Modeling of Internal Dose from Insoluble Cesium

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- Introduction
  - ✓ Characteristics of insoluble cesium particles
  - ✓ General method of internal dose estimation
- Modeling for insoluble cesium
  - ✓ Stochastic method of internal dose estimation
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- Result of internal dose estimation for insoluble cesium
  - ✓ Probability density function of lung doses
  - ✓ Difference in lung doses between the new method and the existing one
- Summary

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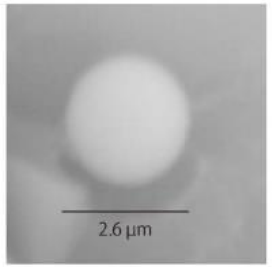
Characteristics of Insoluble Cesium Particles

Cesium-bearing particles were found after the accident at TEPCO's Fukushima Daiichi Nuclear Power Station.



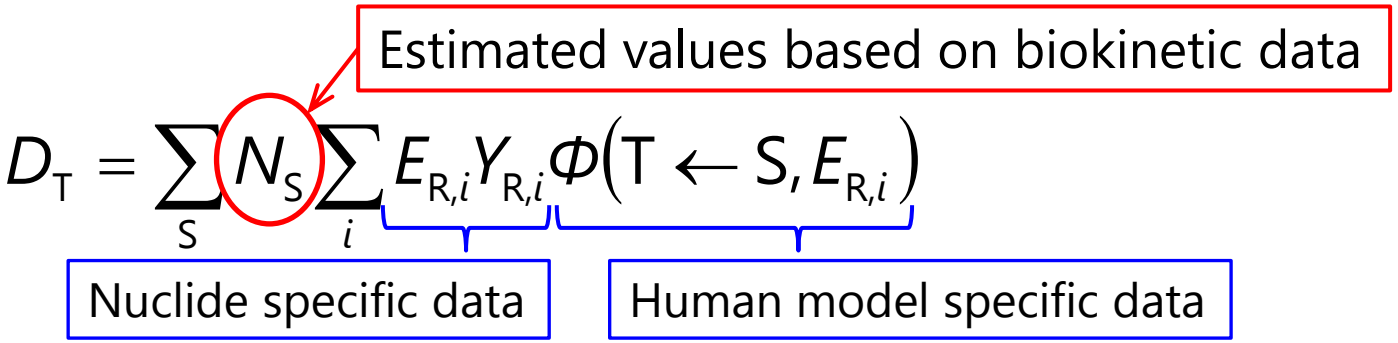
Adachi et al., Sci. Rep. (2013).

	Cs-bearing particles	Cs aerosols
Chemical property	Insoluble (even in nitric acid)	Generally soluble
Physical property (diameter)	Micrometer-sized	Log-normal distribution
State of radioactivity	Small number of particles with high specific activity	Dispersed to countless aerosols
Biokinetics	Stochastic movement in the state of a particle	Distributed throughout the body

Internal dose estimation considering these characteristics

General Method of Internal Dose Estimation

Absorbed dose to tissue or organ, D_T (Gy):



N_s: the number of disintegrations in source region, S

$E_{R,i}$: the energy of i^{th} radiation of type R emitted in disintegration

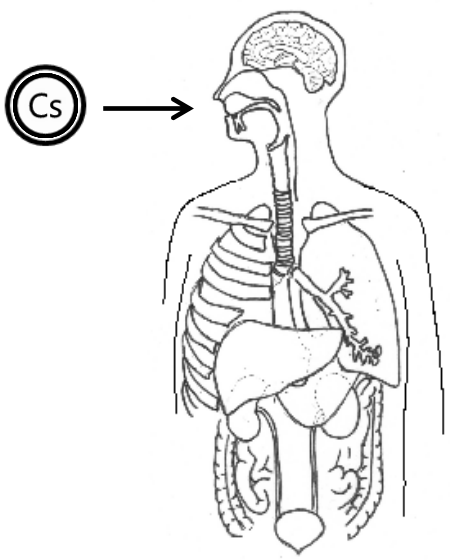
$Y_{R,i}$: the yield of i^{th} radiation of type R per disintegration

$\Phi(T \leftarrow S, E_{R,i})$: the specific absorbed fraction from S to target region, T

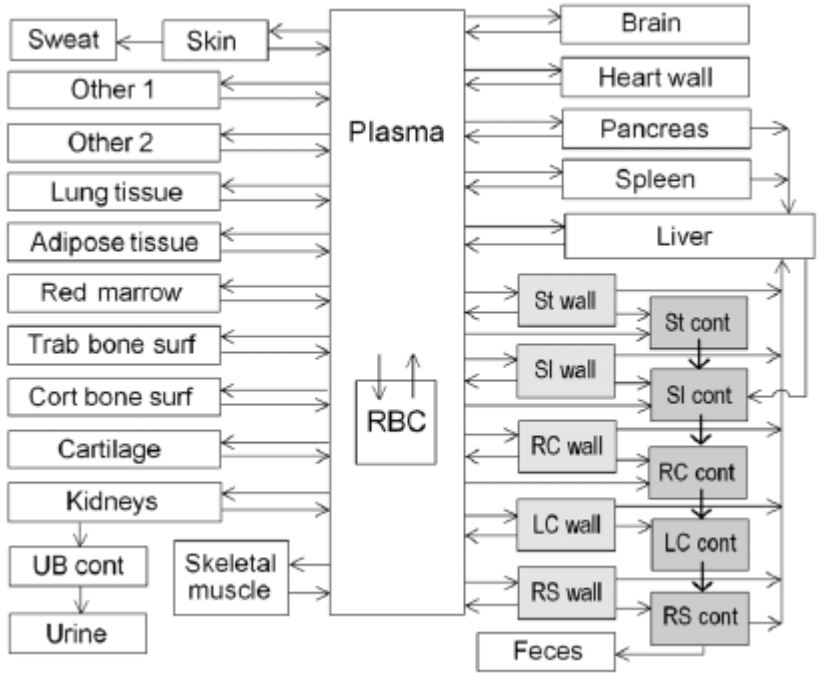
N_S depends on the biokinetics

Representation of Biokinetics

Compartment model



Radioactivity is distributed



R.W. Reggett, J. Radiol. Prot. (2013).

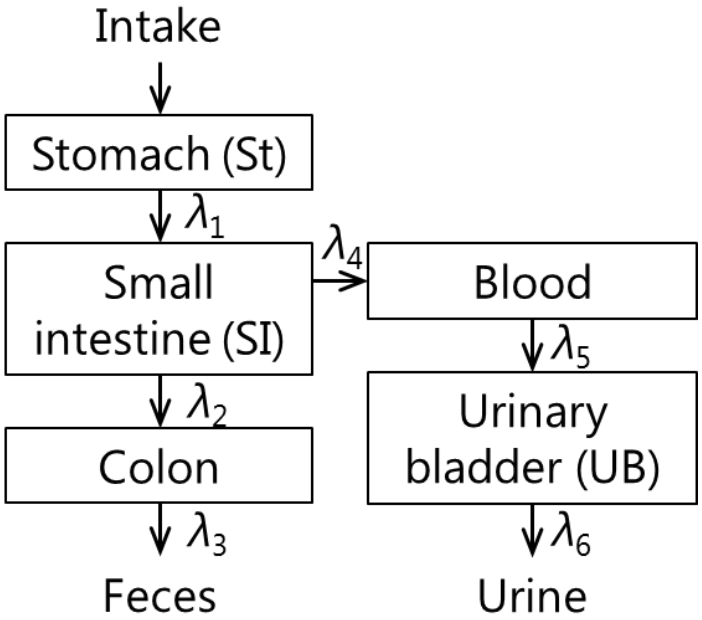
- Organs and tissues,
- Pathways of radioactivity

  are represented by

  "Compartments"

Commonly Used Method of Estimation of N_S

1. Construct a compartment model



(λ_i: transfer coefficient)

2. Form a system of ordinary differential equations (ODEs)

$$\begin{cases} \dfrac{da_{St}(t)}{dt} = -\lambda_1 a_{st}(t) \\ \dfrac{da_{SI}(t)}{dt} = -(\lambda_2 + \lambda_4) a_{SI}(t) + \lambda_1 a_{St}(t) \\ \dfrac{da_{Colon}(t)}{dt} = -\lambda_3 a_{Colon}(t) + \lambda_2 a_{SI}(t) \\ \dfrac{da_{Blood}(t)}{dt} = -\lambda_5 a_{Blood}(t) + \lambda_4 a_{SI}(t) \\ \dfrac{da_{UB}(t)}{dt} = -\lambda_6 a_{UB}(t) + \lambda_5 a_{Blood}(t) \end{cases}$$

3. Solve the ODEs and integrate $a_s(t)$

$$N_S = \int a_S(t) dt$$

This is a *"Deterministic"* method.

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Expected Biokinetics of Cs-bearing Particle

Cs-bearing particle:

- Insoluble
- Number is very small

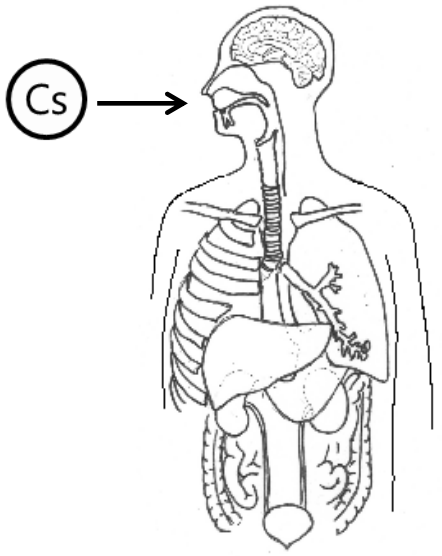
If incorporated into the body ...

- Pathway in the body
- Timing of transfer
  from an organ to another one
  (retention time),

will be different by a particle.

The particle will move *"Stochastically"*.

Deterministic method of estimating N_S cannot be applicable.



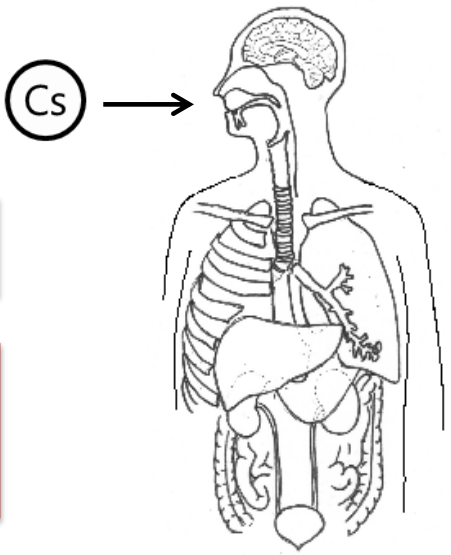
Ex. 1

Lung

→ Liver

→ Kidneys

→ Urine



Ex. 2

Lung

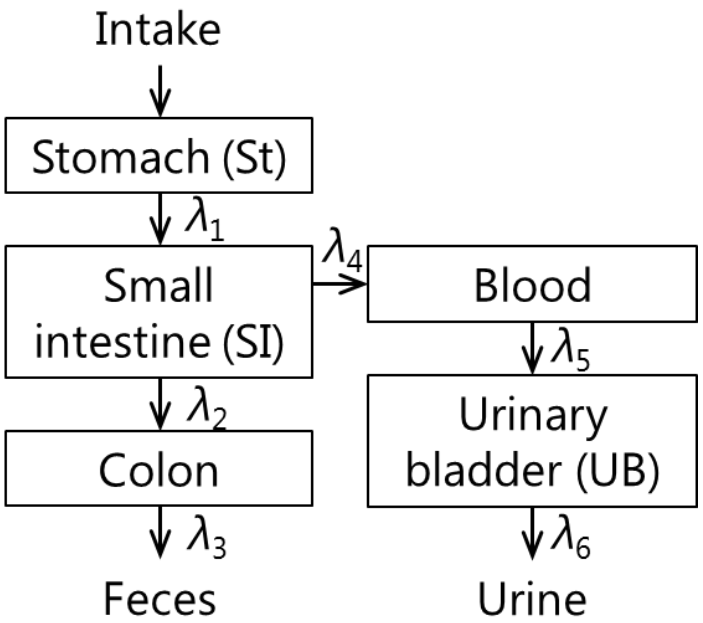
→ Stomach

→ Intestine

→ Feces

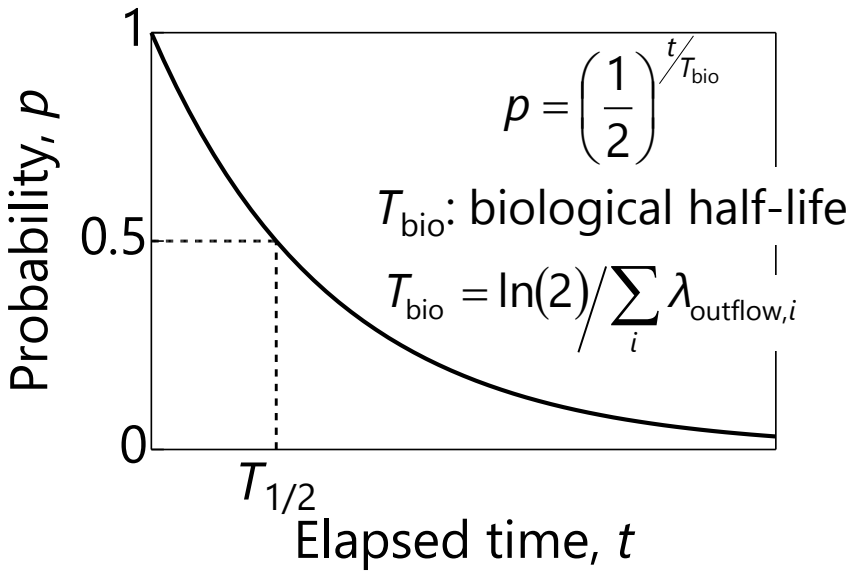
Stochastic Method of Internal Dose Estimation (1)

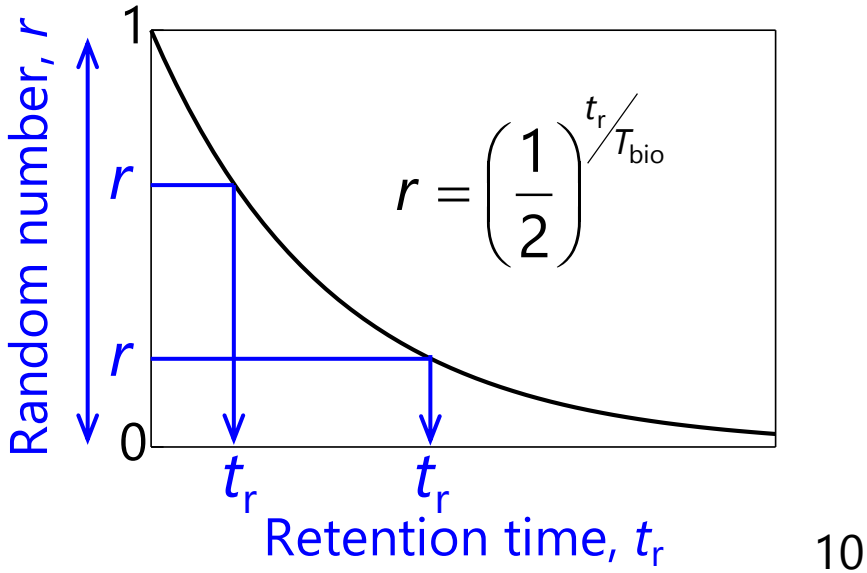
1. Construct the possible pathways



(λ_i: transfer coefficient)

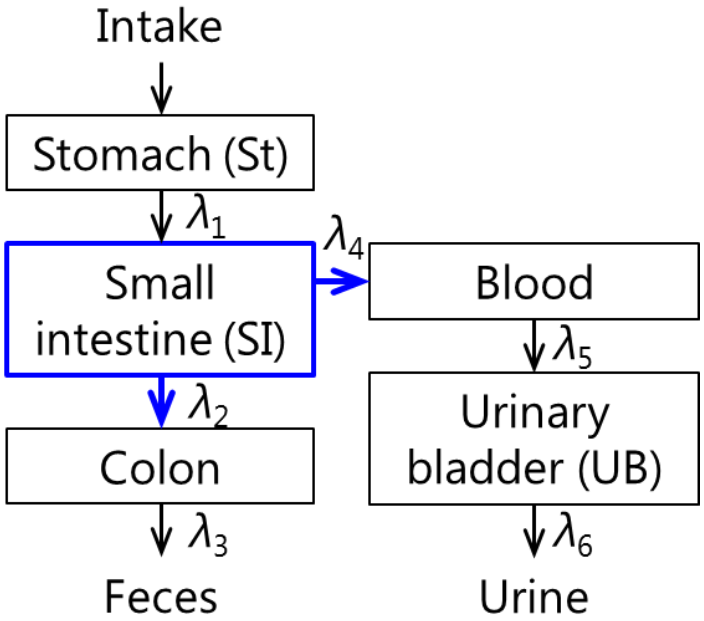
2. Determine the retention time





Stochastic Method of Internal Dose Estimation (2)

3. Determine the target compartment



(λ_i: transfer coefficient)

Proportion of migration

SI→Colon : SI→Blood

$= \lambda_2 : \lambda_4$

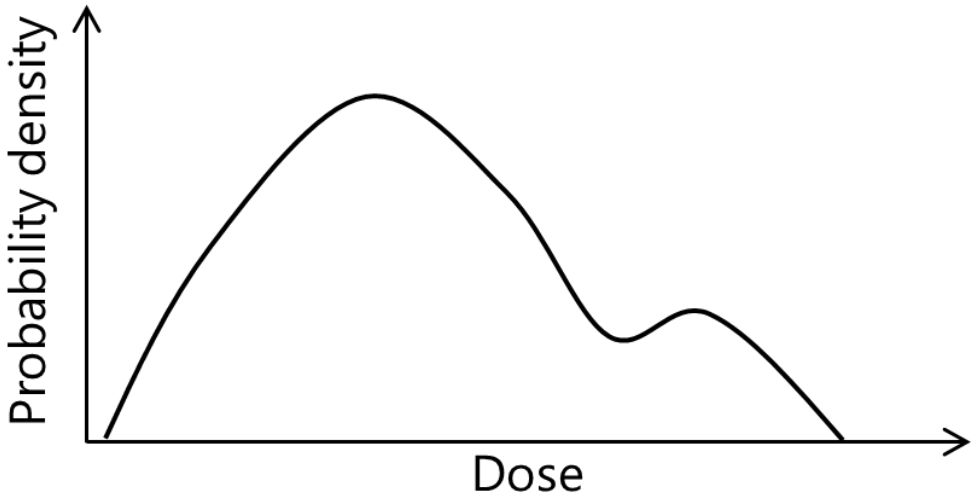
4. Repeat the step 2 and 3

r_T in each compartment → N_S → D_T can be determined *"Stochastically"*.

Probability Density Function of Doses

- One time execution of the Stochastic Biokinetic (SB) method: one history produces one stochastic value of internal dose.
- Repeat execution of the SB method produces a statistical population of internal doses.

⇒ Probability Density Function (PDF)



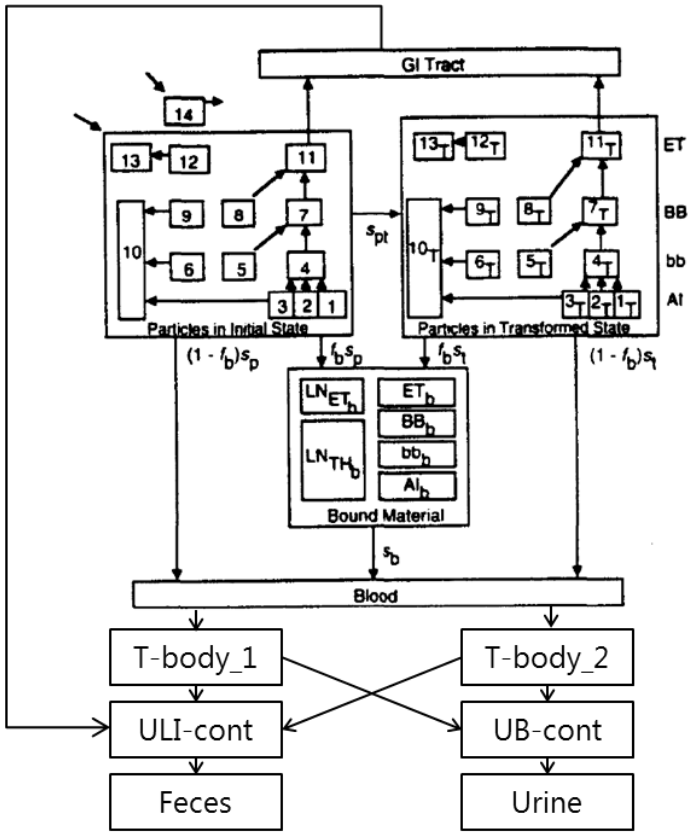
PDF of doses

Computation program executing the SB method

Verification of the SB Method Program

Arithmetic mean by infinite repeat of SB method	=	Estimated value by a deterministic method: DCAL code

^{134}Cs inhalation type S



- Values of N_S and D_T were compared for the number of histories: 10^4, 10^5, 10^6, 10^7.

ICRP publication 56 and 66.

Result of Verification

$$\text{Ratio} = \frac{\text{Values by the SB method}}{\text{Values by DCAL code}}$$

Ratio for N_S

Source regions	Deposition fraction	Number of histories 10^4	10^5	10^6	10^7	DCAL
Alveolar-interstitium	1.1E-01	1.0	1.0	1.0	1.0	4.0E+06
Bronchiole-fast	9.9E-03	1.0	1.0	1.0	1.0	3.4E+03
Bronchiole-slow	9.5E-03	1.2	1.1	1.0	1.0	2.6E+04
Bronchiole-sequestered	1.4E-04	0.0	1.1	1.0	1.0	1.1E+03
Bronchi-fast	6.8E-03	1.0	1.0	1.0	1.0	8.1E+02
Bronchi-slow	6.0E-03	1.0	1.0	1.0	1.0	1.7E+04
Bronchi-sequestered	9.0E-05	1.3	0.8	1.0	1.0	7.1E+02
Lymphatic nodes-Thoracic	—	0.8	0.9	1.0	1.0	3.4E+04
ET1-surface	1.5E-01	1.0	1.0	1.0	1.0	1.3E+04
ET2-surface	1.9E-01	1.0	1.0	1.0	1.0	2.5E+02
ET2-sequestered	9.5E-05	0.0	0.8	1.1	1.0	4.1E+03
Lymphatic nodes-ET	—	0.0	1.1	1.0	1.0	4.0E+03

Good agreement for 10^7 histories

Ratio for D_T

Tissue	Number of histories 10^4	10^5	10^6	10^7	DCAL (Sv)
Lungs	1.0	1.0	1.0	1.0	1.4E-07
ET region	0.5	0.9	1.0	1.0	2.3E-08
Stomach	1.0	1.0	1.0	1.0	5.5E-09
Small intestine	1.0	1.0	1.0	1.0	1.7E-09
Colon	1.0	1.0	1.0	1.0	3.3E-09
Urinary bladder	1.0	1.0	1.0	1.0	5.1E-10

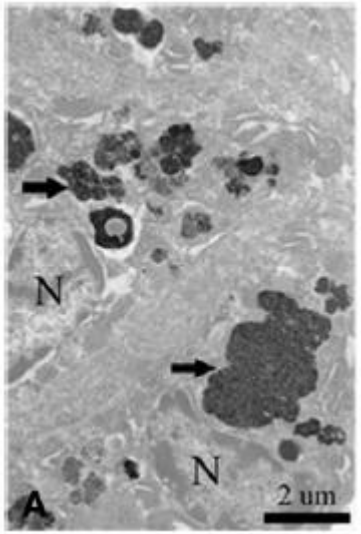
Good agreement for 10^6 histories

Verified

Expected Biokinetics of Cs-bearing Particle

Biokinetics of inhaled insoluble material

	Majority	~ 1%
Clearance mechanism from respiratory tract	Ciliary movement	Englobement by macrophage
Destination of migration	Feces via alimentary tract	Organs via lymphatic nodes, trapped there
Retention time in the body	Short	**Long**



Material trapped in Kupffer cell (liver).

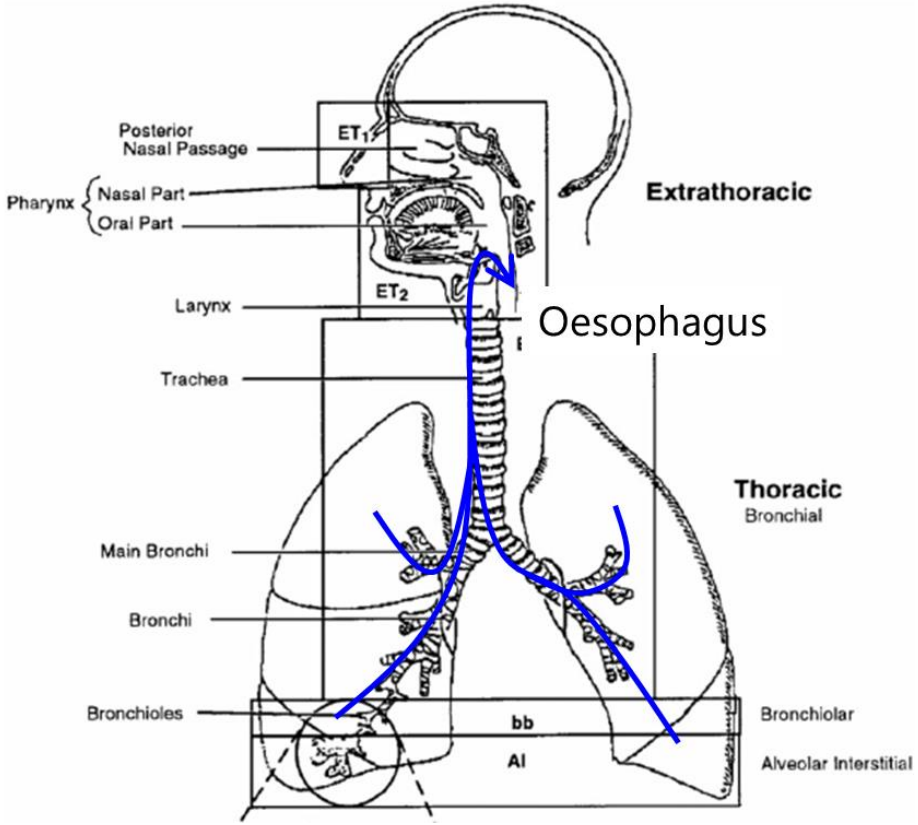
Yokel et al., Nanomedicine (2013).

Existing biokinetic models do not suppose long retention in organs.

Modeling of Biokinetics for Insoluble Cs (1)

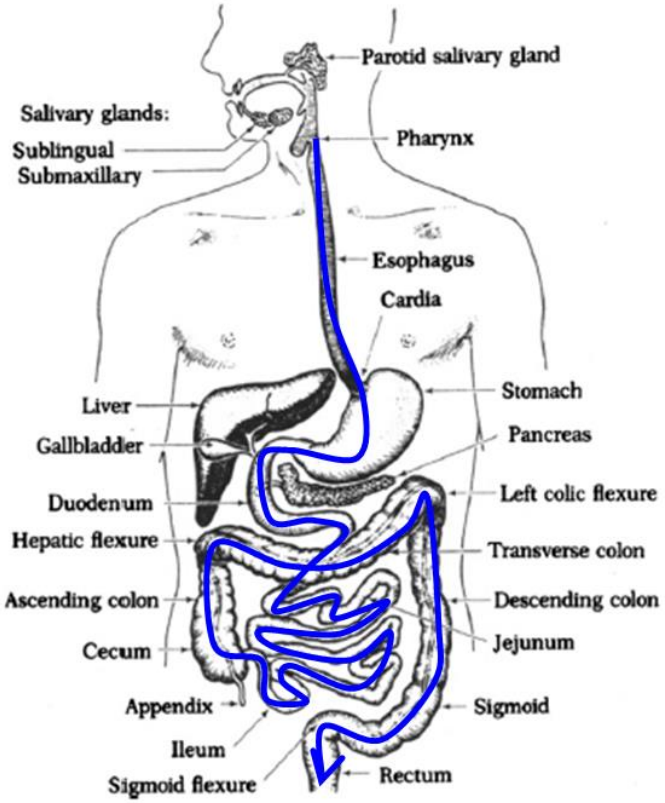
Clearance from the respiratory tract

From the regions of the respiratory tract
To the oesophagus (the alimentary tract)



Revised Human Respiratory Tract Model
(ICRP Publ. 130)

From the oesophagus
To feces



Human Alimentary Tract Model
(ICRP Publ. 100)

Modeling of Biokinetics for Insoluble Cs (2)

Modifications for insoluble cesium

- Bound state* compartments of organs and tissues were added for the particles via lymphatic nodes based on rats data[1, 2],

[1] Geraets et al., Toxicol. Sci. (2012). [2] Creutzenberg et al., J. Appl. Toxicol. (2016).

*Bound state: the **particles will not move** till the end of committed period.

- Pathways from the respiratory tract regions to blood were omitted because of the size of the particles (ICRP Publ. 66),
- Systemic model and f_1 value† for Pu inhalation type S were applied because they are designed for insoluble chemical form (ICRP Publ. 67, 71).

†Absorption fraction to blood from small intestine

Conservative assumptions

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Calculation Conditions

Parameters of cesium-bearing particles*

*Adachi et al., Sci. Rep. (2013).

- Diameter: 2.0 μm
- Density: 2.0 g/cm^{-3}
- Shape factor: 1.0 (Sphere)
- Activity: ^{134}Cs 0.5 Bq + ^{137}Cs 0.5 Bq (^{137m}Ba was included)

Calculation conditions of deposition probability

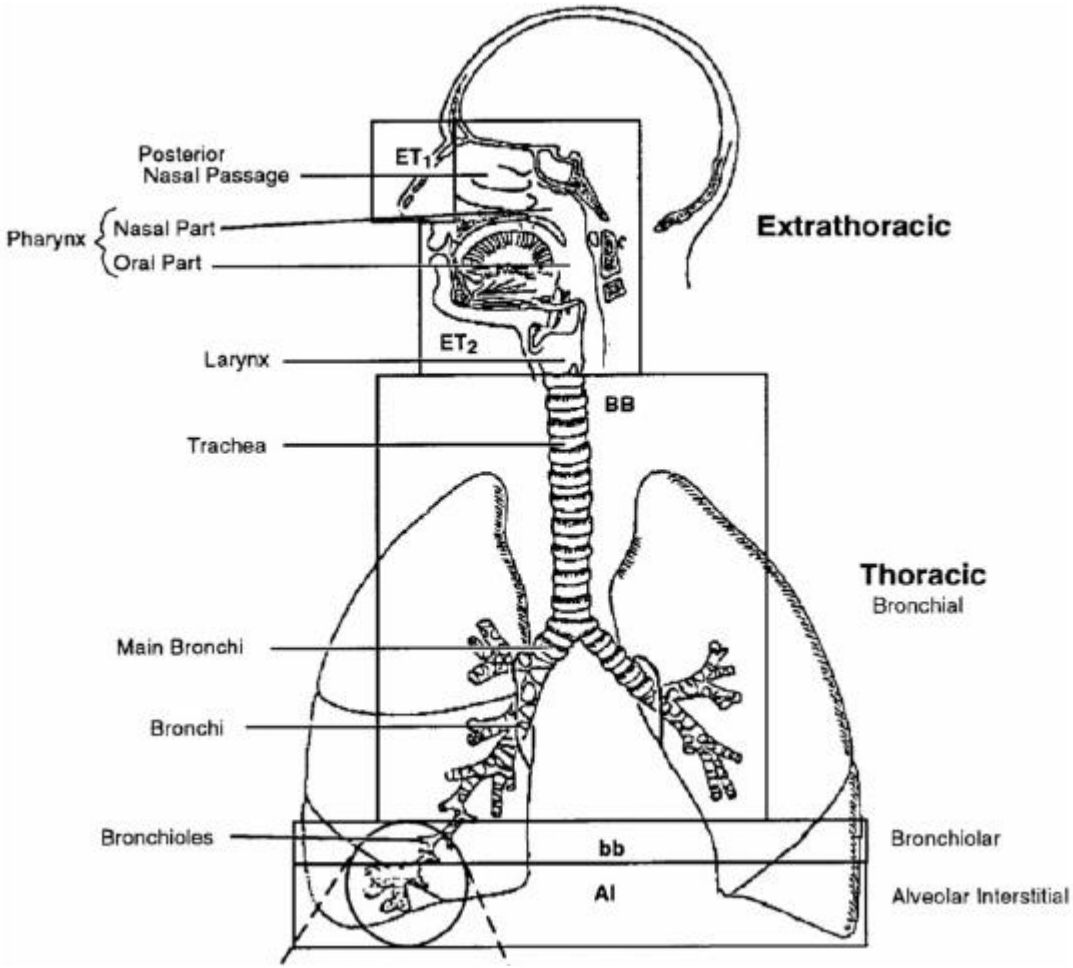
- Human subject: Adult male worker
- Activity level: Light exercise
- Breathing habit: Nose breather

Data used for calculating absorbed dose

- Nuclear decay data: ICRP Publ. 107
- Specific absorbed fractions: ICRP Publ. 133 (for reference adult male)

PDF of lung doses were estimated
by repeating the SB method for 10^6 histories.

Deposition Probability



Compartment	Probability
ET1	0.46
ET2	0.25
ET2-seq*	0.00049
BB	0.025
BB-seq	0.000049
bb	0.016
bb-seq	0.000032
Alveoli	0.12
Total	0.87

*"Sequesterd" means a component retained there

Particle is not deposited to any compartment in 13%.

Multiple Particles Inhalation

In the actual situation

Multiple particles inhalation is assumed.

⇒ How will PDF change?

Procedure

- Repeat histories as many times as the number of inhaled particles.
  Name a group of histories an event.
- Assume each particle moves independently.
- Define a dose for one event as the sum of the dose for each history.

Number of particles	2	4	8	16	32	64	10^2	10^3	10^4
Number of events	$10^6/2$	$10^6/4$	$10^6/8$	$10^6/16$	$10^6/32$	$10^6/64$	10^4	10^4	10^4

Summary

- To estimate internal doses considering the characteristics of cesium-bearing particles, we constructed:
  - ✓ Stochastic biokinetic method (SB method),
  - ✓ Biokinetic model for insoluble materials.
- PDF of lung doses was estimated by using the SB method and the biokinetic model.
  - ✓ For single particle inhalation, large uncertainty of the doses was observed owing to the insolubility of the particle.
  - ✓ The uncertainty decreased with increasing the number of inhaled particles.
- Comparing to the dose based on the existing model, larger doses were induced by the insolubility of cesium-bearing particles.

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  Dr. T. Ishikawa, Dr. M. Kai, Dr. T. Sato, Dr. A. Sorimachi and Dr. I. Yamaguchi, and Dr. Y. Moriguchi

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