The Fundamentals of Internal Dosimetry

TG 95 Webinar

Internal Dose Coefficients for Workers and Members of the Public

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ICRP

Overview of the Fundamentals

- What is an internal dose coefficient?

- How are the committed effective dose coefficients computed?

- What improvements are represented in the new internal dose coefficients?

What is an internal dose coefficient?

- **It gives the radiation dose per unit activity taken into the body**

$$Internal\ Dose\ Coefficient = \frac{Dose}{Total\ Activity\ Taken\ Into\ Body}$$

- **What is its purpose?**
  - Prospective radiation protection
    - Dose for an intake scenario
  - Retrospective dosimetry
    - Couple to an estimate of the intake

For inhalations, the denominator includes the activity which is promptly exhaled.

Which dose?

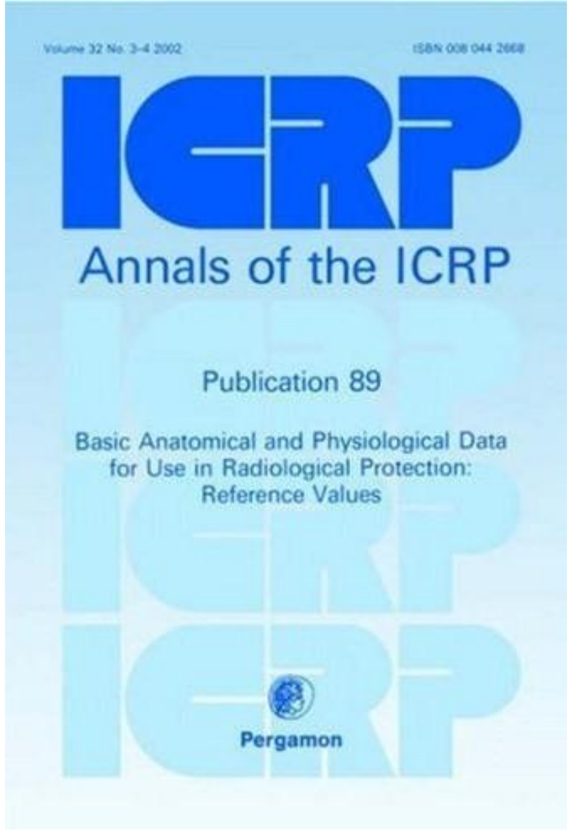
$$Internal\ Dose\ Coefficient = \frac{Dose}{Activity\ Intake}$$

- **Absorbed dose coeff.** $d_T = \frac{D_T}{A_{intake}}$ (Gy/Bq)
- **Equivalent dose coeff.** $h_T = \frac{H_T}{A_{intake}}$ (Sv/Bq) ← radiation-weighted
- **Effective dose coeff.** $e = \frac{E}{A_{intake}}$ (Sv/Bq) ← radiation- & tissue-weighted

- **Committed dose coeff.** – the integration of any of the above over a commitment period

Reference Individuals

- **Reference Individuals**
  - A set of idealised males and females with anatomical and physiological characteristics defined by the ICRP for the purpose of radiological protection.
  - 6 ages of each sex (Newborn, 1y, 5y, 10y, 15y, Adult)
- **Largely defined in Publication 89**
  - Masses, blood distributions, elemental composition of tissues, some geometrical information
  - With some modification and supplemental information
  - Age-dependent Blood distribution (Wayson et al. 2018)
- **Reference Person and Representative Person**
  - Sex-averaged conceptual person (Ref. Female and Ref. Male) from whom the effective dose is defined.



Back to our question at the beginning…

- **From Publication 103, paragraph (146):**
  - The dose coefficients used [to determine committed effective dose] are those specified by the Commission **with no departure from the anatomical, physiological, and biokinetic characteristics of the Reference Male and the Reference Female.** Account may be taken of the physical and chemical characteristics of the intake, including the activity median aerodynamic diameter (AMAD) of the inhaled aerosol and the chemical form of the particulate matter to which the specified radionuclide is attached. **The effective dose assigned in the worker's record is that value which the Reference Person would experience owing to the radiation fields and activity intakes encountered by the worker.**

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New methodology implemented in ICRP internal dose coefficient series

- Implemented Pub. 103 recommendations (including revised tissue weighting)
- Use of whole-body, non-hermaphrodite voxel phantoms
- Improved energy-absorption models for charged particles in the alimentary tract, gall bladder, and the skeleton.
- Improvements to respiratory, alimentary, and systemic biokinetic models
- Inclusion of whole-body blood as a source region
- Independent biokinetics for members of a decay chain
- Improved nuclear decay data

Equivalent Dose Rate

Biokinetic or Source term
Activity in source region S

Energy absorption or Physics term
S-coefficient
Equivalent dose to a target per transformation in the source region (or equivalently, the equivalent dose rate per activity.)

$$\dot{H}_T = \sum_{r_S} A_S \, S_w(r_T \leftarrow r_S)$$

Breaking down the two terms

Biokinetic or Source term

Activity in source region S

$$A_S$$

Integrating the activity over a commitment period gives the total number of nuclear transformations.

ICRP Pub. 103 radiation weighting factors	
Radiation type	w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see ICRP Pub. 103)

Energy absorption or Physics term

S-coefficient

Equivalent dose to a target per transformation in the source region (or equivalently, the equivalent dose rate per activity.)

$$S_w(r_T \leftarrow r_S) = \sum_R w_R \sum_i E_{R,i} Y_{R,i} \Phi(r_T \leftarrow r_S, E_{R,i})$$

Radiation weighting factor (equivalent → effective dose)

Energy and **yield** of radiation emission from the radionuclide (ICRP Pub. 107)

$$S_{w-beta}(r_T \leftarrow r_S) = \int_{i=0}^{imax} w_R E_{R,i} Y_{R,i} \Phi(r_T \leftarrow r_S, E_{R,i})$$

Specific Absorbed Fraction

$$\Phi(r_T \leftarrow r_S, E_{R,i}) = \frac{\phi(r_T \leftarrow r_S, E_{R,i})}{m_T}$$

Absorbed Fraction – fraction of energy emitted from a source region which is deposited in a target region

Mass of Target – should be consistent with the geometry used to compute ϕ

79 source regions (from biokinetic models)
43 target regions (from definition of effective dose targets plus others)
6 ages (newborn, 1y, 5y, 10y, 15y, adult)
2 sexes
4 radiation types (alpha, electron, photon, neutrons from spontaneous fission)
28 (electron, photon) or 24 (alpha) points on energy grid
→ **more than 3 million data points!**

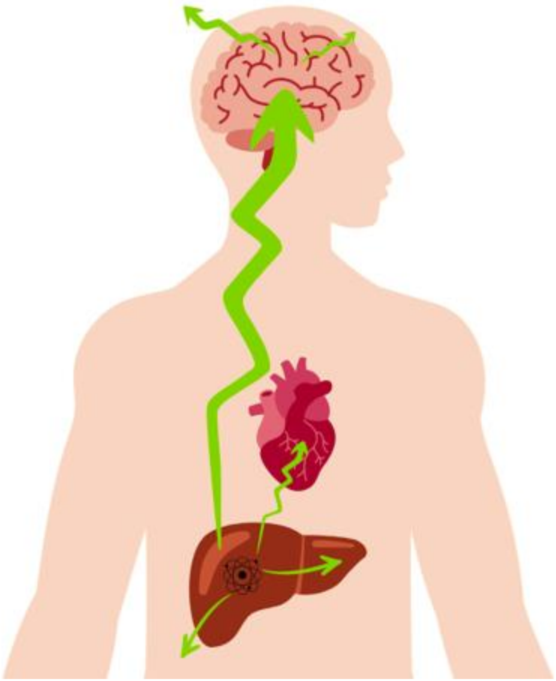
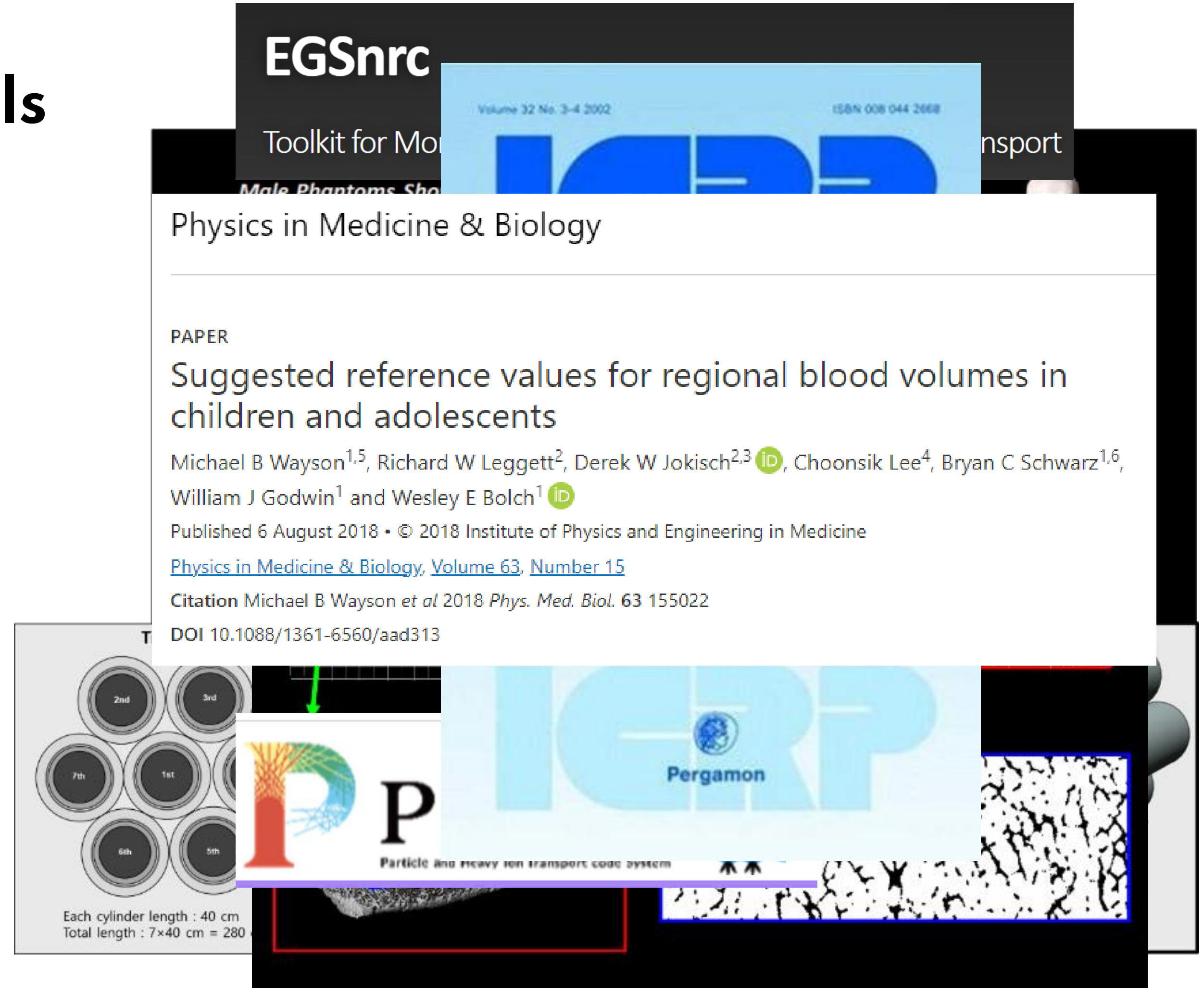
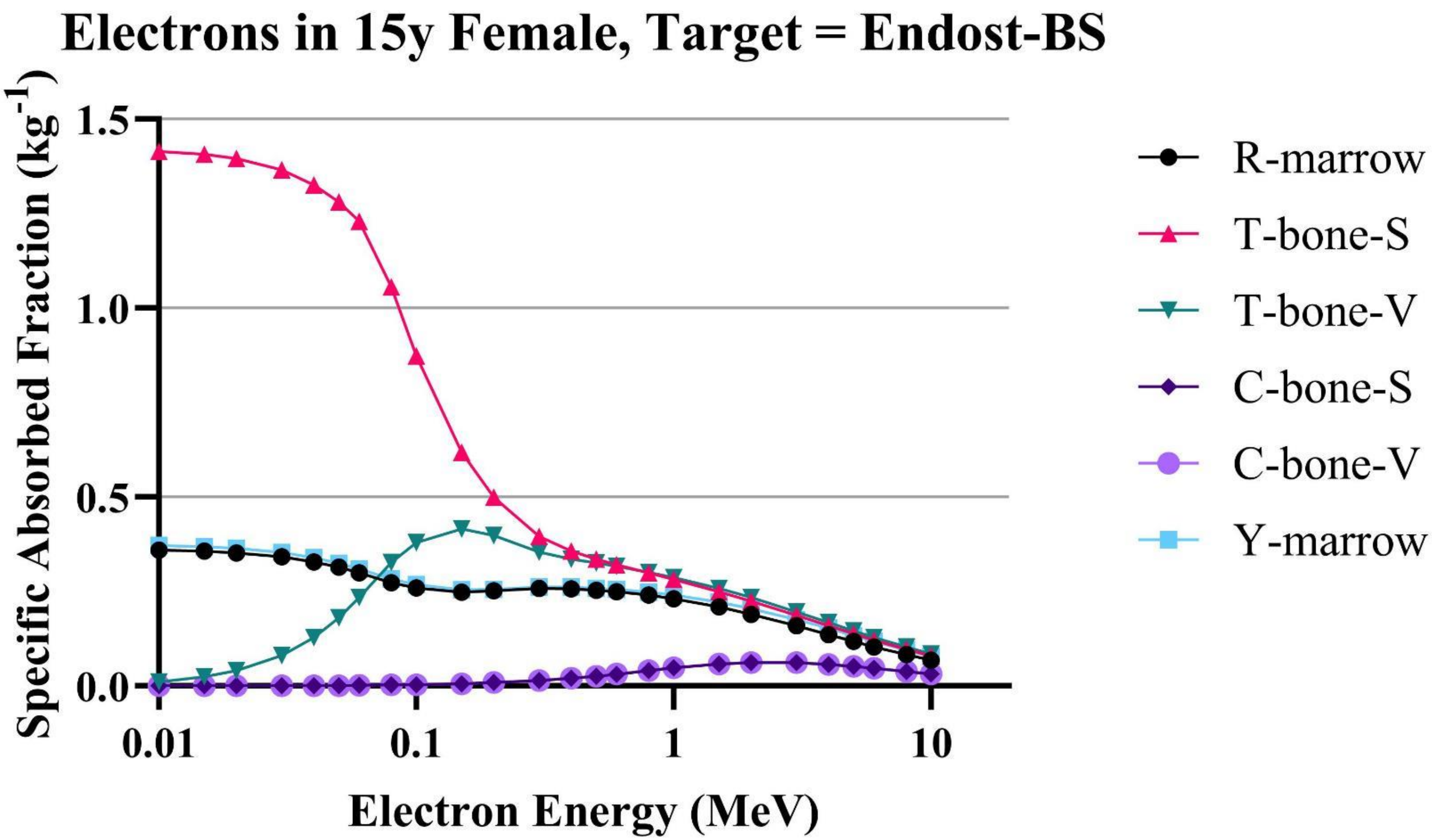


Image courtesy of Charlotte White

Methods for computing SAFs

- **Definition of reference individuals**
  - Need to supplement Pub. 89
- **Models of tissue geometries and composition**
  - Whole-body phantoms (voxel)
  - Image-based models (skeleton)
  - Mathematically defined stylized models (GI/lung)
- **Models for radiation transport physics**




Electrons in 15y Female, Target = Endost-BS
Specific Absorbed Fraction (kg-1)
1.5
1.0
0.5
0.0
0.01
0.1
1
10
Electron Energy (MeV)
R-marrow
T-bone-S
T-bone-V
C-bone-S
C-bone-V
Y-marrow

Committed Effective Dose Coefficients

Adult

- *S*-coefficient is invariant with time

$$h_T = \sum_{r_S} \tilde{a}(r_S, \tau) S_w(r_T \leftarrow r_S)$$

Children

- *S*-coefficient (SAF) varies with time

$$h_T = \sum_{r_S} \int_{t_o}^{t_o+\tau} a_S(t) S_w(r_T \leftarrow r_S, t) dt$$

$$e(\tau) = \sum_T w_T \left[\frac{h_T^F(\tau) + h_T^M(\tau)}{2} \right]$$

Sex-averaged!

For the adult (worker or member of the public) the commitment period, tau, is 50 years. $(\tau = 50\text{y})$

For paediatric individuals, the commitment period extends until age 70y. $(t_o + \tau = 70\text{y})$

Tissue weighting factors

$$e(\tau) = \sum_T w_T \left[\frac{h_T^F(\tau) + h_T^M(\tau)}{2}\right]$$

ICRP 103 tissue weighting factors		
Tissue	w_T	$\sum w_T$
Bone marrow (red), colon, lung, stomach, breast, remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1.00

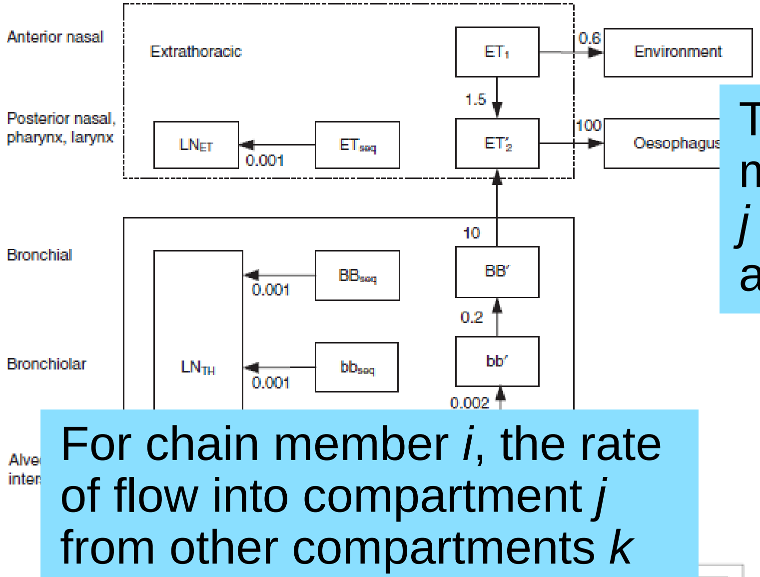
*** Remainder tissues: adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix.**

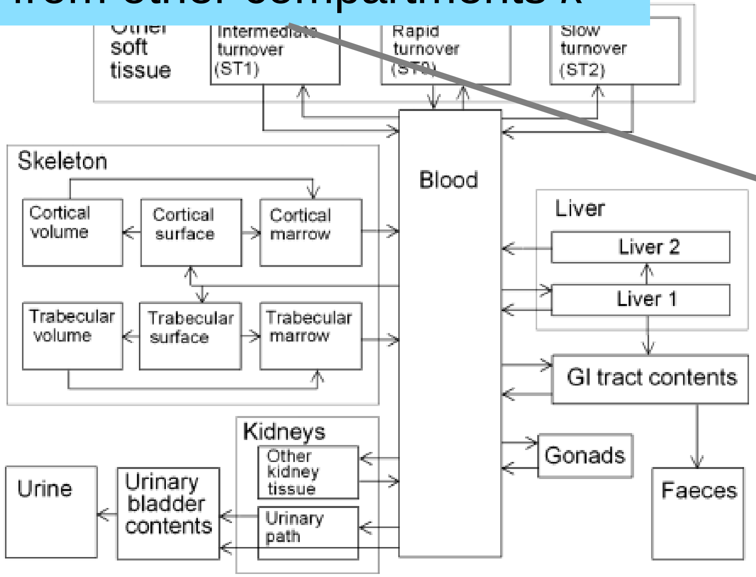
$$h_{Remainder} = \frac{1}{13} \sum_T h_T$$

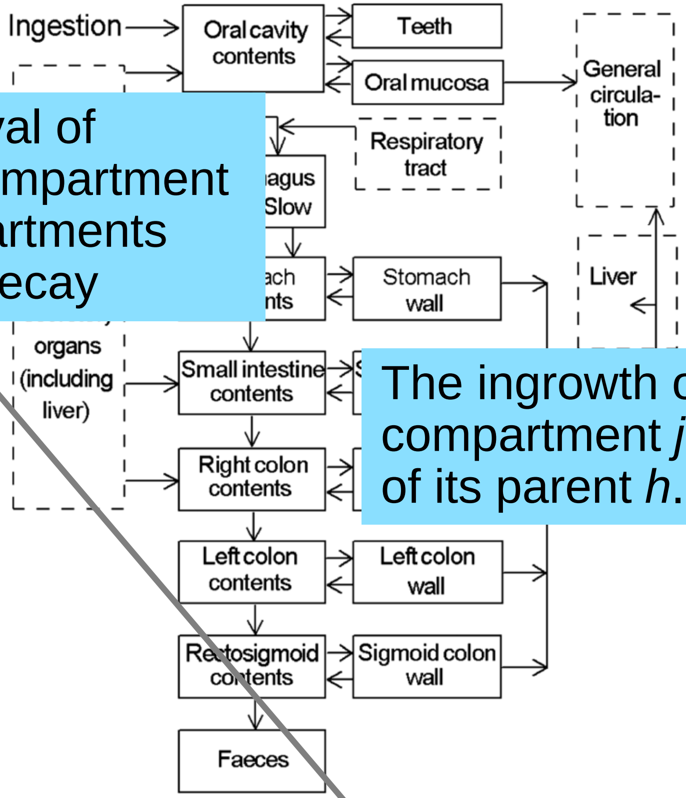
Target tissues comprised of sub-regions

Target Tissue, T	Constituent tissue, r_T	Abbreviation	$f(r_T, T)$
Extrathoracic region	ET_1 basal cells	ET1-bas	0.001
	ET_2 basal cells	ET2-bas	0.999
Lung	Bronchi basal cells	Bronch-bas	1/6
	Bronchi secretory cells	Bronch-sec	1/6
	Bronchiolar secretory cells	Bchiol-sec	1/3
	Alveolar-interstitial	AI	1/3
Colon	Right colon	RC-stem	0.4
	Left colon	LC-stem	0.4
	Rectosigmoid colon	RS-stem	0.2
Lymphatic nodes	Extrathoracic lymph nodes	LN-ET	0.08
	Thoracic lymph nodes	LN-Th	0.08
	Systemic lymph nodes	LN-Sys	0.84

Biokinetic models → Activity distributions







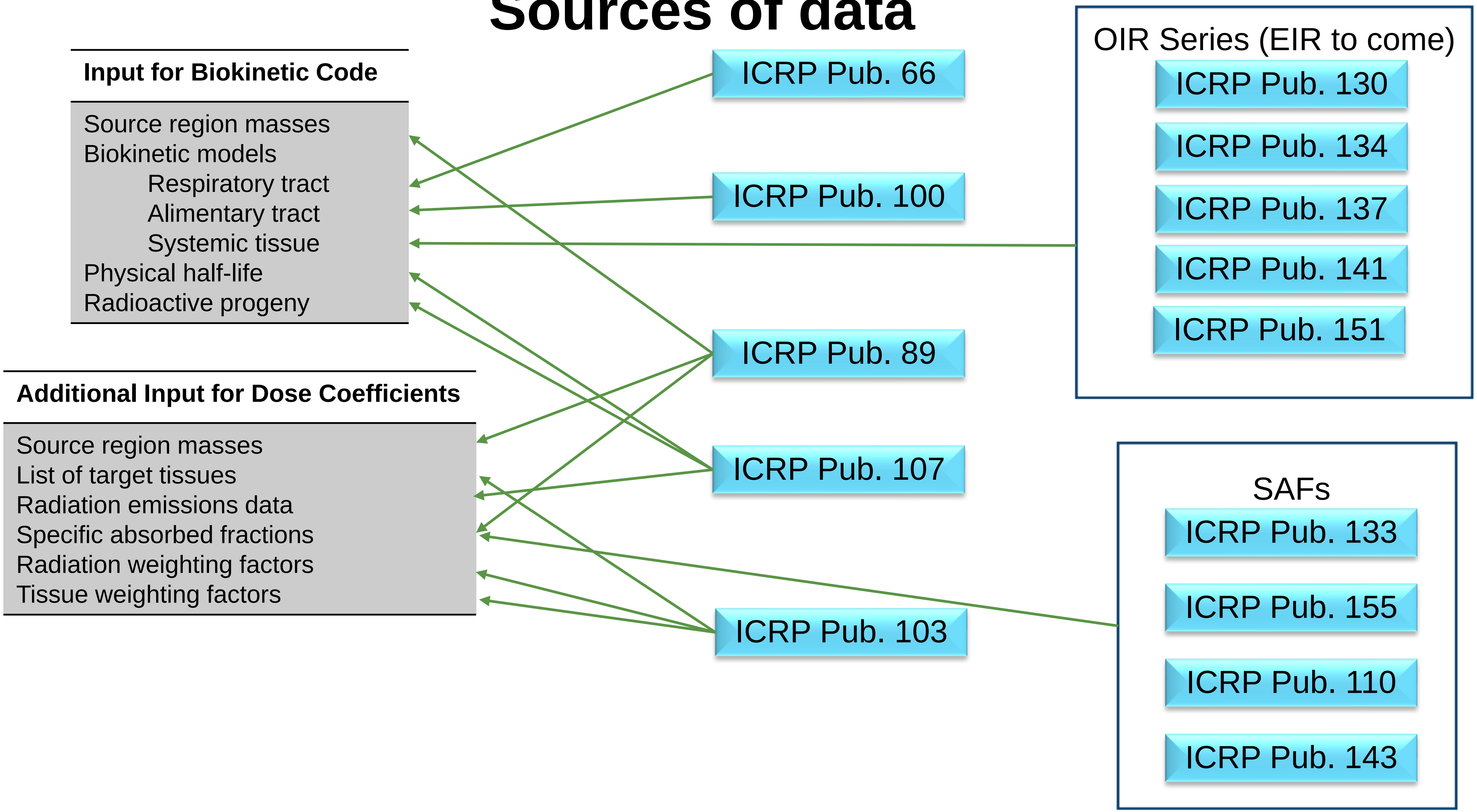
The rate of removal of member *i* from compartment *j* into other compartments and by physical decay

For chain member *i*, the rate of flow into compartment *j* from other compartments *k*

The ingrowth of member *i* in compartment *j* due to decay of its parent *h*.

$$\frac{dA_{i,j}(t)}{dt} = \sum_{\substack{k=1\\k\neq j}}^{M} A_{i,k}\lambda_{i,k,j} - A_{i,j}\left[\sum_{\substack{k=1\\k\neq j}}^{M}\lambda_{i,j,k} + \lambda_i^P\right] + \sum_{h=1}^{i-1} A_{h,j}\beta_{h,i}\lambda_i^P$$

Sources of data



Other details…

- **SAFs are tabulated on a monoenergetic grid**
  - Energy interpolation using piecewise cubic Hermite spline (PCHIP) (Fritsch and Carlson 1980)
- **For intakes to children, *S*-coefficients computed at each reference age**
  - Time interpolation of the *S*-coefficient with PCHIP except for from 0y to 1y (modified linear interpolation)
- **Integration techniques**
  - Trapezoidal integration improved by using Fritsch and Carlson interpolation
- **Decay chains**
  - Internal dose coefficients include contributions from radioactive progeny born inside the body

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Wrapping up the fundamentals

- Committed Effective Dose Coefficients provided for the Reference Person at each age for use in radiation protection

- They are specific to radionuclide and its chemical form

- Take advantage of significant improvements in both the biokinetic (source term) and dosimetric (energy deposition term) modeling.

$$\dot{H}_T = \sum_{r_S} A_S \, S_w(r_T \leftarrow r_S)$$

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