HelmholtzZentrum münchen
German Research Center for Environmental Health

# Internal Dosimetry: A Global Perspective

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

**US NRC RAMP Users Group**
**Virtual Meeting**
**October 28, 2020**

# Overview

- Concepts of radiation dosimetry
  - Roentgen, *r* / Absorbed dose, *D*
- Internal dosimetry
  - A short history
  - Radiation physics, biology and chemistry
  - Human physiology and anatomy
  - Biokinetic models
  - Computational phantoms and Monte Carlo simulations
  - Dosimetric model (ICRP and MIRD)
- Uncertainty and sensitivity
- Internal microdosimetry
- Applications and computer codes
  - Radiation protection / Radon and thoron / Skin dosimetry
  - Radiation epidemiology / Assessment of risk
  - Internal monitoring / Regulation
  - Radiation biology / Radiation medicine
- Future developments

# Concepts of Radiation Dosimetry

- **1895 Wilhelm Röntgen discovered X-rays**
- **1896 Henri Becquerel discovered radioactivity**
- **1925 Measurement of X-rays by free-air chamber**
- **1928 ICRU established a unit "roentgen" for that "quantity" which was measured by free-air chamber**
- **1953 ICRU established "absorbed dose"**
- **1956 ICRU used the unit "roentgen" for established "exposure dose" and later "exposure" (ICRU 1962), now the SI unit "C $kg^{-1}$"**

- **1538 Paracelsus "Dosis sola facit venenum" – the dose makes the poison**

- ***Radiation Dosimetry deals with the measurement of absorbed dose / dose rate resulting from the interaction of ionizing radiation with matters***

# Absorbed Dose

- **The *absorbed dose*, *D*, is the quotient of d$\bar{\varepsilon}$ by d*m*, where d$\bar{\varepsilon}$ is the <u>mean</u> energy imparted by ionizing radiation to matter of mass d*m*, thus**

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}.$$

**Unit: J kg$^{-1}$ (special name is gray: Gy)**

Note: The absorbed dose, *D*, is considered a point quantity, but it should be recognized that the physical process does not allow d*m* to approach zero in the mathematical sense.

The *energy imparted*, $\varepsilon$ , to the matter in a given volume is the sum of all energy deposits in the volume, thus

$$\varepsilon = \sum_i \varepsilon_i,$$

where the summation is performed over all energy deposits, $\varepsilon_i$, in that volume.

Unit: J

The *energy deposit*, $\varepsilon_i$, is the energy deposited in a single interaction, $i$, thus

$$\varepsilon_i = \varepsilon_{\mathrm{in}} - \varepsilon_{\mathrm{out}} + Q,$$

where $\varepsilon_{\mathrm{in}}$ is the energy of the incident ionizing particle (excluding rest energy), $\varepsilon_{\mathrm{out}}$ is the sum of the energies of all charged and uncharged ionizing particles leaving the interaction (excluding rest energy), and $Q$ is the change in the rest energies of the nucleus and of all elementary particles involved in the interaction ($Q > 0$: decrease of rest energy; $Q < 0$: increase of rest energy).

Unit: J

ICRU 85a, 2011

# Internal Dosimetry

**…to measure, <u>calculate</u>, <u>estimate</u>, assay, <u>predict</u> and otherwise quantify the radiative energy absorbed by the ionization and excitation of atoms in human tissues as a result of emission of energetic radiation by internally deposited radionuclides...**

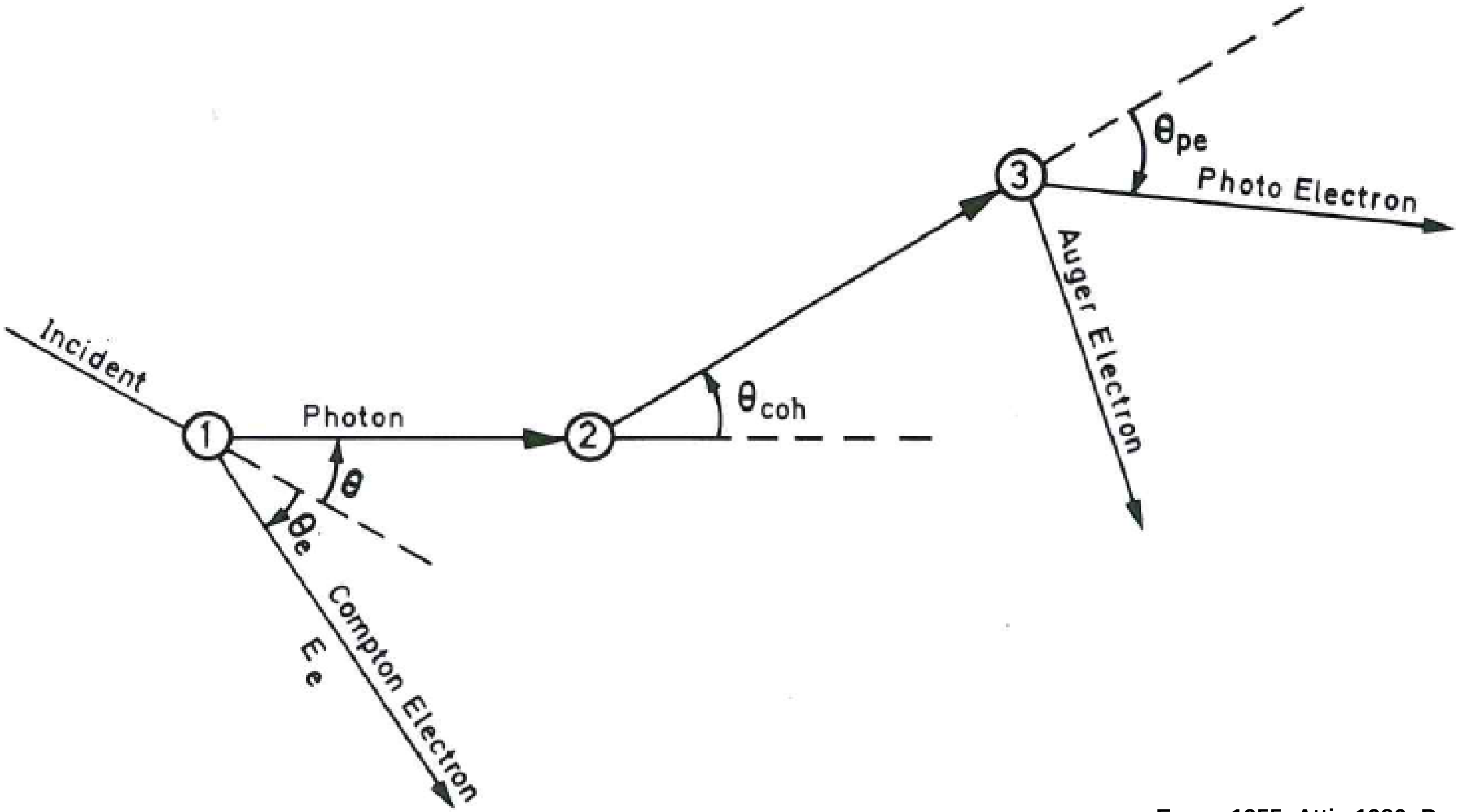
**Otto G. Raabe, Internal Radiation Dosimetry, 1994**

# Internal Dosimetry – A short history

- 1896 Henri Becquerel discovered radioactivity
- 1898 Marie Curie separated polonium and radium
- 1934 Joliot and Curie discovered artificial radioactivity
- 1942 Marinelli calculation of dosage
- 1948 Quimby organs as approx. by sphere, used by ICRP
- 1953 Loevinger outlined a technique for internal dosimetry
- 1966 Loevinger and Berman unified an approach to internal dosimetry
- 1968 Snyder developed math. models of human body and Monte Carlo code for internal dosimetry for MIRD and for ICRP for workers
- 1979 ICRP 30 for workers
- 1989 ICRP (53,80,106,128), (56,67,69,71,72), (68,78,119)
- 2009 MIRD pamphlet No. 21 with ICRP
- 2015 ICRP OIR Part 1,2,3,4,5 for workers
- 202x ICRP EIR for members of the public

Personal

# Interactions of Radiation with Matters




Evans 1955; Attix 1986; Paretzke, 1987

# Radiation Chemistry

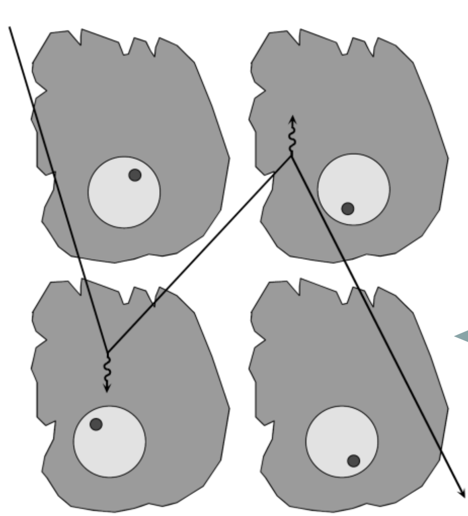
| | |
|---|---|
| **Physicochemical stage** | |
| $10^{-15}$ | Electronic excitation: $H_2O \longrightarrow H_2O^*$ |
| $10^{-14}$ | Ion-molecule reactions, e.g. $H_2O^+ + H_2O \longrightarrow {}^\bullet OH + H_3O^+$ |
| $10^{-13}$ | Molecular vibration $\rightarrow$ dissociation of excited state: $H_2O^* \longrightarrow H^\bullet + {}^\bullet OH$ |
| $10^{-12}$ | Rotation relation, thermalization of hot electrons, hydration of electrons: $e^- \rightarrow e^-_{aq}$ |
| **Chemical stage** | |
| $<10^{-12}$ | Reactions of $e^-$ before hydration with reactive solute at high concentrations |
| $10^{-10}$ | Reactions of $e^-_{aq}$ and other radicals with reactive solute (concentration $\sim 1$ mol·dm$^{-3}$) |
| $<10^{-7}$ | Reactions in spurs |
| $10^{-7}$ | Homogeneous distribution of radicals |
| $10^{-3}$ | Reactions of $e^-_{aq}$ and other radicals with reactive solutes (concentration $\sim 10^{-7}$ mol·dm$^{-3}$, i.e. $\sim 0.01$ ppm) |
| 1 | Free-radical reactions largely completed |
| $10^3$ | Biochemical processes |

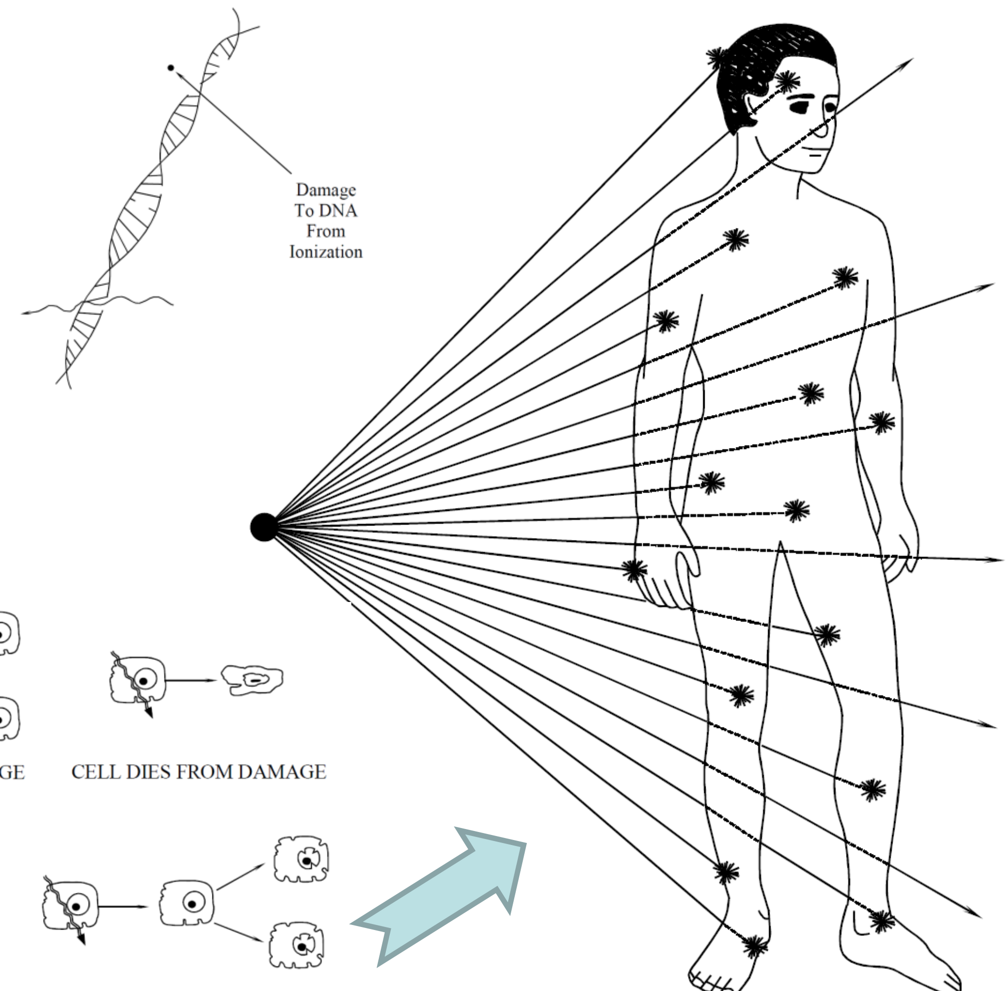
**von Sonntag, 1987; 2006; Magee and Chatterjee, 1987**

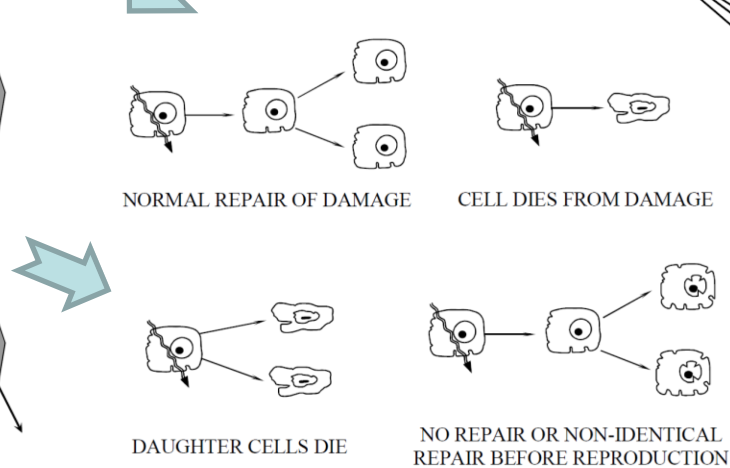
# Biological Effects of Radiation

## ➔Biological effects

- Molecular damages
- Cellular effects
- Tissue effects
- Organ effects
- Whole body

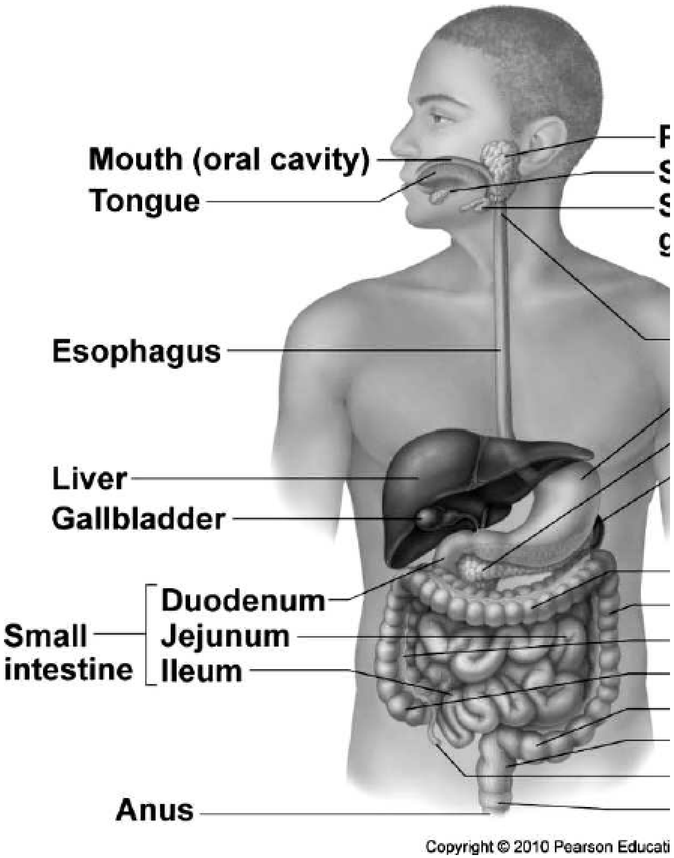


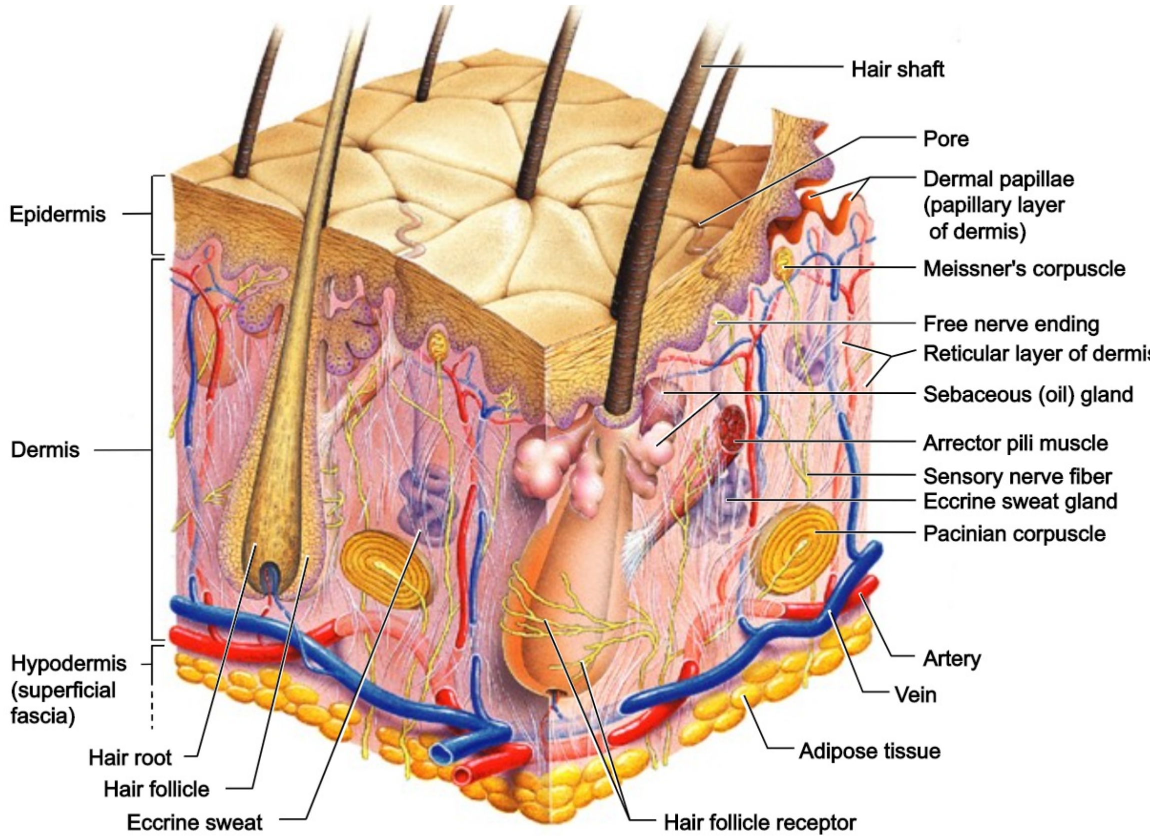




Hall, 2000; Source: https://www.nrc.gov/

# Human Physiological and Anatomical Bases

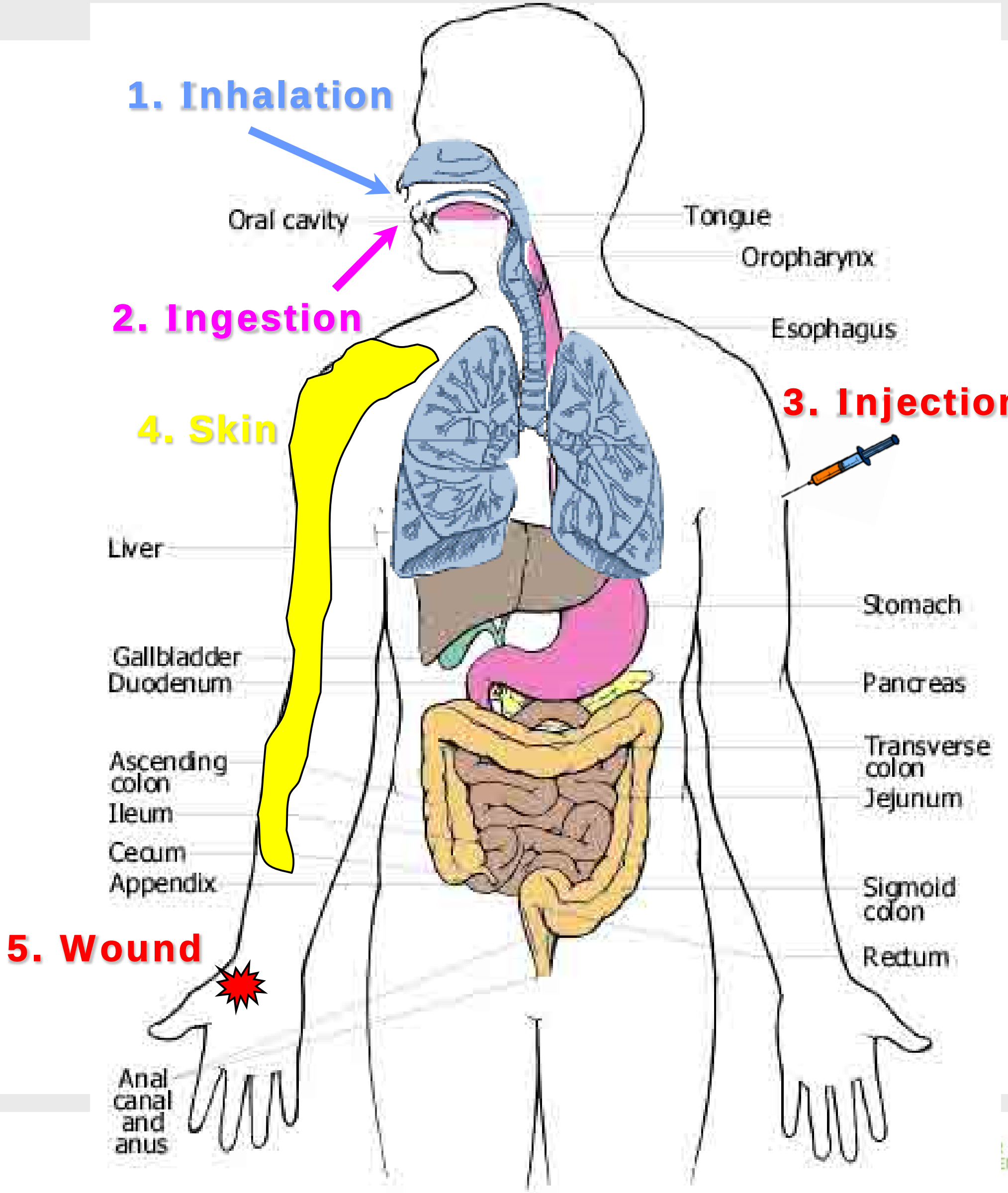


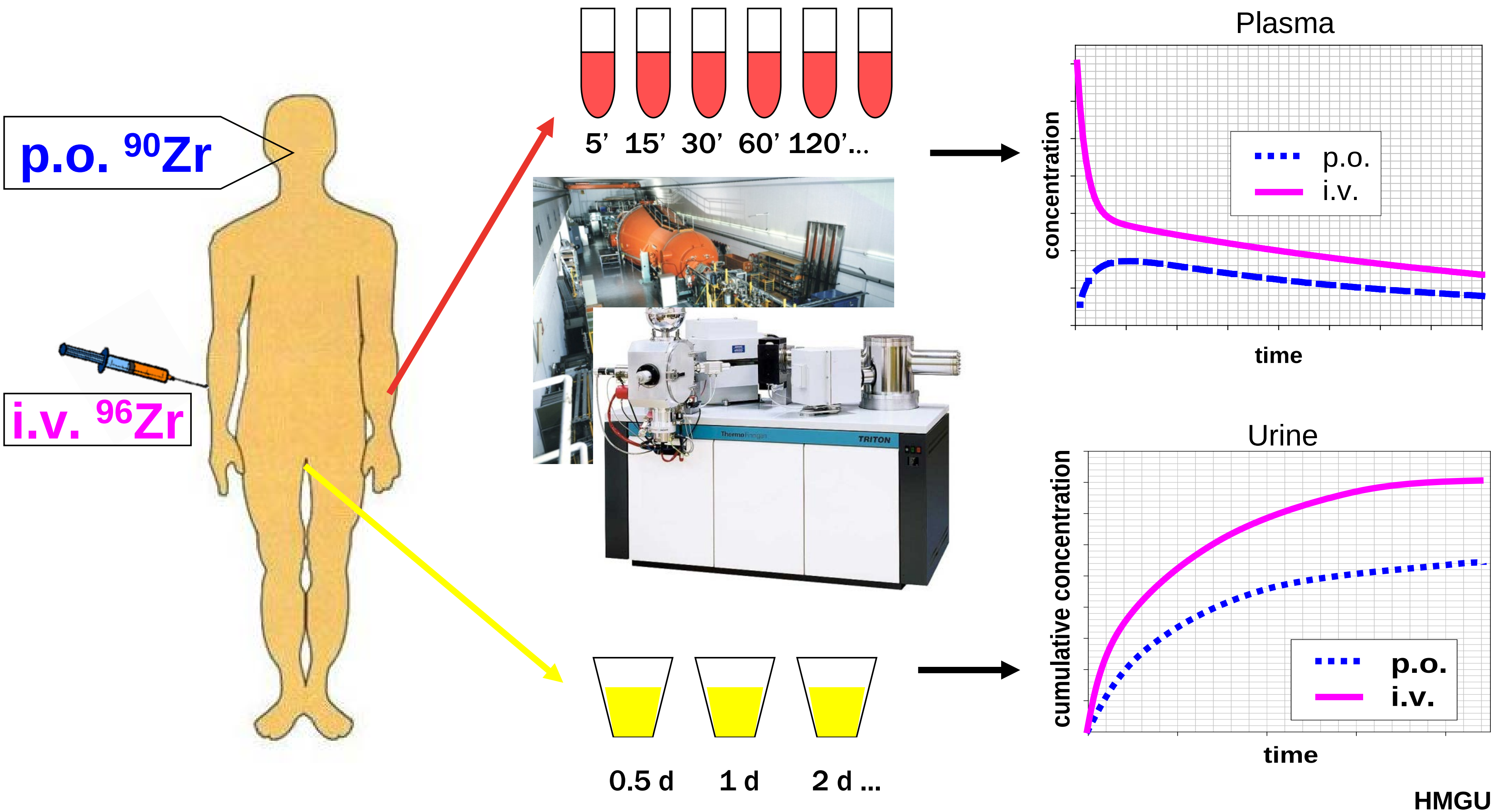

**Marieb and Hoehn,**
**Human Anatomy & Physiology, 8th 2010**

# Incorporation of Radionuclide in Human Body

1. **Inhalation**
2. **Ingestion**
3. **Injection**
4. **Wound**
5. **Percutaneous resorption**
6. **Instillation**
7. **Other orifice in the body**

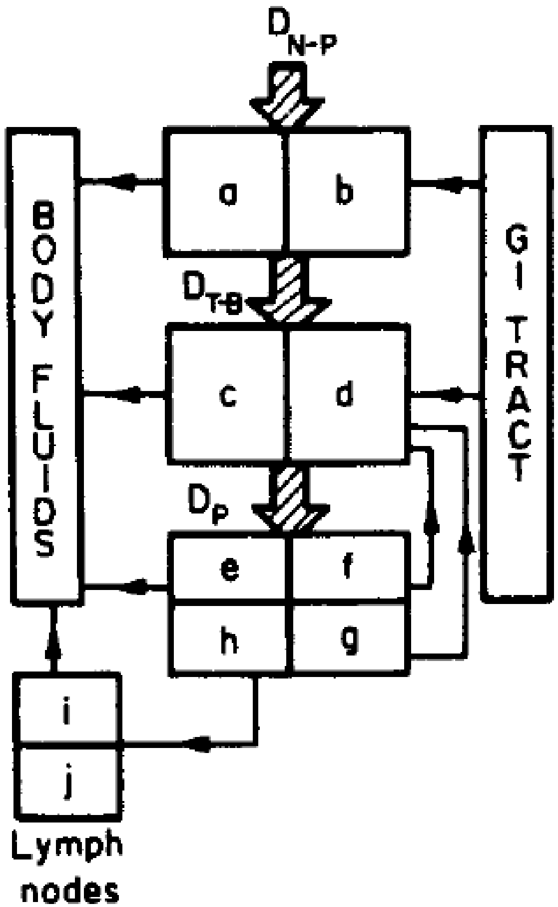


# Biokinetic Investigations of Stable Isotopes

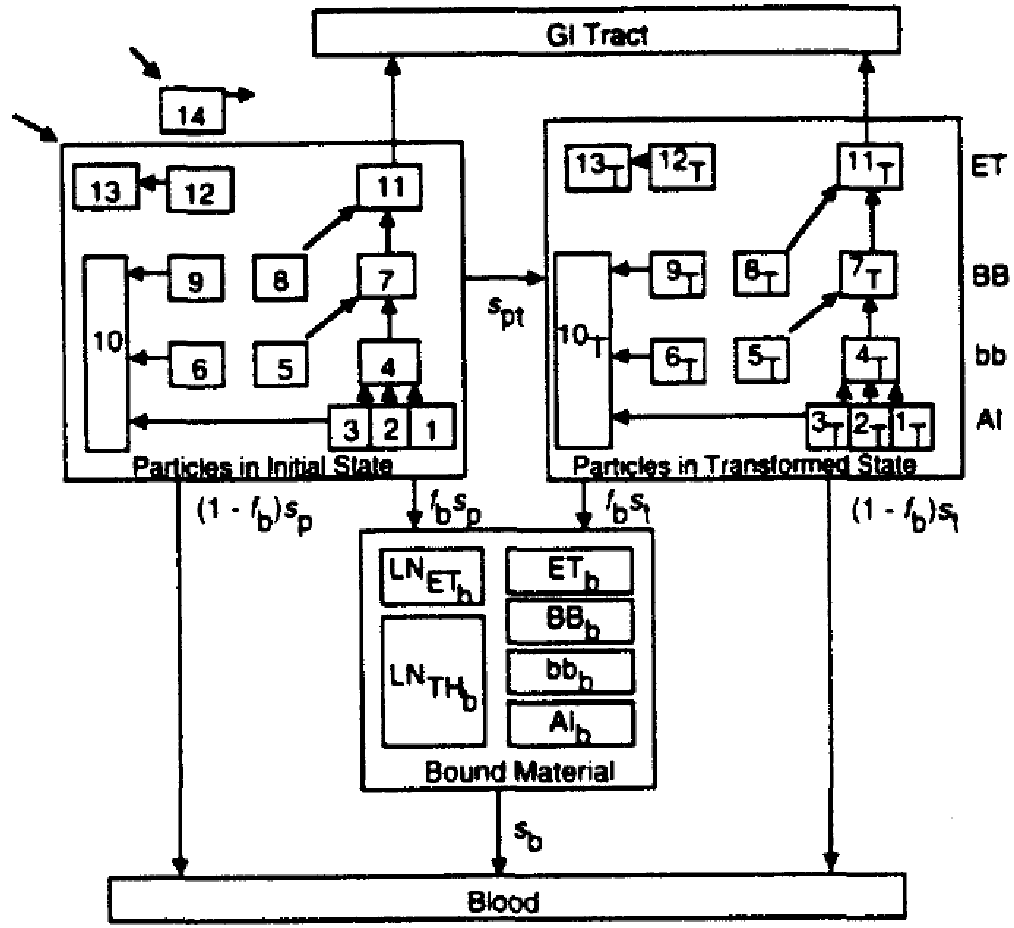


# Biokinetic Models for Lungs

- From simple mathematical lung model (1979) to human respiratory tract model (1994)



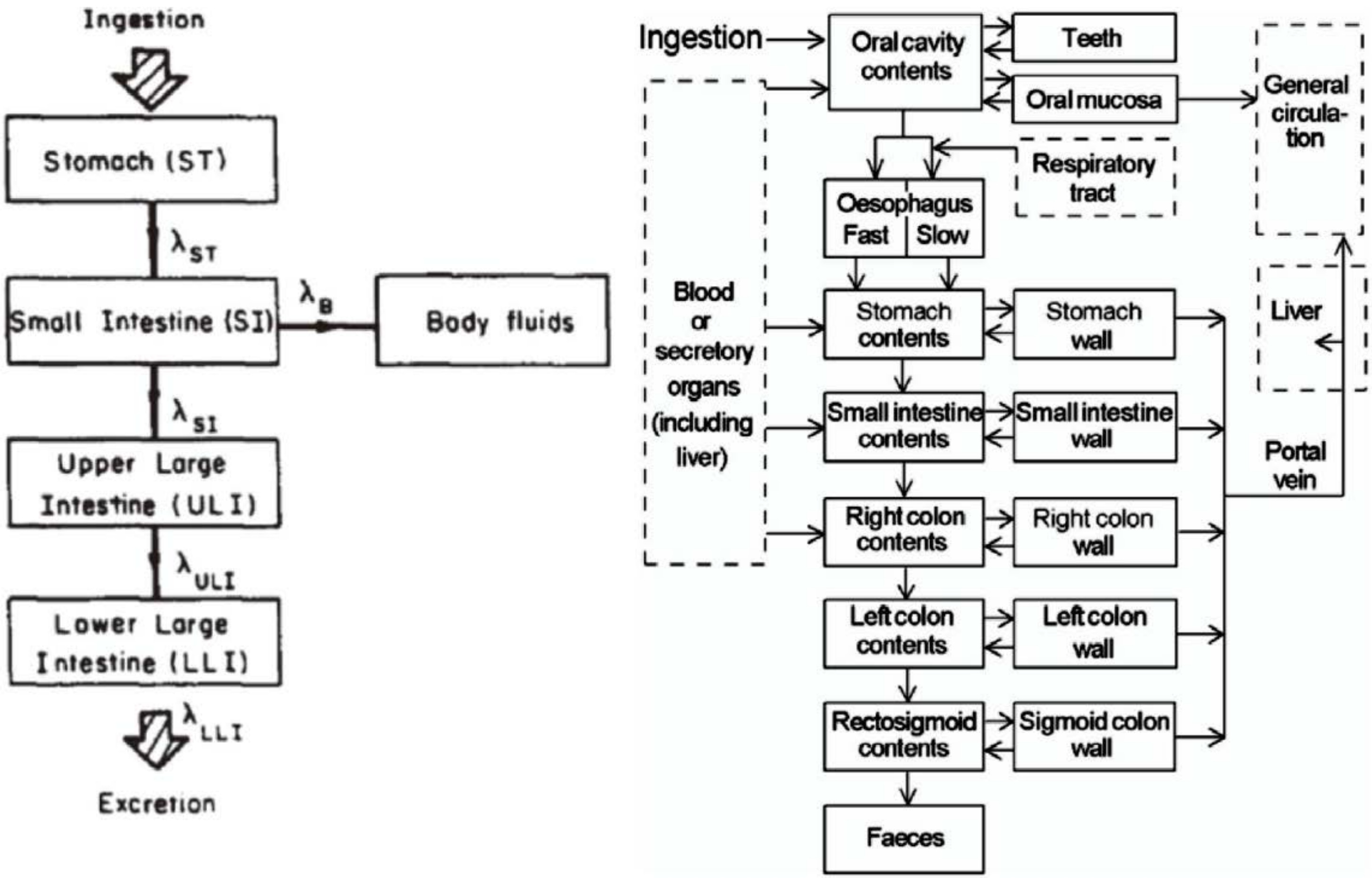

ICRP 30




ICRP 66

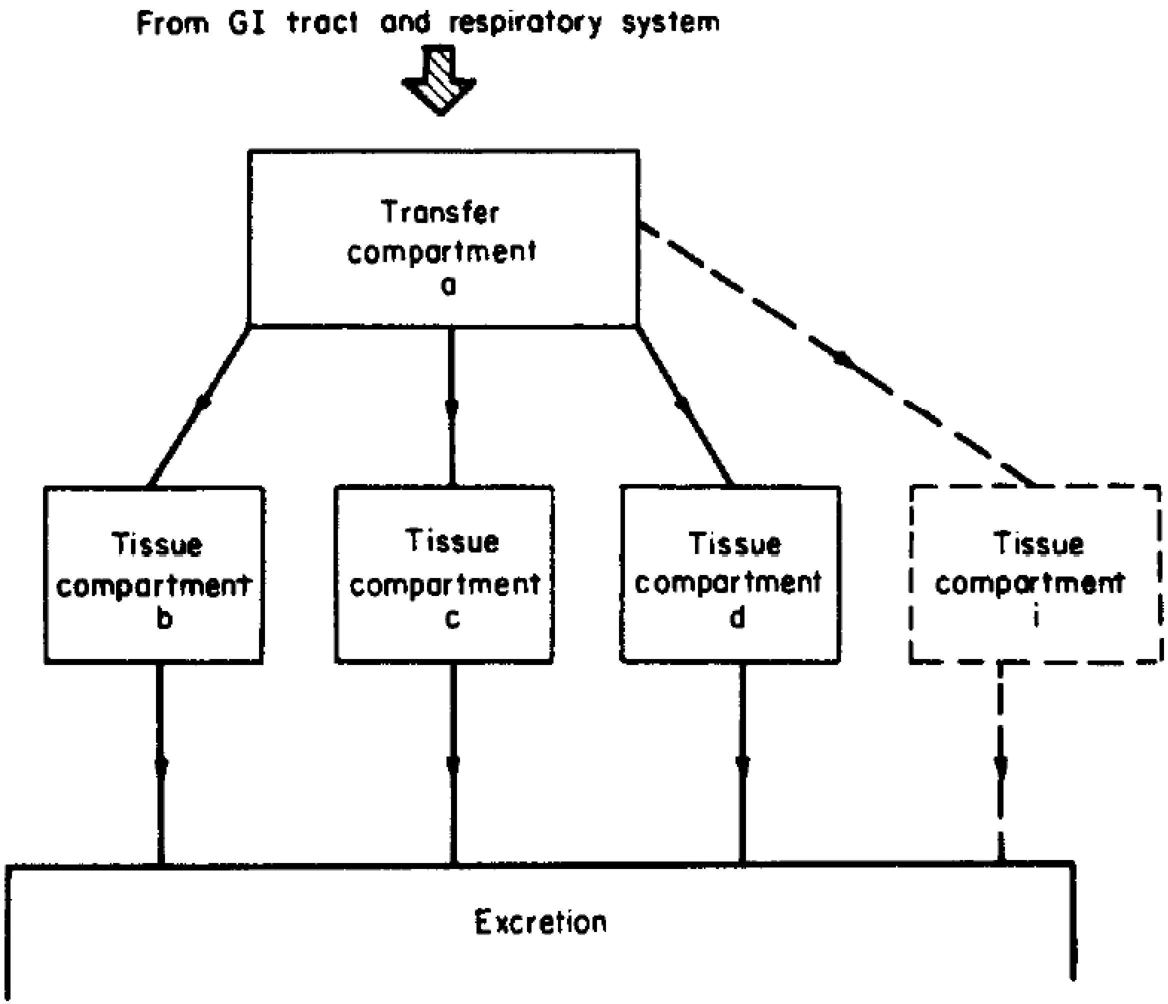
# Biokinetic Models for Alimentary Tract

- From gastrointestinal tract model (A, 1979) to human alimentry tract model (B, 2006)



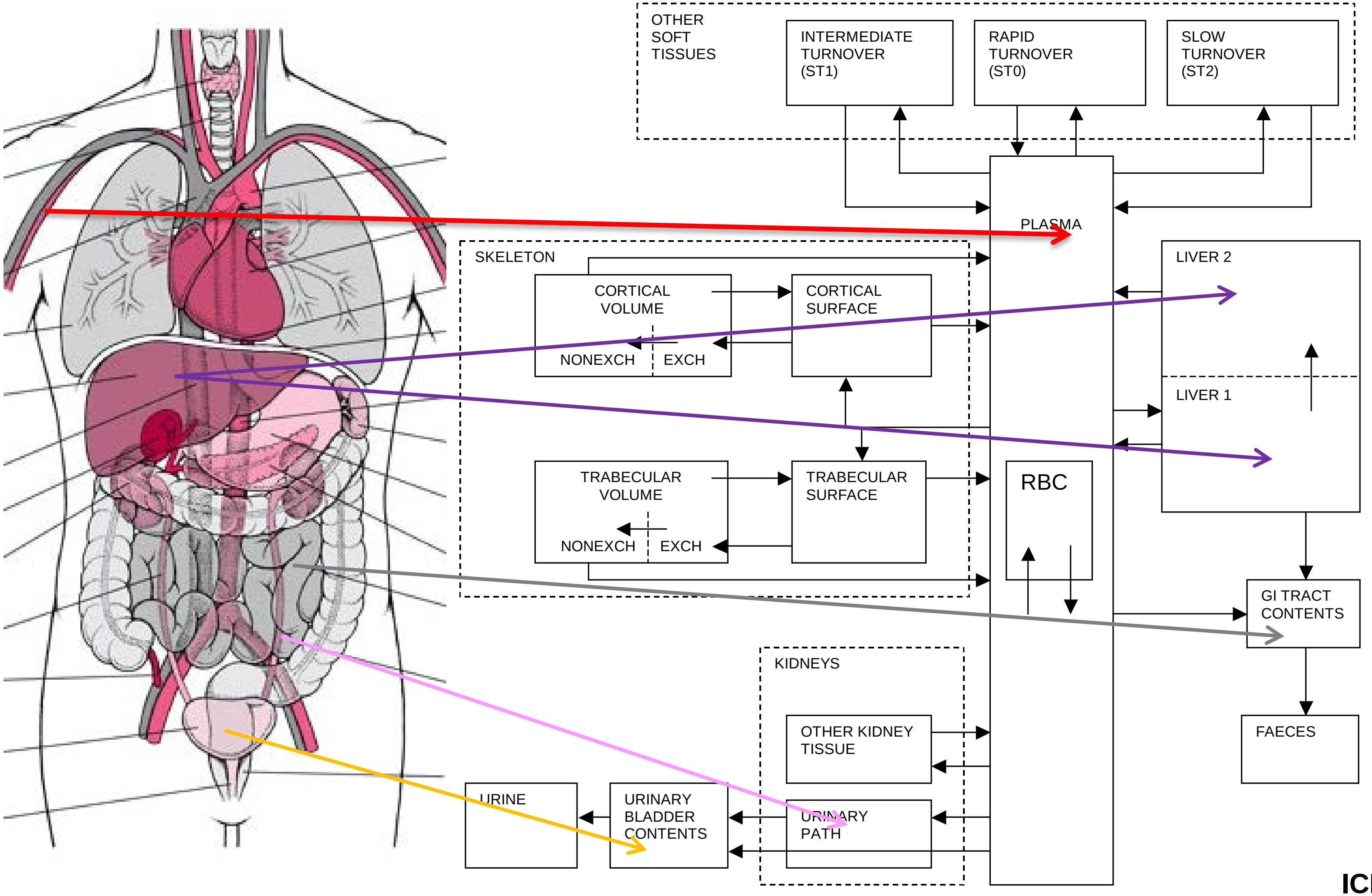

ICRP 30 A - GIT model B - HATM ICRP 100

# Mathematical Model for Kinetic Description of Radionuclides in Body - Systemic




ICRP 30

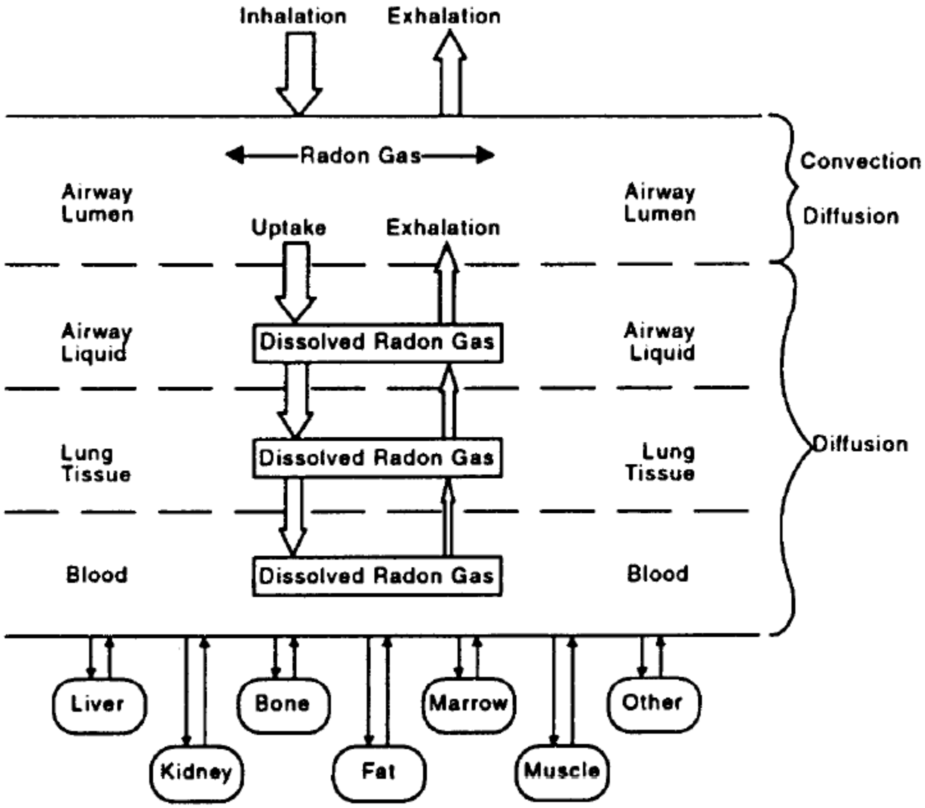
# Systemic Biokinetic Model for U, Pb and Ra

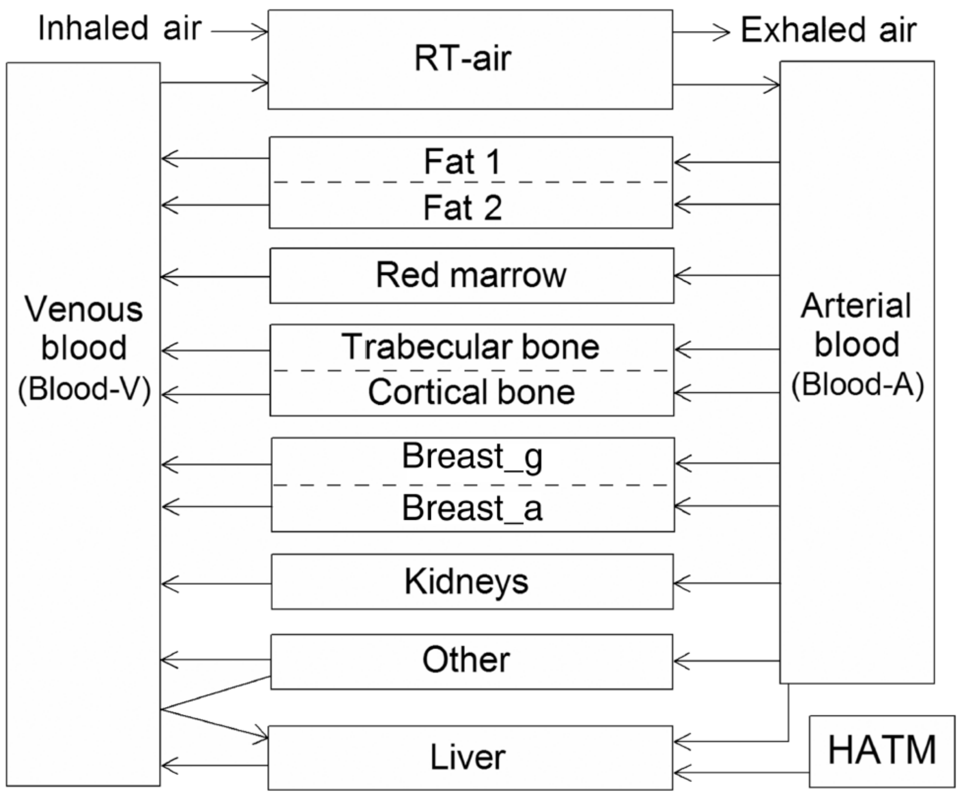



ICRP 67

# Biokinetic Model for Radon Gas

- From ICRP 66 (1994) to ICRP OIR Part 3 (2017)

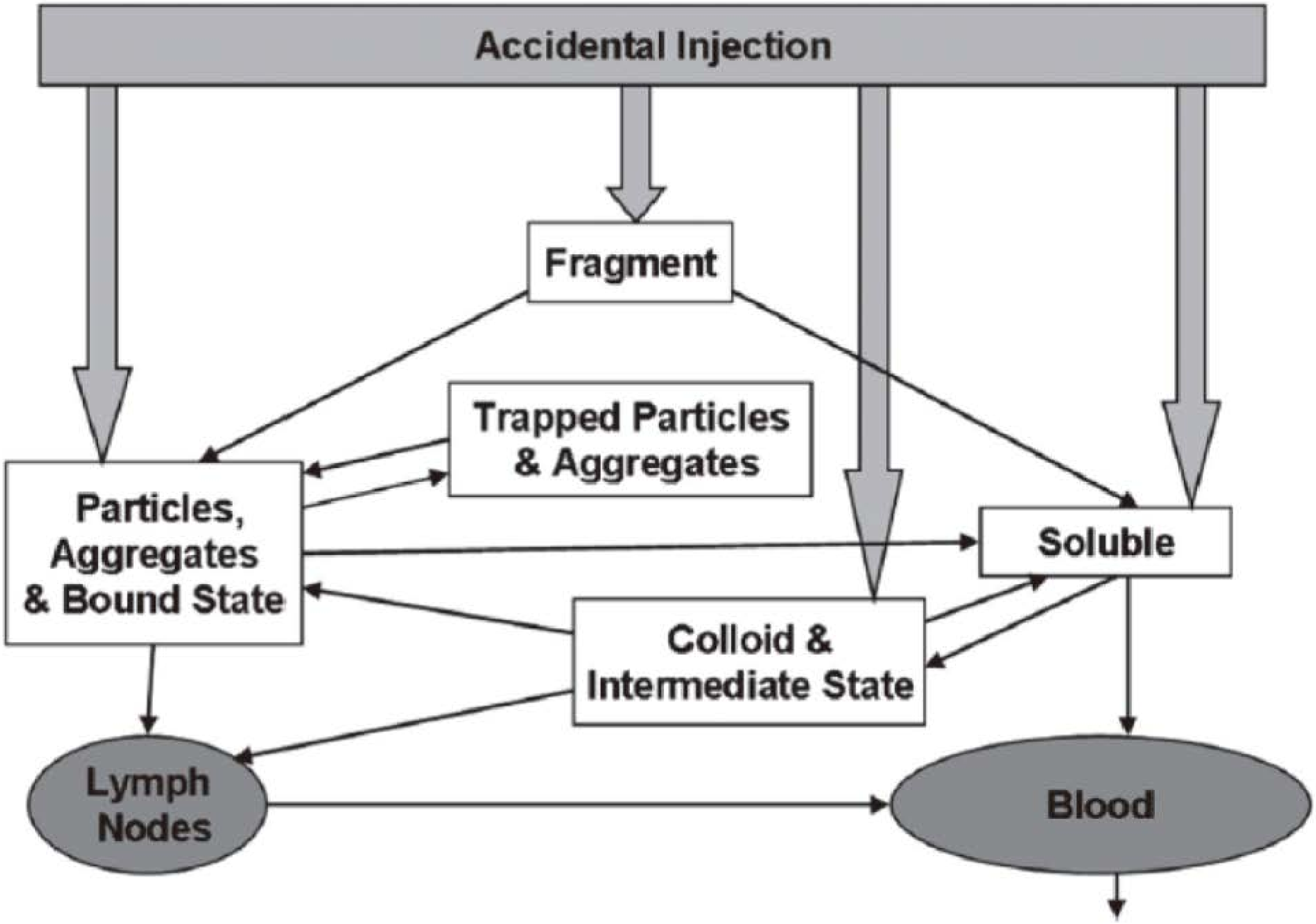



ICRP 66

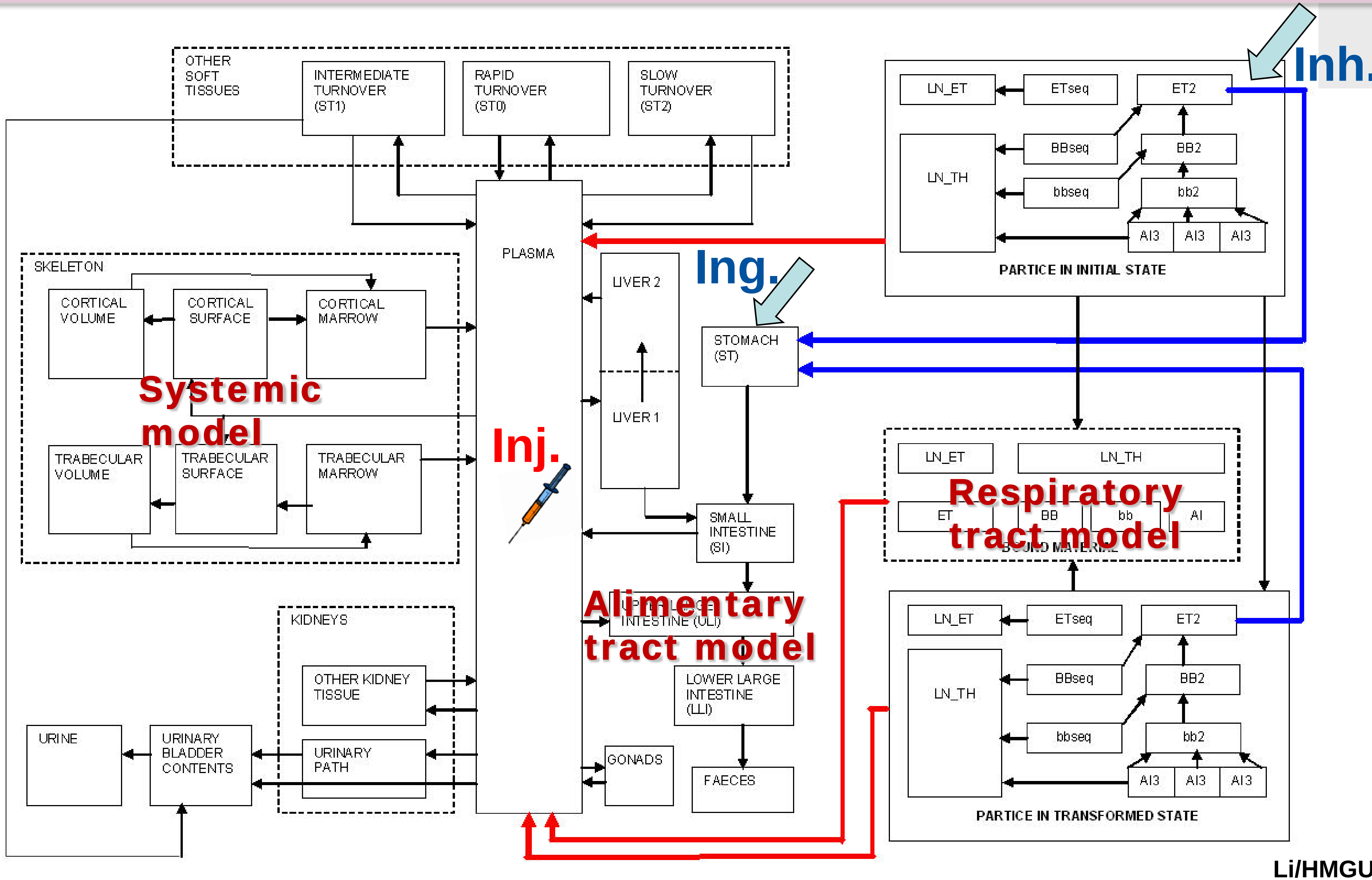
ICRP 137

# Biokinetic Model for Radionuclide-Contaminated Wounds

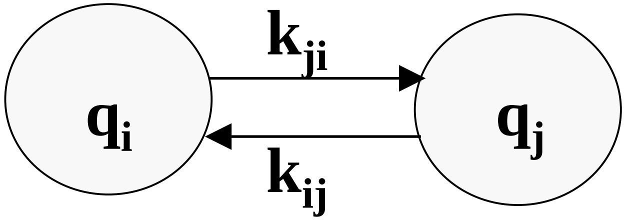



NCRP 156

# Generic Biokinetic Models for Incorporated Radionuclides



# Mathematical Formulation – System of First-Ordor Ordinary Differential Equations




The ordinary differential equations describe the time-dependent behaviour of the materials in each compartment:

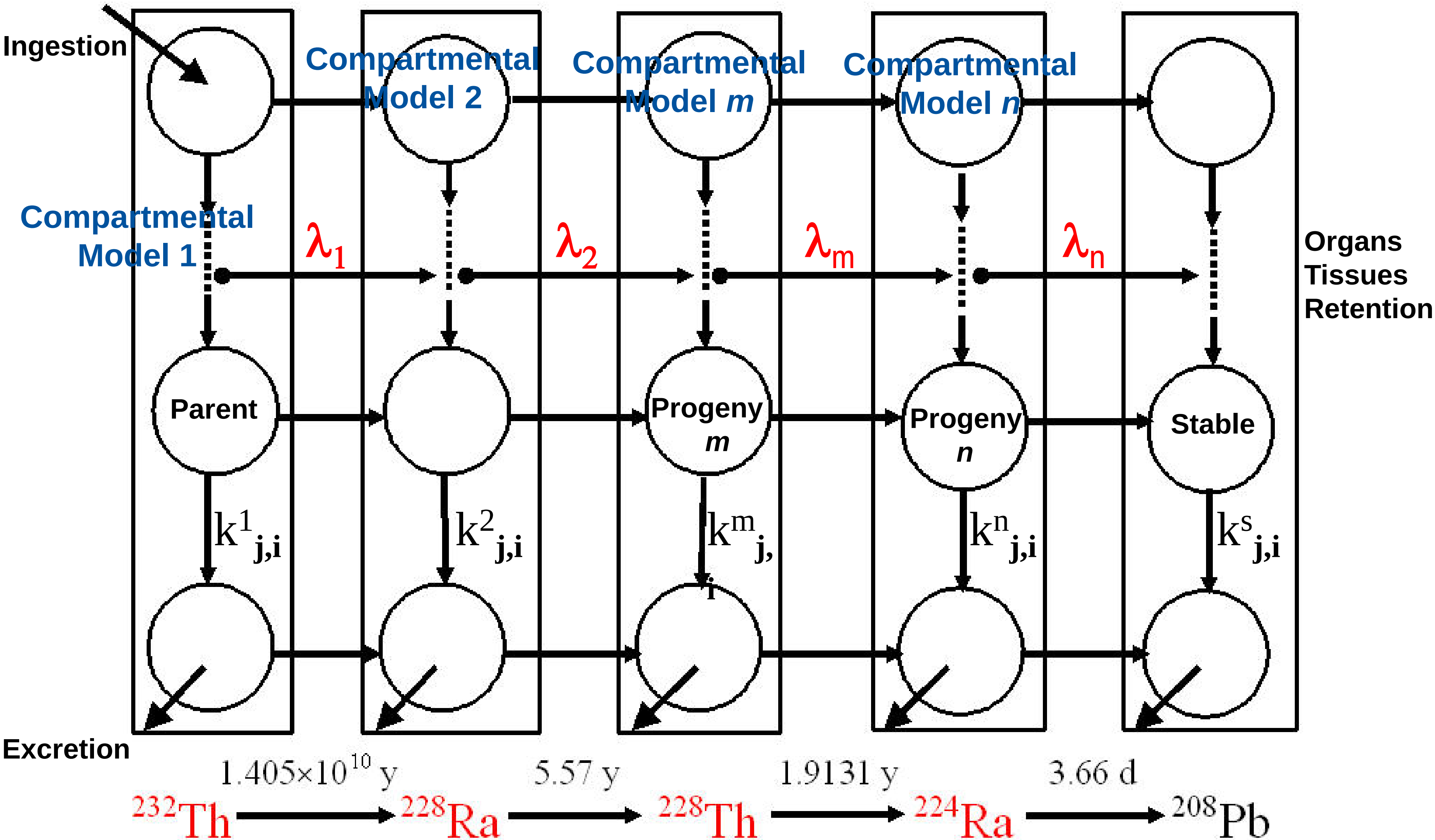
$$\frac{dq_i}{dt} = \sum_{j=1}^{n} k_{ij} q_j - q_i \sum_{j=1}^{n} k_{ji} \qquad j \neq i$$

The exchange processes are assumed linear processes of first order

- ► The retention in the compartments can be expressed by biological half lives
- ► The solution of the ordinary differential equation system is a linear combination of exponential functions:

$$q_i(t) = \sum_{j=1}^{n} a_{lj} e^{-\lambda_j t} \qquad l = 1,2,\ldots n$$

# Treatment of Decay Products of Radionuclides



# Skin Model – in between external and internal exposure

**SPECIAL SYMPOSIUMS**

FALL 2020

**RAMP USERS GROUP**

VIRTUAL MEETING

RAMP

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
*Protecting People and the Environment*

Pacific Northwest
NATIONAL LABORATORY

## October 27, 2020

**VARSKIN TECHNICAL MEETING**

**9:30-9:35 | VARSKIN Introduction**

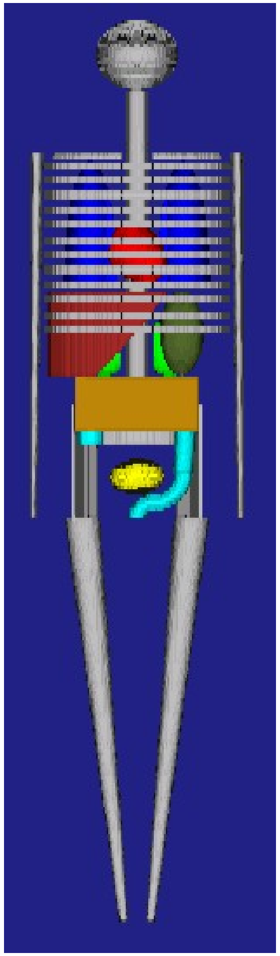
**Vered Shaffer** | Office of Nuclear Regulatory Research, U.S. NRC

**11:05-11:30 | VARSKIN's New Wound Dosimetry Model**

**David Hamby** | Renaissance Code Development

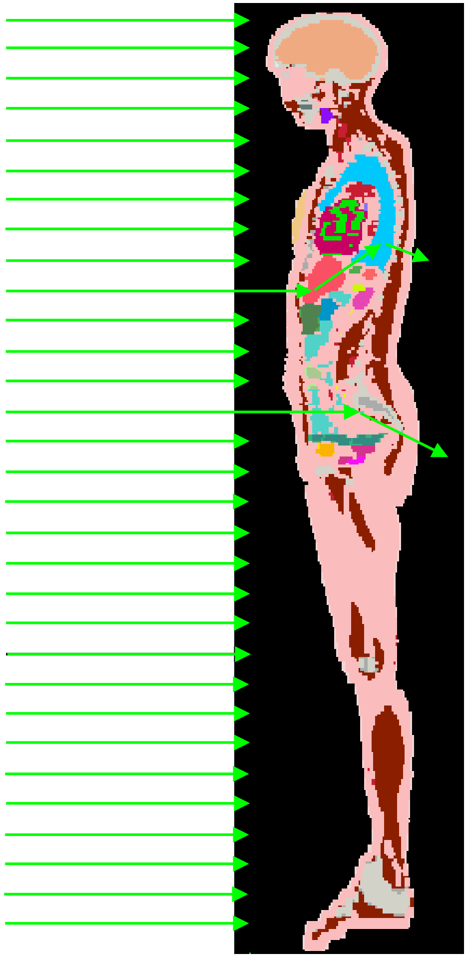
# Computational Phantoms

Past



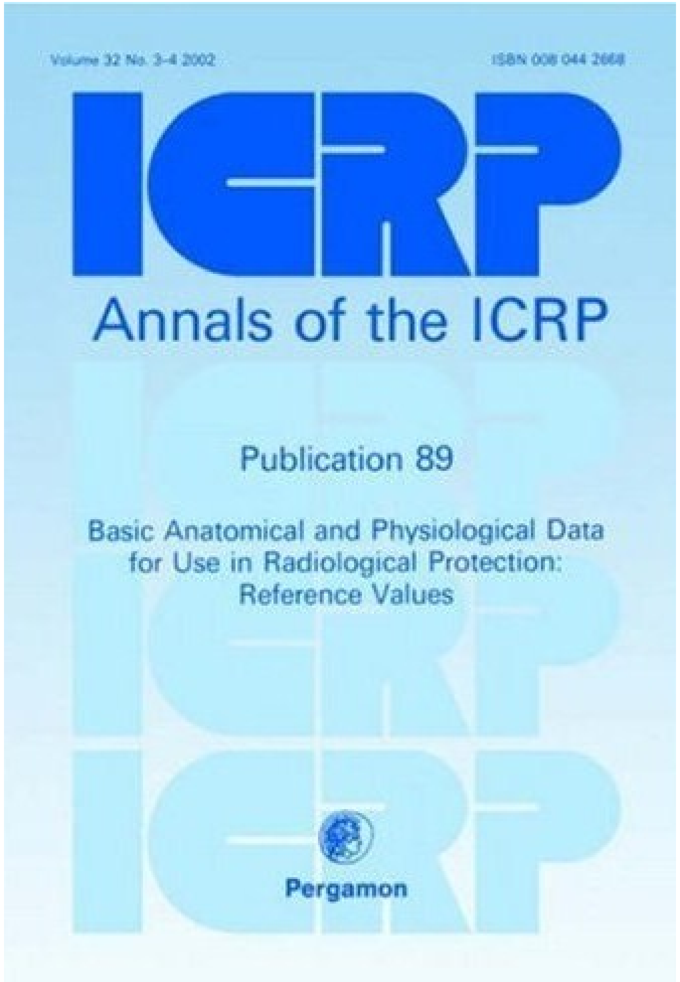
- Model of the radiation source
- Model of the body
- Physical models of
  - radiation interactions
  - energy depositions

Present



Zankl

# Developing Phantoms according to ICRP Reference Persons




Main characteristics specified in ICRP Publication 89:

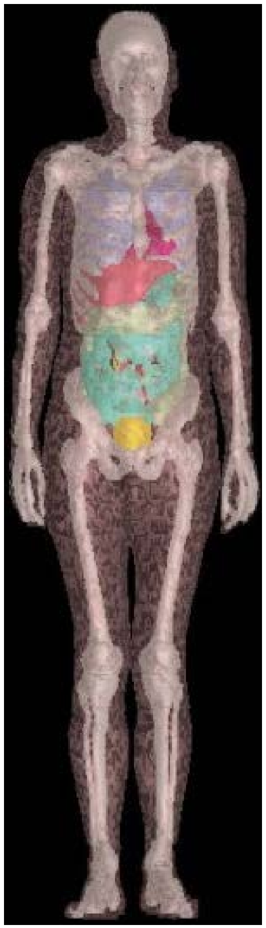
**Table 2.9. Reference values for height, mass, and surface area of the total body**

| Age | Height (cm) | | Mass (kg) | |
|---|---|---|---|---|
| | Male | Female | Male | Female |
| Newborn | 51 | 51 | 3.5 | 3.5 |
| 1 year | 76 | 76 | 10 | 10 |
| 5 years | 109 | 109 | 19 | 19 |
| 10 years | 138 | 138 | 32 | 32 |
| 15 years | 167 | 161 | 56 | 53 |
| Adult | 176 | 163 | 73 | 60 |

Reference masses for 56 organs, organ groups, and tissues

**Zankl**

# Reference Computational Phantoms (ICRP)



- Select segmented voxel models of male and female individual whose body height and mass closely resemble the ICRP 89 reference values

| | | | | |
|---|---|---|---|---|
| „Golem“: | 176 cm, | 69 kg | (176 cm, | 73 kg) |
| „Laura“: | 167 cm, | 59 kg | (163 cm, | 60 kg) |

- Modify these segmented voxel models in several steps

Golem

Laura

Zankl

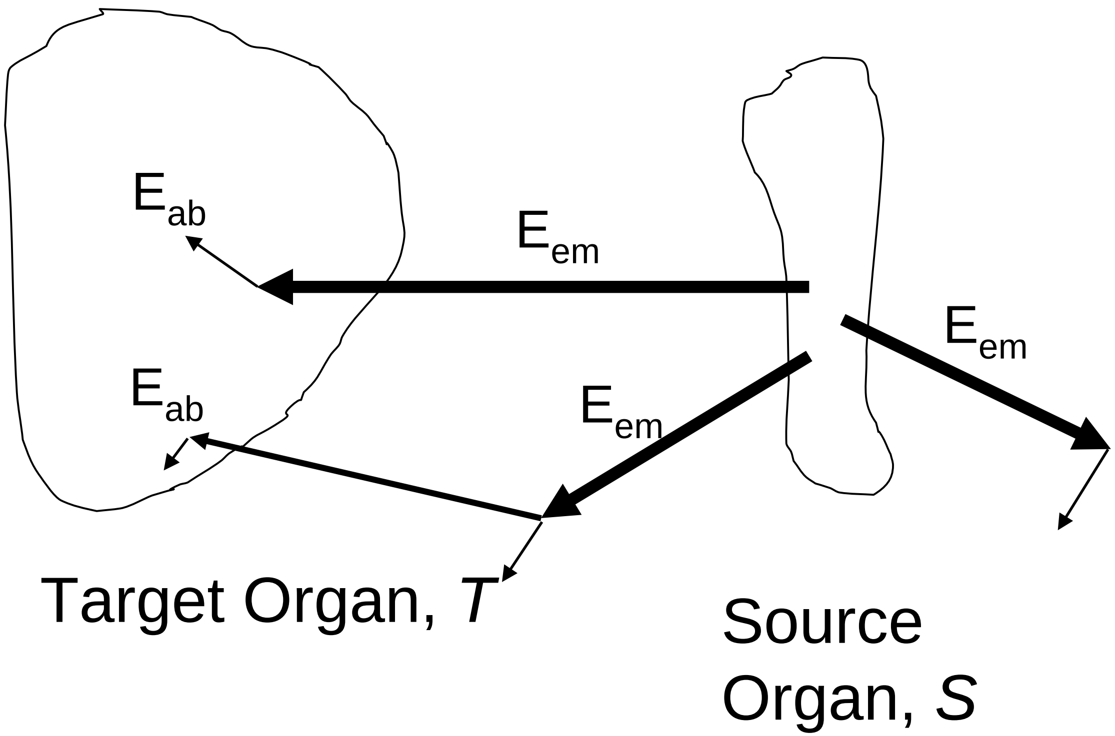
# Computational Voxel Phantoms at HMGU

Zankl

# Calculation of AFs using Monte Carlo Radiation Transport Codes with Phantoms

**AF($T \leftarrow S$)**
absorbed fraction, i.e. fraction of the energy absorbed by target organ *T* in relation to the energy emitted by source organ *S*

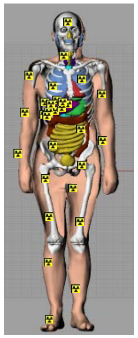
$$AF(T \leftarrow S) = \frac{\sum E_{abs}}{\sum E_{em}}$$

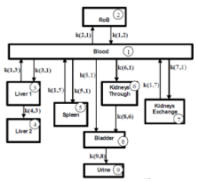


# Generalized Formalism for Internal Dosimetry

## Mean organ absorbed dose (MIRD/ICRP)

$$d(r_T, T_D) = \sum_{r_S} \int_0^{T_D} a(r_S, t)\, S(r_T \leftarrow r_S, t)\, dt$$





$$S(r_T \leftarrow r_S, t) = \frac{1}{M(r_T, t)} \sum_i E_i Y_i\, \phi(r_T \leftarrow r_S, E_i, t)$$

$$= \frac{1}{M(r_T, t)} \sum_i \Delta_i\, \phi(r_T \leftarrow r_S, E_i, t)$$

## Organ equivalent dose

$$h(r_T, T_D) = \sum_{r_s} \tilde{a}(r_s, T_D)\, S_w(r_T \leftarrow r_S)$$

## Effective dose

$$S_w(r_T \leftarrow r_S) = \sum_R w_R \sum_i \frac{E_{R,i}\, Y_{R,i}\, \phi(r_T \leftarrow r_S, E_{R,i})}{M(r_T)}.$$

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

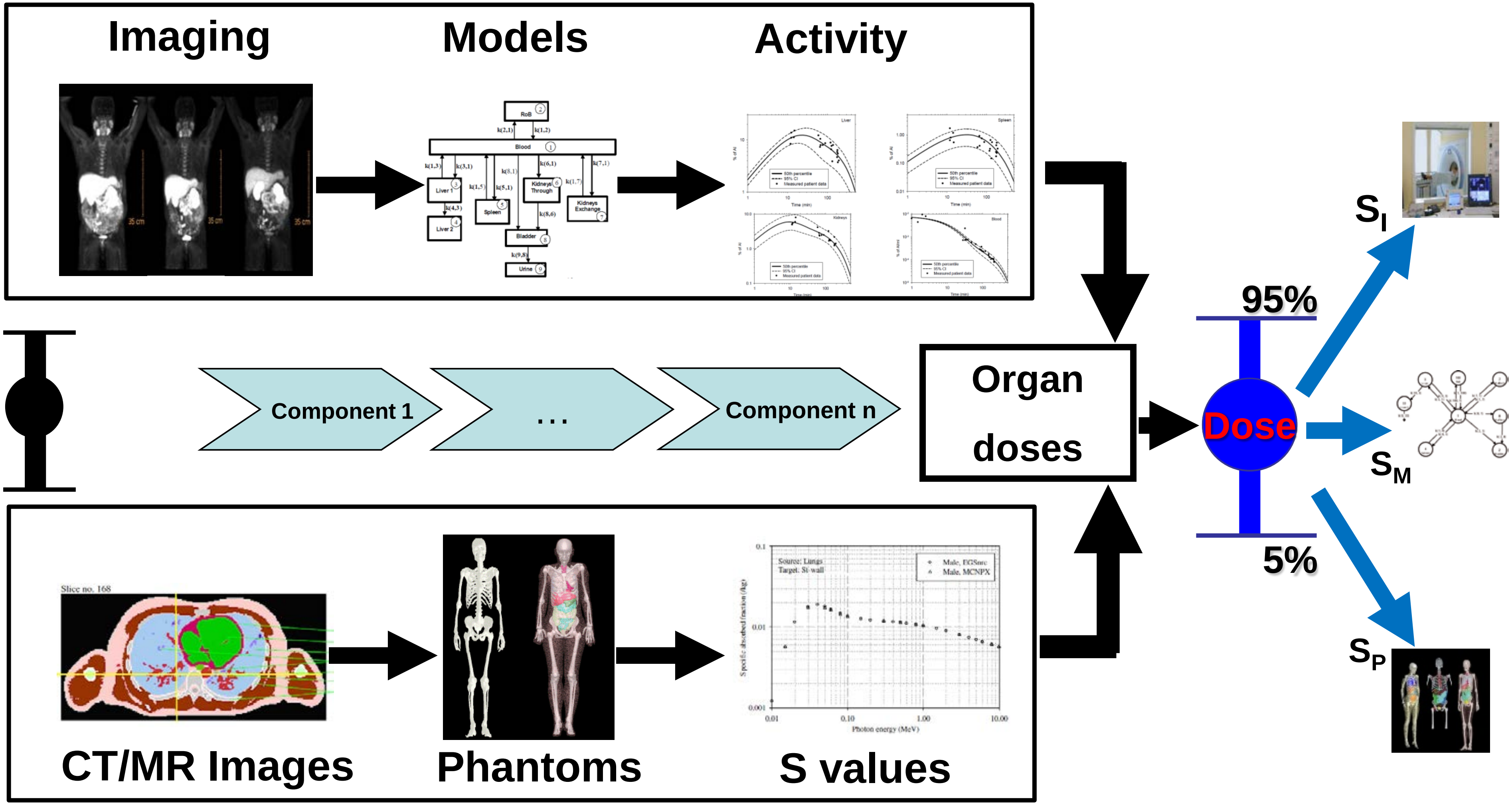
**Bolch et al. 2009**

# Computer Codes for Internal Dosimetry

- Not complete

- **SAAM II** – biokinetic modeling
- **MATLAB** – biokinetic modeling and dosimetry
- **MATHEMATICA** – biokinetic modeling and dosimetry
- **SEECAL / DCAL** – dose coefficients
- **IMBA** -> TAURUS
- **TAURUS** – dose coefficients and internal monitoring
- **IDEA System** – dose coefficients and internal monitoring
- **IDSS** – dose coefficients and internal monitoring
- **AIDE** – dose coefficients and internal monitoring
- **MONDAL** – dose coefficients
- **DOSAGE** – dose coefficients
- **PLEIADES** – dose coefficients
- **OLINDA/EXM** – nuclear medicine dosimetry
- **IDAC-Dose** – dose for radiopharmaceuticals

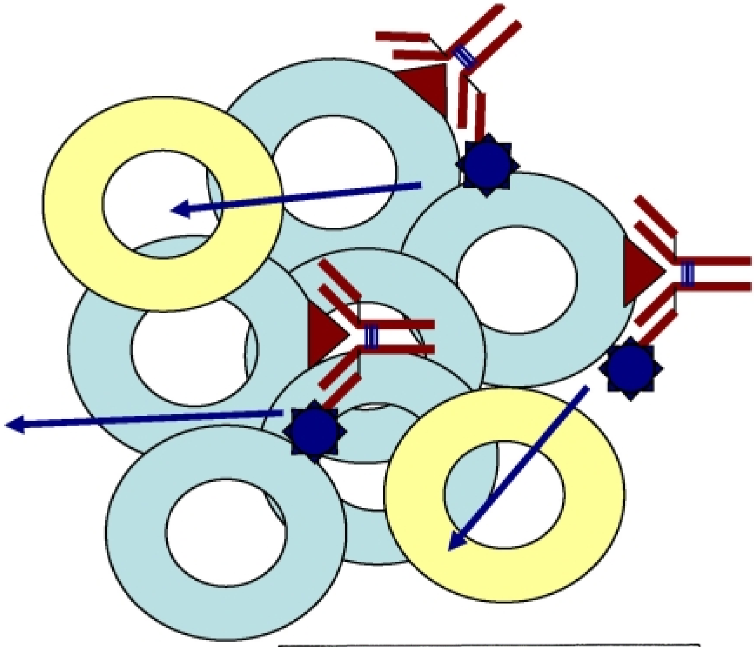
# Uncertainty and Sensitivity Analysis

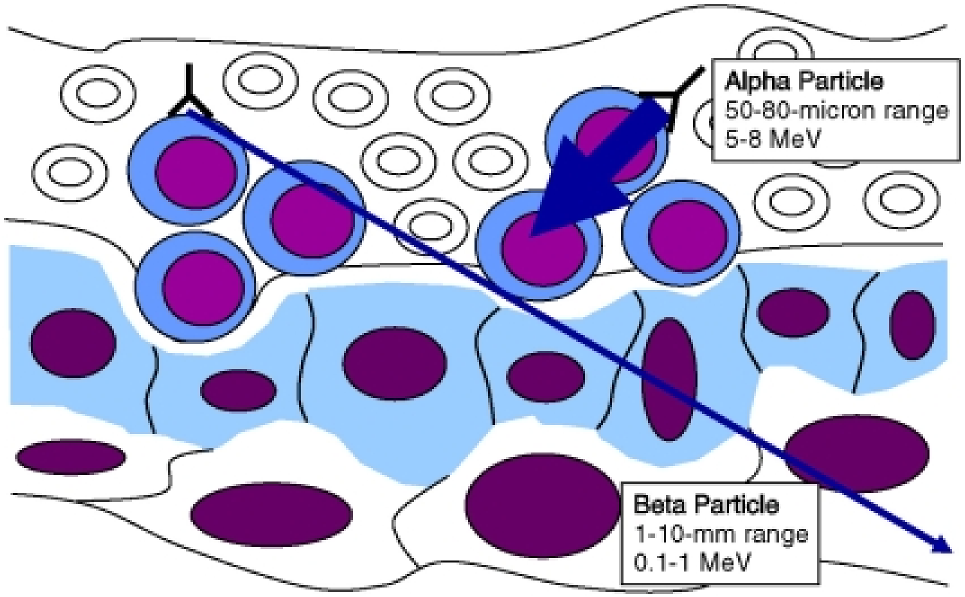


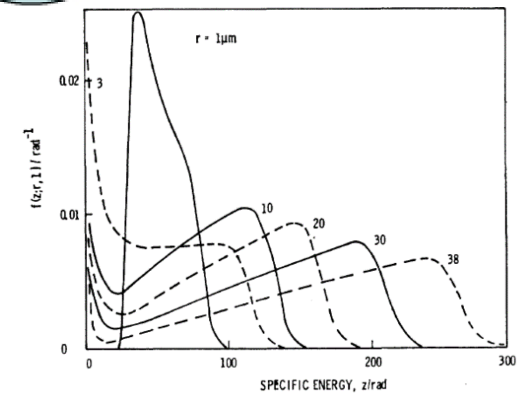

Li et al. 2010; 2014; Spielmann et al. 2015

# Internal Microdosimetry

# $\alpha$- and $\beta$- targeted Radiopharmaceuticals in Cells






$$f_\nu(z) = \int_0^z f_1(x) f_{\nu-1}(z - x)\, dx \qquad (\nu = 2, 3, \ldots)$$

$$f(z; D) = \sum_{\nu=0}^{\infty} e^{-n} \frac{n^\nu}{\nu!} f_\nu(z), \qquad \text{with} \quad n = \frac{D}{\bar{z}_F}$$

NAP 2007; Li et al. 2018

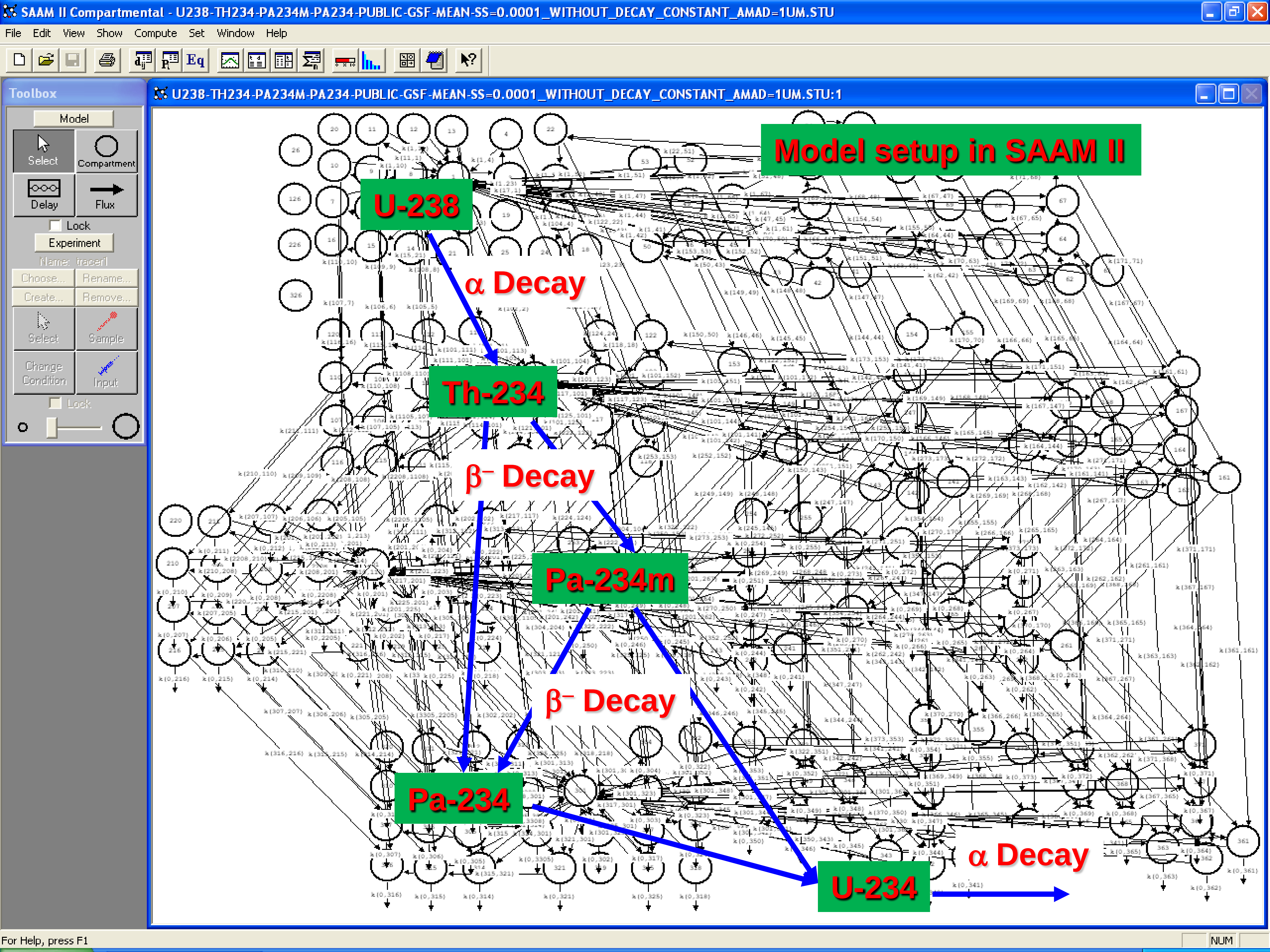
# Applications of Internal Dosimetry

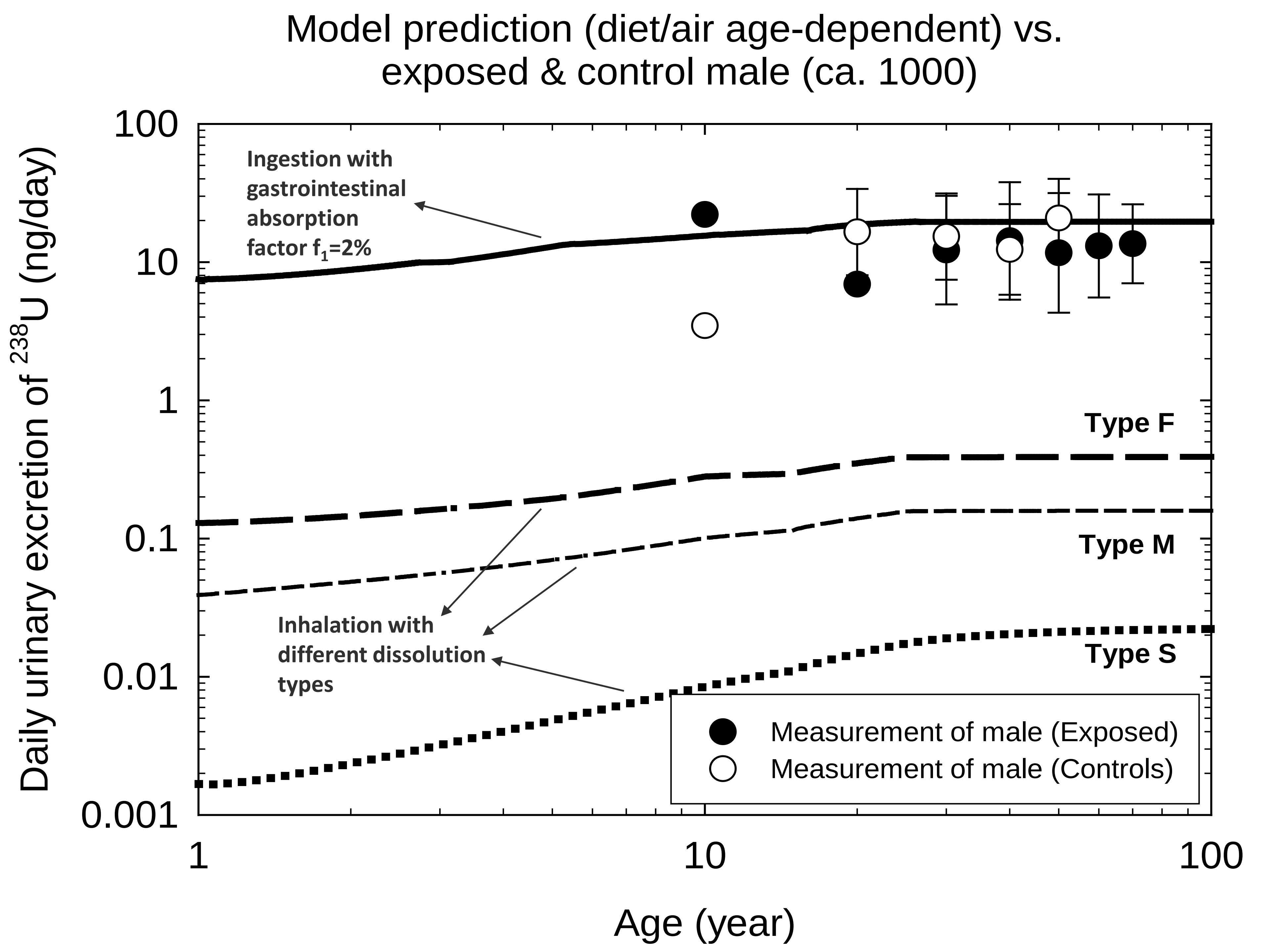
- Modeling of $^{238}U$ in human body from ingestion and inhalation

## Input for biokinetic modeling and dose calculation

- $^{238}U$ is a naturally occurring element, can be found in soil and rock and in water
- $^{238}U$ can be found in the air and in the foodstuffs
- We are inhaling $^{238}U$ everyday (20 mBq/day)
- We are taking $^{238}U$ everyday by eating and drinking (16 mBq/day)
- **Modeling the content and calculating the dose of $^{238}U$**
- **We are taking 1.3 mg $^{238}U$ everyday totally**
- **There is about 10 – 60 mg $^{238}U$ in our body**
- **Urinary excretion of $^{238}U$ per day ~ 20 ng**

**Li et al. 2005; 2006; 2009**


SAAM II Compartmental - U238-TH234-PA234M-PA234-PUBLIC-GSF-MEAN-SS=0.0001_WITHOUT_DECAY_CONSTANT_AMAD=1UM.STU
File Edit View Show Compute Set Window Help
Toolbox
Model
Select
Compartment
Delay
Flux
Lock
Experiment
Name: tracer1
Choose...
Rename...
Create...
Remove...
Select
Sample
Change Condition
Input
Lock
U238-TH234-PA234M-PA234-PUBLIC-GSF-MEAN-SS=0.0001_WITHOUT_DECAY_CONSTANT_AMAD=1UM.STU:1
Model setup in SAAM II
U-238
α Decay
Th-234
β⁻ Decay
Pa-234m
β⁻ Decay
Pa-234
U-234
α Decay
For Help, press F1
NUM


Model prediction (diet/air age-dependent) vs.
exposed & control male (ca. 1000)
Daily urinary excretion of 238U (ng/day)
Age (year)
100
10
1
0.1
0.01
0.001
1
10
100
Ingestion with gastrointestinal absorption factor f1=2%
Type F
Type M
Type S
Inhalation with different dissolution types
Measurement of male (Exposed)
Measurement of male (Controls)

$r_S$

$r_T$

| $r_T$ \ $r_S$ | UB_Cont | C_Bone-S | C_Bone-V |
|---|---|---|---|
| | 7.06E+02 | 8.68E+03 | 1.44E+06 |
| Adrenals | 5.93E-19 | 4.93E-18 | 8.94E-18 |
| UB_Wall | 5.68E-13 | 1.53E-18 | 2.99E-18 |
| Bone_Sur | 2.58E-18 | 2.80E-11 | 1.12E-12 |
| Brain | 7.37E-21 | 1.10E-17 | 1.10E-17 |
| Breasts | 1.44E-19 | 3.28E-18 | 3.28E-18 |
| St_Wall | 1.07E-18 | 3.19E | [illegible] |
| SI_Wall | 8.07E-18 | 4.41E | [illegible] |
| ULI_Wall | 6.30E-18 | 3.97E | [illegible] |
| LLI_Wall | 2.33E-17 | 5.94E | [illegible] |
| Kidneys | 1.14E-18 | 5.17E | [illegible] |
| Liver | 7.52E-19 | 3.97E | [illegible] |

$\tilde{A}(r_S)$

$S_w(r_T \leftarrow r_S)$

| Tissue or o | Tissue weighting facto |
|---|---|
| Gonads | 0.2 |
| Bone marr | 0.12 |
| Colon | 0.12 |
| Lung | 0.12 |
| Stomach | 0.12 |
| Bladder | 0.05 |
| Breast | 0.05 |
| Liver | 0.05 |
| Oesophagu | 0.05 |
| Thyroid | 0.05 |
| Skin | 0.01 |
| Bone surfa | 0.01 |
| Remainder | 0.05 |

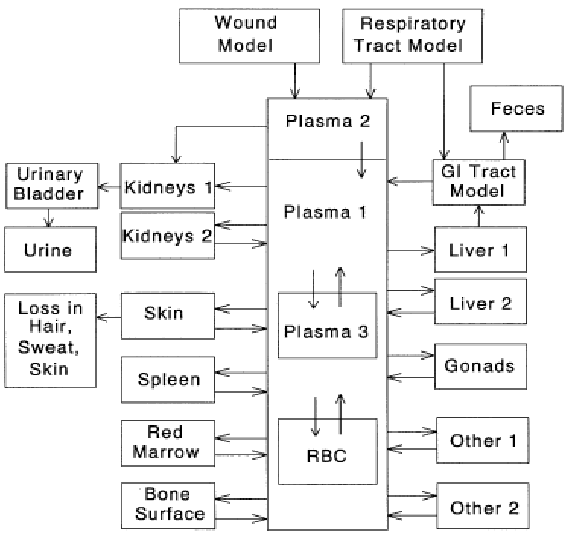
$W_T$

**Sv/Bq**

U-238 inhalation f1=0.02

| Organ | Eqv Dose |
|---|---|
| Adrenals | 1.22E-07 |
| Bladder Wall | 1.22E-07 |
| Bone Surface | 3.48E-06 |
| Brain | 1.22E-07 |
| Breast | 1.22E-07 |
| Oesophagus | 1.22E-07 |
| St Wall | 1.22E-07 |
| SI Wall | 1.22E-07 |
| ULI Wall | 1.26E-07 |
| LLI Wall | 1.34E-07 |
| Colon | 1.29E-07 |
| Kidneys | 1.27E-06 |
| Liver | 4.76E-07 |

# The Case of Mr. Alexander Litvinenko




Leggett and Eckerman, 2001

SPIEGEL ONLINE

30. November 2006, 11:02 Uhr

**CHRONIK**

## Der Fall Litwinenko

**Der mysteriöse Tod des Alexander Litwinenko: Wer vergiftete den Kreml-Kritiker? Eine Chronik der Affäre.**

**1. November:** Litwinenko trifft in einem Londoner Hotel mit dem ehemaligen KGB-Spion Andrej Lugowoi und zwei w einem Sushi-Restaurant den italienischen Sicherheitsexperten Mario Scaramella, um diesen zur Ermordung der krit Später wird ihm schlecht.

**3. November:** Litwinenko wird in das Barnet General Hospital in London gebracht.

**11. November:** Litwinenko teilt dem Radiosender BBC mit, dass er vergiftet worden sei und sich in sehr schlechter

**17. November:** Litwinenko wird ins University College Hospital verlegt und unter bewaffneten Schutz gestellt.

**20. November:** Litwinenko wird auf die Intensivstation verlegt. Die Polizei nimmt Ermittlungen auf. Ein Kreml-Spre verwickelt sei.

**22. November:** Die Klinik teilt mit, dass sich Litwinenkos Zustand erheblich verschlechtert hat.

**23. November:** Litwinenko stirbt um 21.21 Uhr (22.21 Uhr MEZ).

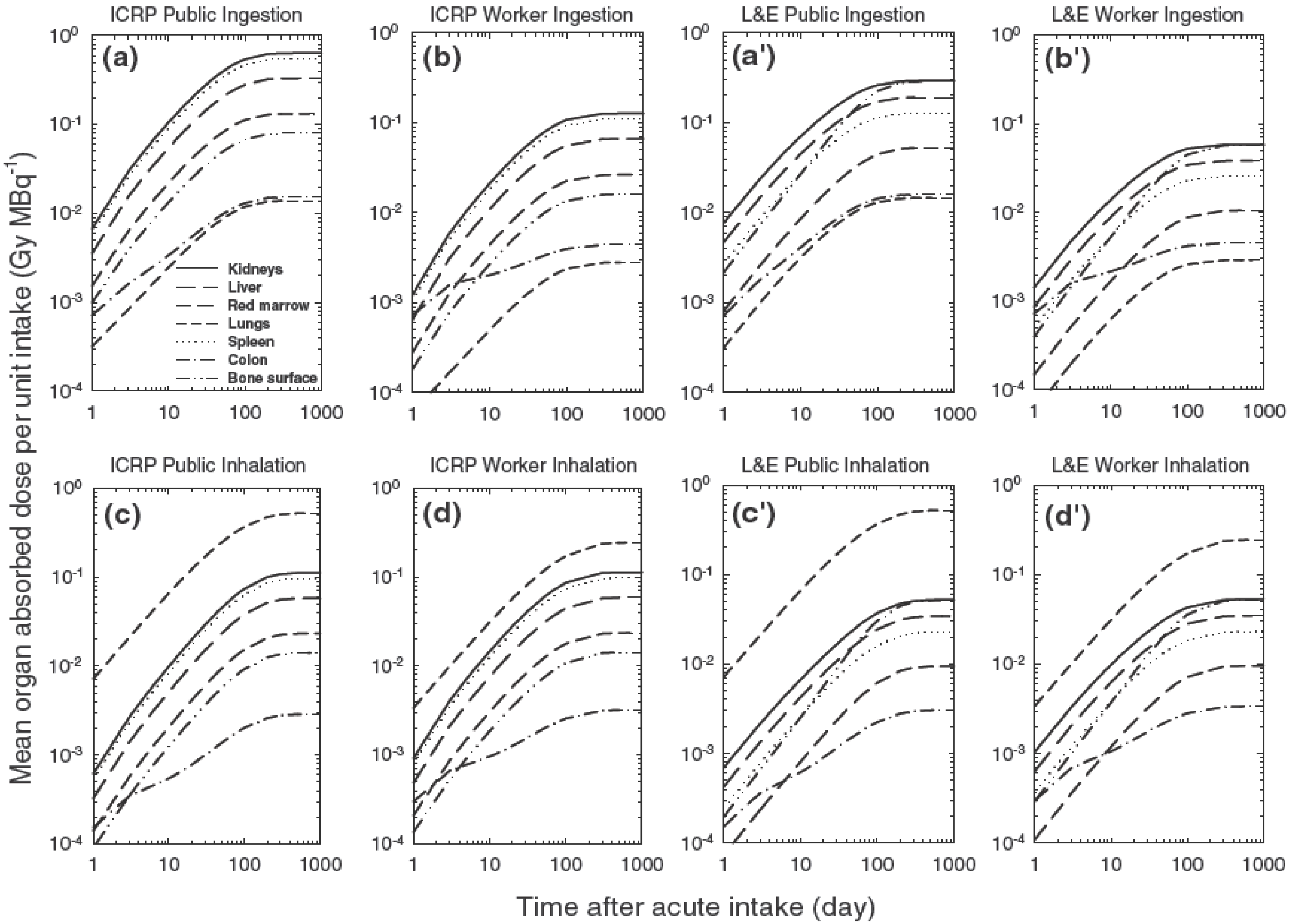
**24. November:** Eine von Litwinenko auf dem Sterbebett diktierte Erklärung wird veröffentlicht. Darin macht er den Der Kreml weist die Vorwürfe zurück. Die britische Gesundheitsbehörde HPA teilt mit, dass in Litwinenkos Urin die r Spuren werden auch in Litwinenkos Haus im Norden von London, in dem am 1.11. besuchten Sushi-Restaurant un

**27. November:** Die britische Regierung leitet eine offizielle Untersuchung zum Tod Litwinenkos ein.

**29. November:** Die Gesundheitsbehörde HPA kündigt Untersuchungen der Krankenschwestern, Pfleger und Ärzte einer radioaktiven Substanz an Bord von Flugzeugen der British Airways.

**30. November:** In weiteren Maschinen werden radioaktive Spuren gefunden.

# Organ Absorbed Dose




Li, et al. 2008

# The Amount of Po-210 Mr. A. Litvinenko Might Have Ingested or Drunk

**Table 3** Possible incorporation of $^{210}Po$ estimated for Mr. Alexander Litvinenko using the biokinetic [illegible] and L&E [15] with the assumption of different damaged organ and the lethal absorbed dose

| | Red bone marrow[a] (5 Gy[b]) | | | | Kidneys[a] (6 Gy[b]) | | | | [illegible]er[a] (8 Gy[b]) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Biokinetic model | ICRP | L&E | ICRP | L&E | ICRP | [illegible] | [illegible] | L&E | ICRP | L&E | ICRP | L&E |
| $f_1$ Value | 0.1 | 0.1 | 0.5 | 0.5 | [illegible] | [illegible] | 0.5 | 0.5 | 0.1 | 0.1 | 0.5 | 0.5 |
| Estimated intake | | | | | | | | | | | | |
| (MBq) | 546 | 1,408 | 109 | [illegible] | [illegible] | 230 | 27 | 46 | 351 | 473 | 70 | 94 |
| (µg) | 3.3 | 8.5 | [illegible] | [illegible] | [illegible].8 | 1.4 | 0.2 | 0.3 | 2.1 | 2.9 | 0.4 | 0.6 |

[a] Critical organ

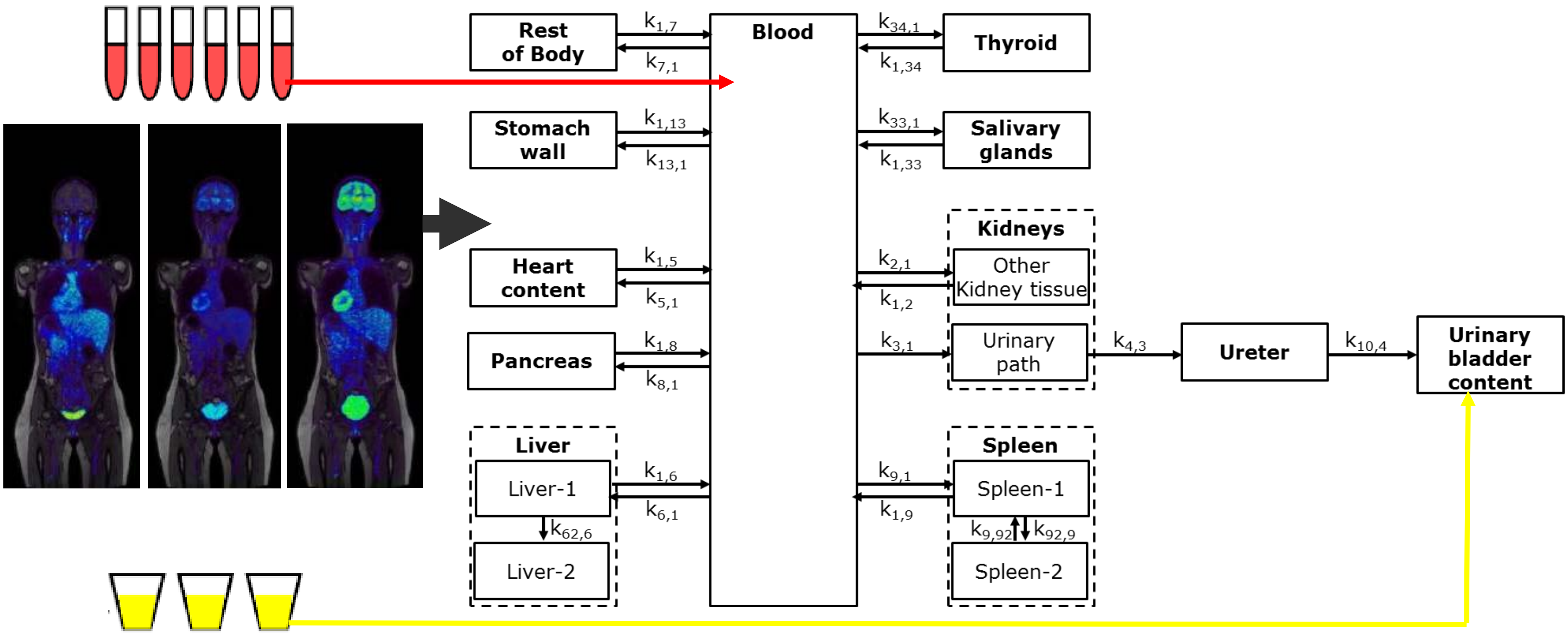
[b] Lethal absorbed dose

**10 µg of Po-210 can kill one person !**

Li, et al. 2008

# Applications of Internal Dosimetry

- Image-based biokinetic model and dosimetry for new radiopharmaceuticals

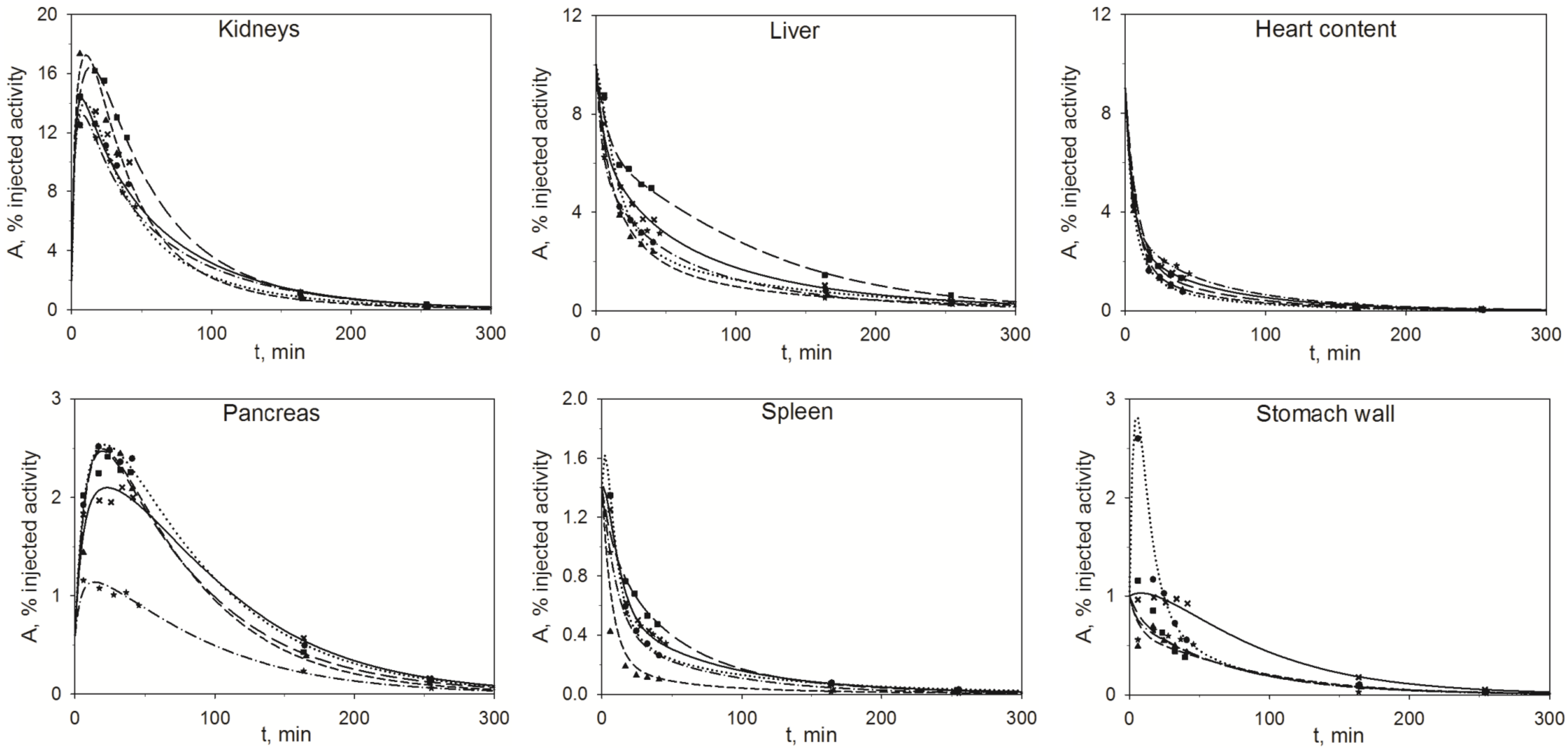



**Radiopharmaceutical: BAY94-9392 for five patients**

Zvereva et al., 2016

# Organ Activity Kinetics for Patients

**BAY94-9392:**



# Organ Doses and Effective Doses for Patients

## The doses can be used to estimate the patient health risk

**Table 2.** Organ absorbed-dose coefficients, [mGy/MBq] and effective-dose coefficients, [mSv/MBq]

| | 1101/94-female | | | 1102/94-female | | | 1103/94-male | | | 1104/94-female | | | 1105/94-male | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Target organ | Concept-1 | Concept-2 | %Diff | Concept-1 | Concept-2 | %Diff | Concept-1 | Concept-2 | %Diff | Concept-1 | Concept-2 | %Diff | Concept-1 | Concept-2 | %Diff |
| Red marrow | 8.30E-03 | 8.26E-03 | 0.6% | 7.79E-03 | 7.78E-03 | 0.2% | 7.76E-03 | 7.78E-03 | -0.3% | 7.73E-03 | 7.66E-03 | 1.0% | 6.55E-03 | 6.18E-03 | 6.0% |
| **Colon** | 1.19E-02 | 1.06E-02 | 12.0% | 1.06E-02 | 9.67E-03 | 9.9% | 1.03E-02 | 9.30E-03 | 10.4% | 1.13E-02 | 1.01E-02 | 12.4% | 1.01E-02 | 7.93E-03 | 27.0% |
| **Lungs** | 9.57E-03 | 6.36E-03 | 50.4% | 8.62E-03 | 6.18E-03 | 39.6% | 7.82E-03 | 5.85E-03 | 33.7% | 8.73E-03 | 5.63E-03 | 54.9% | 8.27E-03 | 4.31E-03 | 91.9% |
| Stomach wall | 2.87E-02 | 2.87E-02 | 0.0% | 1.89E-02 | 1.89E-02 | 0.0% | 1.37E-02 | 1.38E-02 | -0.3% | 2.58E-02 | 2.57E-02 | 0.2% | 1.51E-02 | 1.48E-02 | 1.9% |
| Bladder wall | 6.29E-02 | 6.32E-02 | -0.5% | 5.27E-02 | 5.29E-02 | -0.5% | 6.83E-02 | 6.87E-02 | -0.6% | 6.17E-02 | 6.19E-02 | -0.4% | 6.16E-02 | 6.20E-02 | -0.6% |
| **Oesophagus** | 9.10E-03 | 7.21E-03 | 26.2% | 8.36E-03 | 6.92E-03 | 20.7% | 7.94E-03 | 6.74E-03 | 17.9% | 8.09E-03 | 6.26E-03 | 29.4% | 7.52E-03 | 4.93E-03 | 52.6% |
| Liver | 2.13E-02 | 2.08E-02 | 2.3% | 2.68E-02 | 2.65E-02 | 1.3% | 1.38E-02 | 1.36E-02 | 1.9% | 1.85E-02 | 1.80E-02 | 2.8% | 1.39E-02 | 1.31E-02 | 6.6% |
| Thyroid | 1.89E-02 | 1.87E-02 | 1.1% | 1.21E-02 | 1.20E-02 | 1.2% | 1.36E-02 | 1.36E-02 | 0.2% | 1.49E-02 | 1.47E-02 | 1.6% | 9.45E-03 | 9.03E-03 | 4.6% |
| Salivary glands | 7.93E-03 | 7.98E-03 | -0.6% | 5.78E-03 | 5.84E-03 | -1.1% | 6.20E-03 | 6.35E-03 | -2.4% | 6.35E-03 | 6.38E-03 | -0.4% | 4.85E-03 | 4.80E-03 | 1.1% |
| Heart wall | 1.62E-02 | 1.53E-02 | 5.8% | 1.69E-02 | 1.63E-02 | 4.1% | 1.57E-02 | 1.53E-02 | 2.9% | 9.28E-03 | 8.41E-03 | 10.5% | 7.51E-03 | 6.33E-03 | 18.5% |
| Kidneys | 1.16E-01 | 1.16E-01 | 0.2% | 1.41E-01 | 1.41E-01 | 0.1% | 9.22E-02 | 9.19E-02 | 0.3% | 1.02E-01 | 1.01E-01 | 0.3% | 9.64E-02 | 9.58E-02 | 0.7% |
| Adrenals | 1.98E-02 | 1.87E-02 | 5.9% | 2.20E-02 | 2.12E-02 | 3.9% | 1.77E-02 | 1.70E-02 | 4.1% | 1.78E-02 | 1.67E-02 | 6.5% | 1.81E-02 | 1.64E-02 | 10.1% |
| Pancreas | 7.29E-02 | 7.27E-02 | 0.3% | 7.17E-02 | 7.12E-02 | 0.7% | 3.27E-02 | 3.25E-02 | 0.8% | 7.66E-02 | 7.61E-02 | 0.7% | 5.88E-02 | 5.77E-02 | 1.9% |
| **Small intestine** | 1.57E-02 | 1.43E-02 | 10.1% | 1.44E-02 | 1.33E-02 | 8.2% | 1.17E-02 | 1.07E-02 | 9.1% | 1.49E-02 | 1.35E-02 | 10.4% | 1.15E-02 | 9.32E-03 | 23.3% |
| Spleen | 2.10E-02 | 2.04E-02 | 3.0% | 2.27E-02 | 2.22E-02 | 2.0% | 1.39E-02 | 1.35E-02 | 3.0% | 1.97E-02 | 1.91E-02 | 3.2% | 1.11E-02 | 9.95E-03 | 11.3% |
| **Extrathoracic airways (ET)** | 4.54E-03 | 4.24E-03 | 7.1% | 3.91E-03 | 3.70E-03 | 5.4% | 3.88E-03 | 3.72E-03 | 4.2% | 4.22E-03 | 3.91E-03 | 8.0% | 3.09E-03 | 2.48E-03 | 24.6% |
| **Thymus** | 6.62E-03 | 5.45E-03 | 21.3% | 5.86E-03 | 4.99E-03 | 17.5% | 5.67E-03 | 5.04E-03 | 12.6% | 5.94E-03 | 4.80E-03 | 23.8% | 4.94E-03 | 3.43E-03 | 44.2% |
| Effective dose coefficient | 1.68E-02 | 1.61E-02 | 4.4% | 1.47E-02 | 1.42E-02 | 3.7% | 1.24E-02 | 1.20E-02 | 3.2% | 1.55E-02 | 1.48E-02 | 4.8% | 1.18E-02 | 1.07E-02 | 10.0% |

**Zvereva et al., 2016**

# Future Developments

- Biokinetic data and models including radiopharmaceuticals
- Next generation mesh-type computational phantoms
- Next generation age-dependent dose coefficients (DCs) for members of the public
- Implementation of new biokinetic models and DCs in monitoring and in regulation
- Special topic – hot particles
- Patient specific internal dosimetry in medicine
- Microdosimetry in molecular radiotherapy
- Machine learning & Deep learning applications

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**Thank you for your attention!**