Basic Concepts of Internal Dosimetry

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Learning Objectives

- Define the dosimetric quantities used in internal dosimetry
- Identify the parameters used in internal dose calculation
- Identify the regulatory limits on internal dose
- Define the derived quantities ALI and DAC
- Identify compilations of dose coefficients

Major Changes in Internal Dosimetry

NRC Regulation 10 CFR 20 (and DOE Regulation 10 CFR 835) now use models for internal dose developed by the International Commission on Radiological Protection (ICRP) since 1977.

KEY: No difference in handling internal and external dose.

Dose limits apply to total dose, i.e., sum of external and (weighted) internal doses.

ICRP Dosimetry Systems

- ICRP 2 (1959)
  - MPCs and MPBBs
  - 5 rem WB or RM, 15 rem organ annually
- ICRP 26 (1977) and ICRP 30 (1978)
  - Committed dose (5 rem, 50 rem organ)
  - ALIs and DACs
- ICRP 60 (1990)
  - 2 rem
- ICRP 103 (2007)
  - A few tweaks plus detriment

Goals of Internal Dosimetry

- Protect people
  - prevent acute (short-term) effects (rare)
  - minimize risk of long-term effects
- Verify adequacy of workplace controls
- Demonstrate regulatory compliance

Dose Limitation

- Since risk is assumed to be a direct function dose, we limit risk by limiting dose (a generic term for now)
- External dose limitation methods of time, distance, and shielding do not apply
- Once radioactive material is inside the body, dose is protracted
- Thus, internal doses have commonly been considered to be “worse” than external doses

Dose Limitation

- Best way to limit dose is to prevent intakes, and, if an intake occurs, mitigate effects
- Intake prevention:
  - at the source
  - in a controlled environment
  - in the general environment
  - at the individual
- Mitigation: decorporation therapy

At the Source

- Most effective
- Sealed sources
- Controlled storage
- Periodic inventory
- Leak testing
- Limited handling

In a Controlled Environment

- Required for quantities of unencapsulated radioactive materials greater than certain limits
- Glove boxes
- Fume hoods
- Hot cells

In the General Environment

- Contamination control
- Air monitoring and ventilation control
  - air purification (filtration)
  - negative pressure

At the Individual

- Least desirable control method
- Respiratory protection
- Protective clothing
- Good laboratory practice

Types of Effects

- Somatic effects:
  - occur in the exposed individual
- Genetic effects:
  - occur in the progeny of the exposed individual
- Stochastic effects:
  - probability of effect depends on dose
- Non-stochastic (deterministic effects):
  - severity of effects depends on dose

Stochastic Effects

- Random
- Severity independent of dose
- Probability of induction depends on dose
- No threshold for induction assumed
- Examples: fatal cancers & genetic effects
  - Lethal mutations in next two generations
  - ICRP 103 introduced “detriment” including non-fatal cancers

Non-stochastic (Deterministic) Effects

- Non-random
- Severity depends on dose
- Threshold for induction
- Examples:
  - cataract formation (? No, now it's stochastic!)
  - radiation burns: epilation, erythema, dry and moist desquamation, ulceration
  - acute radiation syndromes

ICRP Principles

- Justification
  - no practice should be authorized without good reason
- Limitation
  - no dose should exceed prescribed limits
- Optimization
  - doses should be maintained below limits, taking into account economic, societal, and other relevant considerations, i.e., ALARA

Dose Control Process

- Evaluate extent of exposure
- Evaluate resulting radiation doses
- Assess potential short- and long-term impacts on exposed individual
- Take any actions necessary to preclude further exposure to protect the individual and satisfy regulatory requirements
- Record and report relevant data and results

Parameters Affecting Internal Dose & Effects

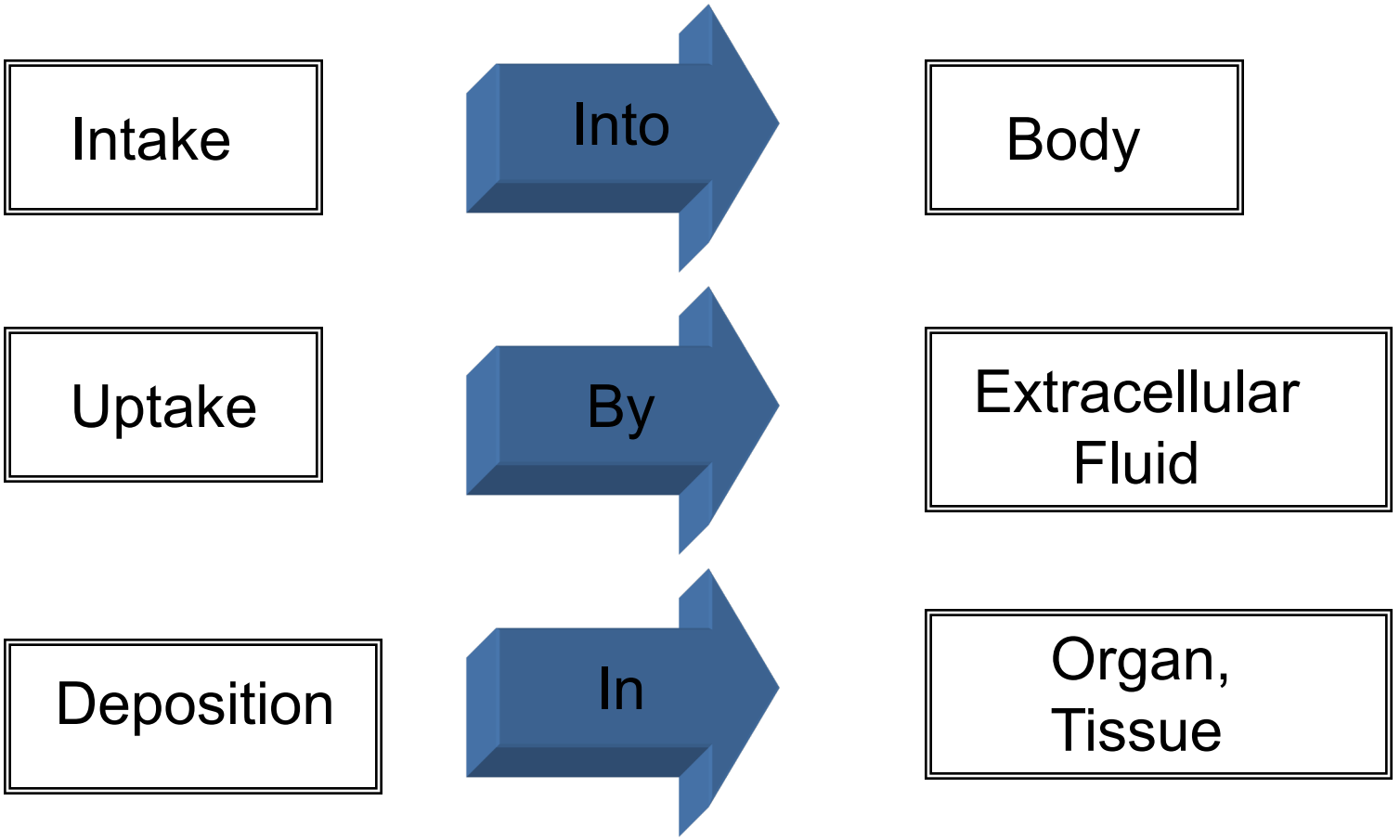
Physical

- Radionuclide
- Chemical & physical form
- Emitted radiations
- Physical half-life
- Intake route
- Duration of intake
- Total intake

Biological

- Metabolic behavior
- Biological half-life
- Tissue sensitivity
- Age of individual
- Individual health
- Personal habits
- Chemical toxicity

The Basic Definitions



Example

A worker inhales 100 Bq of a 1 μm AMAD aerosol.

ICRP 30 model predicts 63% deposition in lungs.

Only 58% of material deposited in lungs reaches the systemic circulation.

Only 25% of material in circulation is deposited in bone.

Intake = 100 Bq

Initial lung deposition = (0.63) (100 Bq) = 63 Bq

Uptake = (0.58) (63 Bq) = 36.5 Bq

Bone deposition = (0.25) (36.5) = 9.1 Bq

Intake Routes

- Inhalation (usually of greatest concern)
- Ingestion (also follows inhalation)
- Injection (contaminated wounds)
- Skin Absorption (usually only tritium)

- Multiple pathways are not uncommon
- In an accident, conventional trauma may also be present

Dose Estimates

- Under the current ICRP systems, all internal dose estimates use the intake as the basis for calculation
- Therefore, the key problem is to estimate the intake
- Normally internal dosimetry practices and procedures focus on intake estimation
- Non-standard dose calculations are usually performed only for very high intakes, i.e, well above regulatory limits

Dosimetric Quantities

- Absorbed dose: D = dE/dm, where
  - dE is the mean energy imparted by ionizing radiation into a volume whose mass is dm
  - units: MeV/g, erg/g, J/kg, rad, Gy
- Dose equivalent: H = D x Q, where
  - Q is a measure of the relative biological risk caused by a particular type of radiation
  - Q is end-point specific
  - Q also depends on the reference radiation

In-Class Exercise

- What do you need to know to calculate the dose equivalent rate to an organ?

Calculating Internal Dose

- To calculate dose rate, all we need to know is:
  - the activity in the source organ
  - the energy emitted per disintegration
  - the fraction of the emitted energy that is absorbed in the target organ
  - the mass of the target organ
- To calculate committed dose, we integrate the dose rate
- What could be simpler?

Dose Calculation Parameters

- D = absorbed dose
- H = dose equivalent
- A = activity
- E = energy of emitted radiation
- n = abundance of emitted radiation
- φ = fraction of energy absorbed
- m = mass of target organ
- Q = quality factor
- k = proportionality constant

Generic Equation for Dose Rate

$$\dot{D} = \frac{k\, A \sum n_i\, E_i\, \varphi_i}{m}$$

$$\dot{H} = \frac{k\, A \sum n_i\, E_i\, \varphi_i\, Q_i}{m}$$

Specific Equation: ICRP 2

$$\dot{H} = \frac{51.2\ A\ \xi}{m}$$

$$\xi = \Sigma\ n_i\ E_i\ \varphi_i\ Q_i$$

$$k = 51.2\ \frac{\text{rem-g}}{\mu\text{Ci-day-MeV}}$$

Specific Equation: MIRD

$$\dot{D} = A\,S$$

$$S = \frac{k \sum n_i E_i \varphi_i}{m}$$

$$k = 2.13 \quad \frac{\text{rad-g}}{\mu\text{Ci-hr-MeV}}$$

Specific Equation: ICRP-30

$$\dot{H} = k\, A\, SEE$$

$$SEE = \frac{\Sigma\, n_i\, E_i\, \varphi_i\, Q_i}{m}$$

$$k = 1.6 \times 10^{-10}\ \frac{Sv\text{-}g}{Bq\text{-}sec\text{-}MeV}$$

Integrated Dose

- All these equations give dose rate
- To get the total dose, we need to integrate over time
- But only one variable is time-dependent, the activity A

THE Equation

Almost all of internal dosimetry is based on one simple equation:

$$A = A_0 \exp(-\lambda t)$$

$$\int A\, dt = \frac{A_0\{1-\exp(-\lambda_e t)\}}{\lambda_e}$$

$$= 1.44\, T_{1/2e}\, A_0\{1-\exp(-\lambda_e t)\}$$

$$= 1.44\, T_{1/2e}\, A_0 \text{ if } t >> T_{1/2e}$$

Time Dependence of Activity

- The activity depends on two things:
  - radiological decay
  - biological elimination
- The two processes act independently

Elimination Routes

- Urinary excretion
  - soluble materials following uptake
- Fecal excretion
  - inhaled or ingested insoluble materials
- Exhalation
  - noble gases, tritium or ^{14}C compounds
- Perspiration
  - tritium, iodines, others?

Biological Elimination

- Element-specific
- Assumed to be a first-order process (perhaps with several components)
- $A = A_0 \exp(-\lambda t)$
- $A = \Sigma A_{0i} \exp(-\lambda_i t)$
- Biokinetic models are published in ICRP publications 30, 48, 68, 78 and elsewhere

Effective Half-Life

- The appropriate decay constant to be used in internal dosimetry is the effective decay constant, defined as the sum of the physical and biological decay constants:

$$\lambda(e) = \lambda(p) + \lambda(b)$$

Or in terms of half-lives:

$$1/T(e) = 1/T(p) + 1/T(b)$$

or

$$T(e) = \frac{T(p)T(b)}{T(p) + T(b)}$$

Example Problem

- The physical half-life of Ce-144 is 285 d, and its biological half-life is about 500 d. If a worker had an initial body burden of 16 kBq, what would be the body burden two years later?

Solution

1. T(e) = (285x500)/(285+500)

   = 142,500/785 = 181.5

   2 yr = about 4 T(e) = factor of 16

   so remaining body burden = 1 kBq

2. λ(e) = .693/285 + .693/500

   = 0.0038 day^{-1}

   16 kBq x exp(-.0038x730)

   = 16 kBq x 0.0624 = 1 kBq

Generic Equation for Dose

$$H = 1.443 T_e A_0 k \frac{\Sigma n_i E_i \varphi_i Q_i}{m}$$

All the specific systems merely rearrange and group these same parameters

The proportionality constant is controlled by the time, energy, and dose units

Example: the Unfortunate Mr. Litvinenko

- **ICRP 68 (1994): 10% of soluble Po-210 is absorbed from the GI tract (i.e., following ingestion, the uptake = 10% of the intake)**
- **Polonium deposits in the reticuloendothelial system:**
  - **30% in the liver**
  - **10% in the kidney**
  - **4% in red marrow**
  - **10% in spleen**
  - **40% distributed in other soft tissue**
- **Biological half-life = 50 d, physical half-life = 138 d, so effective half-life = 38 d**

One Data-Point Dose Estimate

- **Data point: a post-mortem analysis of approximately 1 GBq (27 mCi) of Po-210 in the whole body on 22 Nov 2006. Correcting for the effective half-life, this would be 1.5 GBq on 1 Nov, resulting from an estimated intake of 15 GBq, or about 10 µg as the chloride.**

One Data-Point Dose Estimate

- **Given an intake of 15 GBq:**

  10% of intake absorbed from G.I. tract = 1.5 GBq

  4% of 1.5 GBq deposited in red marrow

  5.3 MeV alpha per decay

  Conversion factor = 1.609E-13 J/MeV

  Mass of red marrow = 1.5 kg

Dose rate and dose

- **Therefore initial dose rate would have been:**

  (1.5 GBq x 0.04 x 5.3 MeV x 1.609E-13 J/MeV)/1.5 kg

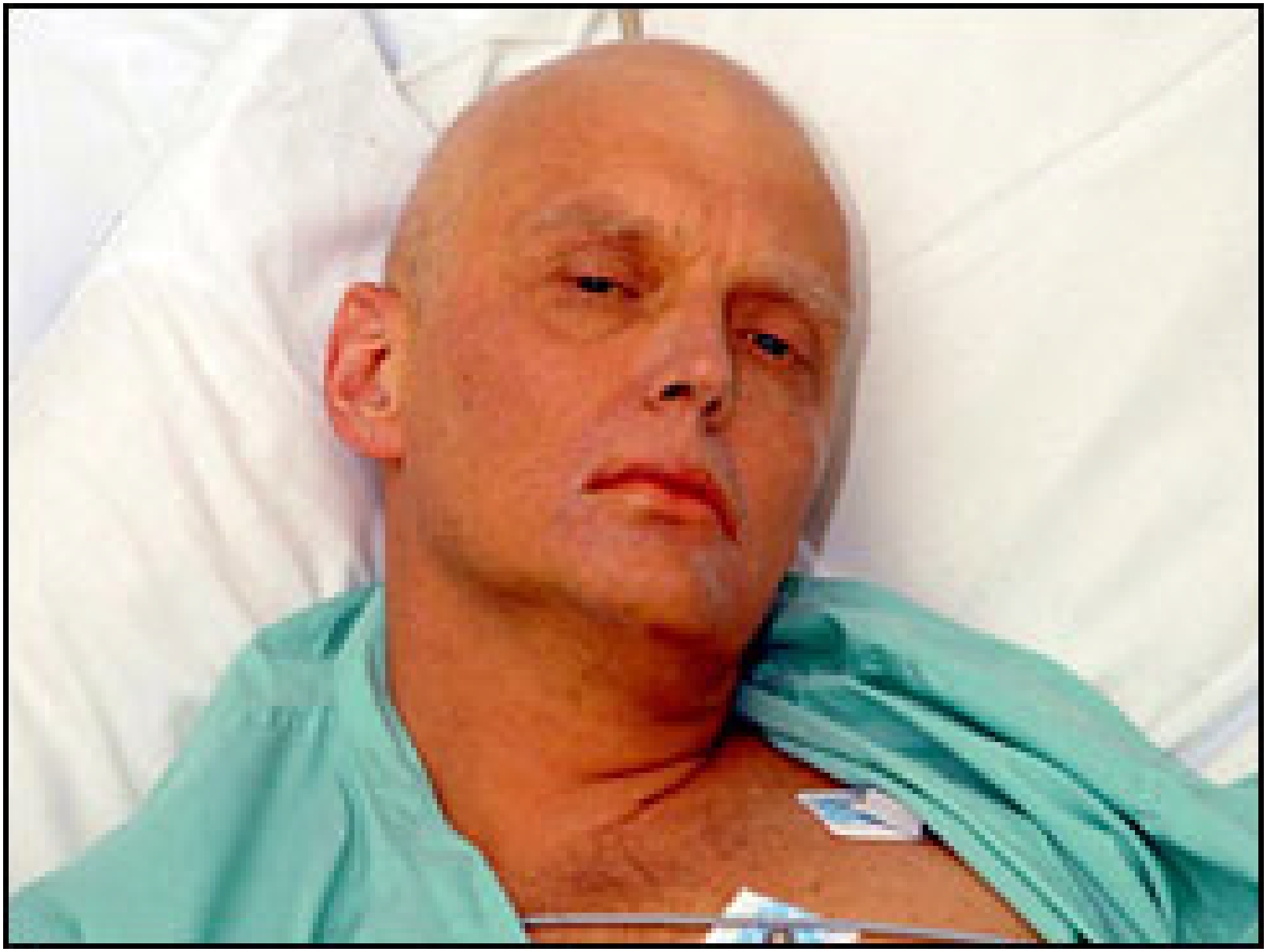
  = 34 μGy/sec

  34 μGy/sec x 3600 x 24 = 2.9 Gy (290 rad) per day.

  After 22 days, this would have decreased to 1.9 Gy/d.

  The integrated dose to RM would have been 52 Gy.

- **Litvenenko died of multiple organ failure on 21 November 2006.**



Committed Organ Dose Equivalent CODE - $H_{50,T}$

- The committed organ dose equivalent is the organ dose equivalent received over a period of 50 years from the intake.
- All ICRP dose limits are based on the *committed* organ dose equivalent.
- The committed organ dose equivalent is assigned to the year of intake, whether it is all received in that year or not

Total Organ Dose Equivalent TODE - $H_{50,T}$

- The total organ dose equivalent is the sum of the committed organ dose equivalent from internal sources and the deep dose equivalent (DDE) from external sources

$$TODE = CODE + DDE$$

- The ICRP limit to prevent non-stochastic effects is a TODE of 0.5 Sv (50 rem) per year (DDE from external sources plus CODE from all intakes in a year)

Committed Effective Dose Equivalent (CEDE)

- Problem: how to handle CODE's for different organs and keep track of dosimetry data?

  Answer: Committed Effective Dose Equivalent
- The CEDE equals the CODE for each organ or tissue multiplied by a tissue weighting factor, w_T, and summed over all organs or tissues, T
- As with TODE, we also have TEDE = CEDE + DDE

Tissue Weighting Factors

- Weighting factors equate the risk of cancer induction in the critical organ to the risk of cancer induction from uniform irradiation of the body
- e.g., w_T (lung) = 0.12
- 100 rem to the lung gives same cancer risk as 12 rem to the whole body

ICRP30 Tissue Weighting Factors

Organ	Weighting factor
gonads	0.25
breast	0.15
bone marrow	0.12
lung	0.12
thyroid	0.03
bone surface	0.03
all other organs (spleen, small intestine, etc.)	0.06

Note: If $w_T < 0.1$, non-stochastic limit will apply

Other Organs & Tissues

- Those five organs or tissues receiving the highest organ dose equivalents, among the following: spleen, stomach, small intestine, upper large intestine, lower large intestine, muscle, kidneys, liver, pancreas, thymus, uterus and adrenals, but excluding skin and lens.
- Each has $w_T = 0.06$; total w_T for other organs and tissues = 0.30.
- Sum of all $w_T = 1.0$.

Total Effective Dose Equivalent

- The Total EDE is the sum of the committed effective dose equivalent from internal sources and the deep dose equivalent (DDE) from external sources

  Total EDE = CEDE + DDE

- The ICRP limit to prevent stochastic effects is a Total EDE of 0.05 Sv (5 rem) from external exposure and all intakes of radioactive material in a year

ICRP30 Limits

- *Both* the stochastic and non-stochastic limits must be met, i.e.,

  Total ODE < 0. 5 Sv (50 rem) per year

  AND

  Total EDE < 0.05 Sv (5 rem) per year

- If w_T for the target organ is < 0.1, the non-stochastic limit will usually apply and take precedence (a lot more on this later)

Annual Limit on Intake (ALI)

- **Defined as the dose limit divided by the dose coefficient**
- **In U.S., dose limit may be either stochastic (SALI) (50 mSv y^{-1}) or non-stochastic (NALI) (500 mSv y^{-1})**
- **Elsewhere, only stochastic limit (20 mSv y^{-1})**
- **Different ALI's for inhalation and ingestion**
- **Only one significant figure, e.g., Cs-137**
  - **0.05 Sv/8.6 x 10^{-9} Sv Bq^{-1} = 6 x 10^{8} Bq**

Some ALIs of Interest (ICRP-30)

Radionuclide	ALI (inhalation)		ALI (ingestion)	
	MBq	µCi	MBq	µCi
Hydrogen-3	3,000	80,000	3,000	80,000
Phosphorus-32	10	400	20	600
Cobalt-60	1	30	10	200
Strontium-90	0.1	4	10	400
Cesium-137	10	200	4	100
Radium-226	0.02	0.6	0.07	2
Uranium-238	0.03	0.8	7	200
Plutonium-239	0.0002	0.006	0.03	0.8

Derived Air Concentration (DAC)

- **The DAC is the inhalation ALI divided by the volume of air breathed in a year by a worker**
- **Breathing rate = 20 liters per minute**
- **20L x 60 x 40 x 50 = 2400 m^3**
- **DAC's are in Bq m^{-3} or μCi cm^{-3}**
- **There are separate DAC's for submersion (noble gases)**

DAC-hours

- If we assume constant, standard breathing rate, we can compute intake from DAC-hour values
- DAC is based on 2000 working hours per year, so 2000 DAC-hours = 1 ALI
- Can then compute dose from DAC-hours, as fraction of ALI
- Can correct for respiratory protection, if used
- But remember that in U.S., ALI is based on more restrictive dose limit (CEDE or CODE)

Some DAC's of Interest

Radionuclide	DAC, MBq m^{-3}	DAC, μCi cm^{-3}
H-3	0.8	2×10^{-5}
P-32(D)	0.01	4×10^{-7}
P-32(W)	0.006	$2 \times 1\ 0^{-7}$
Co-60	5×10^{-4}	1×10^{-8}
Sr-90	6×10^{-5}	2×10^{-9}
Pu-239	1×10^{-7}	3×10^{-12}
Ar-41 (sub)	0.1	3×10^{-6}
Xe-133m (sub)	5	1×10^{-4}

	Inhalation			Ingestion	
		ALI	DAC		ALI
Nuclide	Class/f_1	MBq	MBq/m^3	f_1	MBq
Cobalt					
Co-55	W 0.05	100	0.04	0.05	40
17.54 h	Y 0.05	100	0.04	0.3	60
Co-56	W 0.05	10	0.005	0.05	20
78.76 d	Y 0.05	7	0.003	0.3	20
Co-57	W 0.05	100	0.04	0.05	300
270.9 d	Y 0.05	20	0.01	0.3	200
Co-58	W 0.05	40	0.02	0.05	60
70.80 d	Y 0.05	30	0.01	0.3	50
Co-58m	W 0.05	3000	1	0.05	2000
9.15 h	Y 0.05	2000	1	0.3	2000
Co-60	W 0.05	6	0.003	0.05	20
5.271 y	Y 0.05	1	$5\ 10^{-4}$	0.3	7
Co-60m	W 0.05	$1\ 10^5$	60	0.05	$4\ 10^4$
10.47 m	Y 0.05	$1\ 10^5$	40	0.3	$4\ 10^4$
Co-61	W 0.05	2000	1	0.05	700
1.65 h	Y 0.05	2000	0.9	0.3	800
Co-62m	W 0.05	6000	3	0.05	1000
13.91 m	Y 0.05	6000	2	0.3	1000

Nuclide	Class/f_1	Inhalation ALI μCi	Inhalation DAC μCi/cm^3	Ingestion f_1	Ingestion ALI μCi
Cobalt					
Co-55	W 0.05	3000	$1\ 10^{-6}$	0.05	1000
17.54 h	Y 0.05	3000	$1\ 10^{-6}$	0.3	2000
Co-56	W 0.05	300	$1\ 10^{-7}$	0.05	500
78.76 d	Y 0.05	200	$8\ 10^{-8}$	0.3	400
Co-57	W 0.05	3000	$1\ 10^{-6}$	0.05	8000
270.9 d	Y 0.05	700	$3\ 10^{-7}$	0.3	4000
Co-58	W 0.05	1000	$5\ 10^{-7}$	0.05	2000
70.80 d	Y 0.05	700	$3\ 10^{-7}$	0.3	1000
Co-58m	W 0.05	$9\ 10^4$	$4\ 10^{-5}$	0.05	$6\ 10^4$
9.15 h	Y 0.05	$6\ 10^4$	$3\ 10^{-5}$	0.3	$7\ 10^4$
Co-60	W 0.05	200	$7\ 10^{-8}$	0.05	500
5.271 y	Y 0.05	30	$1\ 10^{-8}$	0.3	200
Co-60m	W 0.05	$4\ 10^6$	0.002	0.05	$1\ 10^6$
10.47 m	Y 0.05	$3\ 10^6$	0.001	0.3	$1\ 10^6$
Co-61	W 0.05	$6\ 10^4$	$3\ 10^{-5}$	0.05	$2\ 10^4$
1.65 h	Y 0.05	$6\ 10^4$	$2\ 10^{-5}$	0.3	$2\ 10^4$
Co-62m	W 0.05	$2\ 10^5$	$7\ 10^{-5}$	0.05	$4\ 10^4$

Things to Remember about ALI's and DAC's:

- **Different ALI's for inhalation and ingestion**
- **ALI is based on more restrictive of stochastic or non-stochastic limit**
- **ALI and DAC depend on chemical form of radionuclide (solubility class)**
- **Do not confuse volume of air breathed (2400 m^3) with hours worked (2000); 1 ALI = 2000 DAC-hours**
- **DAC based on submersion for noble gases**

Dose Coefficients

- **Relate dose in Sv to intake in Bq (multiply by 3.7 to get rem/pCi)**
- **Coefficients are given for individual organs, and also for effective dose**
- **Computed for each radionuclide, and for different chemical forms of the radionuclide**
- **Published in Federal Guidance Report #11 (U.S. EPA), based on older (1977) ICRP methods**
- **Published in later ICRP and IAEA reports, based on newer methods**

Table 2.1, Cont'd.

Nuclide	Class/f_1	Committed Dose Equivalent per Unit Intake (Sv/Bq)							
		Gonad	Breast	Lung	R Marrow	B Surface	Thyroid	Remainder	Effective
Sr-87m	D 3 10^{-1}	4.54 10^{-12}	2.74 10^{-12}	4.47 10^{-11}	3.29 10^{-12}	2.33 10^{-12}	2.11 10^{-12}	1.38 10^{-11}	**1.16 10^{-11}**
	Y 1 10^{-2}	2.48 10^{-12}	1.43 10^{-12}	5.81 10^{-11}	1.66 10^{-12}	1.04 10^{-12}	8.54 10^{-13}	1.03 10^{-11}	**1.12 10^{-11}**
Sr-89	D 3 10^{-1}	4.16 10^{-10}	4.16 10^{-10}	2.16 10^{-9}	5.63 10^{-9}	8.37 10^{-9}	4.16 10^{-10}	1.32 10^{-9}	**1.76 10^{-9}**
	Y 1 10^{-2}	7.95 10^{-12}	7.96 10^{-12}	8.35 10^{-8}	1.07 10^{-10}	1.59 10^{-10}	7.96 10^{-12}	3.97 10^{-9}	**1.12 10^{-8}**
Sr-90	D 3 10^{-1}	2.64 10^{-9}	2.64 10^{-9}	3.73 10^{-9}	3.36 10^{-7}	**7.27 10^{-7}**	2.64 10^{-9}	3.36 10^{-9}	6.47 10^{-8}
	Y 1 10^{-2}	2.69 10^{-10}	2.69 10^{-10}	2.86 10^{-6}	3.28 10^{-8}	7.09 10^{-8}	2.69 10^{-10}	5.73 10^{-9}	**3.51 10^{-7}**
Sr-91	D 3 10^{-1}	6.41 10^{-11}	4.45 10^{-11}	9.21 10^{-10}	1.23 10^{-10}	1.14 10^{-10}	4.08 10^{-11}	3.33 10^{-10}	**2.52 10^{-10}**
	Y 1 10^{-2}	5.65 10^{-11}	1.74 10^{-11}	2.13 10^{-9}	2.23 10^{-11}	1.27 10^{-11}	9.64 10^{-12}	5.78 10^{-10}	**4.49 10^{-10}**
Sr-92	D 3 10^{-1}	3.03 10^{-11}	2.44 10^{-11}	7.12 10^{-10}	3.68 10^{-11}	2.56 10^{-11}	2.19 10^{-11}	2.25 10^{-10}	**1.70 10^{-10}**
	Y 1 10^{-2}	1.02 10^{-11}	6.49 10^{-12}	1.05 10^{-9}	6.98 10^{-12}	4.36 10^{-12}	3.92 10^{-12}	2.90 10^{-10}	**2.18 10^{-10}**

Available Compilations

- ICRP Publications
  - ICRP 68 (workers)
  - ICRP 56, 67, 69, 71 and 72 (public)
  - ICRP 88 (embryo/fetus)
- EPA Federal Guidance Reports
  - FGR 11, 12 and 13
- CDs (ICRP & EPA)

ICRP Dose Coefficients

- Age-specific coefficients
  - Six ages at intake (3 mo, 1-, 5-, 10-, 15- yr, and adult)
  - Publications 56, 67, 69, and 71 coefficients based on evaluated biokinetics of 31 elements
  - Publication 72 (effective dose coefficient for all radionuclides in Publication 38)

ICRP Dose Coefficients

- Worker
  - Publication 68 (effective dose coefficient for radionuclides of Publication 38)
  - Used biokinetic models reviewed in Publication 56 series
  - Publication 78 presents bioassay data for selected radionuclides

Pu-239, adult worker
Inhalation Type S, AMAD = 5.0 micron, f1 = 0.00001

	Dose coefficient (Sv/Bq)									
Time	1 d	7 d	30 d	1 y	5 y	10 y	20 y	30 y	45 y	50 y
Adrenals	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Bladder Wall	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Bone Surface	1.1E-10	2.3E-09	1.5E-08	5.2E-07	5.9E-06	1.5E-05	3.4E-05	5.4E-05	8.2E-05	9.1E-05
Brain	4.8E-12	1.9E-11	5.5E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Breast	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
GI-Tract										
Oesophagus	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
St Wall	5.0E-10	5.2E-10	5.7E-10	1.8E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
SI Wall	1.2E-09	1.3E-09	1.3E-09	2.6E-09	1.3E-08	2.7E-08	5.6E-08	8.7E-08	1.4E-07	1.6E-07
ULI Wall	5.5E-09	7.6E-09	7.8E-09	9.4E-09	2.0E-08	3.4E-08	6.3E-08	9.4E-08	1.4E-07	1.6E-07
LLI Wall	6.1E-09	2.2E-08	2.3E-08	2.5E-08	3.6E-08	5.1E-08	8.0E-08	1.1E-07	1.6E-07	1.8E-07
Colon	5.8E-09	1.4E-08	1.4E-08	1.6E-08	2.7E-08	4.2E-08	7.0E-08	1.0E-07	1.5E-07	1.7E-07
Kidneys	8.8E-12	1.1E-10	6.4E-10	1.2E-08	7.1E-08	1.3E-07	2.1E-07	2.8E-07	3.6E-07	3.9E-07
Liver	2.1E-11	3.7E-10	2.4E-09	8.6E-08	1.1E-06	3.0E-06	7.4E-06	1.2E-05	1.7E-05	1.9E-05
Muscle	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Ovaries	5.1E-12	3.2E-11	1.6E-10	5.2E-09	6.6E-08	1.8E-07	4.5E-07	7.1E-07	1.1E-06	1.2E-06
Pancreas	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Red Marrow	1.4E-11	2.3E-10	1.5E-09	5.1E-08	5.4E-07	1.2E-06	2.3E-06	3.1E-06	4.2E-06	4.5E-06
Respiratory Tract										
ET Airways	8.8E-08	6.1E-07	2.6E-06	2.6E-05	6.9E-05	7.8E-05	8.0E-05	8.0E-05	8.0E-05	8.0E-05
Lungs	8.3E-07	4.2E-06	1.3E-05	2.7E-05	3.7E-05	4.1E-05	4.4E-05	4.6E-05	4.6E-05	4.7E-05
Skin	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Spleen	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Testes	5.0E-12	3.2E-11	1.6E-10	5.3E-09	6.7E-08	1.8E-07	4.5E-07	7.2E-07	1.1E-06	1.2E-06
Thymus	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Thyroid	4.8E-12	1.9E-11	5.5E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Uterus	4.8E-12	1.9E-11	5.6E-11	1.2E-09	1.2E-08	2.6E-08	5.5E-08	8.6E-08	1.4E-07	1.5E-07
Remainder	7.4E-11	3.4E-10	1.3E-09	1.4E-08	4.6E-08	6.5E-08	9.5E-08	1.3E-07	1.8E-07	2.0E-07
Effective dose	1.0E-07	5.0E-07	1.5E-06	3.2E-06	4.6E-06	5.4E-06	6.4E-06	7.2E-06	8.0E-06	8.3E-06

Adult Member of Public, Ingestion Intake

	HTO	C-14	Co-60	Sr-90	Cs-137	Ra-226	U-238	Pu-239	Am-241
Adrenals	1.8E-11	5.7E-10	2.5E-09	6.6E-10	1.4E-08	4.1E-08	2.5E-08	1.4E-08	1.5E-08
Bladder Wall	1.8E-11	5.7E-10	2.6E-09	1.5E-09	1.4E-08	4.0E-08	2.5E-08	1.4E-08	1.5E-08
Bone Surface	1.8E-11	5.7E-10	2.0E-09	4.1E-07	1.4E-08	1.2E-05	7.1E-07	8.2E-06	9.0E-06
Brain	1.8E-11	5.7E-10	1.4E-09	6.6E-10	1.2E-08	4.1E-08	2.4E-08	1.4E-08	1.5E-08
Breast	1.8E-11	5.7E-10	1.3E-09	6.6E-10	1.1E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
GI-Tract									
Oesophagus	1.8E-11	5.7E-10	1.7E-09	6.6E-10	1.3E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
St Wall	1.8E-11	6.3E-10	2.5E-09	9.0E-10	1.3E-08	4.1E-08	2.5E-08	1.6E-08	1.7E-08
SI Wall	1.8E-11	5.7E-10	4.2E-09	1.1E-09	1.4E-08	4.2E-08	2.7E-08	1.7E-08	1.9E-08
ULI Wall	1.8E-11	5.8E-10	6.5E-09	5.8E-09	1.4E-08	6.4E-08	3.9E-08	3.3E-08	3.5E-08
LLI Wall	1.8E-11	6.0E-10	1.2E-08	2.2E-08	1.7E-08	1.5E-07	6.9E-08	6.7E-08	7.4E-08
Colon	1.8E-11	5.9E-10	8.7E-09	1.3E-08	1.5E-08	9.9E-08	5.2E-08	4.8E-08	5.2E-08
Kidneys	1.8E-11	5.7E-10	2.4E-09	6.6E-10	1.3E-08	5.9E-08	2.5E-07	3.4E-08	4.6E-08
Liver	1.8E-11	5.7E-10	4.4E-09	6.6E-10	1.3E-08	1.8E-07	9.6E-08	1.7E-06	5.5E-07
Muscle	1.8E-11	5.7E-10	1.9E-09	6.6E-10	1.2E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Ovaries	1.8E-11	5.7E-10	4.3E-09	6.6E-10	1.4E-08	4.1E-08	2.5E-08	1.1E-07	1.8E-07
Pancreas	1.8E-11	5.7E-10	2.6E-09	6.6E-10	1.4E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Red Marrow	1.8E-11	5.7E-10	2.1E-09	1.8E-07	1.3E-08	8.7E-07	7.5E-08	3.9E-07	3.1E-07
Respiratory Tract									
ET Airways	1.8E-11	5.7E-10	1.7E-09	6.6E-10	1.3E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Lungs	1.8E-11	5.7E-10	1.8E-09	6.6E-10	1.3E-08	4.0E-08	2.5E-08	1.4E-08	1.5E-08
Skin	1.8E-11	5.7E-10	1.3E-09	6.6E-10	1.1E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Spleen	1.8E-11	5.7E-10	2.1E-09	6.6E-10	1.3E-08	5.3E-08	2.4E-08	1.4E-08	1.5E-08
Testes	1.8E-11	5.7E-10	1.8E-09	6.6E-10	1.2E-08	4.0E-08	2.5E-08	1.1E-07	1.7E-07
Thymus	1.8E-11	5.7E-10	1.7E-09	6.6E-10	1.3E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Thyroid	1.8E-11	5.7E-10	1.7E-09	6.6E-10	1.3E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Uterus	1.8E-11	5.7E-10	3.0E-09	6.6E-10	1.4E-08	4.0E-08	2.4E-08	1.4E-08	1.5E-08
Remainder	1.8E-11	5.7E-10	1.9E-09	6.7E-10	1.2E-08	4.0E-08	2.7E-08	1.5E-08	1.6E-08
Effective dose	1.8E-11	5.8E-10	3.4E-09	2.8E-08	1.3E-08	2.8E-07	4.5E-08	2.5E-07	2.0E-07

I-131, 1-year-old member of the public

	Dose Coefficients (Sv/Bq)					
	Inhalation					
	Vapor	CH3I	F	M	S	Ingest
Adrenals	3.0E-10	2.3E-10	1.7E-10	2.0E-10	2.1E-10	3.4E-10
Bladder Wall	1.4E-09	1.1E-09	7.2E-10	3.5E-10	2.9E-10	1.5E-09
Bone Surface	4.1E-10	3.1E-10	2.4E-10	1.7E-10	1.6E-10	4.4E-10
Brain	3.5E-10	2.7E-10	2.0E-10	5.6E-11	3.3E-11	3.8E-10
Breast	3.9E-10	2.9E-10	2.3E-10	1.7E-10	1.6E-10	4.2E-10
GI-Tract						
Oesophagus	1.6E-09	1.2E-09	1.0E-09	4.4E-10	3.4E-10	1.7E-09
St Wall	6.3E-10	2.1E-10	5.1E-10	9.2E-10	9.7E-10	2.0E-09
SI Wall	2.8E-10	2.1E-10	1.6E-10	2.2E-09	2.5E-09	3.6E-10
ULI Wall	7.4E-10	5.3E-10	4.2E-10	9.9E-09	1.1E-08	1.0E-09
LLI Wall	1.5E-09	1.0E-09	8.5E-10	2.5E-08	2.9E-08	2.2E-09
Colon	1.1E-09	7.5E-10	6.1E-10	1.6E-08	1.9E-08	1.5E-09
Kidneys	2.6E-10	2.0E-10	1.4E-10	1.5E-10	1.6E-10	2.9E-10
Liver	3.0E-10	2.3E-10	1.7E-10	2.1E-10	2.2E-10	3.3E-10
Muscle	6.1E-10	4.6E-10	3.8E-10	2.3E-10	2.1E-10	6.6E-10
Ovaries	2.8E-10	2.2E-10	1.5E-10	7.5E-10	8.5E-10	3.3E-10
Pancreas	3.1E-10	2.3E-10	1.8E-10	2.2E-10	2.3E-10	3.7E-10
Red Marrow	3.4E-10	2.6E-10	2.0E-10	1.4E-10	1.4E-10	3.7E-10
Respiratory Tract						
ET Airways	8.6E-09	2.8E-10	2.6E-08	3.0E-08	3.1E-08	4.0E-10
Lungs	2.1E-09	3.8E-10	3.4E-10	1.4E-08	1.6E-08	5.4E-10
Skin	3.1E-10	2.4E-10	1.8E-10	9.6E-11	8.2E-11	3.4E-10
Spleen	2.9E-10	2.2E-10	1.6E-10	1.9E-10	1.9E-10	3.3E-10
Testes	2.3E-10	1.8E-10	1.2E-10	1.3E-10	1.3E-10	2.5E-10
Thymus	1.6E-09	1.2E-09	1.0E-09	4.4E-10	3.4E-10	1.7E-09
Thyroid	3.2E-06	2.5E-06	1.7E-06	2.5E-07	1.7E-08	3.6E-06
Uterus	2.8E-10	2.2E-10	1.5E-10	3.9E-10	4.3E-10	3.2E-10
Remainder	5.6E-10	4.2E-10	3.5E-10	2.5E-10	1.5E-08	6.0E-10
Effective dose	1.6E-07	1.3E-07	8.6E-08	1.6E-08	6.2E-09	1.8E-07

I-131, adult member of the public

	Dose Coefficient (Sv/Bq)				
			-- Particulate Form --		
	Vapor	CH3I	F	M	S
Adrenals	4.4E-11	3.4E-11	1.7E-11	7.4E-11	8.4E-11
Bladder Wall	6.9E-10	5.3E-10	2.6E-10	6.2E-11	2.9E-11
Bone Surface	1.2E-10	8.8E-11	4.6E-11	4.5E-11	4.5E-11
Brain	1.3E-10	1.0E-10	5.4E-11	1.6E-11	9.8E-12
Breast	5.5E-11	4.2E-11	2.1E-11	7.4E-11	8.3E-11
GI-Tract					
Oesophagus	1.4E-10	1.1E-10	5.7E-11	9.5E-11	1.0E-10
St Wall	9.4E-11	3.0E-11	4.0E-11	1.0E-10	1.1E-10
SI Wall	4.1E-11	3.0E-11	1.6E-11	1.7E-10	2.0E-10
ULI Wall	5.3E-11	3.5E-11	2.0E-11	6.8E-10	7.9E-10
LLI Wall	8.0E-11	4.7E-11	3.2E-11	1.7E-09	2.0E-09
Colon	6.5E-11	4.0E-11	2.5E-11	1.1E-09	1.3E-09
Kidneys	4.0E-11	3.1E-11	1.5E-11	3.3E-11	3.6E-11
Liver	4.4E-11	3.3E-11	1.7E-11	6.5E-11	7.3E-11
Muscle	1.2E-10	8.9E-11	4.7E-11	4.6E-11	4.6E-11
Ovaries	4.4E-11	3.4E-11	1.7E-11	7.6E-11	8.6E-11
Pancreas	4.7E-11	3.5E-11	1.8E-11	6.0E-11	6.7E-11
Red Marrow	9.3E-11	7.1E-11	3.7E-11	5.6E-11	5.9E-11
Respiratory Tract					
ET Airways	1.8E-09	1.0E-10	2.1E-09	2.6E-09	2.6E-09
Lungs	6.9E-10	7.2E-11	6.0E-11	9.6E-09	1.1E-08
Skin	6.4E-11	4.9E-11	2.5E-11	2.2E-11	2.1E-11
Spleen	4.4E-11	3.3E-11	1.7E-11	5.6E-11	6.2E-11
Testes	3.6E-11	2.8E-11	1.4E-11	9.3E-12	8.6E-12
Thymus	1.4E-10	1.1E-10	5.7E-11	9.5E-11	1.0E-10
Thyroid	3.9E-07	3.1E-07	1.5E-07	2.2E-08	1.1E-09
Uterus	5.2E-11	4.0E-11	1.9E-11	3.8E-11	4.1E-11
Remainder	1.2E-10	8.7E-11	4.7E-11	4.8E-11	4.9E-11
Effective dose	2.0E-08	1.5E-08	7.4E-09	2.4E-09	1.6E-09

Age-Specific ICRP-71 Inhalation Dose Coefficients

		---------- e(age)/e(adult) ----------					e (Sv Bq^{-1})
Nuclide	**Type**	**3 mo**	**1 yr**	**5 yr**	**10 yr**	**15 yr**	**Adult**
H-3	V	3.6	2.7	1.7	1.3	1.0	1.8E-11
Co-60	M	4.2	3.4	2.1	1.5	1.2	1.0E-08
Sr-90	M	4.2	3.1	1.8	1.4	1.4	3.6E-08
I-131	V	8.5	8.0	4.7	2.4	1.5	2.0E-08
Cs-137	F	1.9	1.2	0.78	0.80	0.96	4.6E-09
Ra-226	M	4.3	3.1	2.0	1.4	1.3	3.5E-06
Th-232	S	2.2	2.0	1.5	1.0	1.0	2.5E-05
U-238	M	4.1	3.2	2.0	1.4	1.2	2.9E-06
Pu-239	M	1.6	1.5	1.2	0.96	0.94	5.0E-05

Limitations in Compilations

- No coefficients available for wounds
  - NCRP report on wound models not yet in
  - Available in REAC/TS publications
- Coefficients for early effects
  - Consider dose rate and absorbed dose
  - Compilations to be published

Keep in mind

- Possible non-linear behavior
- Medical treatment may alter biokinetics
  - KI to block thyroid uptake
  - Prussian Blue blocks absorption from GI tract of Cs, Rb, and Tl
  - Zn- & Ca-DTPA by chelation increases elimination of actinides
  - Forced fluid intake to increase elimination of HTO
- Surgical intervention of wounds