their studies of the systemic behaviour of the lanthanide elements La, Ce, Pr, Pm, Eu, Gd, Tb, and Yb in rats following intravenous administration but described their results in terms of increasing atomic weight rather than decreasing ionic radius. They found that the lighter lanthanides La, Ce, Pr accumulated mainly in the liver (~70%) and to some extent in the skeleton (~20%); the relatively heavy lanthanides Tb and Yb accumulated mainly in the skeleton (~80%) and to some extent in the liver (<20%); and the elements Pm, Eu, and Gd with intermediate atomic weight occupied intermediate places in this scheme. Elimination of the lanthanide elements in urine and faeces also was found to depend on atomic weight. The light elements La, Ce, Pr were excreted primarily in faeces, and only a few percent was excreted in urine over the observation period. With increasing atomic number the percentage eliminated in faeces decreased proportionally to the decline in accumulation in the liver.
4. Findings of Ando et al. (Durbin, 1959, 1962) regarding the early systemic behaviour of the lanthanide elements Ce, Sm, Gd, Tb, Tm, Yb, and Lu in rats support Durbin’s conclusions that bone and liver are the dominant deposition sites for the lanthanides and that the deposition in bone tends to increase and deposition in liver tends to decrease with decreasing ionic radius. Data on uptake of lanthanide elements in tissues other than liver and bone do not reveal any clear relation with ionic radius of the lanthanide elements.

Table 3.1. Distribution of trivalent lanthanide elements in rats 4 d post administration, as a function of ionic radius and atomic number\*.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Element | Ionic radius  (pm) | Atomic number | % injected activity | | | | |
| Bone | Liver | Other tissues | Faeces | Urine |
| Lanthanum | 106 | 57 | 18 | 65 | 11 | 3 | 3 |
| Cerium | 103 | 58 | 28 | 51 | 6 | 9 | 6 |
| Praesodymium | 101 | 59 | 27 | 48 | 9 | 9 | 7 |
| Neodymium | 100 | 60 | 31 | 27 | 10 | 10 | 22 |
| Promethium | 98 | 61 | 36 | 41 | 7 | 6 | 10 |
| Samarium | 96 | 62 | 33 | 35 | 6 | 13 | 13 |
| Europium | 95 | 63 | 36 | 25 | 11 | 11 | 17 |
| Gadolinium | 94 | 64 | 41 | 12 | 10 | 10 | 27 |
| Terbium | 92 | 65 | 60 | 7 | 10 | 7 | 16 |
| Dysprosium | 91 | 66 | 60 | 3 | 7 | 6 | 24 |
| Holmium | 89 | 67 | 56 | 2 | 8 | 13 | 21 |
| Erbium | 88 | 68 | 56 | 1 | 9 | 7 | 27 |
| Thulium | 87 | 69 | 64 | 2 | 7 | 5 | 22 |
| Ytterbium | 86 | 70 | 58 | 3 | 13 | 7 | 19 |
| Lutetium | 85 | 71 | 68 | 3 | 4 | 7 | 16 |

\*Based on data reported by Durbin (1959, 1962, 1973).

1. Buldakov and Burov (1967) examined the behaviour of 144Ce administered intravenously or orally as the chloride to sheep at different ages. Uptake by the skeleton decreased and uptake by the liver increased with increasing age at administration. Twenty-four hours after intravenous injection, lambs in the first month of life retained on average 59.4% of the injected amount in the skeleton and 14.4% in the liver. Sheep of age 6 months at injection retained 32.2% in the skeleton and 25.5% in the liver. Activity in the skeleton increased up to 16 d post administration in lambs and up to 31 days post administration in adult sheep, due to redistribution from soft tissues.
2. Yorkshire piglets were orally administered 144Ce during the first or fourth day after birth (Mraz and Eisele, 1977). At 4–18 d post injection the skeleton of rats dosed on day 1 contained ~91% of the total-body content excluding the gastrointestinal tract and skin. At 3–21 d the skeleton of rats dosed on day 4 contained ~87% of the total-body content minus GI tract and skin.
3. Guilmette et al. (1987) investigated age-related biokinetics of 144Ce and 239Pu in immature (age 3 mo), young adult (18 mo), and old (8–10.5 y) beagle dogs following a single inhalation exposure to an aerosol of 144Ce in a fused aluminosilicate matrix or 239PuO2. The most consistent age-related patterns for both cerium and plutonium were observed in the skeleton. A fivefold greater amount of plutonium and a twofold greater amount of cerium were found in the skeleton of immature animals than old animals. Roughly a 30% higher skeletal deposition was seen in young adults than in old animals for both cerium and plutonium. This is consistent a pattern of change with age observed in a number of bone-seeking elements.
4. Matusaka et al. (1970) investigated the absorption and distribution of 144Ce administered via stomach tube to mice of different ages. In newborn mice most of the absorbed activity deposited in the skeleton. The liver contained about 15% of the body burden 21 d after administration.
5. Mahlum and Sikov (1968) administered 144Ce intravenously to pregnant rats and examined the retention and distribution of activity in the mother, fetus, and newborn. A substantially greater fraction of the body burden was present in the skeletons of the fetal and newborn rats than in the mother.
   * + 1. Systemic model
6. A set of systemic biokinetic models for lanthanide elements in adult humans developed by Taylor and Leggett (2003) were adopted in *Publication 141* for application to workers. A common model structure was applied to all lanthanides. On the basis of the apparently gradual change in the distribution and excretion of the lanthanides with decreasing ionic radius and a recognition of the uncertainty in interspecies extrapolation of the available biokinetic data, Taylor and Leggett divided the lanthanide elements into five sets of neighboring or individual elements for the purpose of developing set-specific systemic biokinetic models:

* lanthanum, cerium, praseodymium (called the cerium group for expository purposes)
* neodymium, promethium, samarium (promethium group)
* europium
* gadolinium
* terbium, dysprosium, holmium, erbium, thulium, lutetium (holmium group).

1. In the development of parameter values, preference was given to data on human subjects, dogs, and swine when available. Because biokinetic data for human subjects or laboratory animals other than rodents were sparse or absent for some lanthanide elements, the development of some generic or set-specific parameter values also relied on the assumption that the general trends in the initial distribution and urinary excretion of the lanthanides observed in rats also hold for man. In contrast to data for rats, human studies of the biokinetics of Pm and Gd in human subjects indicated relatively slow removal loss from the liver. Based on these human data as well as analogy with actinide elements, it was assumed that the lanthanide elements are tenaciously retained in the liver. The model for update and removal by other soft tissues was based on collective data on the lanthanides in laboratory animals, and analogy with the actinide elements. The model for uptake and removal by the gonads was based on analogy with the actinide elements.
2. As in *Publication 141* (ICRP, 2019), a single model structure (Fig 3.1) is applied in this report to all lanthanide elements. Also, the groupings of lanthanide elements used in that report are used here to assign common biokinetic models to subsets of the lanthanide family. For example, all elements in the cerium group are assigned a common set of age-specific parameter values.

Diagram

Description automatically generated

Fig 3.1. Structure of the systemic biokinetic models for the lanthanide elements.

The compartments ST0, ST1, and ST2 represent relatively fast, intermediate, and relatively slow turnover, respectively, of activity in Other soft tissue. SI =Small intestine, RC = Right colon, LC = Left colon, RS = Rectosigmoid colon.

1. The systemic models applied in *Publication 141* to occupational intakes of lanthanides are applied here to adult members of the public. The lanthanide models for adults in *Publication 141* all share the following generic parameter values, which are also applied in this report to preadult ages (except that assigned bone turnover rates are age-specific):

* Percentage of outflow from blood going to rapid-turnover soft tissue (ST0): 30%
* Deposition fractions (applied to activity “leaving the circulation”, i.e., activity other than that deposited in the fast-turnover soft tissue compartment ST0):

Kidneys 1: 1.5% (i.e., 0.015 × 70% of outflow from blood)

Kidneys 2: 0.5%

ST2 (soft tissues with tenacious retention): 2%

Testes: 0.035%

Ovaries: 0.011%

* Removal half-time from:

Blood (to all destinations): 0.5 h

ST0 (to blood): 0.5 d

ST2 (to blood): 15 y

Kidneys 1 (to urinary bladder contents): 7 d

Kidneys 2 (to blood): 500 d

Liver 1 (to SI content + Liver 2): 30 d

Gonads to blood: 5 y

* Rate of transfer from:

Liver 1 to SI content: 0.84 y-1 (10% of outflow from Liver 1)

Liver 1 to Liver 2: 7.59 y-1 (90% of outflow from Liver 1)

Trabecular or cortical marrow to blood, 2.77 y-1 (half-time of 0.25 y)

Trabecular surface to trabecular volume (age-dependent in this report)

Cortical surface to cortical volume (age-dependent in this report)

Trabecular surface or volume to trabecular marrow (age-dependent in this report)

Cortical surface or volume to cortical marrow (age-dependent in this report)

1. Age-dependence indicated above for transfer from bone compartment as estimated as follows:

* The rate of transfer from trabecular bone surface to trabecular bone volume is assumed to be A times the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages
* The rate of transfer from cortical bone surface to cortical bone volume is assumed to be 0.5 times the reference age-specific rate of remodeling of cortical bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages
* The rate of transfer from trabecular bone surface or volume to trabecular marrow is assumed to be the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002)
* The rate of transfer from cortical bone surface or volume to cortical marrow is assumed to be the reference age-specific rate of remodeling of cortical bone (ICRP, 2002)

1. As in *Publication 141*, set-specific (non-generic) parameter values are assigned here to:

* the deposition fractions for liver, bone surface, urinary bladder content, right colon content, and intermediate-term soft tissue compartment (ST1 in Fig 3.1)
* removal half-times from ST1 to blood and from the long-term liver compartment Liver 2 to blood

1. Extension of the non-generic parameter values for adults to preadult ages is based on a general pattern of age related systemic biokinetics observed for a number of bone-seeking elements including cerium. That is, the deposition fraction in bone is higher in immature animals than in mature animals and tends to decrease with age from early life to adolescence to adulthood. Also, biokinetic studies of bone-seeking elements show that the rate of turnover of the skeletal deposit is higher in immature than mature animals, presumably due to a faster rate of bone restructuring at younger ages.
2. As indicated in the above summary of data for cerium, the age-specific behaviour of cerium in laboratory animals indicate that skeletal uptake amounts to two-thirds or more of cerium entering the systemic circulation during early life. A deposition fraction of 0.7 in bone is applied to cerium, lanthanum, and praseodymium during the first year of life. It is assumed that the amount deposited in bone is equally divided between cortical and trabecular bone surface. For ages 5–15 y, a deposition fraction in bone of 0.5 is assigned, as an average of the value 0.3 for adults and 0.7 through age 1 y. In view of the relatively low deposition of cerium at sites other than liver and bone, it is assumed for simplicity that uptake by bone is in competition only with uptake by liver. This is implemented by requiring that the sum of deposition fractions in bone and liver at all ages is equal to 0.8, the value in the model for adults. As indicated earlier, other deposition fractions in the model are assumed to be invariant with age.
3. The non-generic deposition fractions in the model for cerium, lanthanum, and praseodymium are listed in Table 3.2.

Table 3.2. Non-generic (group-specific) parameter values for the cerium group (cerium, lanthanum, and praseodymium).

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 100 d | | 1 y | | 5 y | | 10 y | | 15 y | | Adult |
|  | Deposition (% of activity leaving the circulation) | | | | | | | | | | |
| Liver | 10 | | 10 | | 30 | | 30 | | 30 | | 50 |
| Bone | 70 | | 70 | | 50 | | 50 | | 50 | | 30 |
| ST1 | 7.95 | | 7.95 | | 7.95 | | 7.95 | | 7.95 | | 7.95 |
| Urinary bladder content | 2 | | 2 | | 2 | | 2 | | 2 | | 2 |
| Right colon content | 0.06 | | 0.06 | | 0.06 | | 0.06 | | 0.06 | | 0.06 |
|  |  |  | |  | |  | |  | |  | |
|  | Removal half-time (y) | | | | | | | | | | |
| ST1 to Blood | 1 y | | 1 y | | 1 y | | 1 y | | 1 y | | 1 y |
| Liver 2 to Blood | 2 y | | 2 y | | 2 y | | 2 y | | 2 y | | 2 y |

1. The behaviour of cerium in bone is assumed to follow the generic skeletal model for bone-surface-seeking radionuclides. That is, activity deposited on bone surface is transferred to bone marrow and bone volume at reference rates based on the age-specific rate of bone turnover. Activity in bone volume is transferred to bone marrow at the rate of bone turnover. Activity is lost from bone marrow to blood with a half-time of 0.25 y and is subsequently redistributed to tissues and excretion pathways based on age-specific deposition fractions.
2. Table 3.3 lists the full set of transfer coefficients in the age-specific model for the cerium group.

Table 3.3. Age-specific transfer coefficients for the cerium group

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 2.33E+00 | 2.33E+00 | 6.98E+00 | 6.98E+00 | 6.98E+00 | 1.16E+01 |
| Blood to ST0 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 |
| Blood to ST1 | 1.85E+00 | 1.85E+00 | 1.85E+00 | 1.85E+00 | 1.85E+00 | 1.85E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Kidneys 1 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 |
| Blood to RC content | 1.40E+00 | 1.40E+00 | 1.40E+00 | 1.40E+00 | 1.40E+00 | 1.40E+00 |
| Blood to Kidneys 2 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.15E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.56E-03 |
| Blood to UB content | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Liver 2 to Blood | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 |
| Liver 1 to SI content | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 |
| Liver 1 to Liver 2 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST2 to Blood | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to UB content | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, RC = Right colon, SI = Small intestine, UB = Urinary bladder

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of cerium is described in Section 4.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for cerium

Table 3.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 139Ce compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 5.8E-09 | 4.5E-09 | 2.2E-09 | 1.4E-09 | 1.1E-09 | 1.1E-09 |
| Dioxide | 5.5E-09 | 4.8E-09 | 2.7E-09 | 1.8E-09 | 1.4E-09 | 1.4E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 6.1E-09 | 4.2E-09 | 1.8E-09 | 1.0E-09 | 8.1E-10 | 8.6E-10 |
| Type M | 5.5E-09 | 4.4E-09 | 2.2E-09 | 1.4E-09 | 1.1E-09 | 1.1E-09 |
| Type S, Irradiated fuel fragments | 5.6E-09 | 5.0E-09 | 2.8E-09 | 1.9E-09 | 1.4E-09 | 1.5E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 6.0E-10 | 3.4E-10 | 1.9E-10 | 1.3E-10 | 9.1E-11 | 8.8E-11 |

Table 3.5. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 141Ce compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 5.3E-09 | 4.1E-09 | 2.1E-09 | 1.3E-09 | 1.0E-09 | 9.4E-10 |
| Dioxide | 6.3E-09 | 5.2E-09 | 2.9E-09 | 1.9E-09 | 1.5E-09 | 1.4E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 4.3E-09 | 3.1E-09 | 1.3E-09 | 6.9E-10 | 5.8E-10 | 4.6E-10 |
| Type M | 5.7E-09 | 4.5E-09 | 2.4E-09 | 1.6E-09 | 1.2E-09 | 1.1E-09 |
| Type S, Irradiated fuel fragments | 6.3E-09 | 5.2E-09 | 2.9E-09 | 1.9E-09 | 1.5E-09 | 1.4E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 4.5E-10 | 2.7E-10 | 1.6E-10 | 1.1E-10 | 7.6E-11 | 6.2E-11 |

Table 3.6. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 144Ce compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.4E-07 | 1.2E-07 | 6.4E-08 | 3.9E-08 | 3.3E-08 | 3.0E-08 |
| Dioxide | 1.6E-07 | 1.5E-07 | 8.7E-08 | 5.8E-08 | 4.7E-08 | 4.7E-08 |
| Type F, — NB: Type F should not be assumed without evidence | 1.2E-07 | 1.1E-07 | 4.5E-08 | 2.4E-08 | 2.2E-08 | 1.7E-08 |
| Type M | 1.3E-07 | 1.2E-07 | 6.1E-08 | 3.8E-08 | 3.1E-08 | 2.9E-08 |
| Type S, Irradiated fuel fragments | 1.7E-07 | 1.6E-07 | 9.8E-08 | 6.7E-08 | 5.4E-08 | 5.5E-08 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 1.0E-08 | 4.4E-09 | 2.5E-09 | 1.7E-09 | 1.1E-09 | 9.8E-10 |

# Praseodymium (Z = 59)

## Routes of Intake

### Inhalation

1. No information was found on the behaviour of inhaled praseodymium (Pr) in humans. Information on absorption from the respiratory tract is available from experimental studies of praseodymium chloride. The studies reported were of short duration because they used 143Pr, which has a half-life of only 13.7 d. For details see Section 5 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including praseodymium, are given in Table 2.1 and Table 2.2 of the lanthanum section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019) information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For praseodymium, Section 5 of *Publication 141* reported results of animal studies showing fractional absorption less than 5 × 10-4. The value of *f*A = 5 × 10–4 is adopted here for intakes of praseodymium by adult members of the public.
2. *Children*. The age-dependency of praseodymium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for praseodymium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The biokinetics of 143Pr inhaled as liquid aerosols was investigated in mice. Absorbed activity was stored mainly in the liver and skeleton, with low activity concentrations in other organs. The systemic biokinetics of 143Pr was broadly similar to that observed in similar studies involving 144Ce, but excretion was faster for 143Pr than for 144Ce (Gensicke and Nitschke, 1964).
2. The distribution and excretion of praseodymium closely resembled that of cerium following parenteral administration of radioisotopes of these elements to rats (Durbin, 1959, 1962; Moskalev et al., 1974).
3. No information was found regarding age dependence in the biokinetics of systemic praseodymium.
   * + 1. Systemic model
4. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
5. A common set of transfer coefficients is applied in this report to the “cerium group”, lanthanum, cerium, and praseodymium. The basis for the parameter values underlying those transfer coefficients is described is the section on cerium. Transfer coefficients for the cerium group are listed in Table 3.2 and Table 3.3 of that section.
   * + 1. Treatment of radioactive progeny
6. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of praseodymium is described in Section 5.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for praseodymium

Table 4.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 143Pr compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 4.3E-09 | 3.3E-09 | 1.7E-09 | 1.1E-09 | 8.3E-10 | 7.4E-10 |
| Dioxide | 5.2E-09 | 4.2E-09 | 2.3E-09 | 1.5E-09 | 1.2E-09 | 1.1E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 3.4E-09 | 2.5E-09 | 1.0E-09 | 6.0E-10 | 4.8E-10 | 3.7E-10 |
| Type M | 4.7E-09 | 3.7E-09 | 2.0E-09 | 1.3E-09 | 1.0E-09 | 9.3E-10 |
| Type S, Irradiated fuel fragments | 5.2E-09 | 4.2E-09 | 2.3E-09 | 1.5E-09 | 1.2E-09 | 1.1E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 8.4E-10 | 6.0E-10 | 3.8E-10 | 2.7E-10 | 1.7E-10 | 1.4E-10 |

# Neodymium (Z = 60)

## Routes of Intake

### Inhalation

1. No reports of experimental studies of neodymium were found. Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including neodymium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. McAughey (1996) measured the absorption of neodymium in eight adults humans with a median absorption fraction of 5 × 10–4. The value of *f*A = 5 × 10–4 is adopted here for intakes of neodymium by adult members of the public.
2. *Children*. The age-dependency of neodymium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for neodymium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. In rats (Durbin, 1959, 1962), neodymium showed somewhat lower liver uptake and higher urinary excretion than its neighbours in the periodic chart and thus did not closely fit the trend indicated by the collective data for the lanthanides, that is, a continuous change with ionic radius across the lanthanide family with regard to deposition fractions in major repositories. However, the rate of urinary excretion of neodymium during the first week after injection into human subjects (Roth et al., 1995) was similar to that observed in human subjects injected with promethium (Palmer et al., 1970) and was much lower than that measured in rats (Durbin, 1959, 1962). The mean faecal to urinary excretion ratio over the first 7 d (~0.11) and mean whole-body retention of absorbed neodymium after 7 d (94 ± 3%) in the human subjects are also similar to values determined for promethium in human subjects.
2. No information was found regarding age dependence in the biokinetics of systemic neodymium.
   * + 1. Systemic model
3. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
4. A common set of age-specific transfer coefficients is applied to the “promethium group”, neodymium, promethium, and samarium. The transfer coefficients are based largely on generic parameter values for the lanthanides, i.e., parameter values assumed to be invariant across the lanthanide family. The generic parameter values are listed in the section on cerium. The model for each lanthanide element includes a smaller set of non-generic transfer coefficients, i.e., transfer coefficients reflecting group-specific or element-specific systemic behaviour. Specific parameter values for the promethium group are listed in the section on promethium. The full set of transfer coefficients of the model is listed in Table 6.2 of the section on promethium.
   * + 1. Treatment of progeny
5. Chain members addressed in the derivation of dose coefficients for radioisotopes of neodymium are also lanthanides. A radioactive progeny produced in a systemic compartment following intake of a lanthanide is assumed to follow the characteristic model of the progeny from its time of production.

## Dosimetric data for neodymium

Table 5.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 147Nd compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 4.0E-09 | 3.1E-09 | 1.6E-09 | 1.0E-09 | 8.1E-10 | 7.3E-10 |
| Dioxide | 4.9E-09 | 3.9E-09 | 2.2E-09 | 1.5E-09 | 1.2E-09 | 1.1E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 3.1E-09 | 2.2E-09 | 9.9E-10 | 5.9E-10 | 4.7E-10 | 3.9E-10 |
| Type M | 4.5E-09 | 3.5E-09 | 1.9E-09 | 1.2E-09 | 9.9E-10 | 9.1E-10 |
| Type S, Irradiated fuel fragments | 4.9E-09 | 3.9E-09 | 2.2E-09 | 1.5E-09 | 1.2E-09 | 1.1E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 7.8E-10 | 6.0E-10 | 3.7E-10 | 2.6E-10 | 1.7E-10 | 1.5E-10 |

# Promethium (Z = 61)

## Routes of Intake

### Inhalation

1. No information was found on the behaviour of inhaled promethium (Pm) in humans. Information on absorption from the respiratory tract is available from experimental studies of promethium as chloride and oxide. For details see Section 7 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including promethium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For promethium, Section 7 of *Publication 141* reported results of animal studies showing fractional absorption from 7 × 10-5 to less than 5 × 10-4. In one human study, the fractional absorption was estimated as 10–5 (Palmer et al., 1970). The value of *f*A = 5 × 10–4 is adopted here for intakes of promethium by adult members of the public.
2. *Children.* The age-dependency of promethium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for promethium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. Palmer et al. (1970) investigated the systemic behaviour of 143Pm in six human subjects following its intravenous administration as chloride. Roughly half of the injected activity accumulated in the liver within a few minutes. Most of the remaining activity deposited in bone over the next 5 h. More than 10% of the injected amount was excreted within the first 20 d. Biological removal represented only a few percent of the administered amount over the remainder of the observation period (~1 y). The urinary excretion rate was greater than the faecal excretion rate during the first week. Measurement on day 15 suggested that the faecal excretion rate was greater than the urinary excretion rate. The excretion rates observed in the human subjects were broadly similar to those observed by the investigators in experiments involving pigs and dogs. The data indicated an initially high rate of secretion into the gastrointestinal tract but substantially slower secretion thereafter.
2. McConnon et al (1971) compared the behaviour of intravenously injected PmCl3 in swine and normal human subjects. No major differences were seen in the systemic biokinetics of promethium in the two species. In beagle dogs exposed to 147Pm2O3 by inhalation, about 40–50% of the total body burden was in the lungs, 25% in liver, and 20% in bone at five months after exposure (Stuart, 1967). At 10 d after intravenous administration of 147Pm as chloride to miniature swine, the skeleton, liver, kidneys, and spleen contained on average about 40%, 40%, 0.3%, and 0.1%, respectively, of the administered amount.
3. The distribution of 147Pm was investigated in mice following inhalation of 147PmCl3 liquid aerosols (Gensicke and Nitschke, 1964; Hölzer and Gensicke, 1965). Activity was rapidly absorbed to blood or transferred to the gastrointestinal contents. Absorbed activity accumulated mainly in the liver and skeleton. Activity in bone (femur) was found mainly in the osteoblastic tissue of the perichondrium and on the surfaces of the primary spongiosa.
4. Priest (2007) compared the distribution of promethium with that of two other trivalent elements with similar ionic radii, americium and curium, following their intravenous administration to rats. Activity concentrations were measured in the liver, kidneys, femur, spleen, and gastrointestinal tract at 1, 4, 14, and 32 d. The distributions of the two elements with virtually the same crystal ionic radius promethium and curium, were indistinguishable. The distribution of americium, which has a slightly larger crystal ionic radius, was similar but not identical to the distributions of promethium and curium.
5. No information was found regarding the effect of age on the biokinetics of systemic promethium.
   * + 1. Systemic model
6. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
7. A common set of age-specific transfer coefficients is applied to the “promethium group”, neodymium, promethium, and samarium. The transfer coefficients are based largely on generic parameter values for the lanthanides, i.e., parameter values assumed to be invariant across the lanthanide family. The generic parameter values are listed in the section on cerium. The generic parameter values are assumed to be invariant with age except for the following:

* The rate of transfer from trabecular bone surface to trabecular bone volume is assumed to be A times the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from cortical bone surface to cortical bone volume is assumed to be 0.5 times the reference age-specific rate of remodeling of cortical bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from trabecular bone surface or volume to trabecular marrow is assumed to be the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002).
* The rate of transfer from cortical bone surface or volume to cortical marrow is assumed to be the reference age-specific rate of remodeling of cortical bone (ICRP, 2002).

1. For each lanthanide element, non-generic (element- or group-specific) parameter values are assigned here to:

* the deposition fractions for liver, bone surface, urinary bladder content, right colon content, and intermediate-term soft tissue compartment (ST1);
* removal half-times from ST1 to blood and from the long-term liver compartment Liver 2 to blood.

1. Extension of the non-generic parameter values for adults to preadult ages is based on a general pattern of age related systemic biokinetics observed for a number of bone-seeking elements including the lanthanide cerium. That is, the deposition fraction in bone is higher in immature animals than in mature animals and tends to decrease with age from early life to adolescence to adulthood. Also, biokinetic studies of bone-seeking elements show that the rate of turnover of the skeletal deposit is higher in immature than mature animals, presumably due to a faster rate of bone restructuring at younger ages.
2. Based on analogy with the most extensively studied lanthanide cerium, a bone deposition fraction of 0.7 is assigned to ages 100 d and 1 y for all lanthanide elements. For ages 5–15 y, the assigned deposition fraction is a rounded average of the value for the first year of life and the element- or group-dependent bone deposition fraction for adults, which is 0.35 for the promethium group. The deposition fraction 0.50 is assigned to the promethium group for ages 5–15 y. It is assumed that uptake by bone is in competition with uptake by liver. This is implemented by requiring that the sum of deposition fractions in bone and liver at all ages is equal to 0.8, the value in the model for adults. Other deposition fractions in the model are assumed to be invariant with age.
3. Based on trends in systemic kinetics of the lanthanide associated with decreasing ionic radius (Durbin, 1959, 1962) the deposition fractions for the urinary bladder content and right colon content for the promethium group are assumed to be 0.07 and 0.01, respectively, compared with values of 0.02 and 0.06, respectively, for the cerium group.
4. The non-generic deposition fractions in the model for the promethium group are listed in Table 6.1.

Table 6.1. Non-generic (group-specific) parameter values for the promethium group (neodymium, promethium, and samarium).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
|  | Deposition (% of activity leaving the circulation) | | | | | |
| Liver | 10 | 10 | 30 | 30 | 30 | 45 |
| Bone | 70 | 70 | 50 | 50 | 50 | 35 |
| ST1 | 7.95 | 7.95 | 7.95 | 7.95 | 7.95 | 7.95 |
| UB content | 7 | 7 | 7 | 7 | 7 | 7 |
| RC content | 1 | 1 | 1 | 1 | 1 | 1 |
|  |  |  |  |  |  |  |
|  | Removal half-time | | | | | |
| ST1 to Blood | 1 y | 1 y | 1 y | 1 y | 1 y | 1 y |
| Liver 2 to Blood | 2 y | 2 y | 2 y | 2 y | 2 y | 2 y |

1. The behaviour of the promethium group in bone is assumed to follow the generic skeletal model for bone-surface-seeking radionuclides. That is, activity deposited on bone surface is transferred to bone marrow and bone volume at reference rates based on the age-specific rate of bone turnover. Activity in bone volume is transferred to bone marrow at the rate of bone turnover. Activity is lost from bone marrow to blood with a half-time of 0.25 y and is subsequently redistributed to tissues and excretion pathways based on age-specific deposition fractions.
2. Table 6.2. lists the full set of transfer coefficients in the age-specific model for the promethium group.

Table 6.2. Age-specific transfer coefficients for the promethium group (neodymium, promethium, and samarium)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 2.33E+00 | 2.33E+00 | 6.98E+00 | 6.98E+00 | 6.98E+00 | 1.05E+01 |
| Blood to ST0 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 |
| Blood to ST1 | 1.85E+00 | 1.85E+00 | 1.85E+00 | 1.85E+00 | 1.85E+00 | 1.85E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 4.08E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 4.08E+00 |
| Blood to Kidneys 1 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 |
| Blood to RC content | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Kidneys 2 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.15E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.56E-03 |
| Blood to UB content | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 |
| Liver 2 to Blood | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 |
| Liver 1 to SI content | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 |
| Liver 1 to Liver 2 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST2 to Blood | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to UB content | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, RC = Right colon, SI = Small intestine, UB = Urinary bladder

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of promethium is described in Section 7.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for promethium

Table 6.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 147Pm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.4E-08 | 1.2E-08 | 5.8E-09 | 3.4E-09 | 2.8E-09 | 2.5E-09 |
| Dioxide | 1.3E-08 | 1.2E-08 | 6.8E-09 | 4.4E-09 | 3.5E-09 | 3.3E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 1.4E-08 | 1.2E-08 | 5.1E-09 | 2.8E-09 | 2.3E-09 | 2.0E-09 |
| Type M | 1.3E-08 | 1.1E-08 | 5.4E-09 | 3.2E-09 | 2.6E-09 | 2.3E-09 |
| Type S, Irradiated fuel fragments | 1.5E-08 | 1.4E-08 | 8.3E-09 | 5.4E-09 | 4.4E-09 | 4.4E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 6.5E-10 | 5.9E-11 | 2.7E-11 | 1.6E-11 | 1.2E-11 | 8.4E-12 |

# Samarium (Z=62)

## Routes of Intake

### Inhalation

1. Information on absorption from the respiratory tract is available from experimental studies of samarium as chloride and oxide. For details see Section 8 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including samarium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For samarium, Section 8 of *Publication 141* reported qualitative results indicating the gastrointestinal absorption of samarium to be very small. The value of *f*A = 5 × 10–4 is adopted here for intakes of samarium by adult members of the public.
2. *Children*. The age-dependency of samarium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for samarium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of the data base

1. Shipler et al. (1976) compared the kinetics of 145Sm and 143Pm in rats and dogs exposed by inhalation to an aerosol containing 145Sm2O3 and 143Pm2O3. The animals were sacrificed at 0, 14, and 30 days after exposure. Quantitative analysis for several tissues and excreta indicates that the two radionuclides behaved virtually identically in each of these animal species.
2. Biokinetic studies of samarium and promethium in rodents also indicate similar systemic behaviour of these elements (Durbin, 1959, 1962).
3. No information was found regarding age dependence in the biokinetics of systemic samarium.
   * + 1. Systemic model
4. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
5. A common set of age-specific transfer coefficients is applied to the promethium group, neodymium, promethium, and samarium. Transfer coefficients for the promethium group are listed in Table 6.2 of the section on promethium.
   * + 1. Treatment of radioactive progeny
6. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of samarium is described in Section 8.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for samarium

Table 7.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 153Sm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.3E-09 | 9.7E-10 | 5.3E-10 | 3.6E-10 | 2.9E-10 | 2.5E-10 |
| Dioxide | 1.6E-09 | 1.2E-09 | 6.8E-10 | 4.6E-10 | 3.7E-10 | 3.4E-10 |
| Type F, — NB: Type F should not be assumed without evidence | 1.0E-09 | 7.6E-10 | 3.8E-10 | 2.6E-10 | 2.0E-10 | 1.7E-10 |
| Type M | 1.5E-09 | 1.1E-09 | 6.2E-10 | 4.2E-10 | 3.4E-10 | 3.0E-10 |
| Type S, Irradiated fuel fragments | 1.6E-09 | 1.2E-09 | 6.8E-10 | 4.6E-10 | 3.7E-10 | 3.4E-10 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 4.6E-10 | 3.7E-10 | 2.3E-10 | 1.7E-10 | 1.1E-10 | 8.7E-11 |

# Europium (Z = 63)

## Routes of Intake

### Inhalation

1. One study was found on the behaviour of europium radioisotopes in humans following accidental inhalation. Information on absorption from the respiratory tract is available from experimental studies of europium as chloride, nitrate and oxide. For details see Section 9 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including europium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019) information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For europium, Section 9 of *Publication 141* reported results of animal studies showing fractional absorption from 7.8 × 10-5 to 1.6 × 10-2. The value of *f*A = 5 × 10–4 is adopted here for intakes of europium by adult members of the public.
2. *Children*. The age-dependency of europium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for europium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The biokinetics of europium has been studied in rodents (Berke, 1968, 1970; Bingham and Dobrota, 1994; Durbin, 1962; Durbin et al., 1956; Johnson and Ziemer, 1971; Moskalev et al., 1974; Ohnishi et al., 2011; Suzuki et al., 1969) and accidentally exposed workers (Ziemer et al., 1968). However, the data for workers provide little insight into the systemic kinetics of europium.
2. At 4 d after intramuscular injection of 152–154Eu into rats, bone and liver contained on average about 36% and 25%, respectively, of the administered amount (Durbin, 1959). During the first 4 d about 17% of the administered was lost in urine and 11% was lost in faeces.
3. Following intravenous administration of 152Eu to rats, the liver initially accumulated more activity than the skeleton but lost much of the activity over a period of days or weeks, while activity continued to accumulate in the skeleton (Moskalev et al., 1974). At 128 d after administration the liver and skeleton contained about 0.5% and 36%, respectively, of the administered amount.
4. Berke (1968) studied the systemic behaviour of 152–154Eu in rats following its intravenous administration as chloride. Activity cleared quickly from the circulation and accumulated primarily in the skeleton, with elevated concentration also seen in the liver and kidneys. Skeletal tissues contained about 85% of the body burden at 252 d and virtually the entire body burden at 445 d. After the first few days excretion was primarily via the gastrointestinal tract. Whole-body retention could be described as a sum of two exponential terms indicating biological half-times of 4.4 d and 3.5 y.
5. No information was found regarding the effect of age on the biokinetics of systemic europium.
   * + 1. Systemic model
6. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
7. As for all lanthanide elements, the transfer coefficients for europium are based largely on generic parameter values, i.e., parameter values assumed to be invariant across the lanthanide family. The generic parameter values are listed in the section on cerium. These generic values are assumed here to be invariant with age except for the following:

* The rate of transfer from trabecular bone surface to trabecular bone volume is assumed to be A times the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from cortical bone surface to cortical bone volume is assumed to be 0.5 times the reference age-specific rate of remodeling of cortical bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from trabecular bone surface or volume to trabecular marrow is assumed to be the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002).
* The rate of transfer from cortical bone surface or volume to cortical marrow is assumed to be the reference age-specific rate of remodeling of cortical bone (ICRP, 2002).

1. For each lanthanide element, non-generic (element- or group-specific) parameter values are assigned here to:

* the deposition fractions for liver, bone surface, urinary bladder content, right colon content, and intermediate-term soft tissue compartment (ST1)
* removal half-times from ST1 to blood and from the long-term liver compartment Liver 2 to blood

1. Extension of the non-generic parameter values for adults to preadult ages is based on a general pattern of age related systemic biokinetics observed for a number of bone-seeking elements including the lanthanide cerium. That is, the deposition fraction in bone is higher in immature animals than in mature animals and tends to decrease with age from early life to adolescence to adulthood. Also, biokinetic studies of bone-seeking elements show that the rate of turnover of the skeletal deposit is higher in immature than mature animals, presumably due to a faster rate of bone restructuring at younger ages.
2. Based on analogy with the most extensively studied lanthanide cerium, a bone deposition fraction of 0.7 is assigned to ages 100 d and 1 y for all lanthanide elements. For ages 5–15 y, the assigned deposition fraction is a rounded average of the value for the first year of life and the element- or group-dependent bone deposition fraction for adults, which is 0.35 for europium. The deposition fraction 0.50 is assigned to the europium for ages 5–15 y. In contrast to the models for the lighter lanthanides, the elevated uptake of europium by the skeleton at preadult ages is not balanced entirely by reducing the deposition fraction assigned to the adult liver, because the latter value for europium (0.25) is too small to accommodate this assumption for the youngest ages. Rather, the increased uptake of europium by bone in preadults is balanced by decreases in the deposition fractions for liver, the intermediate soft-tissue compartment ST1 (~0.15 for europium in adults), and the urinary bladder content (0.2 for europium in adults). The age-adjusted deposition fractions for each age are liberally rounded in view of the sizable uncertainties involved.
3. The non-generic deposition fractions in the model for europium are listed in Table 8.1.

Table 8.1. Non-generic parameter values for europium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
|  | Deposition (% of activity leaving the circulation) | | | | | |
| Liver | 5 | 5 | 15 | 15 | 15 | 25 |
| Bone | 70 | 70 | 50 | 50 | 50 | 35 |
| ST1 | 10 | 10 | 15 | 15 | 15 | 14.95 |
| UB content | 10 | 10 | 15 | 15 | 15 | 20 |
| RC content | 1 | 1 | 1 | 1 | 1 | 1 |
|  |  |  |  |  |  |  |
|  | Removal half-time | | | | | |
| ST1 to Blood | 100 d | 100 d | 100 d | 100 d | 100 d | 100 d |
| Liver 2 to Blood | 1 y | 1 y | 1 y | 1 y | 1 y | 1 y |

1. The behaviour of europium in bone is assumed to follow the generic skeletal model for bone-surface-seeking radionuclides. That is, activity deposited on bone surface is transferred to bone marrow and bone volume at reference rates based on the age-specific rate of bone turnover. Activity in bone volume is transferred to bone marrow at the rate of bone turnover. Activity is lost from bone marrow to blood with a half-time of 0.25 y and is subsequently redistributed to tissues and excretion pathways based on age-specific deposition fractions.
2. Table 8.2 lists the full set of transfer coefficients in the age-specific model for the europium.

Table 8.2. Age-specific transfer coefficients for europium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 1.16E+00 | 1.16E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 5.82E+00 |
| Blood to ST0 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 |
| Blood to ST1 | 2.33E+00 | 2.33E+00 | 3.48E+00 | 3.48E+00 | 3.48E+00 | 3.48E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 4.08E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 4.08E+00 |
| Blood to Kidneys 1 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 |
| Blood to RC content | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Kidneys 2 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.15E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.56E-03 |
| Blood to UB content | 2.33E+00 | 2.33E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 4.66E+00 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| Liver 1 to SI content | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 |
| Liver 1 to Liver 2 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to UB content | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, RC = Right colon, SI = Small intestine, UB = Urinary bladder

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of europium is described in Section 9.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for europium

Table 8.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 152Eu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.2E-07 | 1.1E-07 | 5.9E-08 | 4.2E-08 | 4.0E-08 | 4.0E-08 |
| Dioxide | 9.4E-08 | 8.9E-08 | 5.6E-08 | 3.9E-08 | 3.6E-08 | 3.8E-08 |
| Type F, — NB: Type F should not be assumed without evidence | 1.5E-07 | 1.3E-07 | 6.6E-08 | 4.6E-08 | 4.5E-08 | 4.5E-08 |
| Type M | 1.1E-07 | 1.0E-07 | 5.5E-08 | 3.8E-08 | 3.7E-08 | 3.7E-08 |
| Type S, Irradiated fuel fragments | 1.3E-07 | 1.3E-07 | 9.5E-08 | 7.4E-08 | 7.4E-08 | 8.0E-08 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 8.8E-09 | 2.3E-09 | 1.3E-09 | 9.4E-10 | 6.9E-10 | 6.5E-10 |

Table 8.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 154Eu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.6E-07 | 1.4E-07 | 7.2E-08 | 4.8E-08 | 4.3E-08 | 4.2E-08 |
| Dioxide | 1.3E-07 | 1.2E-07 | 7.3E-08 | 5.0E-08 | 4.3E-08 | 4.5E-08 |
| Type F, — NB: Type F should not be assumed without evidence | 1.9E-07 | 1.6E-07 | 7.6E-08 | 4.9E-08 | 4.6E-08 | 4.3E-08 |
| Type M | 1.4E-07 | 1.3E-07 | 6.6E-08 | 4.4E-08 | 3.9E-08 | 3.8E-08 |
| Type S, Irradiated fuel fragments | 1.7E-07 | 1.6E-07 | 1.1E-07 | 8.4E-08 | 8.2E-08 | 8.7E-08 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 1.1E-08 | 2.7E-09 | 1.5E-09 | 1.1E-09 | 7.7E-10 | 7.2E-10 |

Table 8.5. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 155Eu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 2.0E-08 | 1.7E-08 | 8.3E-09 | 5.0E-09 | 4.2E-09 | 3.9E-09 |
| Dioxide | 1.8E-08 | 1.7E-08 | 9.4E-09 | 6.1E-09 | 5.0E-09 | 4.9E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 2.3E-08 | 1.9E-08 | 7.7E-09 | 4.4E-09 | 3.8E-09 | 3.4E-09 |
| Type M | 1.9E-08 | 1.6E-08 | 7.6E-09 | 4.6E-09 | 3.9E-09 | 3.6E-09 |
| Type S, Irradiated fuel fragments | 2.2E-08 | 2.0E-08 | 1.3E-08 | 8.6E-09 | 7.4E-09 | 7.6E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 1.1E-09 | 1.9E-10 | 9.5E-11 | 6.5E-11 | 4.7E-11 | 4.4E-11 |

# Gadolinium (Z = 64)

## Routes of Intake

### Inhalation

1. Information on absorption from the respiratory tract is available from experimental studies of gadolinium (Gd) as chloride, citrate and oxide, including one volunteer experiment. For details see Section 10 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including gadolinium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For gadolinium, Section 10 of *Publication 141* reported results of animal studies showing fractional absorption from 7.6 × 10-5 to 2 × 10-4. The value of *f*A = 5 × 10–4 is adopted here for intakes of gadolinium by adult members of the public.
2. *Children*. The age-dependency of gadolinium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for gadolinium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of the database

1. The biokinetics of 153Gd was studied in human subjects following inhalation and intravenous injection (Shutt et al., 2002; Shutt and Etherington, 2003). The early distribution, retention, and excretion are consistent with the observed systemic behaviour of gadolinium in rats (Ando et al., 1989; Durbin, 1959). For example, the human data indicate relatively low uptake by the liver (~15% of the injected amount), relatively high urinary excretion, and relatively low faecal excretion. External measurements indicated that about one-fourth of the injected amount was excreted over the first 3 weeks, and 5–10% was excreted during the next 7–8 months.
2. Zalikin (1974) investigated the biokinetics of 153Gd in female rats following intravenous or intratracheal administration. Most of the injected activity accumulated in the liver (~42%) and skeleton (~32%). Liver retention represented about 15% of the administered amount at 8 d and 1.5% at 64 d. The skeleton accumulated activity more slowly than the liver but released the activity much more slowly than the liver. The maximum skeletal content was about 47% of the injected amount at 4 d. The skeletal content declined to about 41% at 64 d and 35% at 256 d. The kidneys contained about 6.5% of the injected amount at 6 h, 4.8% at 1 d, 2.5% at 8 d, 1.6% at 16 d, and 0.5% at 256 d.
3. No information was found regarding the effect of age on the biokinetics of systemic gadolinium.
   * + 1. Systemic model
4. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
5. As for all lanthanide elements, the transfer coefficients for gadolinium are based largely on generic parameter values, i.e., parameter values assumed to be invariant across the lanthanide family. The generic parameter values are listed in the section on cerium. The generic parameter values are assumed here to be invariant with age except for the following:

* The rate of transfer from trabecular bone surface to trabecular bone volume is assumed to be A times the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from cortical bone surface to cortical bone volume is assumed to be 0.5 times the reference age-specific rate of remodeling of cortical bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from trabecular bone surface or volume to trabecular marrow is assumed to be the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002).
* The rate of transfer from cortical bone surface or volume to cortical marrow is assumed to be the reference age-specific rate of remodeling of cortical bone (ICRP, 2002).

1. For each lanthanide element, non-generic (element- or group-specific) parameter values are assigned to:

* the deposition fractions for liver, bone surface, urinary bladder content, right colon content, and intermediate-term soft tissue compartment (ST1 in Fig 3.1)
* removal half-times from ST1 to blood and from the long-term liver compartment Liver 2 to blood

1. Extension of the non-generic parameter values for adults to preadult ages is based on a general pattern of age related systemic biokinetics observed for a number of bone-seeking elements including the lanthanide cerium. That is, the deposition fraction in bone is higher in immature animals than in mature animals and tends to decrease with age from early life to adolescence to adulthood. Also, biokinetic studies of bone-seeking elements show that the rate of turnover of the skeletal deposit is higher in immature than mature animals, presumably due to a faster rate of bone restructuring at younger ages.
2. Based on analogy with the most extensively studied lanthanide cerium, a bone deposition fraction of 0.7 is assigned to ages 100 d and 1 y for all lanthanide elements. For ages 5–15 y, the assigned deposition fraction is a rounded average of the value for the first year of life and the element- or group-dependent bone deposition fraction for adults, which is 0.45 for gadolinium. The deposition fraction 0.55 is assigned to the gadolinium for ages 5–15 y. In contrast to the models for relatively light lanthanides, the elevated uptake of gadolinium by the skeleton at preadult ages is not balanced entirely by reducing the deposition fraction assigned to the adult liver, because the latter value for gadolinium (0.15) is too small to accommodate this assumption for the youngest ages. Rather, the increased uptake of gadolinium by bone in preadults is balanced by decreases in the deposition fractions for liver, the intermediate soft-tissue compartment ST1 (~0.15 for gadolinium in adults), and the urinary bladder content (0.2 for gadolinium in adults). The age-adjusted deposition fractions for each age are liberally rounded in view of the sizable uncertainties involved.
3. The non-generic deposition fractions in the model for gadolinium are listed inTable 9.1.

Table 9.1. Non-generic parameter values for gadolinium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
|  | Deposition (% of activity leaving the circulation) | | | | | |
| Liver | 5 | 5 | 10 | 10 | 10 | 15 |
| Bone | 70 | 70 | 55 | 55 | 55 | 45 |
| ST1 | 10 | 10 | 15 | 15 | 15 | 15 |
| UB content | 10 | 10 | 15 | 15 | 15 | 20 |
| RC content | 1 | 1 | 1 | 1 | 1 | 1 |
|  |  |  |  |  |  |  |
|  | Removal half-time | | | | | |
| ST1 to Blood | 100 d | 100 d | 100 d | 100 d | 100 d | 100 d |
| Liver 2 to Blood | 1 y | 1 y | 1 y | 1 y | 1 y | 1 y |

1. The behaviour of gadolinium in bone is assumed to follow the generic skeletal model for bone-surface-seeking radionuclides. That is, activity deposited on bone surface is transferred to bone marrow and bone volume at reference rates based on the age-specific rate of bone turnover. Activity in bone volume is transferred to bone marrow at the rate of bone turnover. Activity is lost from bone marrow to blood with a half-time of 0.25 y and is subsequently redistributed to tissues and excretion pathways based on age-specific deposition fractions.
2. Table 9.2. lists the full set of transfer coefficients in the age-specific model for the gadolinium.

Table 9.2. Age-specific transfer coefficients for gadolinium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 1.16E+00 | 1.16E+00 | 2.33E+00 | 2.33E+00 | 2.33E+00 | 5.82E+00 |
| Blood to ST0 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 |
| Blood to ST1 | 2.33E+00 | 2.33E+00 | 3.48E+00 | 3.48E+00 | 3.48E+00 | 3.48E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 6.41E+00 | 6.41E+00 | 6.41E+00 | 5.24E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 6.41E+00 | 6.41E+00 | 6.41E+00 | 5.24E+00 |
| Blood to Kidneys 1 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 |
| Blood to RC content | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Kidneys 2 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.15E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.56E-03 |
| Blood to UB content | 2.33E+00 | 2.33E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 4.66E+00 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| Liver 1 to SI content | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 |
| Liver 1 to Liver 2 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to UB content | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, RC = Right colon, SI = Small intestine, UB = Urinary bladder

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of gadolinium is described in Section 10.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for gadolinium

Table 9.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 153Gd compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 8.5E-09 | 6.7E-09 | 3.1E-09 | 1.9E-09 | 1.5E-09 | 1.4E-09 |
| Dioxide | 8.2E-09 | 7.2E-09 | 4.0E-09 | 2.6E-09 | 2.0E-09 | 2.0E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 8.9E-09 | 6.3E-09 | 2.3E-09 | 1.2E-09 | 1.0E-09 | 8.5E-10 |
| Type M | 8.0E-09 | 6.5E-09 | 3.1E-09 | 1.9E-09 | 1.5E-09 | 1.4E-09 |
| Type S, Irradiated fuel fragments | 8.5E-09 | 7.6E-09 | 4.4E-09 | 2.9E-09 | 2.2E-09 | 2.3E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 6.5E-10 | 2.7E-10 | 1.5E-10 | 1.0E-10 | 7.1E-11 | 7.0E-11 |

# Terbium (Z = 65)

## Routes of Intake

### Inhalation

1. Information on absorption from the respiratory tract is available from experimental studies of terbium as oxide, including one volunteer experiment. For details see Section 11 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including terbium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019) information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For terbium, Section 11 of *Publication 141* reported results of animal studies showing fractional absorption to be less than 10-3. The value of *f*A = 5 × 10–4 is adopted here for intakes of terbium by adult members of the public.
2. *Children*. The age-dependency of terbium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for terbium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At day 4 after intramuscular injection about 60% of the activity entering blood was contained in bone and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine and faeces through day 4 amounted to 16–27% and 5–13%, respectively, of the amount reaching blood (Durbin, 1959, 1962).
2. Newton (2003) studied the whole-body retention, distribution, and urinary and faecal excretion of 160Tb in four healthy men following acute inhalation of 160Tb-labelled terbium oxide particles. Within a year after exposure most of the retained activity had become systemic, with the principal deposit in bone. Measurements of total-body retention after 1 y suggested a clearance half-time on the order of 5 y.
3. Zalikin and Tronova (1971) investigated the biokinetics of terbium in rats following intravenous injection of 160Tb in chloride or citrate solutions and 161Tb in a chloride solution. Activity accumulated rapidly in the liver and more slowly in the skeleton. The maximum liver content was 26% of the administered amount at 6 h. Thereafter the liver content gradually declined to about 0.3% at 64 d. The skeletal content gradually increased to a maximum of about 40% by the second day and remained at that level throughout the 64–d period of observation. A relatively high activity concentration was also observed in the kidneys, which contained about 5.0% of the administered amount at 6 h, 2.7% at 1 d, 1.8% at 8 d, and 0.5% at 64 d.
4. No information was found regarding the effect of age on the biokinetics of systemic neodymium.
   * + 1. Systemic model
5. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
6. A common set of age-specific transfer coefficients is applied to the “holmium group”, consisting of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Transfer coefficients for the holmium group are listed in Table 12.2 of the section on holmium.
   * + 1. Treatment of radioactive progeny
7. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of terbium is described in Section 11.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for terbium

Table 10.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 160Tb compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 2.2E-08 | 1.7E-08 | 8.3E-09 | 5.1E-09 | 4.0E-09 | 3.8E-09 |
| Dioxide | 2.3E-08 | 1.9E-08 | 1.1E-08 | 7.3E-09 | 5.6E-09 | 5.7E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 2.2E-08 | 1.5E-08 | 5.9E-09 | 3.1E-09 | 2.6E-09 | 2.0E-09 |
| Type M | 2.2E-08 | 1.8E-08 | 8.9E-09 | 5.7E-09 | 4.4E-09 | 4.3E-09 |
| Type S, Irradiated fuel fragments | 2.3E-08 | 2.0E-08 | 1.1E-08 | 7.6E-09 | 5.8E-09 | 6.0E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.9E-09 | 1.9E-09 | 1.1E-09 | 7.7E-10 | 5.3E-10 | 4.9E-10 |

# Dysprosium (Z = 66)

## Routes of Intake

### Inhalation

1. No reports were found of experimental studies on the behaviour of dysprosium following deposition in the respiratory tract. Absorption parameter values based on cerium are applied in this document to the other lanthanides, including dysprosium. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including dysprosium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. The value of *f*A = 5 × 10–4 is therefore used here for intakes of dysprosium by adult members of the public.
2. *Children.* The age-dependency of dysprosium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for dysprosium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At day 4 after intramuscular injection about 60% of the activity entering blood was contained in bone and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine and faeces through day 4 amounted to 16–27% and 5–13%, respectively, of the amount reaching blood (Durbin, 1959, 1962).
2. No information was found regarding the effect of age on the biokinetics of systemic neodymium.
   * + 1. Systemic model
3. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
4. A common set of age-specific transfer coefficients is applied to the “holmium group”, consisting of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Transfer coefficients for the holmium group are listed in Table 12.2 of the section on holmium.
   * + 1. Treatment of radioactive progeny
5. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of dysprosium is described in Section 12.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for dysprosium

Table 11.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 159Dy compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 2.2E-09 | 1.7E-09 | 7.7E-10 | 4.7E-10 | 3.6E-10 | 3.4E-10 |
| Dioxide | 2.1E-09 | 1.8E-09 | 9.8E-10 | 6.5E-10 | 4.8E-10 | 5.0E-10 |
| Type F, — NB: Type F should not be assumed without evidence | 2.4E-09 | 1.6E-09 | 5.9E-10 | 3.1E-10 | 2.5E-10 | 2.1E-10 |
| Type M | 2.1E-09 | 1.6E-09 | 7.7E-10 | 4.8E-10 | 3.6E-10 | 3.5E-10 |
| Type S, Irradiated fuel fragments | 2.1E-09 | 1.9E-09 | 1.0E-09 | 6.9E-10 | 5.2E-10 | 5.4E-10 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.4E-10 | 1.4E-10 | 7.4E-11 | 5.3E-11 | 3.6E-11 | 3.5E-11 |

# Holmium (Z = 67)

## Routes of Intake

### Inhalation

1. No reports were found of experimental studies on the behaviour of holmium following deposition in the respiratory tract. Absorption parameter values based on cerium are applied in this document to the other lanthanides, including holmium. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including holmium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. The value of *f*A = 5 × 10–4 is therefore used here for intakes of holmium by adult members of the public.
2. *Children*. The age-dependency of holmium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for holmium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At day 4 after intramuscular injection about 60% of the activity entering blood was contained in bone and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine and faeces through day 4 amounted to 16–27% and 5–13%, respectively, of the amount reaching blood (Durbin, 1959, 1962).
2. Holmium and the rare earth element yttrium are referred to as geochemical twins because they generally show little fractionation in geological material from metamorphic or weathering processes, due to their closely similar chemical properties and nearly identical ionic radii (Pack et al., 2007; Qu et al., 2009). Measurements on rocks, soils, and meteorites indicate that the Y/Ho mass concentration ratio rarely falls far from the so-called chondritic ratio of ~26. Leggett (2017) reviewed data on the relation of holmium and yttrium in plants and human tissues to assess whether these elements are also closely related in biological systems. The assessment included model-based comparisons of their systemic behaviours in adult humans and model-free comparisons of their concentration ratios in human tissues and various types of vegetation. It was concluded that holmium and yttrium behave similarly in the human body and that their concentration ratios tend to cluster near the chondritic value in human tissues as well as plants. The results of the study provide support for the model for holmium used in this report, at least for adults, because it is consistent with the systemic behaviour of yttrium observed in a controlled study involving healthy adult human subjects (Etherington et al., 1989a, 1989b).
3. No information was found regarding the effect of age on the biokinetics of systemic holmium.
   * + 1. Systemic model
4. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
5. A common set of age-specific transfer coefficients is applied to the “holmium group”, which consists of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. The transfer coefficients are based largely on generic parameter values for the lanthanides, i.e., parameter values assumed to be invariant across the lanthanide family. The generic parameter values are listed in the section on cerium. The generic parameter values are assumed to be invariant with age except for the following:

* The rate of transfer from trabecular bone surface to trabecular bone volume is assumed to be A times the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from cortical bone surface to cortical bone volume is assumed to be 0.5 times the reference age-specific rate of remodeling of cortical bone (ICRP, 2002), where A = 0.5 for adults and A = 1 for preadult ages.
* The rate of transfer from trabecular bone surface or volume to trabecular marrow is assumed to be the reference age-specific rate of remodeling of trabecular bone (ICRP, 2002).
* The rate of transfer from cortical bone surface or volume to cortical marrow is assumed to be the reference age-specific rate of remodeling of cortical bone (ICRP, 2002).

1. For each lanthanide element, non-generic (element- or group-specific) parameter values are assigned here to:

* the deposition fractions for liver, bone surface, urinary bladder content, right colon content, and intermediate-term soft tissue compartment (ST1)
* removal half-times from ST1 to blood and from the long-term liver compartment Liver 2 to blood.

1. Extension of the non-generic parameter values for adults to preadult ages is based on a general pattern of age related systemic biokinetics observed for a number of bone-seeking elements including the lanthanide cerium. That is, the deposition fraction in bone is higher in immature animals than in mature animals and tends to decrease with age from early life to adolescence to adulthood. Also, biokinetic studies of bone-seeking elements show that the rate of turnover of the skeletal deposit is higher in immature than mature animals, presumably due to a faster rate of bone restructuring at younger ages.
2. Based on analogy with the most extensively studied lanthanide cerium, a bone deposition fraction of 0.7 is assigned to ages 100 d and 1 y for all lanthanide elements. For ages 5–15 y, the assigned deposition fraction is a rounded average of the value 0.7 for the first year of life and the element- or group-dependent bone deposition fraction for adults, which is 0.55 for the holmium group. The deposition fraction 0.6 is assigned to the holmium group for ages 5–15 y. In contrast to the models for relatively light lanthanides, the elevated skeletal uptake of elements in holmium group cannot be balanced by reducing the deposition fraction for the adult liver, because the latter value is only 0.05 for this group. Rather, the increased skeletal uptake in preadults is balanced by decreasing the relatively large deposition fractions for the intermediate soft-tissue compartment ST1 (~0.15 for adults), and the urinary bladder content (0.2 for adults). The age-adjusted deposition fractions for each age are liberally rounded in view of the sizable uncertainties involved.
3. The non-generic deposition fractions in the model for the holmium group are listed in Table 12.1.

Table 12.1. Non-generic (group-specific) parameter values for the holmium group (terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
|  | Deposition (% of activity leaving the circulation) | | | | | |
| Liver | 5 | 5 | 5 | 5 | 5 | 5 |
| Bone | 70 | 70 | 60 | 60 | 60 | 55 |
| ST1 | 10 | 10 | 15 | 15 | 15 | 15 |
| UB content | 10 | 10 | 15 | 15 | 15 | 20 |
| RC content | 1 | 1 | 1 | 1 | 1 | 1 |
|  |  |  |  |  |  |  |
|  | Removal half-time | | | | | |
| ST1 to Blood | 100 d | 100 d | 100 d | 100 d | 100 d | 100 d |
| Liver 2 to Blood | 1 y | 1 y | 1 y | 1 y | 1 y | 1 y |

1. The behaviour of the holmium group in bone is assumed to follow the generic skeletal model for bone-surface-seeking radionuclides. That is, activity deposited on bone surface is transferred to bone marrow and bone volume at reference rates based on the age-specific rate of bone turnover. Activity in bone volume is transferred to bone marrow at the rate of bone turnover. Activity is lost from bone marrow to blood with a half-time of 0.25 y and is subsequently redistributed to tissues and excretion pathways based on age-specific deposition fractions.
2. Table 12.2 lists the full set of transfer coefficients in the age-specific model for the holmium group.

Table 12.2. Age-specific transfer coefficients for the holmium group (terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 1.16E+00 | 1.16E+00 | 1.16E+00 | 1.16E+00 | 1.16E+00 | 1.16E+00 |
| Blood to ST0 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 | 9.98E+00 |
| Blood to ST1 | 2.33E+00 | 2.33E+00 | 3.48E+00 | 3.48E+00 | 3.48E+00 | 3.48E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 6.99E+00 | 6.99E+00 | 6.99E+00 | 6.41E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 6.99E+00 | 6.99E+00 | 6.99E+00 | 6.41E+00 |
| Blood to Kidneys 1 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 | 3.49E-01 |
| Blood to RC content | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Kidneys 2 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 | 1.17E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.15E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.56E-03 |
| Blood to UB content | 2.33E+00 | 2.33E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 4.66E+00 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| Liver 1 to SI content | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 | 2.31E-03 |
| Liver 1 to Liver 2 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 | 2.08E-02 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 | 1.28E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to UB content | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, RC = Right colon, SI = Small intestine, UB = Urinary bladder

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of holmium is described in Section 13.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for holmium

Table 12.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 166Ho compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 2.0E-09 | 1.5E-09 | 7.4E-10 | 5.2E-10 | 3.7E-10 | 3.2E-10 |
| Dioxide | 2.2E-09 | 1.6E-09 | 8.6E-10 | 6.0E-10 | 4.4E-10 | 3.9E-10 |
| Type F, — NB: Type F should not be assumed without evidence | 1.8E-09 | 1.3E-09 | 6.2E-10 | 4.3E-10 | 3.0E-10 | 2.4E-10 |
| Type M | 2.1E-09 | 1.6E-09 | 8.1E-10 | 5.7E-10 | 4.1E-10 | 3.6E-10 |
| Type S, Irradiated fuel fragments | 2.2E-09 | 1.6E-09 | 8.6E-10 | 6.0E-10 | 4.3E-10 | 3.9E-10 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 1.6E-09 | 1.3E-09 | 8.0E-10 | 5.7E-10 | 3.6E-10 | 3.0E-10 |

# Erbium (Z = 68)

## Routes of Intake

### Inhalation

1. No reports were found of experimental studies on the behaviour of erbium following deposition in the respiratory tract. Absorption parameter values based on cerium are applied in this document to the other lanthanides, including erbium. Absorption parameter values and Types, and associated *f*A values for particulate forms of erbium are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. The value of *f*A = 5 × 10–4 is therefore used here for intakes of erbium by adult members of the public.
2. *Children*. The age-dependency of erbium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for erbium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At day 4 after intramuscular injection about 60% of the activity entering blood was contained in bone and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine and faeces through day 4 amounted to 16–27% and 5–13%, respectively, of the amount reaching blood (Durbin, 1959, 1962)).
2. No information was found regarding the effect of age on the biokinetics of systemic erbium.
   * + 1. Systemic model
3. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
4. A common set of age-specific transfer coefficients is applied to the “holmium group”, consisting of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Transfer coefficients for the holmium group are listed in Table 12.2 of the section on holmium.
   * + 1. Treatment of radioactive progeny
5. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of erbium is described in Section 14.2.3.3. of *Publication 141* (ICRP, 2019)

## Dosimetric data for erbium

Table 13.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 169Er compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.3E-09 | 1.0E-09 | 5.4E-10 | 3.5E-10 | 2.9E-10 | 2.5E-10 |
| Dioxide | 1.8E-09 | 1.3E-09 | 7.9E-10 | 5.2E-10 | 4.3E-10 | 3.9E-10 |
| Type F, — NB: Type F should not be assumed without evidence | 9.3E-10 | 6.7E-10 | 3.0E-10 | 1.7E-10 | 1.5E-10 | 1.1E-10 |
| Type M | 1.6E-09 | 1.2E-09 | 6.8E-10 | 4.4E-10 | 3.7E-10 | 3.3E-10 |
| Type S, Irradiated fuel fragments | 1.8E-09 | 1.3E-09 | 7.9E-10 | 5.2E-10 | 4.3E-10 | 3.9E-10 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 7.9E-11 | 4.6E-11 | 3.0E-11 | 2.1E-11 | 1.4E-11 | 8.4E-12 |

# Thulium (Z = 69)

## Routes of Intake

Inhalation

1. Studies were found on the behaviour of thulium radioisotopes in humans following accidental inhalation. Information on absorption from the respiratory tract is available from experimental studies of thulium as oxide. For details see Section 15 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including thulium, are given in Table 2.1 and Table 2.2 of the lanthanum Section

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For thulium, Section 15 of *Publication 141* reported results of animal studies showing fractional absorption to be less than 10-3. The value of *f*A = 5 × 10–4 is adopted here for intakes of thulium by adult members of the public.
2. *Children*. The age-dependency of thulium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for thulium..

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At 4 d after intramuscular injection, about 60% of the activity entering blood was contained in bone, and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine through day 4 amounted to roughly 20% of the amount reaching blood.
2. No information was found regarding the effect of age on the biokinetics of systemic thulium.
   * + 1. Systemic model
3. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
4. A common set of age-specific transfer coefficients is applied to the “holmium group”, consisting of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Transfer coefficients for the holmium group are listed in Table 12.2 of the section on holmium.
   * + 1. Treatment of radioactive progeny

The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of thulium is described in Section 15.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for thulium

Table 14.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 171Tm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 4.8E-09 | 4.0E-09 | 1.8E-09 | 1.0E-09 | 8.3E-10 | 6.9E-10 |
| Dioxide | 4.5E-09 | 4.0E-09 | 2.2E-09 | 1.4E-09 | 1.1E-09 | 1.0E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 5.1E-09 | 4.0E-09 | 1.5E-09 | 7.4E-10 | 6.6E-10 | 4.7E-10 |
| Type M | 4.4E-09 | 3.7E-09 | 1.7E-09 | 9.6E-10 | 7.9E-10 | 6.5E-10 |
| Type S, Irradiated fuel fragments | 4.9E-09 | 4.5E-09 | 2.6E-09 | 1.7E-09 | 1.3E-09 | 1.3E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.3E-10 | 1.8E-11 | 6.9E-12 | 3.6E-12 | 2.8E-12 | 2.0E-12 |

# Ytterbium (Z = 70)

## Routes of Intake

### Inhalation

1. Information on absorption from the respiratory tract is available from experimental studies of ytterbium, in water-soluble form and as oxide. Ytterbium-169 (half-life 32 d) has often been used as a gamma-emitting label for relatively insoluble particles (plutonium oxide, fused aluminosilicate) in inhalation experiments. For details see Section 16 of *Publication 141* (ICRP, 2019). Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including ytterbium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. For ytterbium, Moskalev et al. (1974) reported fractional absorption from the gastrointestinal tract of rats to be less than 5 × 10-4. The value of *f*A = 5 × 10–4 is adopted here for intakes of ytterbium by adult members of the public.
2. *Children*. The age-dependency of ytterbium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for ytterbium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At 4 d after intramuscular injection, about 60% of the activity entering blood was contained in bone, and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine through day 4 amounted to roughly 20% of the amount reaching blood.
2. No information was found regarding the effect of age on the biokinetics of systemic ytterbium.
   * + 1. Systemic model
3. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
4. A common set of age-specific transfer coefficients is applied to the “holmium group”, consisting of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Transfer coefficients for the holmium group are listed in Table 12.2 of the section on holmium.
   * + 1. Treatment of radioactive progeny
5. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of ytterbium is described in Section 16.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for ytterbium

Table 15.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 169Yb compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 6.3E-09 | 4.7E-09 | 2.4E-09 | 1.5E-09 | 1.2E-09 | 1.1E-09 |
| Dioxide | 7.3E-09 | 5.9E-09 | 3.4E-09 | 2.2E-09 | 1.7E-09 | 1.7E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 5.3E-09 | 3.6E-09 | 1.5E-09 | 8.1E-10 | 6.7E-10 | 5.3E-10 |
| Type M | 6.7E-09 | 5.2E-09 | 2.8E-09 | 1.8E-09 | 1.4E-09 | 1.4E-09 |
| Type S, Irradiated fuel fragments | 7.4E-09 | 6.0E-09 | 3.4E-09 | 2.3E-09 | 1.8E-09 | 1.7E-09 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 8.4E-10 | 6.2E-10 | 3.5E-10 | 2.5E-10 | 1.7E-10 | 1.7E-10 |

# Lutetium (Z = 71)

## Routes of Intake

### Inhalation

1. No reports of experimental studies of lutetium were found. Absorption parameter values based on cerium are applied in this document to the other lanthanides. Absorption parameter values and Types, and associated *f*A values for particulate forms of lanthanides, including lutetium, are given in Table 2.1 and Table 2.2 of the lanthanum Section.

### Ingestion

1. *Adults*. In Section 2 of *Publication 141* (ICRP, 2019), information relating to the gastrointestinal absorption of different lanthanide elements was compared. Their fractional absorption was found to be below 10-3 in most cases and a *f*A value 5 × 10–4 was adopted for all lanthanides as a reasonably representative value based on experimental results. The value of *f*A = 5 × 10–4 is therefore used here for intakes of lutetium by adult members of the public.
2. *Children*. The age-dependency of lutetium absorption was not observed. On the basis of the chemical analogy with cerium, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for lutetium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The lanthanides terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium showed similar biokinetics in rats (Ando et al., 1989; Durbin, 1959, 1962; Moskalev et al., 1974). At 4 d after intramuscular injection, about 60% of the activity entering blood was contained in bone, and 1–7% was contained in the liver (Durbin, 1959, 1962). Cumulative loss in urine through day 4 amounted to roughly 20% of the amount reaching blood.
2. No information was found regarding the effect of age on the biokinetics of systemic lutetium.
   * + 1. Systemic model
3. The model structure shown in Fig 3.1 of the section on cerium is applied in this report to all lanthanide elements.
4. A common set of age-specific transfer coefficients is applied to the “holmium group”, consisting of the lanthanide elements terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Transfer coefficients for the holmium group are listed in Table 12.2 of the section on holmium.
   * + 1. Treatment of radioactive progeny
5. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of lutetium is described in Section 17.2.3.3. of *Publication 141* (ICRP, 2019).

## Dosimetric data for lutetium

Table 16.1. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 177Lu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride and citrate | 1.5E-09 | 1.2E-09 | 6.2E-10 | 4.0E-10 | 3.3E-10 | 2.9E-10 |
| Dioxide | 2.0E-09 | 1.5E-09 | 8.8E-10 | 5.9E-10 | 4.8E-10 | 4.4E-10 |
| Type F, — NB: Type F should not be assumed without evidence | 1.1E-09 | 7.9E-10 | 3.7E-10 | 2.2E-10 | 1.9E-10 | 1.4E-10 |
| Type M | 1.8E-09 | 1.3E-09 | 7.6E-10 | 5.1E-10 | 4.2E-10 | 3.7E-10 |
| Type S, Irradiated fuel fragments | 2.0E-09 | 1.5E-09 | 8.8E-10 | 5.9E-10 | 4.8E-10 | 4.4E-10 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.1E-10 | 1.6E-10 | 9.9E-11 | 7.1E-11 | 4.7E-11 | 3.5E-11 |

# Actinium (Z=89)

## Routes of Intake

### Inhalation

1. Two studies were found in the literature relating to lung retention of actinium (Ac) in humans following accidental intakes. No experimental studies were found that give information on absorption of actinium from the respiratory tract. For details see Section 19 of *Publication 141* (ICRP, 2019). As noted in Section 18 of *Publication 141*, the general actinide Section, in the absence of relevant information, absorption parameter values for actinium are based on chemical analogy: values chosen for americium (Section 23 of *Publication 141*) are applied in this document to actinium. Absorption parameter values and Types, and associated *f*A values for particulate forms of actinium are given in Table 17.1 (taken from Section 19 of *Publication 141* (ICRP, 2019).

Table 17.1. Absorption parameter values for inhaled and ingested actinium

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | | Absorption parameter values\* | | | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | | *s*r (d–1) | | | *s*s (d–1) | |
| Default parameter values‡ | | | | |  | | |  | | |  | |  | |
| Absorption Type | | | Assigned forms | |  | | |  | | |  | |  | |
| F | | | Citrate | | 1 | | | 0.4 | | | – | | 5 × 10–4 | |
| M§ | | | Chloride, oxide | | 0.2 | | | 0.4 | | | 0.005 | | 1 × 10–4 | |
| S | | | Actinium associated with plutonium oxide compounds | | 0.01 | | | 0.4 | | | 1 × 10–4 | | 5 × 10–6 | |
|  |  | | | |  | |  | | |  | | |  | |
| Ingested material¶ | | | | |  | |  | | |  | | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | | |
| 3 mo | | 1 y | | 5 y | | | 10 y | | | 15 y | | adult |
| All chemical forms | | 5 × 10–3 | | 5 × 10–4 | | 5 × 10–4 | | | 5 × 10–4 | | | 5 × 10–4 | | 5 × 10–4 |

\*It is assumed that for actinium a bound fraction *f*b = 0.002 with an uptake rate *s*b = 0 d–1 is applied throughout the respiratory tract, except in the ET1 region. The values of *s*r for Type F, M and S forms of actinium (1 d–1) are element-specific.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of actinium applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

‡Materials (e.g.chloride) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see Section 23 of *Publication 141* (ICRP, 2019)

§Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

¶Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

### Ingestion

1. *Adults.* Early studies by Hamilton (1948) and by Campbell et al. (1956) indicated that the fractional absorption of actinium in rats is considerably less than 0.01. In *Publications* *30* (ICRP, 1981) and *48* (ICRP, 1986) an absorption fraction of 1 × 10-3 was recommended for actinium. In *Publication 141* (ICRP, 2019), on the basis of results showing similar low levels of absorption in humans for five actinide elements (thorium, neptunium, plutonium, americium and curium) and taking account of animal data showing variations in *f*A values resulting from differences in chemical forms, it was considered that an appropriate general *f*A value for all chemical forms of actinides except uranium was 5 × 10-4. The same *f*A = 5 × 10-4 is recommended here for ingestion of actinium by adult members of the public.
2. *Children.* The age-dependency of actinium absorption was not observed. On the basis of the chemical analogy with the other actinides, the same values of *f*A = 0.005 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for actinium as for thorium, neptunium, plutonium, americium and curium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. Biokinetic studies of actinium in rats indicate that its systemic behaviour is generally consistent with the qualitative pattern found for most other actinide elements. That is, 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 body. Its systemic biokinetics appears to be broadly similar to that of americium.
2. Newton and co-workers (Newton, 1968; Newton and Brown, 1974) reported a case of internal exposure to 227Ac and 231Pa through a puncture wound. An estimated 90% of 227Ac reaching the systemic circulation was retained indefinitely. Three years after the accident, activity appeared to be deposited primarily in bone with some involvement of liver. After 9 y most of the liver content apparently had transferred to the skeleton. During the period 1570–2330 d after the incident, daily urinary excretion of the 231Pa/227Ac chain member 223Ra was approximately 60 times greater than that of 231Pa and 150 times greater than that of 227Ac. Daily faecal excretion of 223Ra during that period was about 1300 times that of 231Pa and 2100 times that of 227Ac.
3. Taylor (1970) studied the biokinetics of 227Ac in rats following its intravenous administration in various chemical forms. Similar tissue distributions were observed when 227Ac was administered as a complex with serum proteins, as nitrate, or as citrate. At 4 d 227Ac was found mainly in the liver and skeleton, and the kidneys contained about 1.5% of the administered amount. By 189 d the liver content was less than 1% of the content at 4 d. There was little if any net loss from bone during the period 4–189 d. Over the first week, cumulative urinary and faecal excretion amount to about 1% and 20%, respectively, of the administered activity.
4. Campbell et al. (1956) investigated the behaviour of 227Ac and its progeny 227Th and 223Ra in young adult male rats following administration of 227Ac alone or in equilibrium with its progeny by intravenous, intramuscular, and subcutaneous injection; orally via a stomach tube; or by absorption through the skin. The skeleton accumulated roughly half of intravenously administered 227Ac. It appeared that activity deposited in the skeleton was not removed. Rats injected with 227Ac in equilibrium with its progeny excreted about half of the administered 227Ac in three months. The remaining 50% was tenaciously retained in the body. Actinium-227 deposited in the skeleton was not removed, but 227Ac deposited in soft tissues was readily excreted. Actinium-227 deposited in the skeleton remained in equilibrium with its progeny, but 227Ac deposited in soft tissues was stripped of its progeny.
5. The plasma disappearance pattern of 227Ac following intravenous administration to rats is similar to that of americium and curium in the same animal. Clearance was about 90% complete in 50 min and 99% complete in 400 min (Durbin, 2001). At 4 d after intramuscular administration of 227Ac to rats, the contents of liver, skeleton, other tissues, cumulative urine, and cumulative faeces accounted for 27%, 56%, 4%, 5%, and 8%, respectively, of the administered activity. This is broadly similar to the distributions of Am and Cm in the same animals.
6. No information was found regarding age dependence in the biokinetics of systemic actinium.
   * + 1. Systemic model
7. The systemic model applied in this report to actinium is a slightly modified version of the model for americium described in the americium section. The only difference in the models for actinium and americium is that a non-zero transfer from cortical marrow to cortical bone surface in the americium model is assumed to be specific to americium and its physiological analogue curium and hence is not applied in the actinium model. Rather, actinium depositing in cortical marrow is assumed to transfer to blood with a half-time of 0.25 y, consistent with the generic model for bone-surface-seeking radionuclides.
8. The structure of the systemic model for actinium is shown in Fig 17.1 Parameter values are listed in Table 17.2.

Diagram

Description automatically generated

Fig 17.1. Structure of the systemic model for actinium.

Table 17.2. Age-specific transfer coefficients for actinium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 2.33E+00 | 2.33E+00 | 6.98E+00 | 6.98E+00 | 6.98E+00 | 1.16E+01 |
| Blood to ST0 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 |
| Blood to ST1 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Kidneys 1 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to RC cont | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 |
| Blood to Kidneys 2 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.20E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.60E-03 |
| Blood to Urinary bladder cont | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 |
| Liver 1 to SI cont | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, cont = content, RC = Right colon, SI = Small intestine

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of actinium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for actinium

Table 17.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 228Ac compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type F, Citrate | 4.2E-08 | 3.1E-08 | 1.4E-08 | 6.7E-09 | 5.3E-09 | 3.9E-09 |
| Type M, Chloride, oxide | 3.9E-08 | 3.3E-08 | 1.7E-08 | 9.4E-09 | 7.3E-09 | 6.2E-09 |
| Type S, Actinium associated with plutonium oxide compounds | 5.1E-08 | 4.7E-08 | 2.8E-08 | 1.8E-08 | 1.4E-08 | 1.4E-08 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.6E-09 | 7.4E-10 | 4.3E-10 | 3.0E-10 | 2.0E-10 | 1.6E-10 |

# Thorium (Z = 90)

## Routes of Intake

### Inhalation

1. Information is available on the biokinetic behaviour of thorium after deposition of various chemical forms in the respiratory tract after accidental human exposure, and from experimental studies with animals, mainly rats. For details, see Section 14 of *Publication 137* (ICRP, 2017). Absorption parameter values and Types, and associated *f*A values for particulate forms of thorium are given in Table 18.1 (taken from Section 14 of *Publication 137*).
2. In referring to default types it should be noted that the biokinetic behaviour of thorium is exceptional in that, following deposition of water-soluble forms in the lungs, a minor fraction of the lung deposit is absorbed very rapidly, after which absorption is minimal. This indicates that there are no commonly encountered Type F forms of thorium.

Table 18.1. Absorption parameter values for inhaled and ingested thorium.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | Absorption parameter values\* | | | | | Absorption from the alimentary tract, *f*A† | | |
| *f*r | *s*r (d–1) | | *s*s (d–1) | |
| Specific parameter values‡ | | |  |  | |  | |  | | |
| Water soluble forms, including thorium chloride, citrate, nitrate and sulphate; thorium fluoride§ | | | 0.1 | 50 | | 0.005 | | 5 × 10–5 | | |
|  | | |  |  | |  | |  | | |
| Default parameter values¶ | | |  |  | |  | |  | | |
| Absorption Type | Assigned forms | |  |  | |  | |  | | |
| F | — NB: Type F should not be assumed without evidence | | 1 | 50 | | - | | 5 × 10–4 | | |
| M\*\* | Thorium hydroxide | | 0.2 | 3 | | 0.005 | | 1 × 10–4 | | |
| S†† | Oxide | | 0.01 | 3 | | 1x10-4 | | 5 × 10–6 | | |
|  | | |  |  |  | | |  | | |
| Ingested material‡‡ | | |  |  |  | | |  | | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | |
| 3 mo | 1 y | 5 y | | | 10 y | | 15 y | adult | |
| All chemical forms | | 5 × 10-3 | 5 × 10-4 | 5 × 10-4 | | | 5 × 10-4 | | 5 × 10-4 | 5 × 10-4 | |

\*It is assumed that for thorium the bound state can be neglected, i.e. *f*b = 0.0. The value of *s*r for Type F forms of thorium (50 d–1) is element-specific. The values for Types M and S (3 d–1) are the general default values.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: i.e. the (rounded) product of *f*A for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of thorium applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

‡See Section 14 of *Publication 137* (ICRP, 2017) for summary of information on which parameter values are based, and on ranges of parameter values observed for individual materials. For water soluble forms of thorium specific parameter values are used for dissolution in the lungs, but the default value of *f*A.

§Progeny radionuclides assigned to Type F.

¶Materials (e.g. thorium hydroxide) are listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see Section 14 of *Publication 137*, ICRP 2017).

\*\*Progeny radionuclides assigned to Type M.

††Default Type S is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

‡‡Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

### Ingestion

1. *Adults*. Rodent and human volunteer studies indicated fractional absorption values in a range from 5 × 10-5 to 6 × 10-3 (For more details, see Section 14 of *Publication 137*, ICRP, 2017). Estimates of thorium absorption have also been derived by Johnson and Lamothe (1989) from human data on skeletal content, dietary intake, estimated inhalation rates and excretion data, giving values of less than 0.001 to 0.01. However, these estimates of absorption are uncertain because they are based on balance studies involving disparate data sources. Dang and Sunta (1990) questioned the higher uptake values reported by Johnson and Lamothe (1989) and reinterpreted the data used by them to suggest absorption values of about 0.001–0.002. Their own data for thorium concentrations in tissues, body fluids, and daily diet for urban Indian populations suggested values lower than 0.001. Roth et al. (2005) measured urinary excretion of 232Th in 11 adults who were not occupationally exposed. Comparison with reference intake values suggested that absorption was around 0.005. In *Publication 30* (ICRP, 1979), an absorption fraction of 2 × 10-4 was recommended. In *Publication 69* (ICRP, 1995a), based on chemical similarities, a general absorption value of 5 × 10-4 was recommended for dietary intake by adults for all actinides other than uranium. The same value of *f*A = 5 × 10-4 was recommended in *ICRP Publication 137* (ICRP, 2017) for all chemical forms of thorium. It is also adopted here for dietary intakes of thorium by adults.
2. *Children.*With the exception of an experiment of Sullivan et al. (1983) with neonatal rats giving an absorption fraction of 0.01, there appears to be no age-dependent information available on the gastro-intestinal absorption of thorium. Following the general approach of *Publication 56* (ICRP, 1990), an absorption fraction of 5 × 10-3 was recommended by *Publication 69* for the 3-mo-old infant. The same value of *f*A = 5 × 10-3 is adopted here for infants. For children of 1 y and older the *f*A value for adults of 5 × 10-4 is adopted here.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. Maletskos et al. (1966, 1969) studied the biokinetics of 234Th following its intravenous administration of citrate into normal human subjects in the age range 63–83 y. Thorium initially disappeared from blood with a half‑time of a few hours. As an average, about 10% of the injected amount remained in blood after 1 d, 3% after 2 d, 1.5% after 3 d, and 0.3% after 10 d. Whole‑body retention was greater than 90% of the injected amount at 3 wk after injection. Cumulative urinary excretion represented about 4.5–6% of the injected amount over the first 5 d after injection and an additional 2–3% over the next 19 d. Little activity was lost in faeces during the first five days. The ratio of urinary to faecal excretion over the first five days averaged about 12 for the male subjects and 25 for the female subjects. External measurements indicated virtually no biological removal from the body during the period from 3–16 wk after injection. There appeared to be no elevated accumulation of thorium in the liver compared with other soft tissues.
2. Long‑term measurements of 227Th or 228Th in the bodies and excreta of accidentally exposed workers suggest a minimum biological half‑time of 10–15 y for the total-body content (Newton et al., 1981; Rundo, 1964). Similar measurements on workers chronically exposed to thorium over 1–3 decades (Dang, Jaiswal, et al., 1992) suggest that the rate of removal of the systemic burden to urine was less than 1% y‑1.
3. Autopsy measurements on subjects who had worked for 3–24 y at a thorium refinery several years before death indicated that total thorium activity in bone was about 20 times greater than total activity in the liver based on reference organ masses (Stehney and Lucas, 2000). The 232Th content of the liver averaged roughly 30 times that of the kidneys. In most tissue samples the activity ratios 228Th:232Th and 230Th:232Th were in the ranges 0.2–0.4 and 0.1–0.2, respectively.
4. Measurements of thorium isotopes in autopsy samples from non‑occupationally exposed subjects (Ibrahim et al., 1983; Singh et al., 1983; Wrenn et al., 1981) indicate that the skeleton typically contains more than three‑fourths of the systemic burden during or after chronic exposure to thorium. The reported contents of the liver and kidneys are variable but typically represent about 2–4% and 0.3–1%, respectively, of the systemic burden. These estimates are based on the assumption that muscle, fat, and skin do not accumulate more than 20% of the systemic content, as suggested by data on laboratory animals (Boecker et al., 1963; Larsen et al., 1984; Stover et al., 1960; Thomas et al., 1963; Traikovich, 1970).
5. Stover et al. (1960) studied the biological behaviour of 228Th in adult beagle dogs over a 1300‑d period following its intravenous administration. Biological retention was about 88% of the injected amount at 3 wk, 80–85% at 3 mo, and 65–70% at 2.5 y. The urinary excretion rate was about 4 times the faecal excretion rate in the first few weeks, but the urinary‑to‑faecal excretion ratio gradually decreased and was close to 1 at 2.5 y after injection. About 70%, 5%, and 3% of injected thorium deposited in the skeleton, liver, and kidneys, respectively. At times greater than 100 d after administration, about 80% of retained thorium was in the skeleton and about 20% was widely distributed in soft tissues, with relatively high concentrations in the liver and kidneys. There was little if any decline in the thorium content of compact bone over 1300 d or in trabecular bone over 800 d, but there was a noticeable decline in activity in trabecular bone over 800–1300 d after administration. The thorium content of the liver and kidneys declined considerably in the first several months after injection but showed little or no decrease thereafter. Retention of thorium in the kidneys and its rate of urinary excretion at times remote from injection may have been affected by radiation damage at high dosage levels (Stover et al., 1960).
6. For tracer levels of thorium administered as the citrate to rats, deposition was considerably greater in bone than other systemic tissues (Thomas et al., 1963). Muscle and pelt accounted for about 20% of the systemic activity at 7–54 d post injection.
7. Boecker et al. (1963) found that the level of absorption of thorium to blood and its subsequent pattern of distribution and excretion following acute inhalation by rats did not depend on the initial lung content of inhaled thorium. The absorbed activity was deposited mainly in the skeleton. The liver content at 0–40 d was about 15–20% of the skeletal content, and the kidney content during that time was about 3% of the skeletal content. The content of pelt and muscle plus connective tissue was about the same as liver. The urinary to faecal excretion ratio increased gradually to a value of about 0.6–0.7 at 40–50 d post inhalation.
8. At 3 d after injection of thorium into mice, about 90% of the systemic burden was found in the skeleton, 6% in liver, 4% in kidneys, and 0.1% in reproductive organs (Larsen et al., 1984). A urinary to faecal excretion ratio of 16 was observed. The systemic distribution of thorium was essentially the same after gastrointestinal absorption as after intravenous injection.
9. No useful information was found regarding the effect of age on the biokinetics of systemic thorium. Based on analogy with other bone-seeking elements, the deposition fraction in bone presumably, is greater at preadult ages than in mature adults.
   * + 1. Systemic model
10. The age-specific systemic model for thorium applied in this report is the model used in *Publication 69* (ICRP, 1995a) with the following modification. The removal half-time from gonads to blood is reduced from 10 y to 5 y, the generic value applied here to the lanthanide and actinide elements.
11. The reader is referred to *Publication 69* for a detailed description of the model and the rationale for age-specific parameter values. Briefly, the model for adults is based as far as feasible on data for human subjects summarized above. Data for laboratory animals, primary dogs, are used to fill gaps in the data for adult humans. It is assumed on the basis of observations for other bone-seeking elements that the deposition fraction for bone is higher for preadults than for adults. The deposition fraction for bone for all preadult ages is set at 0.8, compared with 0.7 for adults. Deposition in bone is equally divided between cortical and trabecular bone surface. The adult deposition fractions for soft tissues (including liver and kidneys) and excretion pathways are reduced by one-third for pre-adult ages to balance the increase in deposition in bone.
12. The structure of the systemic model for thorium is shown in Fig 18.1. Parameter values are listed in Table 18.2.

Diagram

Description automatically generated

Fig 18.1. Structure of the systemic model for thorium.

Table 18.2. Age-specific transfer coefficients for thorium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 9.70E-02 |
| Blood to Cort bone surf | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 6.79E-01 |
| Blood to Trab bone surf | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 6.79E-01 |
| Blood to Urinary bladder cont | 7.11E-02 | 7.11E-02 | 7.11E-02 | 7.11E-02 | 7.11E-02 | 1.07E-01 |
| Blood to Kidneys 1 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 6.79E-02 |
| Blood to Kidneys 2 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.94E-02 |
| Blood to Right colon cont | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 9.70E-03 |
| Blood to Testes | 3.90E-05 | 5.80E-05 | 6.60E-05 | 7.70E-05 | 6.20E-04 | 6.80E-04 |
| Blood to Ovaries | 2.30E-05 | 3.00E-05 | 7.60E-05 | 1.30E-04 | 2.30E-04 | 2.10E-04 |
| Blood to ST0 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 |
| Blood to ST1 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 2.43E-01 |
| Blood to ST2 | 2.59E-02 | 2.59E-02 | 2.59E-02 | 2.59E-02 | 2.59E-02 | 3.88E-02 |
| Liver 1 to Blood | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 |
| Liver 1 to Liver 2 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 |
| Liver 1 to SI cont | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Kidneys 1 to UB cont | 4.62E-02 | 4.62E-02 | 4.62E-02 | 4.62E-02 | 4.62E-02 | 4.62E-02 |
| Kidneys 2 to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| ST0 to Blood | 4.62E-01 | 4.62E-01 | 4.62E-01 | 4.62E-01 | 4.62E-01 | 4.62E-01 |
| ST1 to Blood | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Liver 2 to Blood | 2.11E-04 | 2.11E-04 | 2.11E-04 | 2.11E-04 | 2.11E-04 | 2.11E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, cont = content, SI = Small intestine

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of thorium is described in Section 14.2.3.3. of *Publication 137* (ICRP, 2017).

## Dosimetric data for thorium

Table 18.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 229Th compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate | 2.1E-04 | 2.0E-04 | 1.1E-04 | 7.1E-05 | 5.9E-05 | 5.4E-05 |
| Type F, — NB: Type F should not be assumed without evidence | 5.3E-04 | 4.5E-04 | 2.3E-04 | 1.5E-04 | 1.1E-04 | 1.0E-04 |
| Type M, hydroxide | 1.9E-04 | 1.8E-04 | 1.0E-04 | 6.6E-05 | 5.6E-05 | 5.1E-05 |
| Type S, oxide | 3.4E-04 | 3.4E-04 | 2.5E-04 | 1.8E-04 | 1.8E-04 | 1.8E-04 |
| Ingested materials |  |  |  |  |  |  |
| All forms | 1.1E-05 | 8.9E-07 | 5.0E-07 | 3.2E-07 | 2.5E-07 | 2.1E-07 |

Table 18.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 230Th compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate | 5.0E-05 | 4.6E-05 | 2.7E-05 | 1.8E-05 | 1.6E-05 | 1.5E-05 |
| Type F, — NB: Type F should not be assumed without evidence | 1.3E-04 | 1.1E-04 | 5.9E-05 | 3.9E-05 | 3.2E-05 | 2.8E-05 |
| Type M, hydroxide | 4.6E-05 | 4.2E-05 | 2.5E-05 | 1.7E-05 | 1.5E-05 | 1.4E-05 |
| Type S, oxide | 5.5E-05 | 5.4E-05 | 3.8E-05 | 2.8E-05 | 2.7E-05 | 2.7E-05 |
| Ingested materials |  |  |  |  |  |  |
| All forms | 2.5E-06 | 2.2E-07 | 1.3E-07 | 8.5E-08 | 6.9E-08 | 6.0E-08 |

Table 18.5. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 232Th compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate | 5.2E-05 | 4.9E-05 | 3.1E-05 | 2.1E-05 | 1.8E-05 | 1.7E-05 |
| Type F, — NB: Type F should not be assumed without evidence | 1.3E-04 | 1.2E-04 | 6.9E-05 | 4.9E-05 | 3.9E-05 | 3.3E-05 |
| Type M, hydroxide | 4.7E-05 | 4.5E-05 | 2.9E-05 | 2.0E-05 | 1.8E-05 | 1.6E-05 |
| Type S, oxide | 1.4E-04 | 1.5E-04 | 1.2E-04 | 1.0E-04 | 1.1E-04 | 1.1E-04 |
| Ingested materials |  |  |  |  |  |  |
| All forms | 2.7E-06 | 2.4E-07 | 1.5E-07 | 1.0E-07 | 8.5E-08 | 7.0E-08 |

Table 18.6. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 234Th compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate | 2.1E-08 | 1.7E-08 | 9.4E-09 | 6.0E-09 | 4.7E-09 | 4.4E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 2.6E-08 | 2.0E-08 | 7.4E-09 | 3.4E-09 | 2.9E-09 | 1.5E-09 |
| Type M, hydroxide | 1.9E-08 | 1.6E-08 | 8.6E-09 | 5.5E-09 | 4.4E-09 | 4.0E-09 |
| Type S, oxide | 2.2E-08 | 1.8E-08 | 1.0E-08 | 6.9E-09 | 5.4E-09 | 5.2E-09 |
| Ingested materials |  |  |  |  |  |  |
| All forms | 3.6E-09 | 2.5E-09 | 1.5E-09 | 1.1E-09 | 6.7E-10 | 5.9E-10 |

# Protactinium (Z=91)

## Routes of Intake

### Inhalation

1. One study was found in the literature relating to lung retention of protactinium (Pa) in humans following accidental intake. One experimental study was found that gives information on absorption of protactinium from the respiratory tract. As noted in Section 18 of *Publication 141* (ICRP, 2019), the general actinide Section, as there is so little relevant information available, absorption parameter values for protactinium are based on chemical analogy: values chosen for thorium (Section 14 of *Publication 137*, ICRP, 2017) are applied in this document to protactinium. Absorption parameter values and Types, and associated *f*A values for particulate forms of protactinium are given in Table 19.1. (taken from Section 14 of *Publication 137*).

Table 19.1. Absorption parameter values for inhaled and ingested protactinium (based on thorium, Section 14 of *Publication 137,* ICRP, 2017).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | *s*r (d–1) | | | *s*s (d–1) | |
| Specific parameter values‡ | | | |  | |  | | |  | |  | |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate§ | | | | 0.1 | | 50 | | | 0.005 | | 5 × 10–5 | |
|  | | | |  | |  | | |  | |  | |
| Default parameter values¶ | | | |  | |  | | |  | |  | |
| Absorption Type | Assigned forms | | |  | |  | | |  | |  | |
| F | — NB: Type F should not be assumed without evidence | | | 1 | | 50 | | | - | | 5 × 10–4 | |
| M\*\* | Hydroxide | | | 0.2 | | 3 | | | 0.005 | | 1 × 10–4 | |
| S†† | Oxide | | | 0.01 | | 3 | | | 1 × 10-4 | | 5 × 10–6 | |
|  | | | |  | |  | |  | | |  | |
| Ingested material‡‡ | | | |  | |  | |  | | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | 10 y | | | 15 y | | adult |
| All chemical forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | | 5 × 10-4 | | 5 × 10-4 |

\*It is assumed that for protactinium the bound state can be neglected, i.e. *f*b = 0.0. The value of *s*r for Type F forms of protactinium (50 d–1) is element-specific. The values for Types M and S (3 d–1) are the general default values.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: i.e. the (rounded) product of *f*A for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of protactinium applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

‡See Section 14 of *Publication 137* (ICRP 2017) for summary of information on which parameter values are based, and on ranges of parameter values observed for individual materials. For water soluble forms of protactinium specific parameter values are used for dissolution in the lungs, but the default value of *f*A.

§Decay products assigned to Type F.

¶Materials (e.g. hydroxide) are listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see Section 14 of ICRP, 2017).

\*\*Decay products assigned to Type M.

††Default Type S is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

‡‡Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g.* 5 × 10-4 for adults).

### Ingestion

1. *Adults*. The gastro-intestinal absorption of protactinium has been studied in rats and hamsters. The data reviewed in *Publications 48* (ICRP, 1986), *100* (ICRP, 2006) and *141* (ICRP, 2019) indicate a fractional absorption in the range 3 × 10-4 to 4 × 10-2. In *Publications 30* (ICRP, 1981) and *48* an absorption fraction of 1 × 10-3 was recommended for protactinium. In *Publication 141*, on the basis of results showing similar low levels of absorption in humans for five actinide elements (thorium, neptunium, plutonium, americium and curium) and taking account of animal data showing variations in *f*A values resulting from differences in chemical forms, it was considered that an appropriate general *f*A value for all chemical forms of actinides except uranium was 5 × 10-4. The same *f*A = 5 × 10-4 is recommended here for ingestion of protactinium by adult members of the public.
2. *Children*. One experiment indicates that absorption in the two-day-old rat is about 100 times greater than in adults (Sullivan et al., 1983). It is assumed that, like for plutonium, the increased absorption would probably decrease rapidly during the first few days or weeks of life, adult values being reached by about the time of weaning. The same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are therefore adopted here for protactinium as for thorium, neptunium, plutonium and americium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The systemic behaviour of protactinium has been studied mainly in rats and baboons, and follow-up of an occupational exposure. The findings suggest that the systemic behaviour of protactinium is similar to that of thorium.
2. Newton and Brown (1974) studied the behaviour of 231Pa and 227Ac in an adult male over a 9-y period following their internal deposition via a puncture wound. The investigators estimated that 70–80% of the 231Pa that reached blood was retained with a half-life in the range 70­–125 y. After 3 y total-body activity was contained mainly in bone, with lower accumulation in the liver. After 9 y the body burden was almost completely contained in the skeleton.
3. At 24 h after intravenous administration of 233Pa in citrate buffer to baboons, the skeleton contained about half of the injected amount (Ralston et al., 1986). About 6% of the injected activity was excreted in urine during the first 24 h. By 21 days, when the slowly clearing plasma activity had been reduced to about 2% of the injected, the skeleton and soft tissues contained about 65% and 13%, respectively, of the injected amount. Cumulative urinary and faecal excretion of 233Pa during the first 21 d amount to about 15% and 3%, respectively, of the injected amount.
4. Following intravenous administration of protactinium to rats, ~99% of injected activity was removed from plasma compartment in 3 d. Plasma clearance was comparable to that of plutonium and much slower than that of neptunium, americium, or curium. At 1–7 d the skeleton contained 70–80% and the liver contained 2–3% of the injected amount. The high deposition in the skeleton and low uptake by liver following systemic uptake in rats closely resembled the distribution of thorium (Durbin, 2011; Lanz et al., 1946; Schuppler et al., 1988).
5. Zalikin (1969) investigated the accumulation of 233Pa in tissues of rats during its chronic oral administration. The absorbed activity accumulated primarily in the skeleton. After 150 d of chronic intake the skeleton contained about 10 times as much activity as the liver and about 16 times as much activity as the kidneys.
6. No information was found regarding age dependence in the biokinetics of systemic protactinium.
   * + 1. Systemic model
7. The systemic model for Th described in the thorium section is applied to protactinium. The structure of the systemic model for protactinium is shown in Fig 19.1. Parameter values are listed in Table 19.2.

Diagram

Description automatically generated

Fig 19.1. Structure of the systemic model for protactinium.

Table 19.2. Age-specific transfer coefficients for protactinium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 9.70E-02 |
| Blood to Cort bone surf | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 6.79E-01 |
| Blood to Trab bone surf | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 7.76E-01 | 6.79E-01 |
| Blood to Urinary bladder cont | 7.11E-02 | 7.11E-02 | 7.11E-02 | 7.11E-02 | 7.11E-02 | 1.07E-01 |
| Blood to Kidneys 1 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 6.79E-02 |
| Blood to Kidneys 2 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.94E-02 |
| Blood to Right colon cont | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 9.70E-03 |
| Blood to Testes | 3.90E-05 | 5.80E-05 | 6.60E-05 | 7.70E-05 | 6.20E-04 | 6.80E-04 |
| Blood to Ovaries | 2.30E-05 | 3.00E-05 | 7.60E-05 | 1.30E-04 | 2.30E-04 | 2.10E-04 |
| Blood to ST0 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 |
| Blood to ST1 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 2.43E-01 |
| Blood to ST2 | 2.59E-02 | 2.59E-02 | 2.59E-02 | 2.59E-02 | 2.59E-02 | 3.88E-02 |
| Liver 1 to Blood | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 |
| Liver 1 to Liver 2 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 |
| Liver 1 to SI cont | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 | 4.75E-04 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Kidneys 1 to UB cont | 4.62E-02 | 4.62E-02 | 4.62E-02 | 4.62E-02 | 4.62E-02 | 4.62E-02 |
| Kidneys 2 to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| ST0 to Blood | 4.62E-01 | 4.62E-01 | 4.62E-01 | 4.62E-01 | 4.62E-01 | 4.62E-01 |
| ST1 to Blood | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 | 9.50E-04 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Liver 2 to Blood | 2.11E-04 | 2.11E-04 | 2.11E-04 | 2.11E-04 | 2.11E-04 | 2.11E-04 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, cont = content, SI = Small intestine

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of protactinium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for protactinium

Table 19.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 231Pa compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate | 9.4E-05 | 9.2E-05 | 6.3E-05 | 4.7E-05 | 4.3E-05 | 4.0E-05 |
| Type F, — NB: Type F should not be assumed without evidence | 2.5E-04 | 2.3E-04 | 1.5E-04 | 1.1E-04 | 9.5E-05 | 8.7E-05 |
| Type M, hydroxide | 8.6E-05 | 8.4E-05 | 5.9E-05 | 4.4E-05 | 4.1E-05 | 3.9E-05 |
| Type S, oxide | 1.3E-04 | 1.4E-04 | 1.1E-04 | 9.1E-05 | 9.1E-05 | 9.1E-05 |
| Ingested materials |  |  |  |  |  |  |
| All forms | 5.1E-06 | 4.6E-07 | 3.2E-07 | 2.4E-07 | 2.1E-07 | 1.8E-07 |

Table 19.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 233Pa compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Water soluble forms, including chloride, citrate, fluoride, nitrate and sulphate | 7.7E-09 | 6.1E-09 | 3.2E-09 | 2.1E-09 | 1.6E-09 | 1.5E-09 |
| Type F, — NB: Type F should not be assumed without evidence | 1.0E-08 | 6.9E-09 | 2.4E-09 | 1.1E-09 | 9.4E-10 | 5.8E-10 |
| Type M, hydroxide | 7.1E-09 | 5.5E-09 | 3.0E-09 | 1.9E-09 | 1.5E-09 | 1.4E-09 |
| Type S, oxide | 7.8E-09 | 6.3E-09 | 3.6E-09 | 2.4E-09 | 1.8E-09 | 1.8E-09 |
| Ingested materials |  |  |  |  |  |  |
| All forms | 7.5E-10 | 5.0E-10 | 2.9E-10 | 2.1E-10 | 1.4E-10 | 1.2E-10 |

# Uranium (Z = 92)

## Routes of Intake

### Inhalation

1. There is extensive information available on the behaviour of uranium after deposition in the respiratory tract from animal experiments (mainly in rats), in-vitro dissolution studies, and some accidental human intakes. For details see Section 15 of *Publication 137* (ICRP, 2017). Absorption parameter values and Types, and associated *f*A values for particulate forms of uranium are given in Table 20.1. (taken from Section 15 of *Publication 137*).

Table 20.1. Absorption parameter values for inhaled and ingested uranium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | | | Absorption from the alimentary tract, *f*A § | |
| *f*r | | | *s*r (d–1) | | | *s*s (d–1) | |
| Specific parameter values† | | | |  | | |  | | |  | |  | |
| Intermediate Type F/M: uranyl nitrate UO2(NO3)2; uranium peroxide hydrate UO4; ammonium diuranate; uranium trioxide UO3 | | | | 0.8 | | | 1 | | | 0.01 | | 0.016 | |
| Intermediate Type M/S: uranium octoxide U3O8; uranium dioxide UO2 | | | | 0.03 | | | 1 | | | 5 × 10-4 | | 6 × 10-4 | |
| Uranium aluminide UAlX | | | | ǂ | | | ǂ | | | ǂ | | 0.002 | |
|  | | | |  | | |  | | |  | |  | |
| Default parameter values§, ¶ | | | |  | | |  | | |  | |  | |
| Absorption type | Assigned forms | | |  | | |  | | |  | |  | |
| F | Uranium hexafluoride, UF6; uranyl tri-butyl-phosphate | | | 1 | | | 10 | | | - | | 0.02 | |
| M\*\* | Uranyl acetylacetonate; UF4; depleted uranium aerosols from use of kinetic energy penetrators; vaporised U metal, UF4 | | | 0.2 | | | 3 | | | 0.005 | | 0.004 | |
| S | — | | | 0.01 | | | 3 | | | 1 × 10-4 | | 2 × 10-4 | |
|  | | | |  | |  | | |  | | |  | |
| Ingested materials†† | | | |  | |  | | |  | | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | | 10 y | | | 15 y | | adult |
| Soluble forms (Type F), U in diet | | 0.1 | 0.05 | | 0.05 | | | 0.03 | | | 0.03 | | 0.02 |
| Relatively insoluble forms (as assigned to Types M and S for inhalation) | | 0.01 | 0.005 | | 0.005 | | | 0.003 | | | 0.003 | | 0.002 |

\*It is assumed that the bound state can be neglected for uranium, i.e. *f*b=0.0. The value of *s*r for Type F forms of uranium (10 d–1) is element-specific. The values for Types M and S (3 d–1) are the general default values.

†See Section 15 of *Publication 137* (ICRP, 2017) for summary of information on which parameter values are based, and on ranges of parameter values observed for individual materials. For uranium specific parameter values are used for dissolution in the lungs, and in most cases, where information is available, for absorption from the alimentary tract. However, for ammonium diuranate, the default value of *f*A is used (Footnote §).

ǂ Section 15 of *Publication* 137 (ICRP, 2017): *s*p=1×10-4 d–1, *s*pt=0.004d–1, *s*t=0.004d–1, with *f*A taken to be 0.002.

§For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied; i.e. the (rounded) product of *f*r for the absorption type (or specific value where given) and the *f*A value for ingested soluble forms of uranium applicable to the age-group of interest (*e.g.* 0.02 for adults).

¶Materials (e.g. UF6) are listed here where there is sufficient information to assign to a default absorption type, but not to give specific parameter values (see text).

\*\*Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an absorption type; for example,if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

††Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to re-absorption to blood. The default absorption fraction *f*A for the secreted activity is the highest value for any form of the radionuclide applicable to the age-group of interest (*e.g.* 0.02 for adults).

### Ingestion

1. *Adults.* Information on the absorption of uranium is available from studies involving direct measurements of absorption in human volunteers, dietary balance data for several different human groups, and measurements of absorption in a variety of laboratory animals. Data have been reviewed by Wrenn et al. (1985),Harrison (1991), Leggett and Harrison (1995), Davesne and Blanchardon (2014), and in *Publications 69*, *100* and *137* (ICRP, 1995a, 2006, 2017).
2. In the first controlled human study involving more than one subject, Hursh et al. (1969) administered uranyl nitrate dissolved in Coca-Cola to four hospital patients. The data obtained were taken to suggest absorption in the range of 0.005–0.05. Leggett and Harrison (1995) interpreted the data as suggesting absorption of 0.004, 0.01, 0.02, and 0.06 for the four subjects. Wrenn et al. (1989) estimated absorption in 12 normal healthy adult volunteers given drinking water high in uranium. On the basis that 40–60% of absorbed uranium was excreted in the urine in the first 3 days, Leggett and Harrison (1995) concluded that mean absorption was 0.01–0.015, maximum absorption was in the range of 0.02–0.04, and that six subjects absorbed less than 2.5 × 10-3. Harduin et al. (1994) reported results for the absorption of uranium from drinking water either administered on 1 day or over 15 days. The data for acute administration suggested absorption of 0.005–0.05 with an average value of 0.015– 0.02. The data for 15-day administration suggested absorption of 0.003–0.02 and average absorption of 0.01–0.015. Karpas et al. (1998) studied the uptake of uranium in five volunteers having ingested low levels of uranyl nitrate in grapefruit drink. The results of urine monitoring indicated fractional absorption in the range 0.001–0.005 for four subjects and 0.016 for the fifth.
3. A number of dietary balance studies have indicated mean absorption values in the range of 0.003–0.04 (Chen et al., 2011; Dang, Pullat, et al., 1992; Karpas et al., 2005; Larsen and Orlandini, 1984; Leggett and Harrison, 1995; Spencer et al., 1990; Tolmachev et al., 2006; Wrenn et al., 1989; Yamamoto et al., 1974; Zamora et al., 2002), in reasonable agreement with central values of 0.001–0.02 from con­trolled studies on human volunteers. Yamamoto et al. (1974) measured uranium in food, drink and urine samples from non-occupationally exposed inhabitants of two Japanese villages located near uranium mines and mills and two control villages with low levels of environmental uranium. The ratio of urinary excretion to dietary intake indicated fractional absorptions around 0.01 for the two control villages and 0.02 and 0.03 for the two villages located near uranium facilities. Larsen and Orlandini (1984) measured daily excretion of uranium in two subjects whose drinking water had a high 234U to 238U activity ratio. Combining estimated intake and urinary excretion data for the two isotopes gives a range in absorption of 0.004–0.007. Spencer et al*.* (1990) determined uranium intake and excretion in four adult male subjects in a metabolism ward. The data were interpreted as suggesting that absorption of uranium from food was negligible while absorption from water was about 0.05. Their conclusion has been questioned, however (Leggett and Harrison, 1995). On the assumption that all ingested uranium is equally available for absorption, the data indicate mean absorption of 0.015 (range of 0.005–­0.026). Dang et al (1992) studied the fractional absorption of uranium for an urban Indian population of about 20 individuals aged 30 to 55 y, ingesting 0.25 to 1.0 µg of uranium in daily food and drinking water. They estimated that the mean absorption fraction was 0.016. In another *in situ* study, the gastro-intestinal absorption factor was determined for 50 participants ingesting uranium at natural levels in drinking water and food. The participants, ranged in age from 13 to 87 y, were selected from either a Canadian area with naturally high (2–780 µg L-1) or low (<1µg L-1) uranium levels. The absorption fractions were in a range from 0.001 to 0.06, with a median of 0.009 (Zamora et al., 2002). These values were not gender sensitive and independent of age at the time of the study, duration of exposure and total uranium intake. Karpas et al. (2005) measured uranium in the urine, hair, nails and drinking water of 205 individuals from southern Finland. They estimated an absorption fraction of about 0.004 (range 0.0002 to 0.07) for individuals with an intake above 10 µg.d-1. No statistical difference was found between women and men but the fractional absorption was higher among people below 60 y of age or with an exposure lower than 100 µg.d-1. Tolmachev et al. (2006) estimated a mean absorption fraction of 0.009 (range 0.002 to 0.03) based on the measurement of 168 spot urine samples from Japanese volunteers with no known exposure to uranium and on literature data of uranium dietary intake for Japanese populations. Chen et al. (2011) measured uranium in bone samples from Canadian children and adults aged 7 to 25 y. They evaluated intakes for these individuals based on uranium in diet data obtained by Zamora et al (2002), records of uranium measurement in drinking water and estimates of daily food and water consumption. Applying the age-dependent biokinetic model for uranium of *Publication 69*, they estimated an absorption fraction of 0.02 +/- 0.015 (mean +/- standard deviation, range 0.005–0.07 from 35 samples) for adults aged 18–25 y.
4. Measurements of uranium absorption have been made in rats, hamsters, rabbits, dogs and baboons (reviewed by Davesne and Blanchardon, 2014; Harrison, 1991; Leggett and Harrison, 1995; Wrenn et al., 1985). A number of studies have shown that absorption is substantially greater in fasted than fed animals. For example, Bhattacharyya et al*.* (1989) found that uptake was increased by an order of magnitude in mice and baboons deprived of food for 24 h prior to uranium administration. The values obtained for absorption in mice were 7 × 10-4 in fed animals and 0.008 after fasting, with corresponding values for baboons of 0.005 and 0.045. Animal studies provide information on the relative uptake of uranium ingested in different chemical forms. Absorption generally decreases with decreasing solubility of the compound, being greatest for uranium ingested as UO2(NO3)2∙6H2O, U-TBP, UO2F2 or Na2U2O7, roughly half as great for UO4 or UO3, and one to two orders of magnitude lower for UCl4, U3O8, UO2 and UF4.
5. Studies comparing the time course of the retention and excretion of uranium after oral and intravenous administration suggest that some retention in the intestinal wall may occur, either during a period of prolonged absorption, or temporarily prior to loss into the gut lumen (ICRP, 2006). Urinary excretion data from uranium absorption studies on human volunteers (Harduin et al., 1994; Wrenn et al., 1989) and baboon data (Larsen and Orlandini, 1984) are consistent with the assumption that uranium passes through the intestinal wall with a half-time of 1–3 days and behaves the same as directly injected uranium once it reaches blood. However, since it is assumed that absorption and temporary retention is confined to the villi, no dose will be delivered from alpha-emitting isotopes of uranium to epithelial stem cells at a depth of 130– 150 µm in the crypts (ICRP, 2006).
6. In *Publication 30* (ICRP, 1979) an absorption fraction of 0.05 was recommended for inorganic forms of uranium, relying mainly on the human data reported by Hursh et al.(1969). In *Publication 69* (ICRP, 1995a), an absorption fraction of 0.02 was recommended for dietary intakes of uranium on the basis of human data as reviewed by Wrenn et al. (1985), Harrison (1991) and Leggett and Harrison (1995). In *Publication 137* (ICRP, 2017) an *f*A value of 0.002 was recommended for relatively insoluble compounds (e.g. UO2, U3O8) and an *f*A value of 0.02 was recommended for all other more soluble chemical forms. In view of the latest studies by Dang et al. (1992), Karpas et al. (1998, 2005), Zamora et al (2002), Tolmachev et al. (2006) and Chen et al. (2011), indicating central values of fractional absorption in a range 0.004–0.02, and of the recent review by Davesne and Blanchardon (2014) reporting a median value of fractional absorption from water and food of 0.01, the value of 0.02 appears as a reasonably conservative estimate of the fractional absorption of uranium in diet. An *f*A = 0.02 is therefore adopted here for dietary intakes of uranium by adult members of the public.
7. *Children.* Limited data on the absorption of uranium in children from 5 y of age suggested that uptake did not vary substantially with age (Leggett and Harrison, 1995; Limson Zamora et al., 1992; Sviatkina and Novikov, 1975). However, estimates were based on the assumption that subjects are in uranium balance and hence could underestimate uptake in rapidly growing children who may be expected to show net retention of uranium. From the measurement of bone samples and a survey of dietary intake, Chen et al. (2011) estimated mean absorption fractions of 0.09 +/- 0.1 (from 24 bone samples), 0.05 +/- 0.03 (from 25 bone samples), 0.03 +/- 0.02 (range 0.01 - 0.08 from 16 bone samples), and 0.03 +/- 0.02, (range 0.001–0.07 from 18 bone samples) for children of age under 12 mo, 1 to 7 y, 7 to 12 y, and 12 to 18 y respectively.
8. Increased absorption of uranium has been demonstrated in neonatal rats and pigs (Sullivan, 1980a; Sullivan and Gorham, 1982). Absorption in 2-d-old rats given uranium nitrate was estimated at about 0.01–0.07, two orders of magnitude greater than for adults. In pigs given uranium nitrate on the first day after birth, retention in the skeleton 7 d later accounted for about 30% of the administered uranium. Particularly high absorption in pigs is consistent with the high permeability of the gut in this species to the absorption of intact immunoglobulins in milk, occurring during the first 1–2 d of life (Brambell, 1970).
9. In the absence of quantitative information on human infants, absorption fractions of 0.04 for the 3-mo old and 0.02 for children of 1 y and older were recommended in *Publication 69*. On the basis of the data reported by Chen et al (2011), values of *f*A = 0.1 for the 3-mo old infant, *f*A = 0.05 for the 1 y and 5 y old children and *f*A = 0.03 for the 10 y and 15 y old children are adopted here for ingestion of uranium in diet. Ten times lower values are retained for ingestion of relatively insoluble forms of uranium ingested by children.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The most direct information on the biokinetics of systemic uranium comes from three studies on human subjects who were intravenously injected with uranium isotopes and followed for periods varying from a few days to 1.5 y after injection. The Boston study (Bernard and Struxness, 1957; Leggett, 1994; Luessenhop et al., 1958; Struxness et al., 1956) involved at least 11 comatose patients, ages 26–63 y, in the terminal phases of diseases of the central nervous system. A study by Bassett et al. (1948) involved six ambulatory hospital patients, ages 24–61 y, with diseases that were not immediately life threatening. A study by Tannenbaum et al. (1964) (also see Hursh and Spoor, 1973) involved three control patients and seven patients with various bone disorders. The rate of urinary excretion of uranium was determined in all three studies. Blood clearance of uranium was studied in the Boston study and the study by Bassett and coworkers. The time-dependent distribution of uranium in tissues was examined by autopsy measurement in patients in the Boston study dying from 2.5 to 566 d post injection. Data from these studies indicate that 50–80% or more of uranium entering blood is excreted in urine during the first 24 h, and 60–90% or more is excreted in urine during the first week. Highest concentrations of the retained activity are found in kidneys and bone.
2. Post-mortem measurements of uranium in tissues of occupationally and environmentally exposed subjects (Campbell et al., 1975; Donoghue et al., 1972; Fisenne and Welford, 1986; Igarashi et al., 1985; Kathren et al., 1989; Roberts et al., 1977; Russell and Kathren, 2004; Singh et al., 1987; Singh, Lewis, et al., 1986; Singh, Wrenn, et al., 1986) provide information on the long‑term distribution of uranium in the human body. The collective data indicate that the skeleton typically contains 15–50 (median, ~30) times as much uranium as the liver, and the kidneys typically contain 0.2–0.6 (median, ~0.5) times as much uranium as the liver at times remote from the start of exposure.
3. The biokinetics of uranium has been studied in baboons, dogs, rabbits, rats, mice, monkeys, sheep, and other animal species (see reviews by Durbin, 1984; ICRP, 1995a; Leggett, 1994) . These data can be used to fill gaps in information for humans.
4. The skeletal behaviour of uranium is in some ways qualitatively similar to that of the alkaline earths. It is known that UO22+ exchanges with Ca2+ on the surfaces of bone mineral although it apparently does not participate in crystal formation. Like the alkaline earths, uranium initially deposits on all bone surfaces but is highly concentrated in areas of growth. Perhaps depending on species-dependent microscopic structure of bone, uranium may gradually diffuse into bone volume. This has been observed in dogs (Rowland and Farnham, 1969; Stevens et al., 1980) but not in rats (Priest et al., 1982) or mice (Kisieleski et al., 1952). Also like the alkaline earths, a substantial portion of uranium depositing in bone returns to plasma by processes that occur much more rapidly than bone restructuring. Data for the subjects of the Boston study indicate that 80–90% of the original skeletal deposition was lost from bone over the first 1.5 y.
5. Neuman et al. (1948) studied the biokinetics of uranium in 200-rats following intravenous administration of uranium nitrate. They found that a consistently greater amount accumulated in bones of males than of females, suggesting a physiological factor related to sex was involved in bone deposition of uranium. Subsequent studies revealed that the factor in question was age rather than sex. Male rats of weight 200 g were 9 weeks of age, while females were about 16 weeks old. Because of a greater rate of bone growth at 9 weeks, the males deposited greater quantities of uranium in the skeleton.
   * + 1. Systemic model
6. The age-specific systemic model for uranium applied in this report is the model used in *Publication 69* (ICRP, 1995a). The parameter values for adult member of the public are the same as those applied in *Publication 137* to workers (ICRP, 2017).
7. The reader is referred to *Publication 69* for a detailed description of the model and the rationale for parameter values. Briefly, the model for adults is based largely on data for human subjects summarized above, together with the generic skeletal model for bone-volume seeking radionuclides. Data for laboratory animals including primates and dogs are used to fill gaps in the data for adult humans. Based on general similarities in the skeletal behaviours of uranium and the alkaline earth elements, the age-specific deposition fraction for bone is assumed to be proportional to the age-specific deposition fractions for the alkaline earth elements (see the section on calcium). For preadult ages the deposition fractions for soft tissues and excretion pathways are reduced uniformly from the values for adults to accommodate the higher deposition fractions in bone compared with adults. The removal half-time from bone surface and exchangeable bone volume compartments is assumed to be independent of age. The removal half-time from bone volume compartments to blood are reference age-specific bone turnover rates (ICRP, 2002). Removal half-times from soft-tissue compartments are assumed to be independent of age.
8. The structure of the systemic model for uranium is shown in Fig 20.1. Parameter values are listed in Table 20.2.

Diagram

Description automatically generated

Fig 20.1. Structure of the systemic model for uranium. RBC = Red blood cells, Exch = Exchangeable, Nonexch = Nonexchangeable,

Table 20.2. Age-specific transfer coefficients for uranium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Plasma to ST0 | 1.05E+01 | 1.05E+01 | 1.05E+01 | 1.05E+01 | 1.05E+01 | 1.05E+01 |
| Plasma to RBC | 1.59E-01 | 2.10E-01 | 2.19E-01 | 1.91E-01 | 1.60E-01 | 2.45E-01 |
| Plasma to Urinary bladder cont | 9.99E+00 | 1.33E+01 | 1.38E+01 | 1.21E+01 | 1.01E+01 | 1.54E+01 |
| Plasma to Kidneys 1 | 1.90E+00 | 2.52E+00 | 2.63E+00 | 2.30E+00 | 1.92E+00 | 2.94E+00 |
| Plasma to Kidneys 2 | 7.90E-03 | 1.05E-02 | 1.10E-02 | 9.60E-03 | 8.00E-03 | 1.22E-02 |
| Plasma to Right colon cont | 7.90E-02 | 1.05E-01 | 1.10E-01 | 9.60E-02 | 8.00E-02 | 1.22E-01 |
| Plasma to Liver 1 | 2.38E-01 | 3.16E-01 | 3.29E-01 | 2.87E-01 | 2.40E-01 | 3.67E-01 |
| Plasma to ST1 | 1.05E+00 | 1.40E+00 | 1.46E+00 | 1.27E+00 | 1.07E+00 | 1.63E+00 |
| Plasma to ST2 | 4.76E-02 | 6.31E-02 | 6.57E-02 | 5.74E-02 | 4.81E-02 | 7.35E-02 |
| Plasma to Trab bone surf | 2.20E+00 | 1.32E+00 | 1.31E+00 | 2.07E+00 | 3.03E+00 | 2.04E+00 |
| Plasma to Cort bone surf | 8.82E+00 | 5.29E+00 | 4.57E+00 | 6.16E+00 | 7.84E+00 | 1.63E+00 |
| ST0 to Plasma | 8.32E+00 | 8.32E+00 | 8.32E+00 | 8.32E+00 | 8.32E+00 | 8.32E+00 |
| RBC to Plasma | 3.47E-01 | 3.47E-01 | 3.47E-01 | 3.47E-01 | 3.47E-01 | 3.47E-01 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Plasma | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Liver 1 to Plasma | 9.20E-02 | 9.20E-02 | 9.20E-02 | 9.20E-02 | 9.20E-02 | 9.20E-02 |
| Liver 1 to Liver 2 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST1 to Plasma | 3.47E-02 | 3.47E-02 | 3.47E-02 | 3.47E-02 | 3.47E-02 | 3.47E-02 |
| ST2 to Plasma | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Trab bone surfto Plasma | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 |
| Trab bone surf to Exch trab bone vol | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 |
| Cort bone surf to Plasma | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 |
| Cort bone surf to Exch cort vol | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 | 6.93E-02 |
| Liver 2 to Plasma | 1.90E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 |
| Nonexch trab vol to Plasma | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Nonexch cort vol to Plasma | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Exch trab vol to Trab bone surf | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 |
| Exch trab vol to Nonexch cort vol | 5.78E-03 | 5.78E-03 | 5.78E-03 | 5.78E-03 | 5.78E-03 | 5.78E-03 |
| Exch cort vol to Cort bone surf | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 |
| Exch cort vol to Nonexch cort vol | 5.78E-03 | 5.78E-03 | 5.78E-03 | 5.78E-03 | 5.78E-03 | 5.78E-03 |

aRBC = Red blood cells, Exch = Exchangeable, Nonexch = Nonexchangeable, Cort = Cortical, Trab = Trabecular, surf = surface, vol = volume, cont = content

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of uranium is described in Section 15.3.3. of *Publication 137* (ICRP, 2017).

## Dosimetric data for uranium

Table 20.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 234U compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type FM | 2.9E-06 | 2.2E-06 | 1.3E-06 | 9.2E-07 | 8.0E-07 | 7.0E-07 |
| Type MS | 3.0E-05 | 2.8E-05 | 1.7E-05 | 1.1E-05 | 9.2E-06 | 9.1E-06 |
| UAlx | 1.9E-05 | 1.7E-05 | 1.0E-05 | 6.6E-06 | 5.2E-06 | 4.9E-06 |
| Type F | 1.3E-06 | 8.7E-07 | 5.5E-07 | 4.1E-07 | 4.0E-07 | 3.1E-07 |
| Type M | 9.7E-06 | 8.3E-06 | 4.9E-06 | 3.2E-06 | 2.6E-06 | 2.4E-06 |
| Type S | 5.0E-05 | 4.9E-05 | 3.4E-05 | 2.5E-05 | 2.4E-05 | 2.4E-05 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms | 7.0E-07 | 2.4E-07 | 1.6E-07 | 7.5E-08 | 6.8E-08 | 3.5E-08 |
| Relatively insoluble forms | 7.0E-08 | 2.4E-08 | 1.6E-08 | 7.5E-09 | 6.8E-09 | 3.5E-09 |

Table 20.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 235U compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type FM | 2.6E-06 | 2.0E-06 | 1.2E-06 | 8.4E-07 | 7.3E-07 | 6.4E-07 |
| Type MS | 2.7E-05 | 2.5E-05 | 1.6E-05 | 1.0E-05 | 8.4E-06 | 8.3E-06 |
| UAlx | 1.8E-05 | 1.6E-05 | 9.4E-06 | 6.1E-06 | 4.8E-06 | 4.5E-06 |
| Type F | 1.2E-06 | 7.9E-07 | 5.0E-07 | 3.8E-07 | 3.6E-07 | 2.9E-07 |
| Type M | 8.9E-06 | 7.7E-06 | 4.5E-06 | 3.0E-06 | 2.4E-06 | 2.2E-06 |
| Type S | 4.6E-05 | 4.5E-05 | 3.2E-05 | 2.3E-05 | 2.2E-05 | 2.2E-05 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms | 6.4E-07 | 2.2E-07 | 1.4E-07 | 6.8E-08 | 6.2E-08 | 3.2E-08 |
| Relatively insoluble forms | 6.4E-08 | 2.2E-08 | 1.4E-08 | 7.0E-09 | 6.3E-09 | 3.3E-09 |

Table 20.5. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 238U compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type FM | 2.5E-06 | 1.9E-06 | 1.2E-06 | 8.0E-07 | 7.0E-07 | 6.1E-07 |
| Type MS | 2.6E-05 | 2.4E-05 | 1.5E-05 | 9.7E-06 | 8.0E-06 | 7.9E-06 |
| UAlx | 1.7E-05 | 1.5E-05 | 8.9E-06 | 5.8E-06 | 4.5E-06 | 4.3E-06 |
| Type F | 1.2E-06 | 7.6E-07 | 4.8E-07 | 3.6E-07 | 3.5E-07 | 2.8E-07 |
| Type M | 8.4E-06 | 7.3E-06 | 4.3E-06 | 2.8E-06 | 2.2E-06 | 2.1E-06 |
| Type S | 4.4E-05 | 4.3E-05 | 3.0E-05 | 2.2E-05 | 2.1E-05 | 2.1E-05 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms | 6.1E-07 | 2.1E-07 | 1.4E-07 | 6.6E-08 | 6.0E-08 | 3.1E-08 |
| Relatively insoluble forms | 6.1E-08 | 2.1E-08 | 1.4E-08 | 6.6E-09 | 6.1E-09 | 3.1E-09 |

# Neptunium (Z=93)

## Routes of Intake

### Inhalation

1. No studies were found in the literature relating to lung retention of neptunium (Np) in humans following accidental intakes other than environmental exposure to nuclear weapons fallout. Information on absorption from the respiratory tract is available from experimental studies with neptunium in several chemical forms including nitrate and oxide. For details see Section 21 of *Publication 141* (ICRP, 2019). Absorption parameter values and Types, and associated *f*A values for particulate forms of neptunium are given in Table 21.1 (taken from Section 21 of *Publication 141*).

Table 21.1. Absorption parameter values for inhaled and ingested neptunium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | | Absorption from the alimentary tract, *f*A† | | |
| *f*r | | *s*r (d–1) | | | | *s*s (d–1) |
| Specific parameter values‡ | | | |  | |  | | | |  |  | | |
| Neptunium nitrate | | | | 0.7 | | 30 | | | | 0.005 | 3.5 × 10–4 | | |
|  | | | |  | |  | | | |  |  | | |
| Default parameter values§ | | | |  | |  | | | |  |  | | |
| Absorption Type | Assigned forms | | |  | |  | | | |  |  | | |
| F | — | | | 1 | | 30 | | | |  | 5 × 10–4 | | |
| M¶ | Neptunium citrate, oxalate | | | 0.2 | | 3 | | | | 0.005 | 1 × 10–4 | | |
| S | Neptunium dioxide | | | 0.01 | | 3 | | | | 1 × 10–4 | 5 × 10–6 | | |
|  | | | |  | | |  | |  | |  | | |
| Ingested materials\*\* | | | |  | | |  | |  | |  | | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | | 10 y | | | | 15 y | adult |
| All forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | | 5 × 10-4 | | | | 5 × 10-4 | 5 × 10-4 |

\*It is assumed that for neptunium the bound state can be neglected, i.e., *f*b = 0.0. The value of *s*r for Type F forms of neptunium (30 d–1) is element-specific (although numerically equal to the general default value). The values for Types M and S (3 d–1) are the general default values.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the (rounded) product of *f*r for the absorption Type and the *f*A value for ingested soluble forms of neptunium applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

‡See Section 21 of *Publication 141* (ICRP, 2019) for summary of information on which parameter values are based, and on ranges of parameter values observed in different studies. For neptunium nitrate, specific parameter values are used for dissolution in the lungs, but a default value of *f*A (footnote †).

§Materials (e.g. neptunium citrate) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see Section 21 of ICRP, 2019).

¶Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

\*\*Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g.* 5 × 10-4 for adults).

### Ingestion

1. *Adults*. The gastrointestinal absorption of neptunium is influenced by its initial chemical form, mass and oxidation state. A human volunteer study indicated fractional absorption in the range 1–3 × 10-4 of ingested neptunium citrate (Popplewell et al., 1991). Animal data depend on the administered quantity of neptunium, with observed absorption fractions from 3 × 10-4 to 2 × 10-3 for administered quantities of 0.5 ng to 13 µg. In baboons, when the hydroxy acid and vitamin content is raised with a fruit diet, an increase in total absorption is observed. Fasting causes marked increase in the absorption of neptunium. (For more details see Annex D of *Publication 100* (ICRP, 2006) and Section 21 of *Publication 141* (ICRP, 2019). In *Publication 30* (ICRP, 1980), the absorption fraction was taken to be 1 × 10-2 based on measurements on rats given high masses of 237Np. In *Publication 48* (ICRP, 1986), the effect of mass was discussed and a general value for actinides of 10-3 was applied to neptunium. This value was also recommended in *Publication 56* (ICRP, 1990). In *Publication 67* (ICRP, 1993) and in *Publication 141* (ICRP, 2019), a general value of *f*A = 5 × 10-4 based on the available database was recommended for all actinides other than uranium and applied to all chemical forms of neptunium. This value *f*A = 5 × 10-4 is also adopted here for intakes of neptunium by adults.
2. *Children.* The absorption of neptunium in rodents was observed to decrease by two orders of magnitude from weaning to maturity (David and Harrison, 1984; Sullivan et al., 1984). Studies on baboons also suggested that gastrointestinal absorption of neptunium in infants may be as much as two orders of magnitude greater than in adults but indicate that absorption may decrease to 3–5 times adult levels within a few days or weeks. Absorption appeared to fall to around adult values by approximately 5–6 months of age (Lataillade et al., 1992; Métivier et al., 1987). In *Publication 56*, an absorption fraction of 10-2 was recommended as an average for the first year of life and a value of 10-3 for all succeeding years. The values of *f*A = 5 × 10-3 for 3-month-old infants and *f*A = 5 × 10-4 for older children are adopted here.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. Urinary 239Np was measured in five healthy adult male human subjects over 9–10 days following intravenous injection of this radionuclide in citrate solution (Popplewell et al., 1991). Cumulative urinary excretion during this period represented 23–42% of administered 237Np.
2. The systemic behaviour of neptunium has been investigated in baboons (Cohen, 1987; Ralston et al., 1986), monkeys (Durbin et al., 1987, 1989), tamarins (Cohen, 1987), swine (Sullivan and Gorham, 1982), rabbits (Buldakov et al., 1972), and rodents (Ballou et al., 1962; Lyubchanskiy and Levdik, 1972; Morin et al., 1973; Moskalev et al., 1972; Paquet et al., 1996, 2000; Ramounet et al., 1998; Sontag et al., 1997; Volf and Wirth, 1986; Wirth and Volf, 1984). Results of animal studies indicate the following typical initial distribution of neptunium in adults: about half of absorbed or injected neptunium is deposited in the skeleton, 10% or less is deposited in the liver, about 5% is deposited in kidneys and other soft tissues, a small percentage is excreted in feces, and the remainder is rapidly excreted in urine.
3. The externally viewed removal half-time of neptunium from the liver is no more than a few weeks in mice and rats and a few months in non-human primates (Cohen, 1987; Durbin et al., 1989), but these animals generally lose actinides from the liver at a much greater rate than do humans. Data for rabbits injected subcutaneously with neptunium (Buldakov et al., 1972) are consistent with a rate of loss from liver to blood on the order of 0.5–1.0 y–1. Comparative environmental and human autopsy data for 237Np and 239Pu (Efurd et al., 1984, 1986) are consistent with the assumption that neptunium is removed at a faster rate than plutonium from the human liver.
4. The behaviour of neptunium in the skeleton appears to be similar to that of other actinide elements, excluding uranium. Neptunium is deposited on bone surfaces, and formation of aggregates in bone marrow following bone remodeling is evident (NCRP, 1988; Nenot et al., 1972). The division between trabecular and cortical portions of the skeleton is closer to that of americium and alkaline earth elements than that of plutonium.
5. Following intravenous administration of 237Np nitrate to rats, whole-body and skeletal retention during the first 5 months were about 50% higher in young rats than in adults (Wirth and Volf, 1984).
6. The tissue distribution of 239Np was determined at 4 d after oral administration of 239Np nitrate to baboons of age 17 h to 26 d, and results were compared with previous findings for adult baboons (Métivier et al., 1987). The skeleton to liver ratio in the infant baboons increased with age at intake, from roughly the adult value (31.5 ± 9.9) for intake ages 17 h to 4d to ~1.7 times the adult for intake ages 15–26 d.
   * + 1. Systemic model
7. The age-specific systemic model for thorium applied in this report is the model used in *Publication 67* (ICRP, 1993) with the following modification. The removal half-time from gonads to blood is reduced from 10 y to 5 y, the generic value applied here to the lanthanide and actinide elements.
8. The reader is referred to *Publication 67* for a detailed description of the model and the rationale for age-specific parameter values. Briefly, the model for adults was based largely on data for laboratory animals but was required to reproduce human data when available (e.g., urinary excretion data. Extension of the transfer coefficients to preadult ages are based on age-specific data for neptunium in baboons and rats, and the consistent findings for other actinide elements. It is assumed that the deposition fraction for bone is higher for preadults than for adults. Bone deposition fractions are 0.7 for ages 100 d and 1 y, 0.5 for ages 5–15 y, and 0.45 for adults. Deposition in the liver and urinary bladder contents are assumed to be reduced at preadult ages due to greater competition from the skeleton.
9. The structure of the systemic model for neptunium is shown in Fig 21.1. Parameter values are listed in Table 21.2.

Diagram

Description automatically generated

Fig 21.1. Structure of the systemic model for neptunium.

Table 21.2. Age-specific transfer coefficients for neptunium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 5.82E-02 | 5.82E-02 | 9.70E-02 | 9.70E-02 | 9.70E-02 | 1.94E-01 |
| Blood to Cort bone surf | 8.83E-01 | 8.83E-01 | 6.41E-01 | 6.41E-01 | 6.41E-01 | 3.93E-01 |
| Blood to Trab bone surf | 4.76E-01 | 4.76E-01 | 5.24E-01 | 5.24E-01 | 5.24E-01 | 4.80E-01 |
| Blood to Urinary bladder cont | 2.72E-01 | 2.72E-01 | 4.27E-01 | 4.27E-01 | 4.27E-01 | 6.21E-01 |
| Blood to Kidneys 1 | 2.91E-02 | 2.91E-02 | 2.91E-02 | 2.91E-02 | 2.91E-02 | 2.91E-02 |
| Blood to Kidneys 2 | 9.70E-03 | 9.70E-03 | 9.70E-03 | 9.70E-03 | 9.70E-03 | 9.70E-03 |
| Blood to Right colon cont | 1.36E-02 | 1.36E-02 | 1.36E-02 | 1.36E-02 | 1.36E-02 | 1.36E-02 |
| Blood to Testes | 3.90E-05 | 5.80E-05 | 6.60E-05 | 7.80E-05 | 6.20E-04 | 6.80E-04 |
| Blood to Ovaries | 2.30E-05 | 3.10E-05 | 7.80E-05 | 1.40E-04 | 2.30E-04 | 2.10E-04 |
| Blood to ST0 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 | 8.32E-01 |
| Blood to ST1 | 1.61E-01 | 1.61E-01 | 1.61E-01 | 1.61E-01 | 1.61E-01 | 1.61E-01 |
| Blood to ST2 | 3.88E-02 | 3.88E-02 | 3.88E-02 | 3.88E-02 | 3.88E-02 | 3.88E-02 |
| Liver 1 to Liver 2 | 1.77E-03 | 1.77E-03 | 1.77E-03 | 1.77E-03 | 1.77E-03 | 1.77E-03 |
| Liver 1 to Small intestine cont | 1.33E-04 | 1.33E-04 | 1.33E-04 | 1.33E-04 | 1.33E-04 | 1.33E-04 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Kidneys 1 to Urinary bladder cont | 4.95E-02 | 4.95E-02 | 4.95E-02 | 4.95E-02 | 4.95E-02 | 4.95E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| ST0 to Blood | 6.93E-01 | 6.93E-01 | 6.93E-01 | 6.93E-01 | 6.93E-01 | 6.93E-01 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |

aCort = Cortical, Trab = Trabecular, surf = surface, vol = volume, cont = content

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of neptunium is described in Section 18.2.4 of *Publication 141* (ICRP, 2019).

## Dosimetric data for neptunium

Table 21.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 237Np compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Neptunium nitrate | 5.3E-05 | 4.5E-05 | 2.2E-05 | 1.4E-05 | 1.2E-05 | 1.1E-05 |
| Type F | 6.4E-05 | 5.3E-05 | 2.5E-05 | 1.6E-05 | 1.4E-05 | 1.3E-05 |
| Type M, neptunium citrate, oxalate | 3.1E-05 | 2.8E-05 | 1.5E-05 | 9.8E-06 | 8.7E-06 | 8.2E-06 |
| Type S, neptunium dioxide | 5.3E-05 | 5.2E-05 | 3.7E-05 | 2.7E-05 | 2.6E-05 | 2.6E-05 |
| Ingested materials |  |  |  |  |  |  |
| All chemical forms | 1.5E-06 | 1.3E-07 | 6.2E-08 | 4.1E-08 | 3.5E-08 | 3.0E-08 |

Table 21.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 239Np compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Neptunium nitrate | 1.3E-09 | 9.3E-10 | 4.8E-10 | 3.1E-10 | 2.4E-10 | 2.1E-10 |
| Type F | 9.3E-10 | 6.6E-10 | 2.9E-10 | 1.7E-10 | 1.3E-10 | 9.9E-11 |
| Type M, neptunium citrate, oxalate | 1.9E-09 | 1.4E-09 | 8.1E-10 | 5.5E-10 | 4.5E-10 | 4.0E-10 |
| Type S, neptunium dioxide | 2.1E-09 | 1.6E-09 | 9.3E-10 | 6.3E-10 | 5.2E-10 | 4.7E-10 |
| Ingested materials |  |  |  |  |  |  |
| All chemical forms | 4.3E-10 | 3.7E-10 | 2.1E-10 | 1.6E-10 | 1.0E-10 | 8.5E-11 |

# Plutonium (Z=94)

## Routes of Intake

### Inhalation

1. There is extensive information available on the behaviour of plutonium after deposition in the respiratory tract from animal experiments (mainly in rats, dogs and baboons), in-vitrodissolution studies, some accidental human intakes, and one human volunteer study. For details see Section 22 of *Publication 141* (ICRP, 2019). Absorption parameter values and Types, and associated *f*A values for particulate forms of plutonium are given in Table 22.1 (taken from Section 22 of *Publication 141*).

Table 22.1. Absorption parameter values for inhaled and ingested plutonium.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | Absorption from the alimentary tract, *f*A\*\* | |
| *f*r | | *s*r (d–1) | | *s*s (d–1) | |
| Specific parameter values† | | | |  | |  | |  | |  | |
| Plutonium nitrate, Pu(NO3)4 | | | | 0.2 | | 0.4 | | 0.002 | | 1 × 10-4 | |
|  | | | |  | |  | |  | |  | |
| 239Pu dioxide‡, 239PuO2; plutonium in mixed oxide [(UO2 + PuO2) or (U,Pu)O2] | | | | 0.004 | | 0.4 | | 1 × 10-5 | | 2 × 10-6 | |
| 238Pu dioxide, 238PuO2 ceramic | | | | § | | § | | § | | 5 × 10-8 | |
| 238Pu dioxide, 238PuO2 non-ceramic | | | | ¶ | | ¶ | | ¶ | | 1 × 10-5 | |
| Plutonium dioxide 1-nm nanoparticles, 1-nm PuO2 | | | | 0.7 | | 0.4 | | 0.005 | | 3.5 × 10-4 | |
|  | | | |  | |  | |  | |  | |
| Default parameter values†† | | | |  | |  | |  | |  | |
| Absorption Type | Assigned forms | | |  | |  | |  | |  | |
| F | — | | | 1 | | 0.4 | | — | | 5 × 10-4 | |
| M‡‡ | Plutonium citrate; Plutonium tri-butyl-phosphate (Pu-TBP) ; Plutonium chloride (PuCl3) | | | 0.2 | | 0.4 | | 0.005 | | 1 × 10-4 | |
| S | — | | | 0.01 | | 0.4 | | 1 × 10-4 | | 5 × 10-6 | |
|  | | | |  | |  | |  | |  | |
| Ingested materials§§ | | | |  | |  | |  | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | 10 y | | 15 y | | adult |
| Soluble forms (nitrate, chloride, bicarbonates,..) and plutonium in food | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 |
| Insoluble forms (oxides, ..) | | 1 × 10-4 | 1 × 10-5 | | 1 × 10-5 | | 1 × 10-5 | | 1 × 10-5 | | 1 × 10-5 |

\*It is assumed that for plutonium a bound fraction *f*b = 0.002 with an uptake rate *s*b = 0 d–1 is applied throughout the respiratory tract, except in the ET1 region. The values of *s*r for Type F, M and S forms of plutonium (0.4 d–1) are element-specific.

†See Section 22 of *Publication 141* (ICRP, 2019) for summary of information on which parameter values are based, and on ranges of parameter values observed for individual materials. For plutonium specific parameter values are used for dissolution in the lungs, and in most cases, where information is available, for absorption from the alimentary tract. However, for plutonium dioxide nanoparticles, the default value of *f*A is used (footnote \*\*).

‡Plutonium in the dioxide form used in the production of nuclear fuel is predominantly 239Pu by activity, and for simplicity is here termed 239PuO2. It may, however, contain varying amounts of other isotopes, notably: 238Pu, 240Pu, 241Pu and 242Pu.

§See Section 22 of *Publication 141:* *s*p = 1 × 10–6 d–1, *s*pt = 0.0026 d–1, *s*t = 6 × 10–4 d–1 with *f*A = 5 × 10–8, for ceramic forms.

¶See Section 22 of *Publication 141*: *s*p = 0.001 d–1, *s*pt = 0.008 d–1, *s*t = 0.004 d–1 with *f*A = 1 × 10–5, for non-ceramic forms.

\*\*For inhaled material deposited in the respiratory tract and subsequent cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the (rounded) product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of plutonium applicable to the age-group of interest (*e.g.* 5 × 10–4 for adults).

††Materials (e.g. plutonium citrate) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see Section 22 of *Publication 141*.

‡‡Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

§§Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the highest value for ingestion of the radionuclide applicable to the age-group of interest (e.g. 5 × 10–4 for adults).

### Ingestion

1. *Adults*. Popplewell et al (1994) and Ham and Harrison (2000) measured the absorption of 244Pu administered in citrate solution with a mid-day meal to five volunteers. The values obtained were in the range of 10‑4 to 10-3, with a mean value of 6 × 10-4. The absorption of fallout plutonium from reindeer meat was measured by Mussalo-Rauhamaa et al. (1984). An absorption fraction of 8 × 10-4 was obtained by comparing the ratio of body content to dietary intake of 239/240Pu in persons who had lived in Lappland or the urban areas of southern Finland. Combining the results of two separate studies, in each of which the urinary excretion of 239/240Pu and 241Am was measuredin six men and two women after consumption of winkles from Cumbria, UK (Hunt et al., 1986, 1989, 1990), the estimated absorption fraction was 2 × 10-4 (range 2 × 10-5 to 4.9 × 10-4) for plutonium. A similar volunteer study involved 5 males and 1 female who ate cockles from Cumbria (Hunt, 1998) and provided absorption fractions in the order of 2-3 × 10-4 (range 0–7 × 10-4).
2. Animal data on the absorption of plutonium in species including rodents, pigs, dogs and primates was extensively reviewed in *Publications 48* (ICRP, 1986) and *100* (ICRP, 2006) and by Harrison (1983, 1991), and they were summarized in *Publication 141* (ICRP, 2019). The ingested chemical form is an important factor affecting absorption. The lowest values obtained are for the oxide, ranging from about 3 × 10-8 to about 2 × 10-4. The range of most values of uptake for plutonium administered to animals as the nitrate, chloride or bicarbonate is between 10-5 and 10-4. The greatly expanded body of data on the absorption of plutonium from the gastrointestinal tract indicates that absorption is influenced by the mass ingested, by its initial oxidation state, by fasting, by incorporation into foodstuffs, by complexing anions, such as citrate and DTPA, and by a variety of other factors. Fasting has been shown to increase absorption by up to an order of magnitude. A milk diet and a calcium, iron, vitamin D, or zinc deficient diet have been seen to increase absorption in animals. The absorption of Pu administered to animals as organic complexes or incorporated into food materials is generally greater than for inorganic forms. However, the available data allow no clear conclusion about the magnitude of the influence of biological incorporation into food on the absorption of plutonium (ICRP, 1986).
3. *In Publication 30* (ICRP, 1979), the recommended absorption fractions were 10-5 for oxides and hydroxides and 10-4 for all other forms. In *ICRP Publication 48* (ICRP, 1986) the gastrointestinal absorption of plutonium was extensively reviewed. It was concluded that an absorption fraction of 10-3 would provide an adequate margin of safety for ingestion of unknown forms or mixed compounds of plutonium by adult humans. The same value was used in *Publication 56* (ICRP, 1990). On the basis of results from human studies and taking account of animal data showing wide variations in fractional absorption, an absorption fraction for unknown forms of plutonium, including uptake from food, of 5 × 10-4 was recommended in *Publication 67* (ICRP, 1993). In *Publication 141* (ICRP, 2019), it was considered that the available data provided a sufficient basis for the use of a general value of 5 × 10-4 for all actinides other than uranium. The same value of *f*A = 5 × 10-4 is adopted here for plutonium ingested in food by adults. An *f*A = 5 × 10-4 is also adopted for plutonium ingested in other soluble forms and an *f*A = 1 × 10-5 is adopted for plutonium ingested in insoluble forms.
4. *Children*. *Publication 48* reviewed strong experimental evidence to conclude that plutonium absorption from the gastrointestinal tract may be increased by at least an order of magnitude in the human neonate, but that any increased absorption would probably decrease rapidly during the first few days or weeks of life. The age by which absorption of plutonium might decrease to adult levels is not known, but animal studies indicate that adult values may be reached by about the time of weaning. *Publication 56* recommended an absorption fraction of 10-2 as an average for the first year of life and 10-3 for all succeeding years. In *Publication 67*, the lattest human data were taken into account to update the recommended values to 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older. Harrison et al. (2001) proposed confidence intervals of 1 × 10-4 to 1 × 10-3 for adults and children, and 1 × 10-4 to 1 × 10-2 for 3-month-old infants. The same values as in *Publication 67* are adopted here for children *f*A ingesting plutonium in food and for other soluble forms. For insoluble forms, an *f*A = 1 × 10-4 is adopted for 3-month-old infants and an *f*A = 1 × 10-5 is adopted for older children.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. In the mid-1940s, 18 seriously ill persons were injected with tracer amounts of Pu citrate or nitrate to investigate the relation of the systemic burden and excretion rate of Pu (Langham, 1959; Langham et al., 1950). The life expectancies of the subjects of the “Langham study” were judged to be short at the time of injection, but eight were still alive after 8 y and four survived at least 3 decades (Rowland and Durbin, 1976). Measurements of activity in blood and excreta were made frequently during the early weeks after injection, and a few additional excretion measurements were made for two of the subjects through 4.5 y (Durbin, 1972; Langham et al., 1950). The concentration of Pu in tissues was determined in samples collected at autopsy from subjects dying in the first 15 months after injection (Durbin, 1972; Langham et al., 1950). Langham and coworkers estimated on the basis of the autopsy results that on average 66% of Pu entering blood deposited in the skeleton and 23% deposited in the liver. Durbin (1972) reanalysed the data to account for the non-uniformity of Pu in bone samples and estimated that about 50% of the systemic burden was contained in the skeleton and 30% was contained in the liver at 4–457 d after injection.
2. Excretion data from the Langham study were used by ICRP as the primary basis for bioassay models (e.g. power functions or sums of exponential terms) for Pu until the 1990s, when the systemic model of *Publication 67* was adopted as both a dosimetric and bioassay model (ICRP, 1993, 1997). Parameter values of the *Publication 67* model describing the short- and intermediate-term behaviour of Pu, including its urinary and faecal excretion rates and initial division between bone and liver, were heavily influenced by data from the Langham study. However, modeling of the long-term distribution and excretion of Pu was guided largely by excretion and autopsy data for Pu workers (Kathren et al., 1988; Kathren and McInroy, 1991; Leggett, 1985; Leggett and Eckerman, 1987; McInroy et al., 1989; McInroy and Kathren, 1990), which differed greatly from projections based on the Langham data with regard to long-term urinary and faecal excretion rates.
3. Much additional excretion and autopsy data for Pu workers have been published since the completion of *Publication 67* (*e.g.* Ehrhart and Filipy, 2001; Filipy, 2001, 2003; James and Brooks, 2006; Khokhryakov et al., 1994, 2000; Suslova et al., 1996, 2002, 2009, 2012) Post-1993 information on the systemic behaviour of Pu also includes results of two studies involving intravenous administration of Pu isotopes to healthy volunteers. One of the studies, initiated at the Harwell Laboratory in Great Britain, involved six adult males and six adult females (Newton et al., 1998; Talbot et al., 1993, 1997; Warner et al., 1994). The other, conducted at the National Radiological Protection Board (NRPB) in Great Britain, involved five adult males (Ham and Harrison, 2000; Popplewell et al., 1994). Data from the Harwell study include measurements of urinary and fecal excretion rates up to 5 y, the concentration of Pu in blood up to 6 y, external measurements of Pu in the liver for more than a year after injection, and limited measurements on other tissues. In the NRPB subjects, the urinary excretion rate was determined over two decades after injection.
4. Comparisons of the post-1993 data with information underlying the *Publication 67* (ICRP, 1993) model show reasonable consistency with regard to blood clearance, total-body retention, daily urinary and faecal excretion, the time-dependent fraction of systemic plutonium in skeleton plus liver, and the long-term division of Pu between skeleton and liver. However, the newer information provides a different picture of certain aspects of the early behaviour of Pu, most notably the initial division between the liver and skeleton. In the Harwell injection study, peak estimates of the liver content based on external measurements averaged more than 70% of the administered activity, compared with earlier indications that the liver typically accumulates 30% or less of the Pu reaching blood. The expanded set of autopsy data for Pu workers indicates that there is considerable variability in the division of activity between the liver and skeleton at all measurement times, with the skeleton containing more Pu than the liver in some cases and less in others (Ehrhart and Filipy, 2001; McInroy et al., 1989; Schofield and Dolphin, 1974; Suslova et al., 1996, 2002). The central tendencies of the autopsy data indicate, however, that the liver typically is the more important repository soon after exposure and that there is a gradual shift of activity from the liver to the skeleton.
5. The systemic behaviour of Pu has been studied in a variety of laboratory animals including baboons, monkeys, dogs, swine, rats, mice, hamsters, rabbits, tree shrews, and sheep (Durbin, 1972, 1975, 2011; Taylor, 1984). As is the case for humans, the various animal species generally have shown high deposition and tenacious retention in the skeleton, as well as a high initial concentration in the liver. However, considerable differences among species are seen regarding the residence time of Pu by the liver. For example, the residence time in liver is measured in days, weeks, or months in rats, monkeys, and baboons, but in years or decades in hamsters, dogs, pigs, and humans (Taylor, 1984). The short retention time in the liver seen in humansy species appears to be primarily the result of a high rate of biliary secretion of Pu.
6. Information on variation with age in the biokinetics of plutonium comes mainly from studies of the age-specific behaviour of plutonium and other actinide elements in laboratory animals. In animals of all ages, about 80–90% of the amount entering blood is initially divided between bone and liver. The ratio of the deposition fraction of actinides in bone to that in liver generally is substantially higher in growing animals than in mature animals. For example, the skeletons of beagles injected with 239Pu at ages 2 d, 3 mo, 1.5 y, or 5 y contained about 80%, 63%, 46%, and 43%, respectively, of the injected amount at 1 wk after administration (Bruenger et al., 1989). The rate of removal of plutonium in the skeleton depends on the bone turnover rate, which is also substantially higher in growing animals than mature animals.
   * + 1. Systemic model
7. The systemic model for workers used in *Publication 141* (ICRP, 2019) is applied here to adult members of the public. The model for adults updates the model applied to adult members of the public in *Publication 67* (ICRP, 1993) and to workers in *Publication 68* (ICRP, 1994a) to reflect a substantially expanded database, particularly data from two Pu injection studies involving healthy human subjects and considerably expanded sets of bioassay and autopsy data for Pu workers.
8. The most important change from the model of *Publication 67* concerns the initial distribution of absorbed or injected Pu: *Publication 67* assigns deposition fractions of 0.5 and 0.3 to bone and liver, respectively, while the updated model assigns fractions 0.3 and 0.6, respectively, based on the later human injection studies together with central tendencies indicated by autopsy data for Pu workers whose body burdens represented a wide range of times since exposure.
9. The structure of the updated model for Pu is shown in Fig 22.1. A summary of parameter values for adults is given below. Extension of these parameter values to preadult ages is then described.

##### Circulation

1. Circulating Pu is defined as Pu in blood plus rapid-turnover soft tissues (ST0 in Fig 22.1). Blood consists of two compartments, Blood 1 and Blood 2. Blood 2 receives recycled Pu and feeds ST0, Blood 1, and the urinary bladder contents. This provides a physically meaningful way of implementing the assumption, based on results of human injection studies, that fractional clearance from blood to urine increases for some time after the initial entry of Pu into blood. Specifically, it is assumed that the initial input to blood distributes rapidly (half-time of 1 min) between a blood compartment called Blood 1 (70%) and a soft tissue compartment called ST0 (30%). Pu leaves Blood 1 with a half-time of 0.9 d. Soft tissue compartment ST0 empties into Blood 1 with a half-time of 7 d. All other feeds from tissues back to blood are to Blood 2. Pu is removed from Blood 2 at the rate 100 d-1 (T1/2 ~ 10 min), with 3.5% going to the urinary bladder contents, 0.3 × (100-3.5)% = 28.95% going to ST0, and 0.7 × (100-3.5)% = 67.55% going to Blood 1. In effect, the portion of activity leaving Blood 2 that does not go directly to the urinary bladder contents is assumed to distribute in the same way as the original input to blood.

##### Liver and fecal excretion

1. Rapid, intermediate and slow phases of removal from the liver are depicted. Plutonium moves from Blood 1 to the rapid-turnover compartment Liver 0. Some Pu entering Liver 0 is lost in bile, but most moves to a compartment within the hepatocytes with intermediate-term retention (Liver 1). Most of the activity lost from Liver 1 goes to Blood 2, but a portion enters reticuloendothelial cells (Liver 2), from which it is slowly lost to Blood 2. It is assumed that:

* Age-specific: 60% of activity leaving the circulation goes to Liver 0.
* For all ages, the removal half-time from Liver 0 is 15 d; 2% goes to the contents of the small intestine and 98% to Liver 1.
* For all ages, the removal half-time from Liver 1 is 1 year; 80% goes to Blood 2 and 20% to Liver 2.
* For all ages, the removal half-time from Liver 2 to Blood 2 is 15 years.
* For all ages, 1.5% of Pu leaving the circulation goes to the contents of the upper large intestine.

##### Bone

1. It is assumed that:

* Age-specific: 30% of Pu leaving circulation deposits in bone; 18% goes to trabecular bone and 12% to cortical bone.
* 90% of the trabecular deposit and 95% of the cortical deposit is on bone surface, with the remainder entering bone volume by depositing in bone-forming sites. These values are applied to all age groups.
* Transfer from cortical or trabecular bone surface or volume to cortical marrow is the reference rate of bone remodeling (ICRP, 2002), which varies with age for both bone types (ICRP, 2002).
* The burial rate of surface Pu is one-fourth the reference rate of bone remodeling for both bone types.
* The removal half-time from bone marrow to Blood 2 is 0.25 y.

##### Kidneys and urinary excretion

1. The model of Publication 67 includes a transfer from the intermediate-term soft-tissue compartment, ST1, to the urinary path. This transfer was used to model an increase with time in daily urinary clearance of circulating Pu, as observed in human injection studies. In the present model a blood compartment called Blood 2 is used to model a change with time in urinary clearance of circulating Pu. Plutonium that returns to blood from all systemic compartments except the rapid-turnover soft-tissue compartment ST0 is assumed to be cleared to the urinary bladder content at a higher rate than was the initial input of Pu to blood. It is assumed that:

* 2% of Pu leaving Blood 1 goes directly to the urinary bladder contents.
* 1% of Pu leaving Blood 1 goes to kidneys (Renal tubules in Fig 22.1) and is removed to the bladder contents with T1/2 = 40 d.
* 0.05% of Pu leaving Blood 1 goes to a long-term kidney compartment (Other kidney) from which it is removed to Blood 2 with a half-time of 15 y.

1. As described earlier, 3.5% of Pu leaving Blood 2 (recycled Pu) goes directly to urinary bladder contents. Blood 2 also feeds the urinary bladder contents indirectly, since most of the activity leaving Blood 2 goes to Blood 1.

##### Gonads

1. Deposition fractions for the testes and ovaries are the same as used in the Pu model of *Publication 67*, but the removal half-time from gonads is reduced from 10 y to 5 y based on comparisons of model predictions with updated information for workers and laboratory animals:

* 0.035% of Pu leaving the circulation deposits in the testes.
* 0.011% of Pu leaving the circulation deposits in the ovaries.
* The removal half-time from gonads to Blood 2 is 5 years.

##### Other soft tissues

1. Parameter values for ST0 were given earlier. For ST1 and ST2 it is assumed that:

* 3% of Pu leaving the circulation goes to ST2.
* The removal half-time from ST2 to Blood 2 is 15 y.
* The balance of Pu leaving the circulation (2.404%, after assignment of all other deposition fractions) goes to ST1.
* The removal half-time from ST1 to Blood 2 is 500 d.

1. The extension of transfer coefficients from mature adults to preadult ages is based on assumptions similar to those applied in *Publication 67*. These assumptions reflect the pattern of change with age in plutonium kinetics observed in laboratory animals, including elevated uptake of plutonium and decreased uptake by liver at preadult ages, compared with adult values. The assumptions that the deposition in the gonads represents 0.001% of outflow from blood per gram of tissue is carried over to preadult ages, resulting in lower deposition fractions in gonads at preadult ages due to relatively smaller masses of sex organs. The generic bone model for bone-surface-seeking radionuclides is applied to plutonium depositing in bone, resulting in faster turnover of the bone deposit at preadult ages due to higher bone turnover rates than in adults. For all ages, bone surface and liver are assumed to receive 90% of plutonium leaving the circulation.

Diagram

Description automatically generated

Fig 22.1. Structure of the model for systemic plutonium. SI = Small intestine, RC = Right colon, LC =Left colon, RS = rectosigmoid colon.

1. For adults it is assumed that trabecular bone receives 60% and cortical bone 40% of the amount depositing in bone. For pre-adults it is assumed that trabecular and cortical bone each receive 50% of the skeletal deposit. For all ages 90% of the trabecular deposit is assigned to bone surface and 10% to bone volume. For all ages, 95% of the trabecular deposit is assigned to bone surface and 5% to bone volume.
2. Parameter values in the age-specific model for plutonium that vary with age are listed in Table 22.2. The full set of age-specific transfer coefficients in the model for Pu is given in Table 22.3.

Table 22.2. Parameter values in the model for systemic plutonium that vary with age.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Parameter | Value | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Deposition fraction for trabecular bone | 3.75E-01 | 3.75E-01 | 3.00E-01 | 3.00E-01 | 3.00E-01 | 1.80E-01 |
| Deposition fraction for cortical bone | 3.75E-01 | 3.75E-01 | 3.00E-01 | 3.00E-01 | 3.00E-01 | 1.20E-01 |
| Deposition fraction for liver | 1.50E-01 | 1.50E-01 | 3.00E-01 | 3.00E-01 | 3.00E-01 | 6.00E-01 |
| Deposition fraction for testes | 2.00E-05 | 3.00E-05 | 3.40E-05 | 4.00E-05 | 3.20E-04 | 3.50E-04 |
| Deposition fraction for ovaries | 1.20E-05 | 1.60E-05 | 4.00E-05 | 7.00E-05 | 1.20E-04 | 1.10E-04 |
| Transfer rate from trabecular bone surface or volume to blood | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Transfer rate from cortical bone surface or volume to blood | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Transfer rate from trabecular bone surface to trabecular bone volume | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 1.23E-04 |
| Transfer rate from cortical bone surface to cortical bone volume | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 2.05E-05 |

Table 22.3. Age-specific transfer coefficients for plutonium. Absorbed plutonium is assumed to enter Blood 0.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood 0 to ST0 | 3.00E+02 | 3.00E+02 | 3.00E+02 | 3.00E+02 | 3.00E+02 | 3.00E+02 |
| 0 to Blood 1 | 7.00E+02 | 7.00E+02 | 7.00E+02 | 7.00E+02 | 7.00E+02 | 7.00E+02 |
| Blood 1 to Liver 1 | 1.16E-01 | 1.16E-01 | 2.31E-01 | 2.31E-01 | 2.31E-01 | 4.62E-01 |
| Blood 1 to Cort bone surf | 2.74E-01 | 2.74E-01 | 2.20E-01 | 2.20E-01 | 2.20E-01 | 8.78E-02 |
| Blood 1 to Cort bone vol | 1.44E-02 | 1.44E-02 | 1.16E-02 | 1.16E-02 | 1.16E-02 | 4.62E-03 |
| Blood 1 to Trab bone surf | 2.60E-01 | 2.60E-01 | 2.08E-01 | 2.08E-01 | 2.08E-01 | 1.25E-01 |
| Blood 1 to Trab bone vol | 2.89E-02 | 2.89E-02 | 2.31E-02 | 2.31E-02 | 2.31E-02 | 1.39E-02 |
| Blood 1 to Urinary bladder cont | 1.54E-02 | 1.54E-02 | 1.54E-02 | 1.54E-02 | 1.54E-02 | 1.54E-02 |
| Blood 1 to Kidneys 1 | 7.70E-03 | 7.70E-03 | 7.70E-03 | 7.70E-03 | 7.70E-03 | 7.70E-03 |
| Blood 1 to Kidneys 2 | 3.85E-04 | 3.85E-04 | 3.85E-04 | 3.85E-04 | 3.85E-04 | 3.85E-04 |
| Blood 1 to Right colon cont | 1.16E-02 | 1.16E-02 | 1.16E-02 | 1.16E-02 | 1.16E-02 | 1.16E-02 |
| Blood 1 to Testes | 1.54E-05 | 2.31E-05 | 2.62E-05 | 3.08E-05 | 2.46E-04 | 2.70E-04 |
| Blood 1 to Ovaries | 9.24E-06 | 1.23E-05 | 3.08E-05 | 5.39E-05 | 9.24E-05 | 8.47E-05 |
| Blood 1 to ST1 | 1.85E-02 | 1.85E-02 | 1.85E-02 | 1.85E-02 | 1.85E-02 | 1.85E-02 |
| Blood 1 to ST2 | 2.31E-02 | 2.31E-02 | 2.31E-02 | 2.31E-02 | 2.31E-02 | 2.31E-02 |
| ST0 to Blood 1 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Blood 2 to Urinary bladder cont | 3.50E+00 | 3.50E+00 | 3.50E+00 | 3.50E+00 | 3.50E+00 | 3.50E+00 |
| Blood 2 to Blood 1 | 6.76E+01 | 6.76E+01 | 6.76E+01 | 6.76E+01 | 6.76E+01 | 6.76E+01 |
| Blood 2 to ST0 | 2.90E+01 | 2.90E+01 | 2.90E+01 | 2.90E+01 | 2.90E+01 | 2.90E+01 |
| Kidneys 1 to Urinary bladder cont | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 | 1.73E-02 |
| Kidneys 2 to Blood 2 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 |
| ST1 to Blood 2 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| ST2 to Blood 2 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 |
| Liver 1 to SI cont | 9.24E-04 | 9.24E-04 | 9.24E-04 | 9.24E-04 | 9.24E-04 | 9.24E-04 |
| Liver 1 to Liver 2 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 | 4.53E-02 |
| Liver 2 to Blood 2 | 1.52E-03 | 1.52E-03 | 1.52E-03 | 1.52E-03 | 1.52E-03 | 1.52E-03 |
| Liver 2 to Liver 3 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Liver 3 to Blood 2 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 | 1.27E-04 |
| Testes to Blood 2 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood 2 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 2.05E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 1.23E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Cort marrow to Blood 2 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab marrow to Blood 2 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |

aCort = Cortical, Trab = Trabecular, cont=content, surf=surface, vol = volume, SI = Small intestine

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of plutonium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for plutonium

Table 22.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 238Pu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Plutonium nitrate, Pu(NO3)4 | 5.1E-05 | 4.8E-05 | 3.2E-05 | 2.3E-05 | 2.2E-05 | 2.3E-05 |
| Plutonium-239 dioxide, 239PuO2; Plutonium in mixed oxide (MOX: (UO2 + PuO2) or (U,Pu)O2) | 7.9E-05 | 7.9E-05 | 6.0E-05 | 4.7E-05 | 4.5E-05 | 4.4E-05 |
| Plutonium-238 dioxide, 238PuO2 ceramic | 4.8E-05 | 4.7E-05 | 3.1E-05 | 2.1E-05 | 1.9E-05 | 2.0E-05 |
| Plutonium-238 dioxide, 238PuO2 non-ceramic | 4.7E-05 | 4.5E-05 | 2.9E-05 | 2.1E-05 | 1.9E-05 | 2.1E-05 |
| Plutonium dioxide 1-nm nanoparticles, 1-nm PuO2 | 6.3E-05 | 5.8E-05 | 3.9E-05 | 2.8E-05 | 2.8E-05 | 3.0E-05 |
| Type F | 6.9E-05 | 6.3E-05 | 4.3E-05 | 3.1E-05 | 3.1E-05 | 3.3E-05 |
| Type M, plutonium citrate; Plutonium tri-butyl-phosphate (Pu-TBP) ; Plutonium chloride (PuCl3) | 5.3E-05 | 5.0E-05 | 3.3E-05 | 2.4E-05 | 2.3E-05 | 2.5E-05 |
| Type S | 6.1E-05 | 6.1E-05 | 4.3E-05 | 3.2E-05 | 3.1E-05 | 3.1E-05 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms (nitrate,chloride, bicarbonates,…) | 2.9E-06 | 2.5E-07 | 1.6E-07 | 1.2E-07 | 1.1E-07 | 1.1E-07 |
| Insoluble forms (oxides,…) | 5.9E-08 | 5.1E-09 | 3.2E-09 | 2.4E-09 | 2.1E-09 | 2.2E-09 |

Table 22.5. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 239Pu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Plutonium nitrate, Pu(NO3)4 | 5.2E-05 | 4.9E-05 | 3.4E-05 | 2.5E-05 | 2.3E-05 | 2.5E-05 |
| Plutonium-239 dioxide, 239PuO2; Plutonium in mixed oxide (MOX: (UO2 + PuO2) or (U,Pu)O2) | 8.4E-05 | 8.6E-05 | 6.6E-05 | 5.2E-05 | 5.0E-05 | 4.8E-05 |
| Plutonium dioxide 1-nm nanoparticles, 1-nm PuO2 | 6.5E-05 | 6.1E-05 | 4.3E-05 | 3.2E-05 | 3.1E-05 | 3.3E-05 |
| Type F | 7.2E-05 | 6.6E-05 | 4.7E-05 | 3.5E-05 | 3.5E-05 | 3.7E-05 |
| Type M, plutonium citrate; Plutonium tri-butyl-phosphate (Pu-TBP) ; Plutonium chloride (PuCl3) | 5.4E-05 | 5.2E-05 | 3.5E-05 | 2.6E-05 | 2.5E-05 | 2.7E-05 |
| Type S | 6.3E-05 | 6.2E-05 | 4.5E-05 | 3.4E-05 | 3.3E-05 | 3.3E-05 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms (nitrate,chloride, bicarbonates,…) | 3.0E-06 | 2.6E-07 | 1.8E-07 | 1.3E-07 | 1.2E-07 | 1.2E-07 |
| Insoluble forms (oxides,…) | 6.0E-08 | 5.3E-09 | 3.5E-09 | 2.7E-09 | 2.4E-09 | 2.4E-09 |

Table 22.6. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 240Pu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Plutonium nitrate, Pu(NO3)4 | 5.2E-05 | 5.0E-05 | 3.4E-05 | 2.5E-05 | 2.3E-05 | 2.5E-05 |
| Plutonium-239 dioxide, 239PuO2; Plutonium in mixed oxide (MOX: (UO2 + PuO2) or (U,Pu)O2) | 8.4E-05 | 8.6E-05 | 6.6E-05 | 5.2E-05 | 5.0E-05 | 4.8E-05 |
| Plutonium dioxide 1-nm nanoparticles, 1-nm PuO2 | 6.5E-05 | 6.1E-05 | 4.3E-05 | 3.2E-05 | 3.1E-05 | 3.3E-05 |
| Type F | 7.2E-05 | 6.6E-05 | 4.7E-05 | 3.5E-05 | 3.5E-05 | 3.7E-05 |
| Type M, plutonium citrate; Plutonium tri-butyl-phosphate (Pu-TBP) ; Plutonium chloride (PuCl3) | 5.4E-05 | 5.2E-05 | 3.5E-05 | 2.6E-05 | 2.5E-05 | 2.7E-05 |
| Type S | 6.3E-05 | 6.2E-05 | 4.5E-05 | 3.4E-05 | 3.3E-05 | 3.3E-05 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms (nitrate,chloride, bicarbonates,…) | 3.0E-06 | 2.6E-07 | 1.8E-07 | 1.3E-07 | 1.2E-07 | 1.2E-07 |
| Insoluble forms (oxides,…) | 6.0E-08 | 5.3E-09 | 3.5E-09 | 2.7E-09 | 2.4E-09 | 2.4E-09 |

Table 22.7. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 241Pu compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Plutonium nitrate, Pu(NO3)4 | 3.2E-07 | 3.3E-07 | 2.6E-07 | 2.1E-07 | 2.1E-07 | 2.2E-07 |
| Plutonium-239 dioxide, 239PuO2; Plutonium in mixed oxide (MOX: (UO2 + PuO2) or (U,Pu)O2) | 1.2E-06 | 1.3E-06 | 1.1E-06 | 9.7E-07 | 9.6E-07 | 9.1E-07 |
| Plutonium dioxide 1-nm nanoparticles, 1-nm PuO2 | 5.1E-07 | 5.0E-07 | 4.1E-07 | 3.3E-07 | 3.4E-07 | 3.4E-07 |
| Type F | 6.0E-07 | 5.8E-07 | 4.8E-07 | 3.9E-07 | 4.0E-07 | 4.0E-07 |
| Type M, plutonium citrate; Plutonium tri-butyl-phosphate (Pu-TBP) ; Plutonium chloride (PuCl3) | 3.6E-07 | 3.7E-07 | 3.0E-07 | 2.4E-07 | 2.4E-07 | 2.5E-07 |
| Type S | 5.4E-07 | 5.8E-07 | 5.0E-07 | 4.3E-07 | 4.5E-07 | 4.5E-07 |
| Ingested materials |  |  |  |  |  |  |
| Soluble forms (nitrate,chloride, bicarbonates,…) | 2.0E-08 | 1.9E-09 | 1.5E-09 | 1.2E-09 | 1.1E-09 | 1.1E-09 |
| Insoluble forms (oxides,…) | 4.1E-10 | 3.9E-11 | 3.0E-11 | 2.5E-11 | 2.2E-11 | 2.3E-11 |

# Americium (Z=95)

## Routes of intake

### Inhalation

1. There is a substantial amount of information available on the behaviour of americium (Am) after deposition in the respiratory tract, from animal experiments, in-vitrodissolution studies, and some accidental human intakes. For details see Section 23 of *Publication 141* (ICRP, 2019). As described in Section 18 of *Publication 141*, the general actinide section, absorption parameter values based on plutonium (*s*r = 0.4 d–1; *f*b =0.002; *s*b = 0 d–1) are applied in that document (and hence also in this document) to the transplutonium elements for radiation protection purposes. Absorption parameter values and Types, and associated *f*A values for particulate forms of americium, are given in Table 23.1. (taken from Section 23 of *Publication 141*).

Table 23.1. Absorption parameter values for inhaled and ingested americium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | | Absorption parameter values\* | | | | | | | | Absorption from the alimentary tract, *f*A† | | |
| *f*r | *s*r (d–1) | | | *s*s (d–1) | | | |
| Specific parameter values‡ | | | | |  |  | | |  | | | |  | | |
| Americium nitrate | | | | | 0.6 | 0.4 | | | 0.005 | | | | 3 × 10–4 | | |
|  | | | | |  |  | | |  | | | |  | | |
| Default parameter values§ | | | | |  |  | | |  | | | |  | | |
| Absorption Type | | Assigned forms | | |  |  | | |  | | | |  | | |
| F | | Citrate | | | 1 | 0.4 | | | – | | | | 5 × 10–4 | | |
| M¶ | | Oxide, chloride | | | 0.2 | 0.4 | | | 0.005 | | | | 1 × 10–4 | | |
| S | | Americium associated with plutonium oxide | | | 0.01 | 0.4 | | | 1 × 10–4 | | | | 5 × 10–6 | | |
|  | | | | |  | |  | | | |  | |  | | |
| Ingested material\*\* | | | | |  | | |  | | | |  |  | | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | | | 10 y | | | | 15 y | adult |
| All forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | | | 5 × 10-4 | | | | 5 × 10-4 | 5 × 10-4 | |

\*It is assumed that for americium a bound fraction *f*b = 0.002 with *s*b = 0 d–1 is applied throughout the respiratory tract except in the ET1 region. The values of *s*r for Type F, M and S forms of americium (0.4 d–1) are element-specific.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of americium applicable to the age-group of interest (*e.g*. 5 × 10–4 for adults).

‡See Section 23 of *Publication 141* (ICRP, 2019) for summary of information on which parameter values are based, and on ranges of parameter values observed in different studies. For americium nitrate, specific parameter values are used for dissolution in the lungs, but a default value of *f*A (footnote †).

§Materials (e.g.americium oxide) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values or because specific parameter values would not be significantly different from the default (see Section 23 of *Publication 141*).

¶Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

\*\*Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference for ingestion of the radionuclide applicable to the age-group of interest (*e.g*. 5 × 10-4 for adults).

### Ingestion

1. *Adults*. Compared to plutonium and neptunium, limited data are available on the absorption of americium. The only human data are those from Hunt et al (1998; 1986, 1990) who carried out two studies on the absorption of plutonium and americium by eight volunteers eating shellfish winkles collected on the Cumbrian coast near to the nuclear‑fuel reprocessing plant at Sellafield. The overall absorption fraction obtained for americium was 1 × 10‑4 with a range from 4 × 10‑5 to 3 × 10‑4 (Hunt et al., 1986, 1990). A similar volunteer study involved 6 volunteers who ate cockles from Cumbria (Hunt, 1998) and provided absorption fractions in the order of 1.2 × 10-4 (range 3 × 10-5 to 2.6 × 10-4). Animal data on the absorption of americium was reviewed in *Publications 48* (ICRP, 1986), *100* (ICRP, 2006) and *141* (ICRP, 2019), and by Harrison (Harrison, 1991, 1995). For adult animals of all the species studied, and for all types of ingested compounds, the fractional absorption for americium lies between 3 × 10-6 and 1 × 10-3. Very limited information is available concerning the absorption of americium after biological incorporation into foodstuffs and the available data indicate no greatly enhanced absorption of the element. Several factors such as fasting and iron deficient diet are known to increase the gastrointestinal absorption of americium. In *Publication 30* (ICRP, 1980), an absorption fraction of 5 × 10-4 was recommended. In *Publication 48* (ICRP, 1986), a general value of 1 × 10-3 for actinides was used. This value was also recommended in *Publication 56* (ICRP, 1990). In *Publications 67* (ICRP, 1993) and *141* (ICRP, 2019), on the basis of data showing similar levels of absorption for neptunium, plutonium, americium and curium, and variations in fractional absorption resulting from differences in chemical forms, a general absorption fraction for unknown forms of the four actinides, including uptake from food, of 5 × 10-4 was recommended. The same value of *f*A = 5 × 10-4 is adopted here for all chemical forms of americium ingested by adult members of the public.
2. *Children*. Absorption of americium by neonatal rats is about two orders of magnitude greater than in adult animals; high absorption has also been found in neonatal pigs (ICRP, 1986). *Publication 56* recommended an absorption fraction for americium of 10-2 as an average for the first year of life and 10-3 for all succeeding years. In *Publication 67*, the latest data were taken into account to update the recommended values to 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older. The same values are adopted here for children *f*A.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The biokinetics of systemic americium has been investigated in workers exposed to 241Am or its parent 241Pu, which is tenaciously retained in systemic tissues and decays to 241Am with a half-time of 14.4 y. Reported data for workers include urinary and faecal levels of 241Am, external measurements of 241Am in bone and liver of living subjects, and 241Am in a liver, bone, and other tissues collected at autopsy.
2. Data for direct intake of relatively pure 241Am (i.e., not mixed with a significant amount of its parent 241Pu) are preferred for modelling americium kinetics but are available for only a few subjects, some of whom received chelation therapy that may have altered the systemic kinetics of Am (Breitenstein Jr and Palmer, 1989; Doerfel and Oliveira, 1989; Fry, 1976; Heid and Robinson, 1985; Malátová et al., 2003, 2010; Rosen et al., 1980; Whalen and Davies, 1972; Wrenn et al., 1972). More extensive observations are available for workers whose systemic 241Am burden may have resulted largely from decay of systemic 241Pu (Kathren et al., 1988, 1997; Kathren and McInroy, 1992; Lynch et al., 1989; McInroy et al., 1989; Popplewell and Ham, 1989; Suslova et al., 2013). Data for the latter cases suggest that 241Am migrates from 241Pu over time, resulting in a skeleton to liver activity ratio (ratio of total activity in the skeleton to that in liver) that is typically much larger for 241Am than for its parent 241Pu. However, 241Am produced in bone and perhaps at some soft-tissue sites (e.g. in reticulendothelial cells) may remain with 241Pu for an extended period. Thus, 241Am produced *in vivo* by decay of 241Pu may reflect some combination of the systemic behaviour of americium and that of plutonium.
3. There are broad similarities in the systemic behaviour of plutonium and initially pure americium but also notable differences, particularly in their long-term distributions. For both elements there is early uptake of about 70–90% of the injected amount by the liver and skeleton, with the liver initially containing the greater portion on average in mature humans and in most but not all studied mature laboratory animals. Notable differences in the systemic behaviours of these two elements include an initially higher rate of urinary excretion of americium and faster removal of americium from the liver. There are also differences in the sites of deposition of americium and plutonium on bone surfaces and perhaps associated differences in the net rate of removal of these elements from bone.
4. Americium-241 has been measured in the total body or selected tissues of many Transuranium and Uranium Registries (USTUR) donors with occupational exposures to 241Pu or mixtures of 241Pu and 241Am and in a few cases to relatively pure forms of 241Am. For seven whole body donors (Filipy, 2003; McInroy et al., 1989), the 241Am contents of the skeleton, liver, and other soft tissues represented on average about 74%, 8%, and 18%, respectively, of systemic 241Am.
5. A detailed autopsy study of the tissue distribution of 241Am was conducted for a radiochemist (USTUR Case 0102) thought to have been exposed through contamination of a wound while working with an unsealed 241Am source ~25 y before his death (Breitenstein et al., 1985; Durbin and Schmidt, 1985; Heid and Robinson, 1985; McInroy et al., 1985). The skeleton, liver, kidneys, and other soft tissues contained 82.3%, 6.4%, 0.25%, and 11.0%, respectively, of the systemic burden. About 80% of skeletal activity was contained in compact bone together with the portion of trabecular bone containing fatty marrow, and the remaining 20% was in trabecular bone containing red marrow.
6. Malátová et al. (2003, 2010) measured 241Am in urine and faeces and externally in the skull in seven workers over a period of about 12 y, starting roughly 11–25 y after exposure to 241Am. The source of contamination presumably was AmO2 powder, used in the production of AmBe neutron sources, smoke alarms, and other 241Am sources. The estimated content of 241Am in the skull was extrapolated to the total skeleton based on the assumption that the skull contains 12.5% of skeletal 241Am. The investigators compared their findings with predictions of the model for systemic americium in adults adopted in *Publication 67* (ICRP, 1993) and applied to workers in *Publications 68* *and 78* (ICRP, 1994a, 1997). The data are consistent with the urinary to faecal excretion ratio predicted by that model but indicate a lower than predicted ratio of daily urinary 241Am to skeletal 241Am.
7. Suslova et al. (2013) studied the distribution and excretion of 241Am and plutonium isotopes in workers at the Mayak Production Association. Autopsy data were obtained for 290 workers who died on average 14.7 y ± 12 y (standard deviation) after the end of employment. Urine bioassay measurements were performed about 23–26 y after the end of employment for 47 workers who started work at Mayak from 1949–1964, a period of high inhalation exposures. For a group of workers without liver disease, the skeleton, liver, kidneys, and other soft tissue contained on average 69.3%, 23.1%, 0.44%, and 7.2%, respectively, of systemic 241Am; and 46.4%, 46.0%, 0.17%, and 7.4%, respectively, of systemic plutonium. The ratio of daily urine excretion of 241Am to total systemic 241Am based on whole body counting of 29 reasonably healthy workers was 1.8 × 10-5. For comparison, the model for systemic americium in adults adopted in *Publication 67* predicts a “urinary to systemic” ratio of 2.4 × 10–5 at 25 y and 2.2 × 10–5 at 35 y after acute intake of 241Am to blood.
8. The behaviour of americium in blood has been studied in a variety of animals including baboons (Cohen and Wrenn, 1973; Guilmette et al., 1980; Rosen et al., 1972), monkeys (Durbin, 1973), beagles (Bruenger et al., 1969), sheep (McClellan et al., 1962), rats (Belyayev, 1969; Turner and Taylor, 1968), cows (Sutton et al., 1978), and goats (Sutton et al., 1978). Nearly all americium in blood is found in the plasma fraction. As is the case for plutonium and neptunium, most circulating americium soon becomes bound to plasma proteins, primarily transferrin and citrate. However, the affinity constants are much lower for americium than for plutonium or neptunium, resulting in much faster removal of americium from blood (Paquet and Stather, 1997). Roughly 5–10% of intravenously injected americium remains in blood at 1 h, 0.1 1.5% at 24 h, and 0.03–0.5% at 48 h. Much of the activity that leaves blood in the first hour after injection returns to blood over the next few hours.
9. Data for rats suggest that a third or more of americium leaving blood in the first few minutes after injection entered soft tissues and extracellular fluids and that much of this returned to blood over the next few hours (Belyayev, 1969; Durbin, 1973). In baboons, a substantial portion of systemic americium remained in the non-liver soft tissues at 1 d (Guilmette et al., 1980).
10. Following parenteral administration of 241Am citrate to baboons (Cohen and Wrenn, 1973; Rosen et al., 1972), monkeys (Durbin, 1973), and beagles (Lloyd et al., 1970), cumulative urinary excretion over the first 3 weeks amounted to ~10% of the administered activity. In beagles the urinary excretion rates over the first three weeks were similar for americium and curium isotopes (Lloyd et al., 1970, 1974). Similar urinary excretion rates were observed for americium and curium in rats following parenteral administration (Durbin, 1973).
11. In animals of all ages, most systemic Am (typically 80% or more) accumulates in the skeleton and liver within a few days after parenteral injection (Lloyd et al., 1970; Rosen et al., 1972; Durakovic et al., 1973; Stevens et al., 1977; Guilmette et al., 1980). In monkeys (Durbin, 1973) and beagles (Lloyd et al., 1970) the liver and skeleton contained about 50% and 30%, respectively, of the systemic activity in the first few days or weeks after injection. In baboons (Guilmette et al., 1980) the liver and skeleton contained about 30% and 40%, respectively, of systemic activity in the early weeks after injection.
12. The systemic biokinetics of americium varies somewhat among species, due largely to differences in the handling of americium by the liver. The studied animal species fall into two main groups with regard to the behaviour of americium in the liver (Durbin and Schmidt, 1985; Taylor, 1984). A group including rats, mice, macaque monkeys, and baboons shows a short residence time in the liver and a relatively high rate of removal of activity from the liver in bile. A second group including dogs and hamsters shows much slower removal from the liver with relatively low loss via biliary secretion. Biological half-times of americium in the liver typically are on the order of 5–15 d in rats and mice, 30–150 d in baboons and monkeys, and a few years in dogs and hamsters. Long-term studies on dogs (Lloyd et al., 1970; Mewhinney and Griffith, 1982) indicate that a large portion of the initial liver burden gradually transfers to the skeleton.
13. Hamilton (1948) described the sites of bone deposition of americium and curium in rodents as indistinguishable from those of the trivalent elements cerium, promethium, and actinium but different from sites of deposition of the tetravalent elements plutonium, thorium, and zirconium. Later studies involving a variety of animal species indicate that americium deposits on all types of bone surfaces, including resorbing and forming surfaces (Durbin, 1973; Herring et al., 1962; Ray D. Lloyd et al., 1972; Priest et al., 1983). Deposition on bone surfaces is more uniform than that of plutonium, although there are gradations in the intensity of the americium label. In dogs and monkeys, initial concentrations on surfaces tended to decrease in the order: resorbing surfaces > resting surfaces > growing surfaces (Durbin, 1973; Herring et al., 1962; Ray D. Lloyd et al., 1972). Americium deposits to a greater extent than plutonium on cortical vascular channels (Hamilton, 1948; Herring et al., 1962).
14. Comparison of the long-term gross distributions of skeletal americium and plutonium in dogs indicated more similarities than differences (Ray D. Lloyd et al., 1972). A notable difference was that the skeletal distribution of plutonium changed little with time after injection while the distribution of americium changed noticeably over time. In particular, three bones with high trabecular content (vertebrae, tail, and sternum) exhibited a decreasing fraction of total skeletal americium with increasing time.
15. Differences with age in the systemic behaviour of americium has been observed in dogs, baboons, monkeys, and accidentally exposed human subjects. The changes with age is consistent with that seen for other bone seeking elements, the most notable age-specific feature being substantially greater deposition in immature than in mature bone.
16. The skeletons of immature animals generally accumulate a greater portion of americium or plutonium than do skeletons of mature animals. For example, skeletons of newborn beagle dogs contained 76–84% of injected americium at 1–5 d after administration (Stevens et al., 1977), compared with a skeletal burden of 29% of the injected amount at 1 wk after administration at age 18 mo (Lloyd et al., 1970). Livers of newborn and juvenile beagles (age 3 mo) contained about 7% and 15%, respectively, of injected americium in the first few days after injection, compared with about 50% in mature beagles (Lloyd et al., 1985; Stevens et al., 1977). For example, the skeletons of beagles injected with 239Pu at ages 2 d, 3 mo, 1.5 y, or 5 y contained about 80%, 63%, 46%, and 43%, respectively, of the injected amount at 1 wk after administration (Bruenger et al., 1989).
    * + 1. Systemic model
17. The biokinetic model for systemic Am is a modification of the model for Am adopted in *Publication 67* (ICRP, 1993). That model was based on follow-up of workers acutely or chronically exposed to Am and experimental data including age-specific data for a variety of animal types including baboons, monkeys, dogs, sheep, cows, goats, and rodents.
18. The following changes are made here to the systemic model for Am used in *Publication 67*:

* For consistency with models for other actinide elements, liver is divided into compartments with relatively fast and relatively slow turnover. The biological half-time assigned to the fast-turnover compartment is the generic value of 30 d (Liver 1). A removal half-time of 1 y, the half-time applied in *Publication* 67 to the single-compartment liver, is applied to the compartment with slow turnover (Liver 2).
* The removal half-time from gonads is reduced from 10 y to 5 y, a generic value applied in this report to the actinides and lanthanides.
* The generic bone model is modified for application to Am and its physiological analogue Cm in view of data indicating that the model of *Publication* 67 overestimates long-term excretion of systemic 241Am in workers, when expressed as a fraction of the total bone content. A simple resolution of this discrepancy between model predictions and observations that has some experimental basis for mature cortical bone is to depict explicitly local recycling of a sizable portion of Am resorbed from cortical bone. This requires a modification of the generic bone model for bone-surface seekers. In the generic model, activity removed from bone is assumed to transfer to bone marrow and subsequently from bone marrow to blood. For application to Am and Cm, the generic bone model is modified by assuming that a fraction F of the amount entering cortical marrow subsequently transfers to cortical surface (local recycling), and the fraction 1-F transfers to blood. The removal half-time from cortical marrow to all destinations remains at the generic value of 0.25 y. For adults, a local recycling fraction F = 2/3 is selected for reasonable consistency with occupational data on the long-term relation of 241Am in bone and urinary 241Am, taking account of uncertainties in the reported data. It is assumed that local recycling occurs only in mature bone, i.e., the recycling fraction F from cortical marrow to cortical bone surface is set to 0.

1. The structure of the systemic model for americium is shown in Fig 23.1. Parameter values are listed in Table 23.2.

Diagram

Description automatically generated

Fig 23.1. Structure of the systemic model for americium.

Table 23.2. Age-specific transfer coefficients for americium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 2.33E+00 | 2.33E+00 | 6.98E+00 | 6.98E+00 | 6.98E+00 | 1.16E+01 |
| Blood to ST0 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 |
| Blood to ST1 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Kidneys 1 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Right colon cont | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 |
| Blood to Kidneys 2 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.20E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.60E-03 |
| Blood to Urinary bladder cont | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 |
| Liver 1 to SI cont | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 2.53E-03 |
| Cort marrow to Cort bone surf | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.07E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, SI = Small intestine, cont=content, surf=surface, vol = volume

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of americium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for americium

Table 23.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 241Am compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Americium nitrate | 5.3E-05 | 4.8E-05 | 3.0E-05 | 2.0E-05 | 1.9E-05 | 1.8E-05 |
| Type F, citrate | 6.0E-05 | 5.3E-05 | 3.3E-05 | 2.3E-05 | 2.2E-05 | 2.1E-05 |
| Type M, oxide, chloride | 4.6E-05 | 4.3E-05 | 2.6E-05 | 1.7E-05 | 1.6E-05 | 1.5E-05 |
| Type S, americium associated with plutonium oxide | 6.2E-05 | 6.1E-05 | 4.4E-05 | 3.2E-05 | 3.1E-05 | 3.1E-05 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.5E-06 | 2.1E-07 | 1.2E-07 | 7.9E-08 | 6.3E-08 | 5.9E-08 |

Table 23.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 243Am compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Americium nitrate | 5.2E-05 | 4.7E-05 | 2.9E-05 | 2.0E-05 | 1.8E-05 | 1.8E-05 |
| Type F, citrate | 5.9E-05 | 5.2E-05 | 3.3E-05 | 2.3E-05 | 2.1E-05 | 2.0E-05 |
| Type M, oxide, chloride | 4.5E-05 | 4.2E-05 | 2.5E-05 | 1.7E-05 | 1.5E-05 | 1.5E-05 |
| Type S, americium associated with plutonium oxide | 6.1E-05 | 6.0E-05 | 4.3E-05 | 3.2E-05 | 3.0E-05 | 3.1E-05 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.4E-06 | 2.0E-07 | 1.1E-07 | 7.8E-08 | 6.3E-08 | 5.8E-08 |

# Curium (Z=96)

## Routes of Intake

### Inhalation

1. Some limited information was found on the behaviour of inhaled curium in humans. Information on absorption from the respiratory tract is available from experimental studies of curium, mostly as oxides of variable stoichiometry, and for a few as chloride, nitrate and citrate. For details see Section 24 of *Publication 141* (ICRP, 2019). As described in Section 18 of *Publication 141* (ICRP, 2019), the general actinide section, absorption parameter values based on plutonium (*s*r = 0.4 d–1; *f*b =0.002; *s*b = 0 d–1) are applied in that document (and hence also in this document) to the transplutonium elements for radiation protection purposes. Absorption parameter values and Types, and associated *f*A values for particulate forms of curium, are given in Table 24.1. (taken from Section 24 of *Publication 141*).

Table 24.1. Absorption parameter values for inhaled and ingested curium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | | Absorption parameter values\* | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | *s*r (d–1) | | *s*s (d–1) | |
| Specific parameter values‡ | | | | |  | |  | |  | |  | |
| Curium oxide, nitrate and chloride | | | | | 0.5 | | 0.4 | | 0.01 | | 3 × 10–4 | |
|  | | | | |  | |  | |  | |  | |
| Default parameter values§ | | | | |  | |  | |  | |  | |
| Absorption Type | | Assigned forms | | |  | |  | |  | |  | |
| F | | Citrate | | | 1 | | 0.4 | | – | | 5 × 10–4 | |
| M¶ | | — | | | 0.2 | | 0.4 | | 0.005 | | 1 × 10–4 | |
| S | | — | | | 0.01 | | 0.4 | | 1 × 10–4 | | 5 × 10–6 | |
|  | | | | |  | |  | |  | |  | |
| Ingested material\*\* | | | | |  | |  | |  | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | 10 y | | 15 y | | adult |
| all forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 |

\*It is assumed that for curium a bound fraction *f*b = 0.002 with *s*b = 0 d–1 is applied throughout the respiratory tract except in the ET1 region. The values of *s*r for Type F M and S forms of curium (0.4 d–1) are element-specific.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of curium applicable to the age-group of interest (*e.g*. 5 × 10–4 for adults).

‡See Section 24 of *Publication 141* (ICRP, 2019) for summary of information on which parameter values are based, and on ranges of parameter values observed in different studies. For curium oxide and nitrate, specific parameter values are used for dissolution in the lungs, but a default value of *f*A (footnote †).

§Materials (e.g.curium citrate) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values or because specific parameter values would not be significantly different from the default (see Section 24 of *Publication 141*).

¶Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

\*\*Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g*. 5 × 10–4 for adults).

### Ingestion

1. *Adults*. Popplewell et al (1991) measured the absorption of 242Cm as a citrate in five adult male volunteers by comparing urinary excretion after oral and intravenous administration. The solutions were ingested with a mid-day meal. A mean absorption fraction of 2 × 10-4 was obtained with a range from 1 × 10-4 to 3 × 10-4. The studies informing the gastrointestinal absorption of curium were reviewed in *Publications 48* (ICRP, 1986), *100* (ICRP, 2006) and *141* (ICRP, 2019). The fractional absorption of curium has been measured in adult rats and guinea pigs with a range of observed values from 10-4 to 10-3. Absorption of curium nitrate was increased by fasting and oxidizing agents such as ferric iron and quinhydrone. Very limited information is available concerning the absorption of curium after biological incorporation into foodstuffs and the available data indicate no greatly enhanced absorption. In *Publication 30* (ICRP, 1980), an absorption fraction of 5 × 10-4 was recommended by analogy with americium. In *Publication 48*, a general value of 1 × 10-3 for actinides was used. In *Publication 141*, the use of a general value of 5 × 10-4 for all actinides other than U was recommended on the basis of the available data. The *f*A value of 5 × 10-4 is adopted here for all chemical forms of curium ingested by adult members of the public.
2. *Children*. Absorption of curium by neonatal rats is about two orders of magnitude greater than in adult animals; high absorption of this element has also been found in neonatal pigs (ICRP, 1986). It is assumed that, like for plutonium, the increased absorption would probably decrease rapidly during the first few days or weeks of life, adult values being reached by about the time of weaning. The same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are therefore adopted here for curium as for thorium, neptunium, plutonium and americium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. In five healthy human subjects administered 242Cm by intravenous injection, urinary excretion accounted for 4.5–6% of the injected amount during the first day and 7–10% during the first week after injection (Popplewell et al., 1991). Similar urinary excretion rates during these time periods were observed in baboons (Lo Sasso et al., 1981) and beagles (Lloyd et al., 1974) injected with curium isotopes.
2. The rate of urinary excretion of 244Cm was determined over ~5 mo in two workers who were exposed at different times to acidic solutions of 244Cm(NO3)3, one by puncture wound and the other by acid burn of the skin (Parkinson et al., 1976). The two subjects showed similar relative urinary excretion rates during this period. The rate of decline of urinary curium during the first week after exposure was similar to that determined in the human injection study by Popplewell et al. (1991).
3. In biokinetic studies of the behaviour of curium in laboratory animals a substantial portion of the injected or absorbed curium deposited in the liver and skeleton, and biological removal from the body was slow. In beagles receiving 243,244Cm citrate by intravenous injection, ~35% of injected curium was found in the liver and ~53% in non-liver tissues, mainly skeleton, at 1 wk after injection (Lloyd et al., 1974). In beagles exposed to aerosols of 244CmCl3 or 244CmO1.73, the liver and skeleton contained approximately 30% and 45%, respectively, of the initial lung burden at 256 days after inhalation (McClellan et al., 1972). These data suggest relatively long retention of curium in the liver and skeleton. In another study of beagles exposed by inhalation to 244CmOX, the liver contained ~44% and the skeleton ~33% of systemic 244Cm at 270 d after inhalation (Craig et al., 1976). In baboons receiving 243,244Cm citrate by intravenous injection, ~20% of injected curium deposited in the liver and ~60% in the skeleton (Lo Sasso et al., 1981).
4. Curium is tenaciously retained in the skeleton. The rate of loss of curium from the liver is species dependent, with half-times of a few days in rats (Durbin, 1973) and a few weeks in baboons (Lo Sasso et al., 1981) but with a much longer half-time in dogs (Guilmette and Mewhinney, 1989; McClellan et al., 1972). Based on comparative human and animal data on other actinide or lanthanide elements, it seems reasonable to assume that the pattern of retention of curium in the human liver is broadly similar to that in dogs.
5. In laboratory animals the biological behaviour of curium is similar to that of Am. Turner and Taylor (1968) observed virtually identical rates of circulatory clearance of 244Cm and 241Am in rats during the first day after intravenous injection of 244Cm nitrate or 241Am citrate. In rats receiving intramuscular injection of relatively soluble forms of 241Am and 242Cm, similar initial distributions and nearly identical patterns of excretion of these radionuclides over a period of several months were observed (Durbin, 1973; Durbin et al., 1969; Scott et al., 1948, 1949). In rats injected with 241Am citrate or 242Cm citrate, the concentration of 242Cm at 6 d after administration was virtually the same as that of 241Am in all measured tissues (skeleton, liver, spleen, kidneys, lung, thyroid, adrenals, ovaries), but chelation therapy appeared to be slightly more effective for 242Cm than 241Am (Seidel and Volf, 1972). Stather and Priest (1977) observed similar tissue distributions of 241Am and 242Cm in adult rats at 1 wk, 1 mo, and 5 mo after pulmonary intubation of these radionuclides as nitrates, but 242Cm appeared to be lost from the body at a slightly higher rate than 241Am at 1–5 mo after administration. Crawley and Goddard (1976) found virtually identical systemic distribution and retention of americium and curium in rats during the first week after intubation of these elements into each of three regions of the lung. Nenot et al. (1972) observed similar behaviour of 241Am and 242Cm in rats after administration by inhalation or intramuscular injection of these radionuclides as nitrates, with regard to cumulative urinary excretion, levels of uptake and retention by bone, and sites of binding in bone. In a study of comparative retention of bone-seeking radionuclides in rats, Taylor (1983) found that uptake and long-term retention of 244Cm in bone was similar to that of 241Am.
6. Results of a series of studies at the University of Utah (Atherton et al., 1973; Bruenger et al., 1976; Lloyd et al., 1970, 1974) indicate that the biokinetics of 243/244Cm in beagles is similar but not identical to that of 241Am over the first 3 wk after intravenous injection, the most important differences being that the observed liver-to-skeleton concentration ratio and urinary-to-fecal excretion ratio were both moderately higher for 241Am than 243/244Cm. By contrast, data of Craig et al. (1976) indicate that the time-dependent division of 244Cm between liver and skeleton in beagles is roughly the same as that of 241Am at 10–270 d after inhalation of 241AmO2 or 244CmOx aerosols. In an investigation of the biological behaviour of inhaled 244Cm compounds in beagles, Guilmette and Mewhinney (1989) found that a biokinetic model for Am developed earlier from data on inhaled 241AmO2 in beagles (Mewhinney and Griffith, 1983) applied nearly equally well to 244Cm with regard to the behaviour of absorbed activity.
   * + 1. Systemic model
7. Result of experimental studies on laboratory animals indicate that the chemically similar elements americium and curium are also close physiological analogues. Although quantitative differences in the biokinetics of systemic americium and curium have been observed in some studies, such differences generally have not been statistically significant and in most cases are contradicted by results of separate investigations. In this report, the systemic biokinetic model adopted for americium is also applied to curium.
8. The structure of the systemic model for curium is shown in Fig 24.1. Parameter values are listed in Table 24.2.

Diagram

Description automatically generated

Fig 24.1. Structure of the systemic model for curium.

Table 24.2. Age-specific transfer coefficients for curium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 2.33E+00 | 2.33E+00 | 6.98E+00 | 6.98E+00 | 6.98E+00 | 1.16E+01 |
| Blood to ST0 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 | 1.00E+01 |
| Blood to ST1 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 | 1.67E+00 |
| Blood to ST2 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Cort bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Trab bone surf | 8.15E+00 | 8.15E+00 | 5.82E+00 | 5.82E+00 | 5.82E+00 | 3.49E+00 |
| Blood to Kidneys 1 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 | 4.66E-01 |
| Blood to Right colon cont | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 | 3.03E-01 |
| Blood to Kidneys 2 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 |
| Blood to Testes | 4.70E-04 | 7.00E-04 | 7.90E-04 | 9.30E-04 | 7.50E-03 | 8.20E-03 |
| Blood to Ovaries | 2.80E-04 | 3.70E-04 | 9.30E-04 | 1.60E-03 | 2.80E-03 | 2.60E-03 |
| Blood to Urinary bladder cont | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 | 1.63E+00 |
| Liver 1 to SI cont | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 | 1.39E-02 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 2.53E-03 |
| Cort marrow to Cort bone surf | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 5.07E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 | 1.39E-03 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, SI = Small intestine, cont=content, surf=surface, vol = volume

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of curium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for curium

Table 24.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 242Cm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Curium oxide, nitrate and chloride | 1.2E-05 | 9.4E-06 | 4.4E-06 | 2.6E-06 | 2.2E-06 | 1.9E-06 |
| Type F, citrate | 1.1E-05 | 8.4E-06 | 3.5E-06 | 1.9E-06 | 1.7E-06 | 1.3E-06 |
| Type M | 1.3E-05 | 1.1E-05 | 5.6E-06 | 3.4E-06 | 2.8E-06 | 2.5E-06 |
| Type S | 1.5E-05 | 1.4E-05 | 8.0E-06 | 5.2E-06 | 4.1E-06 | 3.8E-06 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 4.8E-07 | 3.3E-08 | 1.2E-08 | 6.4E-09 | 5.0E-09 | 3.5E-09 |

Table 24.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 243Cm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Curium oxide, nitrate and chloride | 4.7E-05 | 4.2E-05 | 2.4E-05 | 1.5E-05 | 1.4E-05 | 1.4E-05 |
| Type F, citrate | 5.3E-05 | 4.6E-05 | 2.6E-05 | 1.7E-05 | 1.6E-05 | 1.5E-05 |
| Type M | 4.3E-05 | 3.9E-05 | 2.2E-05 | 1.4E-05 | 1.2E-05 | 1.2E-05 |
| Type S | 5.6E-05 | 5.4E-05 | 3.7E-05 | 2.6E-05 | 2.4E-05 | 2.5E-05 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.3E-06 | 1.9E-07 | 9.8E-08 | 6.3E-08 | 4.9E-08 | 4.6E-08 |

Table 24.5. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 244Cm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Curium oxide, nitrate and chloride | 4.4E-05 | 3.9E-05 | 2.1E-05 | 1.3E-05 | 1.2E-05 | 1.2E-05 |
| Type F, citrate | 4.9E-05 | 4.2E-05 | 2.3E-05 | 1.5E-05 | 1.3E-05 | 1.3E-05 |
| Type M | 4.0E-05 | 3.6E-05 | 2.0E-05 | 1.3E-05 | 1.1E-05 | 1.1E-05 |
| Type S | 5.2E-05 | 5.0E-05 | 3.3E-05 | 2.3E-05 | 2.1E-05 | 2.1E-05 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.1E-06 | 1.7E-07 | 8.7E-08 | 5.4E-08 | 4.2E-08 | 3.9E-08 |

# Berkelium (Z=97)

## Routes of Intake

### Inhalation

1. Limited information is available on the biokinetics of inhaled berkelium from an occupational contamination case. For details, see Section 25 of *Publication 141* (ICRP, 2019). As described in Section 18 of *Publication 141*, the general actinide section, absorption parameter values based on plutonium (*s*r = 0.4 d–1; *f*b =0.002; *s*b = 0 d–1) are applied in that document (and hence also in this document) to the transplutonium elements for radiation protection purposes. Absorption parameter values and Types, and associated *f*A values for particulate forms of berkelium, are given in Table 25.1 (taken from Section 25 of *Publication 141*).

Table 25.1. Absorption parameter values for inhaled and ingested berkelium.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | Absorption parameter values\* | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | *s*r (d–1) | | *s*s (d–1) | |
| Default parameter values‡ | | |  | |  | |  | |  | |
| Absorption Type | Assigned forms | |  | |  | |  | |  | |
| F | — | | 1 | | 0.4 | | – | | 5 × 10–4 | |
| M§ | — | | 0.2 | | 0.4 | | 0.005 | | 1 × 10–4 | |
| S | Berkelium oxide | | 0.01 | | 0.4 | | 1 × 10–4 | | 5 × 10–6 | |
|  | | |  | |  | |  | |  | |
| Ingested material¶ | | |  | |  | |  | |  | |
| Assigned forms | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | 10 y | | 15 y | | adult |
| all forms | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 | | 5 × 10-4 |

\*It is assumed that for berkelium a bound fraction *f*b = 0.002 with *s*b = 0 d–1 is applied throughout the respiratory tract except in the ET1 region. The values of *s*r for Type F, M and S forms of berkelium (0.4 d–1, respectively) are element-specific.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of berkelium applicable to the age-group of interest (*e.g* 5 × 10–4 for adults).

‡Materials (e.g. berkelium oxide) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values or because specific parameter values would not be significantly different from the default (see Section 25 of *Publication 141* (ICRP, 2019)).

§Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, *e.g.* if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

¶Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g* 5 × 10–4 for adults).

### Ingestion

1. *Adults*. Very limited information is available on the gastrointestinal absorption of berkelium: an early study by Hungate (1972) indicated that the fractional absorption of intragastrically administered 248Bk chloride in the rat was about 1 × 10-4. In *Publications* 30 (ICRP, 1988) and *48* (ICRP, 1986) an absorption fraction of 1 × 10-3 was recommended for berkelium. In *Publication 141* (ICRP, 2019), on the basis of results showing similar low levels of absorption in humans for five actinide elements (thorium, neptunium, plutonium, americium and curium) and taking account of animal data showing variations in *f*A values resulting from differences in chemical forms, it was considered that an appropriate general *f*A value for all chemical forms of actinides except uranium was 5 × 10-4. The same *f*A = 5 × 10-4 is recommended here for ingestion of berkelium by adult members of the public.
2. *Children*. The age-dependency of berkelium absorption was not observed. On the basis of the chemical analogy with the other actinides, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for berkelium as for thorium, neptunium, plutonium, americium and curium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The biokinetics of berkelium has been studied in rats (Hungate et al., 1972; Zalikin et al., 1984; Zalikin and Nisimov, 1988), beagles (Taylor et al., 1972), and to a limited extent in accidentally exposed human subjects (Rundo and Sedlet, 1973). The data for human subjects reveal little about the systemic behaviour of Bk. Comparative data for Bk and Es in laboratory animals indicate that these elements have broadly similar biokinetics, but Bk has a lower rate of urinary excretion, lower deposition in the skeleton, greater deposition in the liver, and perhaps greater deposition in the kidneys than Es.
2. Following intravenous administration of 249Bk and 253Es to rats, about 8% of injected 249Bk was excreted in urine during the first day, compared with about 35% of injected 253Es (Hungate et al., 1972). The urinary excretion rate of Bk declined more slowly than that of Es. After the first day or two, the rate of faecal excretion of 249Bk exceeded its urinary excretion rate. Total excretion of 249Bk over the first 3 wk amounted to roughly 20% of the injected amount. The liver content of 249Bk decreased from about 23% at 4 h to 3% at 21 d. During the same period the skeletal content, estimated as 20 times the content of one femur, increased from about 30% to 38% of the injected amount. Equilibrium levels in bone appeared to be achieved more slowly for Bk than for Es, possibly due to differences in initial binding of the two elements to blood components.
3. Taylor et al. (1972) found that the microscopic distributions of 249Bk and 249Cf in the soft tissues of beagles at 1–3 wk following intravenous administration of a citrate solution were similar to the distribution of 241Am. Relatively high concentrations of these radionuclides were found in the hepatic cells of liver, glomeruli of kidneys, interfollicular region of the thyroid, the cartilaginous tissues of the lung, and the media of the smaller arterioles of most organs. With the exception of the liver, most of the sites of deposition in soft tissues were extracellular and associated with connective tissue.
4. Smith (1972) concluded from studies of decorporation of internally deposited transuranics in rats that berkelium, einsteinium, and californium are similar in their *in vivo* solubility characteristics, translocation rates in the body, and response to chelation therapy following deposition in liver, kidneys, bone, and muscle.
5. Following intraperitoneal administration of 249Bk nitrate to rats, activity cleared slowly from blood and deposited primarily in the skeleton (up to ~40%) and liver (~18%) (Zalikin et al., 1984). Activity concentrations initially decreased in the order adrenal glands > liver > spleen > kidneys > osseous tissues. Over the first 30 d, about 18% of the administered amount was excreted in urine and 10% was excreted in faeces. Following per os or intravenous administration of 249Bk to rats, the preponderance of the amount entering blood deposited in the skeleton and liver (Zalikin and Nisimov, 1988).
   * + 1. Systemic model
6. Comparisons of systemic data for americium, curium, berkelium, californium, and einsteinium suggest a relation between ionic radius and the relative amounts transferred to bone, liver, and urine analogous to the relation observed for the lanthanides. That is, initial deposition in bone tends to increase, deposition in liver tends to decrease, and the early urinary excretion rate tends to increase with decreasing ionic radius. This pattern was used together with element-specific data for californium, berkelium, and einsteinium to derive transfer coefficients for these three elements, using transfer coefficients as a starting point. A non-zero transfer from cortical marrow to cortical bone surface in the americium model is assumed to be specific to americium and its physiological analogue curium and hence is not applied in the models for berkelium, californium, and einsteinium.
7. The structure of the systemic model for berkelium is shown in Fig 25.1. Parameter values are listed in Table 25.2.

Diagram

Description automatically generated

Fig 25.1. Structure of the systemic model for berkelium.

Table 25.2. Age-specific transfer coefficients for berkelium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 3.23E-02 | 3.23E-02 | 1.29E-01 | 1.29E-01 | 1.29E-01 | 1.94E-01 |
| Blood to ST0 | 2.77E-01 | 2.77E-01 | 2.77E-01 | 2.77E-01 | 2.77E-01 | 2.77E-01 |
| Blood to ST1 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 | 6.47E-02 |
| Blood to ST2 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 |
| Blood to Cort bone surf | 2.10E-01 | 2.10E-01 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 1.29E-01 |
| Blood to Trab bone surf | 2.10E-01 | 2.10E-01 | 1.62E-01 | 1.62E-01 | 1.62E-01 | 1.29E-01 |
| Blood to Kidneys 1 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 | 1.29E-02 |
| Blood to Right colon cont | 3.88E-02 | 3.88E-02 | 3.88E-02 | 3.88E-02 | 3.88E-02 | 3.88E-02 |
| Blood to Kidneys 2 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 | 6.47E-03 |
| Blood to Testes | 1.29E-05 | 1.94E-05 | 2.20E-05 | 2.59E-05 | 2.07E-04 | 2.30E-04 |
| Blood to Ovaries | 7.76E-06 | 1.03E-05 | 2.59E-05 | 4.52E-05 | 7.76E-05 | 7.00E-05 |
| Blood to Urinary bladder cont | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 |
| Liver 1 to SI cont t | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, SI = Small intestine, cont=content, surf=surface, vol = volume

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of berkelium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for berkelium

Table 25.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 249Bk compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type F | 9.7E-08 | 9.0E-08 | 6.1E-08 | 4.5E-08 | 4.5E-08 | 4.4E-08 |
| Type M | 6.7E-08 | 6.4E-08 | 4.1E-08 | 3.0E-08 | 2.9E-08 | 2.9E-08 |
| Type S, berkelium oxide | 1.2E-07 | 1.2E-07 | 9.2E-08 | 7.1E-08 | 7.0E-08 | 7.2E-08 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 3.6E-09 | 3.3E-10 | 2.0E-10 | 1.4E-10 | 1.2E-10 | 1.2E-10 |

# Californium (Z=98)

## Routes of Intake

### Inhalation

1. Limited information on absorption of californium from the respiratory tract is available from a rat inhalation study of the chloride and two occupational exposure cases involving oxide forms. For details, see Section 26 of *Publication 141* (ICRP, 2019). As described in Section 18 of *Publication 141*, the general actinide section, absorption parameter values based on plutonium (*s*r = 0.4 d–1; *f*b =0.002; *s*b = 0) are applied in that document (and hence also in this document) to the transplutonium elements. Absorption parameter values and Types, and associated *f*A values for particulate forms of californium, are given in Table 26.1. (taken from Section 26 of *Publication 141*).

Table 26.1. Absorption parameter values for inhaled and ingested californium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | | | Absorption from the alimentary tract, *f*A‡ | |
| *f*r | | *s*r (d–1) | | | *s*s (d–1) | | |
| Default parameter values† | | | |  | |  | | |  | | |  | |
| Absorption Type | Assigned forms | | |  | |  | | |  | | |  | |
| F | Chloride | | | 1 | | 0.4 | | | – | | | 5 × 10–4 | |
| M§ | Oxide | | | 0.2 | | 0.4 | | | 0.005 | | | 1 × 10–4 | |
| S | — | | | 0.01 | | 0.4 | | | 1 × 10–4 | | | 5 × 10–6 | |
|  | | | |  | | |  | | |  | |  | |
| Ingested material¶ | | | |  | | |  | | |  | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | | 10 y | | | 15 y | | adult |
| all forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | | 5 × 10-4 | | | 5 × 10-4 | | 5 × 10-4 |

\*It is assumed that for californium a bound fraction *f*b = 0.002 with *s*b = 0 d–1 is applied throughout the respiratory tract except in the ET1 region. The values of *s*r for Type F, M and S forms of californium (0.4 d–1) are element-specific.

†Materials (e.g. californium chloride) are generally listed here where there is sufficient information to assign to a default absorption Type, but not to give specific parameter values (see Section 26 of *Publication 141* (ICRP, 2019).

‡For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type and the *f*A value for ingested soluble forms of californium applicable to the age-group of interest (*e.g* 5 × 10–4 for adults).

§Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

¶Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (*e.g* 5 × 10–4 for adults).

### Ingestion

1. *Adults*. Sullivan (Sullivan, 1974, 1980b) studied the gastrointestinal absorption of californium nitrate after gavage administration to adult rats and found absorption fractions of 1.1 × 10-3 and 5.9 × 10-4. In *Publications 30* (ICRP, 1988) and *48* (ICRP, 1986), a general absorption fraction of 1 × 10-3 was recommended for actinides, including californium. In *Publication 141* (ICRP, 2019), on the basis of results showing similar low levels of absorption in humans for five actinide elements (thorium, neptunium, plutonium, americium and curium) and taking account of animal data showing variations in *f*A values resulting from differences in chemical forms, it was considered that an appropriate general *f*A value for all chemical forms of actinides except uranium was 5 × 10-4. The same *f*A = 5 × 10-4 is recommended here for ingestion of californium by adult members of the public.
2. *Children*. Absorption of californium nitrate by newborn rats is 40 to 250 times greater than in adult animals (Sullivan, 1974, 1980a). It is assumed that, like for plutonium, the increased absorption would probably decrease rapidly during the first few days or weeks of life, adult values being reached by about the time of weaning. The same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are therefore adopted here for curium as for thorium, neptunium, plutonium and americium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The biokinetics of inhaled californium has been studied by external measurement and bioassay in a few accidentally exposed workers (Poda and Hall, 1975; Rundo and Sedlet, 1973). The results provide useful information on the lung retention and total body retention of the inhaled material but are difficult to interpret in terms of the systemic biokinetics of californium.
2. The biokinetics of systemic californium has been studied in a variety of laboratory animals including mice, rats, Chinese and Syrian hamsters, and beagles (Atherton and Lloyd, 1972; Bruenger et al., 1972; Durbin, 1973; Graham et al., 1978; Lloyd et al., 1976; R.D. Lloyd et al., 1972; Mewhinney et al., 1971, 1972; Parker et al., 1962; Smith, 1972; Stevens and Bruenger, 1972; Taylor et al., 1972). Its behaviour is qualitatively similar to that of other transuranium elements. Much of the absorbed or injected californium deposits in the skeleton and liver; the skeletal deposit is almost entirely on bone surfaces; and most of the activity reaching the systemic circulation is tenaciously retained in the body. The gross distribution of californium in the skeleton and soft tissues of beagle dogs were found to be particularly close to the distribution of americium (R.D. Lloyd et al., 1972; Taylor et al., 1972). The microscopic distribution of californium in the skeleton was also similar to that of americium in rats, with heaviest deposits on the trabeculae of the primary spongiosa and on epiphyseal and metaphyseal trabeculae (Durbin, 1973).
3. Species differences in the biokinetics of californium have been observed. For example, Mewhinney et al. (1972) found significant differences in the behaviour of 252Cf in rats and Chinese hamsters over 64 d following intraperitoneal injection of the citrate complex, including lower uptake of activity by the liver and kidneys and higher uptake by the skeleton in rats and much faster removal from the liver in rats. The behaviour of californium in beagles receiving 249Cf or 252Cf by intravenous injection (R.D. Lloyd et al., 1972) was broadly similar to that in the hamster with regard to uptake and retention in major repositories. The faecal to urinary excretion ratio was much higher in rats than in dogs, probably due to a higher rate of biliary secretion of californium by rats.
4. Measurements on rats and mice indicate a biological half-time for the whole body on the order of 2 y (400-1000 d). This reflects primarily skeletal retention in these animals because the removal half-time from the liver is short and other soft tissues do not retain much californium. In dogs or hamsters, whole-body retention of californium reflects tenacious retention of in both the liver and skeleton. For the beagle, half-times of 8.5 y and 4.2 y have been estimated for the whole body and liver, respectively.
5. No information was found regarding the effect of age on the biokinetics of systemic californium.
   * + 1. Systemic model
6. Data for californium summarized above indicate that its systemic behaviour resembles that of the frequently studied actinide americium. Comparisons of systemic data for americium, berkelium, californium, and einsteinium suggest a relation between ionic radius and the relative amounts transferred to bone, liver, and urine similar to the relation observed for the lanthanides. That is, initial deposition in bone tends to increase, deposition in liver tends to decrease, and the early urinary excretion rate tends to increase with decreasing ionic radius. This pattern is used together with available element-specific data to develop transfer coefficients describing the systemic biokinetics of berkelium, californium, and einsteinium, with transfer coefficients for americium used as default values in the absence of specific data. A non-zero transfer from cortical marrow to cortical bone surface in the americium model is assumed to be specific to americium and its physiological analogue curium and hence is not applied in the models for berkelium, californium, and einsteinium.
7. The structure of the systemic model for californium is shown in Fig 26.1. Parameter values are listed in Table 26.2.

Diagram

Description automatically generated

Fig 26.1. Structure of the systemic model for californium.

Table 26.2. Age-specific transfer coefficients for californium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 5.82E-01 | 5.82E-01 | 1.75E+00 | 1.75E+00 | 1.75E+00 | 2.33E+00 |
| Blood to ST0 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 |
| Blood to ST1 | 9.26E-01 | 9.26E-01 | 9.26E-01 | 9.26E-01 | 9.26E-01 | 9.26E-01 |
| Blood to ST2 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Cort bone surf | 3.78E+00 | 3.78E+00 | 3.20E+00 | 3.20E+00 | 3.20E+00 | 2.91E+00 |
| Blood to Trab bone surf | 3.78E+00 | 3.78E+00 | 3.20E+00 | 3.20E+00 | 3.20E+00 | 2.91E+00 |
| Blood to Kidneys 1 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Right colon cont | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 |
| Blood to Kidneys 2 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 |
| Blood to Testes | 2.33E-04 | 3.49E-04 | 3.96E-04 | 4.66E-04 | 3.73E-03 | 4.08E-03 |
| Blood to Ovaries | 1.40E-04 | 1.86E-04 | 4.66E-04 | 8.15E-04 | 1.40E-03 | 1.28E-03 |
| Blood to Urinary bladder cont | 1.28E+00 | 1.28E+00 | 1.28E+00 | 1.28E+00 | 1.28E+00 | 1.28E+00 |
| Liver 1 to SI-cont | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, SI = Small intestine, cont=content, surf=surface, vol = volume

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of californium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for californium

Table 26.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 249Cf compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type F, chloride | 5.0E-05 | 4.5E-05 | 2.8E-05 | 2.0E-05 | 2.0E-05 | 1.9E-05 |
| Type M, oxide | 4.0E-05 | 3.7E-05 | 2.3E-05 | 1.6E-05 | 1.4E-05 | 1.4E-05 |
| Type S | 6.5E-05 | 6.4E-05 | 4.6E-05 | 3.4E-05 | 3.2E-05 | 3.3E-05 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.0E-06 | 1.7E-07 | 9.4E-08 | 6.5E-08 | 5.6E-08 | 5.2E-08 |

Table 26.4. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 252Cf compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type F, chloride | 4.7E-05 | 3.8E-05 | 1.8E-05 | 9.4E-06 | 8.3E-06 | 6.8E-06 |
| Type M, oxide | 4.2E-05 | 3.7E-05 | 1.8E-05 | 1.1E-05 | 8.7E-06 | 7.6E-06 |
| Type S | 5.2E-05 | 4.9E-05 | 2.9E-05 | 1.8E-05 | 1.5E-05 | 1.4E-05 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 2.1E-06 | 1.8E-07 | 7.7E-08 | 4.2E-08 | 3.2E-08 | 2.5E-08 |

# Einsteinium (Z=99)

## Routes of Intake

### Inhalation

1. No information was found on the behaviour of inhaled einsteinium (Es) in humans. Information on absorption from the respiratory tract is available from experimental studies of einsteinium chloride and nitrate. For details, see Section 27 of *Publication 141* (ICRP, 2019). As described in Section 18 of *Publication 141*, the general actinide section, absorption parameter values based on plutonium (*s*r = 0.4 d–1; *f*b =0.002; *s*b = 0) are applied in that document (and hence also in this document) to the transplutonium elements. Absorption parameter values and Types, and associated *f*A values for particulate forms of einsteinium, are given in Table 27.1 (taken from Section 27 of *Publication 141*).

Table 27.1. Absorption parameter values for inhaled and ingested einsteinium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | *s*r (d–1) | | | *s*s (d–1) | | |
| Default parameter values | | | |  | |  | | |  | | |  | |
| Absorption Type | Assigned forms | | |  | |  | | |  | | |  | |
| F | Einsteinium chloride | | | 1 | | 0.4 | | | – | | | 5 × 10–4 | |
| M‡ | Einsteinium nitrate | | | 0.2 | | 0.4 | | | 0.005 | | | 1 × 10–4 | |
| S | — | | | 0.01 | | 0.4 | | | 1 × 10–4 | | | 5 × 10–6 | |
|  | | | |  | | |  | | |  | |  | |
| Ingested material§ | | | |  | | |  | | |  | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | | 10 y | | | 15 y | | adult |
| all forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | | 5 × 10-4 | | | 5 × 10-4 | | 5 × 10-4 |

\*It is assumed that for einsteinium a bound fraction *f*b = 0.002 with *s*b = 0 d–1 is applied throughout the respiratory tract except in the ET1 region. The value of *s*r for Type F, M and S forms of einsteinium (0.4 d–1) is element-specific.

†For inhaled material deposited in the respiratory tract and subsequently cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of einsteinium applicable to the age-group of interest (e.g 5 × 10–4 for adults).

‡Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

§Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (e.g 5 × 10–4 for adults).

### Ingestion

1. *Adults*. An early study by Hungate (1972) indicated that einsteinium and berkelium are absorbed from the gastrointestinal tract of the rat to a similar extent. Sullivan (1980b) and Sullivan and Crosby (1975) reported absorption fractions of 3.4 × 10-4 and 4 × 10-4 for nitrates of einsteinium administered by gavage to the adult rat. In *Publications 30* (ICRP, 1988) and *48* (ICRP, 1986) an absorption fraction of 1 × 10-3 was recommended for actinides, including einsteinium. In *Publication 141* (ICRP, 2019), on the basis of results showing similar low levels of absorption in humans for five actinide elements (thorium, neptunium, plutonium, americium and curium) and taking account of animal data showing variations in *f*A values resulting from differences in chemical forms, it was considered that an appropriate general *f*A value for all chemical forms of actinides except uranium was 5 × 10-4. The same *f*A = 5 × 10-4 is recommended here for ingestion of einsteinium by adult members of the public.
2. *Children*. The gastrointestinal absorption of einsteinium nitrate by newborn rats is about two orders of magnitude greater than in adult animals (Sullivan, 1974, 1980a). It is assumed that, like for plutonium, the increased absorption would probably decrease rapidly during the first few days or weeks of life, adult values being reached by about the time of weaning. The same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are therefore adopted here for curium as for thorium, neptunium, plutonium and americium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. The biokinetics of Es has been studied in mice (Parker et al., 1972), rats (Ballou et al., 1975, 1979; Hungate et al., 1972), miniature swine (McClanahan and Ragan, 1984) and beagles (Lloyd et al., 1975). Comparative data for Am, Cf, and Es indicate that skeletal deposition increases in the order Am < Cf < Es. The initial urinary excretion rate is much greater, and the initial fecal excretion rate is much lower, for Es than for Cf or Am.
2. The systemic behaviour of 253Es was studied up to about 8 wk following its intravenous injection as citrate to six young adult beagle dogs (Lloyd et al., 1975). Excluding two dogs with possibly anomalous initial urinary losses, mean losses in urine and faeces over the first three weeks represented about 18% and 7%, respectively, of the administered amount. The skeleton and liver were the main sites of deposition of injected activity, with the skeleton containing about 30–50% and the liver about 10–13% of the administered activity between 7 and 55 d after administration. The investigators compared the behaviour of Es in dogs with that of Pu, Am, Cm, and Cf determined earlier at the same laboratory and concluded that Es most closely resembled Cf in its tissue distribution, retention, and excretion.
3. The biokinetics and adverse effects of 253Es were studied in rats following various routes of administration of different compounds (Hungate et al., 1972). Following intravenous administration of the chloride, about 35% of the injected amount was excreted in urine during the first day. During the next 20 d the urinary and fecal excretion rates were about the same. Total excretion over 21 d amounted to almost 50% of the injected amount. Bone was the primary site of deposition. There was no indication of a change in the bone content from 4 h to 83 d post injection. The liver content declined from about 18% at 4 h to 1.6% at 21 d. The behaviour of 253Es administered as the hydroxide was much different: about 80% of the administered activity was lost from the body within 4 h, and less than 1% remained after 20 d. The authors suggested that the much different results for the hydroxide could be related to damaging effects of the alkaline solution in the lung. The systemic behaviour of 253Es observed in later studies at the same laboratory involving intratracheal administration of 253EsCl3 or inhalation of 253Es(NO3)3 (Ballou et al., 1975, 1979) seem reasonably consistent with the results obtained by Hungate et al. for 253Es injected as the chloride.
4. Parker et al. (1972) studied the distribution, retention, and excretion of 253Es in mice following intramuscular injection and compared the results with previous findings by the same group for americium and californium in mice. Over the first 4 d approximately 30% and 1.4% of the administered 253Es was excreted in urine and faeces, respectively. At 4 d, the liver contained about 7% of the administered 253Es and the skeleton plus carcass contained about 45%. At that time the liver deposition of Es was about the same as the value determined earlier for Cf and about 30% of the value for Am; skeletal retention was somewhat greater for Es than for Cf or Am; urinary excretion of Es was about 5 times that of Cf or Am; and faecal excretion of Es was an order of magnitude lower than that of Cf or Am.
5. At 1 d after intravenous administration of 253Es as the chloride to juvenile miniature swine, the skeleton and liver contained roughly 60–70% and 15%, respectively, of the injected amount (McClanahan and Ragan, 1984). The skeletal content appeared to decrease little if any over the following 70 d, while the liver content decreased by roughly 50%. Over the first 7 d, about 2.4% of the administered amount was removed in urine and 3.3% was removed in faeces.
   * + 1. Systemic model
6. The structure of the systemic model for einsteinium is shown in Fig 27.1. Parameter values are listed in Table 27.2.

Diagram

Description automatically generated

Fig 27.1. Structure of the systemic model for einsteinium.

Table 27.2. Age-specific transfer coefficients for einsteinium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 5.82E-01 | 5.82E-01 | 1.16E+00 | 1.16E+00 | 1.16E+00 | 1.75E+00 |
| Blood to ST0 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 |
| Blood to ST1 | 8.68E-01 | 8.68E-01 | 8.68E-01 | 8.68E-01 | 8.68E-01 | 8.68E-01 |
| Blood to ST2 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Cort bone surf | 3.78E+00 | 3.78E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 3.20E+00 |
| Blood to Trab bone surf | 3.78E+00 | 3.78E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 3.20E+00 |
| Blood to Kidneys 1 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 |
| Blood to Right colon cont | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 |
| Blood to Kidneys 2 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 |
| Blood to Testes | 2.33E-04 | 3.49E-04 | 3.96E-04 | 4.66E-04 | 3.73E-03 | 4.08E-03 |
| Blood to Ovaries | 1.40E-04 | 1.86E-04 | 4.66E-04 | 8.15E-04 | 1.40E-03 | 1.28E-03 |
| Blood to Urinary bladder cont | 1.51E+00 | 1.51E+00 | 1.51E+00 | 1.51E+00 | 1.51E+00 | 1.51E+00 |
| Liver 1 to SI-cont | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, SI = Small intestine, cont=content, surf=surface, vol = volume

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of einsteinium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for einsteinium

Table 27.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 254Es compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type F, einsteinium chloride | 1.6E-05 | 1.2E-05 | 5.5E-06 | 2.8E-06 | 2.6E-06 | 2.0E-06 |
| Type M, einsteinium nitrate | 1.7E-05 | 1.5E-05 | 7.7E-06 | 4.6E-06 | 3.8E-06 | 3.3E-06 |
| Type S | 2.3E-05 | 2.0E-05 | 1.2E-05 | 7.9E-06 | 6.3E-06 | 6.1E-06 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 6.9E-07 | 5.2E-08 | 2.1E-08 | 1.1E-08 | 8.5E-09 | 5.9E-09 |

# Fermium (Z=100)

## Routes of Intake

### Inhalation

1. No reports were found of experimental studies on the behaviour of fermium (Fm) following deposition in the respiratory tract, nor of its retention in the lung following accidental intake. For details, see Section 28 of *Publication 141* (ICRP, 2019). As described in Section 18 of *Publication 141*, the general actinide section, absorption parameter values based on plutonium (*s*r = 0.4 d–1, *f*b =0.002; *s*b = 0 d–1) are applied in that document (and hence also in this document) to the transplutonium elements. Absorption parameter values and Types, and associated *f*A values for particulate forms of fermium, are given in Table 28.1 (taken from Section 28 of *Publication 141*).

Table 28.1. Absorption parameter values for inhaled and ingested fermium.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials | | | | Absorption parameter values\* | | | | | | | | Absorption from the alimentary tract, *f*A† | |
| *f*r | | | *s*r (d–1) | | *s*s (d–1) | | |
| Default parameter values | | | |  | | |  | |  | | |  | |
| Absorption Type | Assigned forms | | |  | | |  | |  | | |  | |
| F | Einsteinium chloride | | | 1 | | | 0.4 | | – | | | 5 × 10–4 | |
| M‡ | Einsteinium nitrate | | | 0.2 | | | 0.4 | | 0.005 | | | 1 × 10–4 | |
| S | — | | | 0.01 | | | 0.4 | | 1 × 10–4 | | | 5 × 10–6 | |
|  | | | |  | |  | | | |  | |  | |
| Ingested material§ | | | |  | |  | | | |  | |  | |
| Assigned forms | | Age-dependent absorption from the alimentary tract, *f*A | | | | | | | | | | | |
| 3 mo | 1 y | | 5 y | | | 10 y | | | 15 y | | adult |
| all forms | | 5 × 10-3 | 5 × 10-4 | | 5 × 10-4 | | | 5 × 10-4 | | | 5 × 10-4 | | 5 × 10-4 |

\*It is assumed that for fermium a bound fraction *f*b = 0.002 with *s*b = 0 d–1 is applied throughout the respiratory tract except in the ET1 region. The value of *s*r for Type F, M and S forms of fermium 0.4 d–1) is element-specific.

†For inhaled material deposited in the respiratory tract and subsequent cleared by particle transport to the alimentary tract, the default *f*A values for inhaled materials are applied: *i.e.*, the product of *f*r for the absorption Type (or specific value where given) and the *f*A value for ingested soluble forms of fermium applicable to the age-group of interest (e.g 5 × 10–4 for adults).

‡Default Type M is recommended for use in the absence of specific information on which the exposure material can be assigned to an Absorption Type, e.g. if the form is unknown, or if the form is known but there is no information available on the absorption of that form from the respiratory tract.

§Activity transferred from systemic compartments into segments of the alimentary tract is assumed to be subject to reabsorption to blood. The default absorption fraction *f*A for the secreted activity is the reference value for ingestion of the radionuclide applicable to the age-group of interest (e.g 5 × 10–4 for adults).

### Ingestion

1. *Adults*. There are no data available on the uptake of fermium from the gastrointestinal tract. By analogy with americium, an absorption fraction of 1 × 10-3 for fermium was therefore recommended in *Publications 30* (ICRP, 1988) and *48* (ICRP, 1986). In *Publication 141* (ICRP, 2019), on the basis of results showing similar low levels of absorption in humans for five actinide elements (thorium, neptunium, plutonium, americium and curium) and taking account of animal data showing variations in *f*A values resulting from differences in chemical forms, it was considered that an appropriate general *f*A value for all chemical forms of actinides except uranium was 5 × 10-4. The same *f*A = 5 × 10-4 is recommended here for ingestion of fermium by adult members of the public.
2. *Children*. The age-dependency of fermium absorption was not observed. On the basis of the chemical analogy with the other actinides, the same values of *f*A = 5 × 10-3 for 3-month-old infants and 5 × 10-4 for children of 1 year and older are adopted here for fermium as for thorium, neptunium, plutonium, americium and curium.

### Systemic Distribution, Retention and Excretion

* + - 1. Summary of biokinetic data

1. No biokinetic data were found for fermium.
   * + 1. Systemic model
2. The biokinetic model for systemic einsteinium is applied in this report to fermium. The structure of the systemic model for fermium is shown in Fig 28.1. Parameter values are listed in Table 28.2.

Diagram

Description automatically generated

Fig 28.1. Structure of the systemic model for fermium.

Table 28.2. Age-specific transfer coefficients for fermium.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pathwaya | Transfer coefficient (d-1) | | | | | |
| 100 d | 1 y | 5 y | 10 y | 15 y | Adult |
| Blood to Liver 1 | 5.82E-01 | 5.82E-01 | 1.16E+00 | 1.16E+00 | 1.16E+00 | 1.75E+00 |
| Blood to ST0 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 | 4.99E+00 |
| Blood to ST1 | 8.68E-01 | 8.68E-01 | 8.68E-01 | 8.68E-01 | 8.68E-01 | 8.68E-01 |
| Blood to ST2 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 | 2.33E-01 |
| Blood to Cort bone surf | 3.78E+00 | 3.78E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 3.20E+00 |
| Blood to Trab bone surf | 3.78E+00 | 3.78E+00 | 3.49E+00 | 3.49E+00 | 3.49E+00 | 3.20E+00 |
| Blood to Kidneys 1 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 | 1.16E-01 |
| Blood to Right colon cont | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 | 6.99E-01 |
| Blood to Kidneys 2 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 | 5.82E-02 |
| Blood to Testes | 2.33E-04 | 3.49E-04 | 3.96E-04 | 4.66E-04 | 3.73E-03 | 4.08E-03 |
| Blood to Ovaries | 1.40E-04 | 1.86E-04 | 4.66E-04 | 8.15E-04 | 1.40E-03 | 1.28E-03 |
| Blood to Urinary bladder cont | 1.51E+00 | 1.51E+00 | 1.51E+00 | 1.51E+00 | 1.51E+00 | 1.51E+00 |
| Liver 1 to SI cont | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 | 6.00E-04 |
| Liver 1 to Liver 2 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 | 2.25E-02 |
| Liver 2 to Blood | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 | 1.90E-03 |
| ST0 to Blood | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 | 1.39E+00 |
| ST1 to Blood | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 | 6.93E-03 |
| ST2 to Blood | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 | 1.90E-05 |
| Cort marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Cort bone surf to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Cort bone surf to Cort bone vol | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 4.11E-05 |
| Cort bone vol to Cort marrow | 8.22E-03 | 2.88E-03 | 1.53E-03 | 9.04E-04 | 5.21E-04 | 8.21E-05 |
| Trab marrow to Blood | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 | 7.60E-03 |
| Trab bone surf to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Trab bone surf to Trab bone vol | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 2.47E-04 |
| Trab bone vol to Trab marrow | 8.22E-03 | 2.88E-03 | 1.81E-03 | 1.32E-03 | 9.59E-04 | 4.93E-04 |
| Kidneys 1 to Urinary bladder cont | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 | 9.90E-02 |
| Kidneys 2 to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Testes to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |
| Ovaries to Blood | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 | 3.80E-04 |

aCort = Cortical, Trab = Trabecular, SI = Small intestine, cont=content, surf=surface, vol = volume

* + - 1. Treatment of radioactive progeny

1. The treatment of radioactive progeny produced in systemic compartments after intake of a radioisotope of fermium is described in Section 18.2.4. of *Publication 141* (ICRP, 2019).

## Dosimetric data for fermium

Table 28.3. Committed effective dose coefficients (Sv Bq-1) for the inhalation or ingestion of 257Fm compounds.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Inhaled particulate materials  (1 µm AMAD aerosols) | Effective dose coefficients (Sv Bq-1) | | | | | |
| 3 mo | 1 y | 5 y | 10 y | 15 y | Adult |
| Type F | 1.4E-05 | 1.0E-05 | 4.3E-06 | 2.1E-06 | 1.9E-06 | 1.3E-06 |
| Type M | 1.7E-05 | 1.4E-05 | 7.4E-06 | 4.4E-06 | 3.6E-06 | 3.1E-06 |
| Type S | 2.1E-05 | 1.9E-05 | 1.1E-05 | 6.9E-06 | 5.4E-06 | 5.1E-06 |
| Ingested materials |  |  |  |  |  |  |
| All compounds | 6.2E-07 | 4.4E-08 | 1.6E-08 | 7.6E-09 | 6.2E-09 | 3.7E-09 |

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# ACKNOWLEDGEMENTS

This report is the second in a series of documents replacing the *Publication 56* series (ICRP, 1989, 1993, 1995b,c, 1996a, 2001, 2004) to provide revised age-dependent dose coefficients for members of the public for environmental intakes of radionuclides by inhalation and ingestion. The revised dose coefficients have been calculated using the Human Alimentary Tract Model (HATM) described in *Publication 100* (ICRP, 2006) and the revised Human Respiratory Tract Model (HRTM) described in *Publication 130* (ICRP, 2015). Revisions have also been made to many of the models that describe the systemic biokinetics of radionuclides absorbed to blood, making them more physiologically realistic representations of uptake and retention in organs and tissues and of excretion.

This second report in the series includes biokinetic and dosimetric models for individual elements and their radioisotopes plus dose coefficients. Additional data accompanying this series are available on the ICRP website and give extensive additional information. This current report provides the above data for the elements already described in OIR Parts 3 and 4 (*Publications 137, 141)* i.e.: Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu), Actinium (Ac), Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einsteinium (Es) and Fermium (Fm). Subsequent reports will provide data for most of the remaining elements.

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