Chapter 16

- MIRD
- Embryo/Fetal Dose

MIRD

Objectives

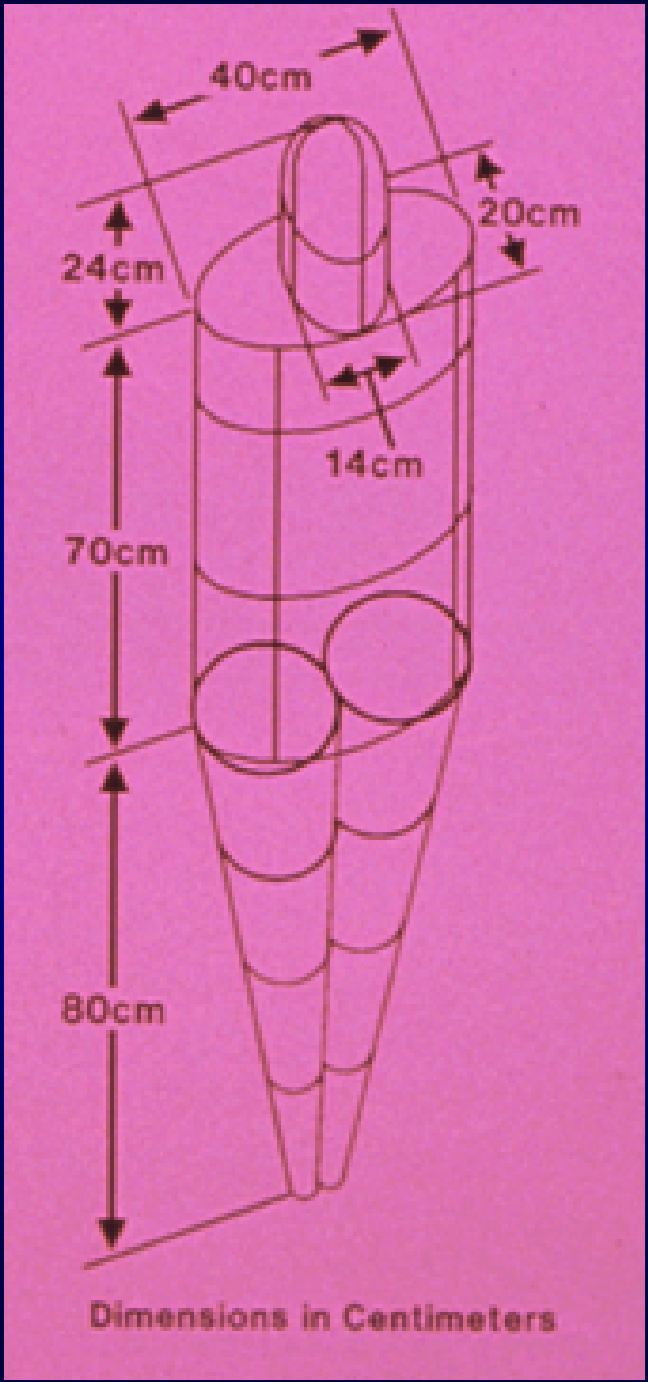
- Describe the MIRD system for internal dose assessment
- Calculate an internal dose using the MIRD technique

MIRD

Medical Internal Radiation Dose

Committee of the
Society of Nuclear Medicine

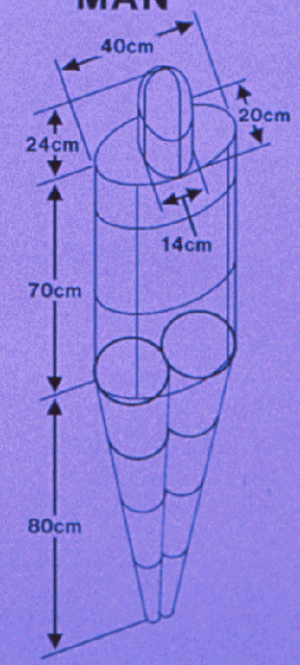
Reference Man



Reference Man
(organs)

MIRD

ABBREVIATIONS for	BODY ORGANS used in REFERENCE MAN
AD	Adrenals
	Bladder
BLADW	Wall
BLADC	Contents
	Gastrointestinal Tract
	Stomach
STW	Wall
STC	Contents
SI	Small Intestine and Contents
	Upper Large Intestine
ULIW	Wall
ULIC	Contents
	Lower Large Intestine
LLIW	Wall
LLIC	Contents
KI	Kidneys (both)
LI	Liver
LU	Lungs (both, including blood)
OT	Other Tissue



Dimensions in Centimeters

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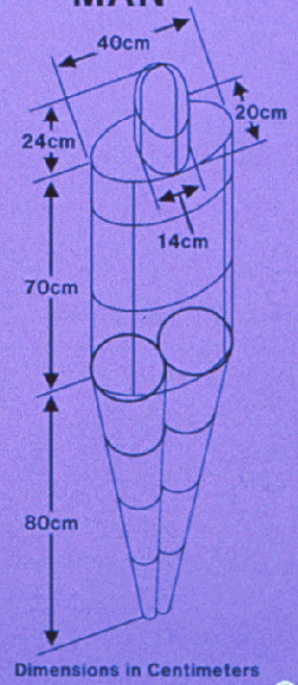
Reference Man
(organs)

M I R D

ABBREVIATIONS for	BODY ORGANS used in REFERENCE MAN
OV	Ovaries (both)
PA	Pancreas
SALG	Salivary Glands
SKEL	Skeleton
CORTB	Cortical Bone
TRAB	Trabecular Bone
RM	Red Marrow
YM	Yellow Marrow
CART	Cartilage
--	Other Constituents
SP	Spleen
TE	Testes
THY	Thyroid
UT	Uterus
TB	Total Body



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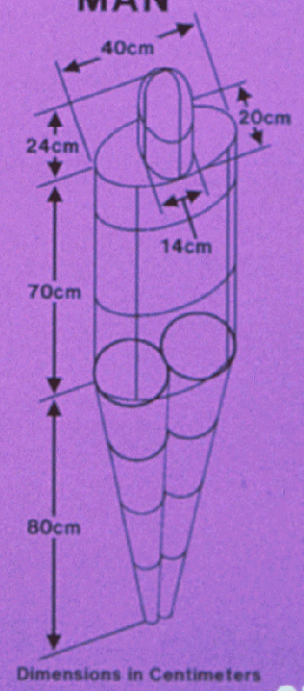
Reference Man
(organs)

MIRD

AVERAGE MASS (g)	BODY ORGANS used in REFERENCE MAN
14	Adrenals
	Bladder
45	Wall
200	Contents
	Gastrointestinal Tract
	Stomach
150	Wall
250	Contents
640 Wall	Small Intestine and Contents
400 Contents	
	Upper Large Intestine
210	Wall
220	Contents
	Lower Large Intestine
160	Wall
135	Contents
310	Kidneys (both)
1,800	Liver
1,000	Lungs (both, including blood)
48,000	Other Tissue



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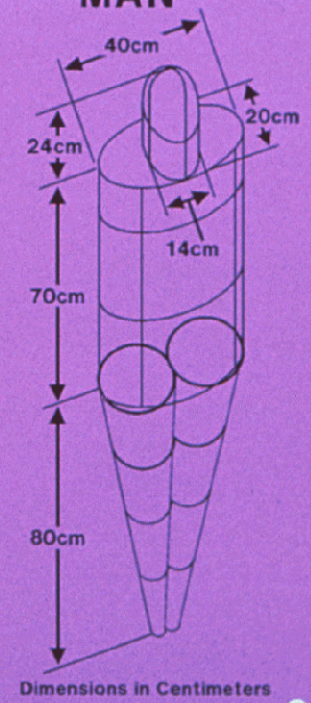
Reference Man
(organs)

MIRD

AVERAGE MASS (g)	BODY ORGANS used in REFERENCE MAN
11	Ovaries (both)
100	Pancreas
85	Salivary Glands
10,000	Skeleton
4,000	Cortical Bone
1,000	Trabecular Bone
1,500	Red Marrow
1,500	Yellow Marrow
1,100	Cartilage
900	Other Constituents
180	Spleen
35	Testes
20	Thyroid
80	Uterus
70,000	Total Body

154 lbs → 70,000



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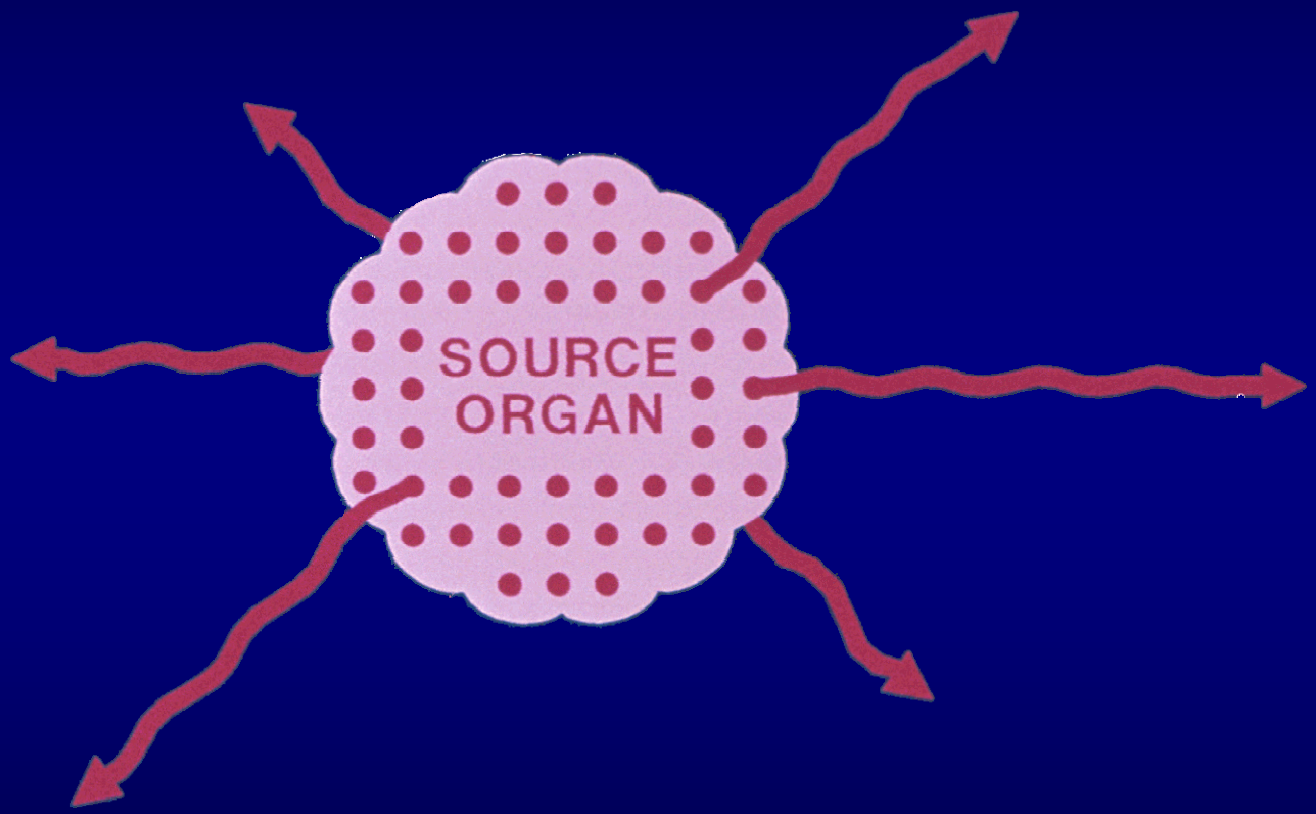
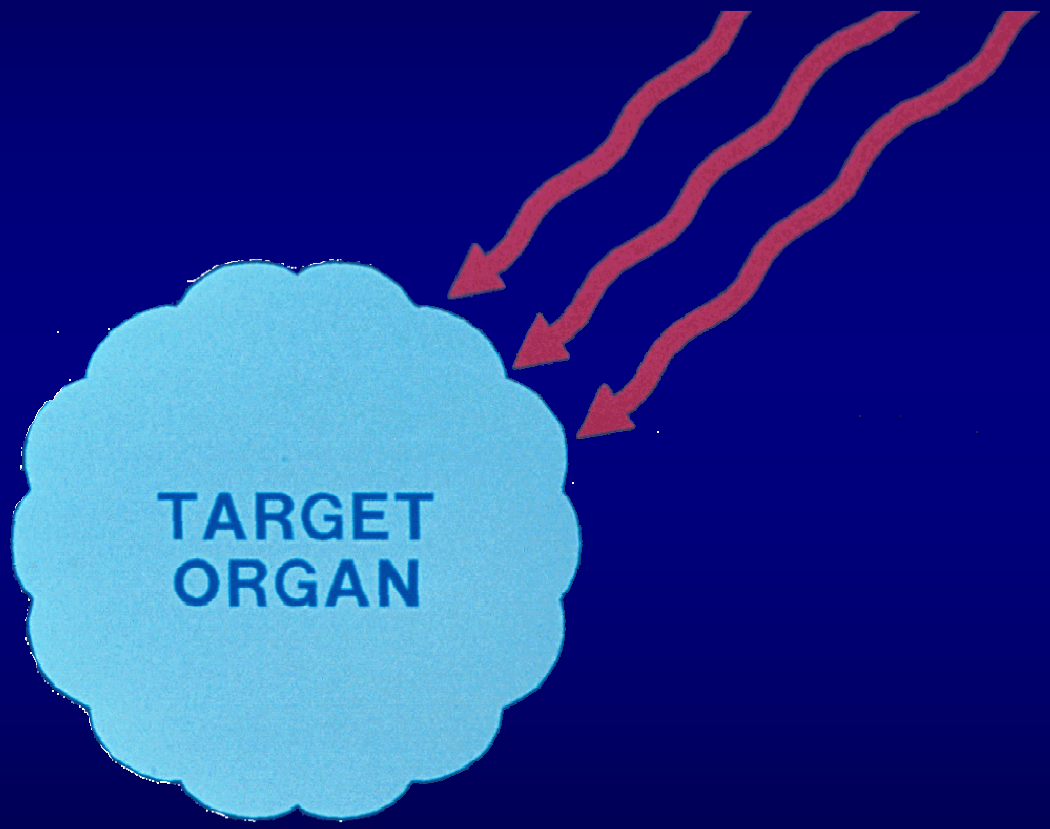
Source Organ

The organ wherein the radionuclide is localized and assumed to be uniformly distributed

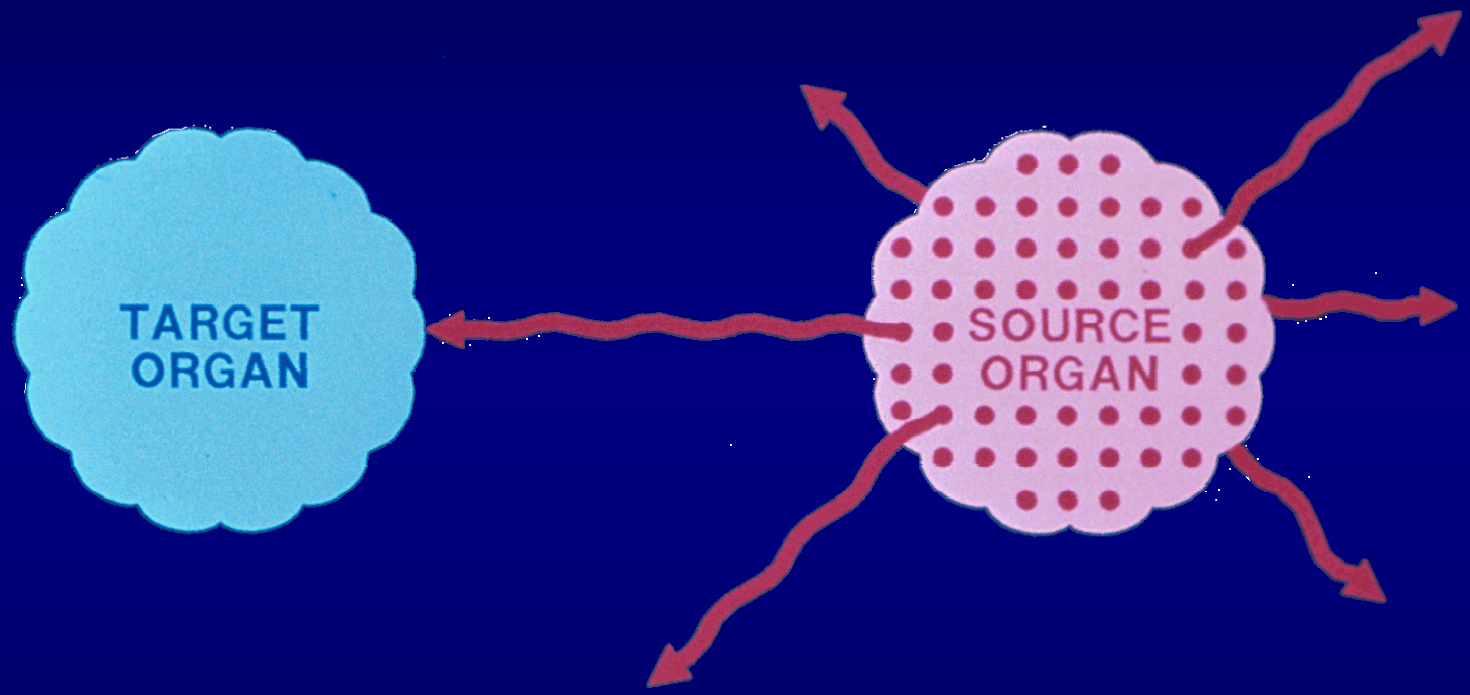


Target Organ

The organ for which the dose is to be calculated

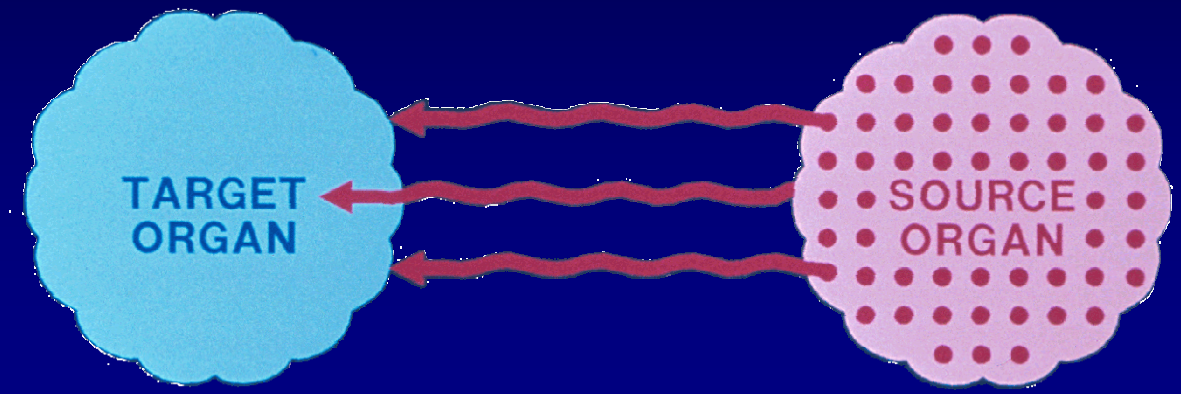


Organ Orientation



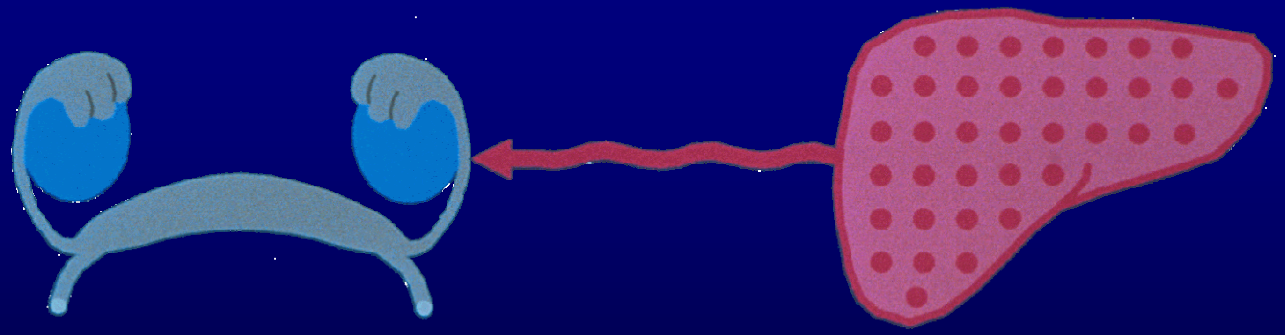
Target and source organs exist in different relationships to each other

Two Organs



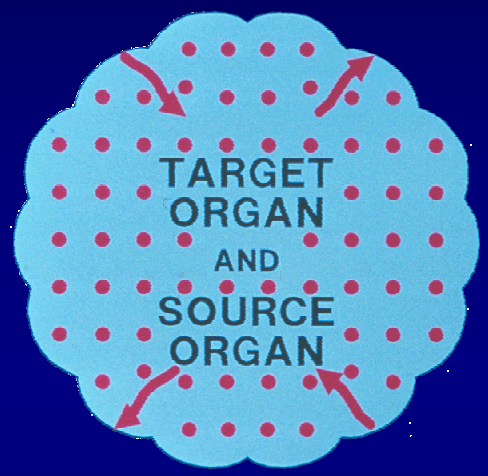
Target and source organ may be different

Example



Dose to ovaries **from liver**

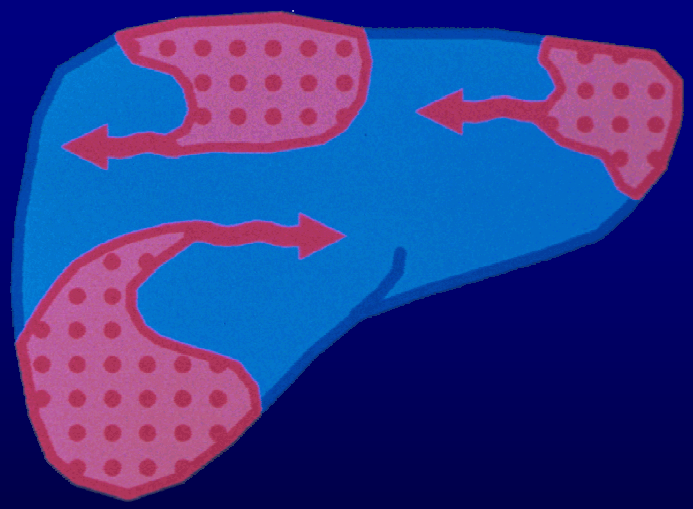
One Organ



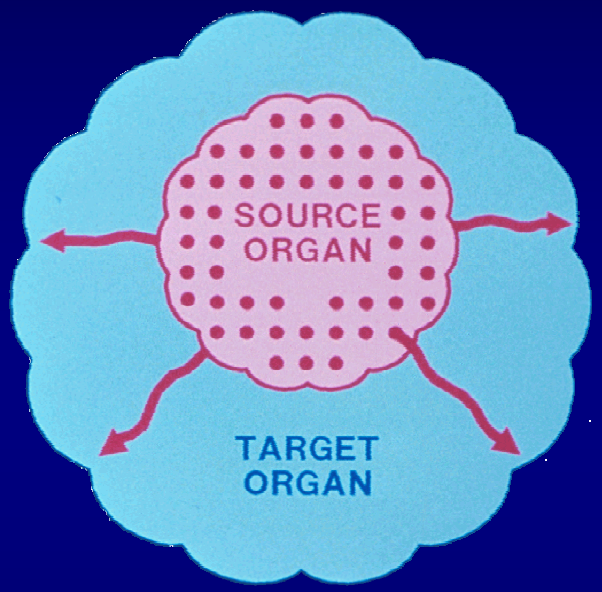
Target and source organ may be the same

Example

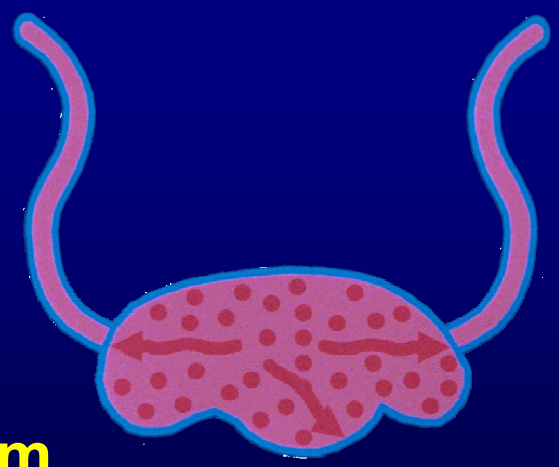
Dose to Liver from liver



Source Inside Target



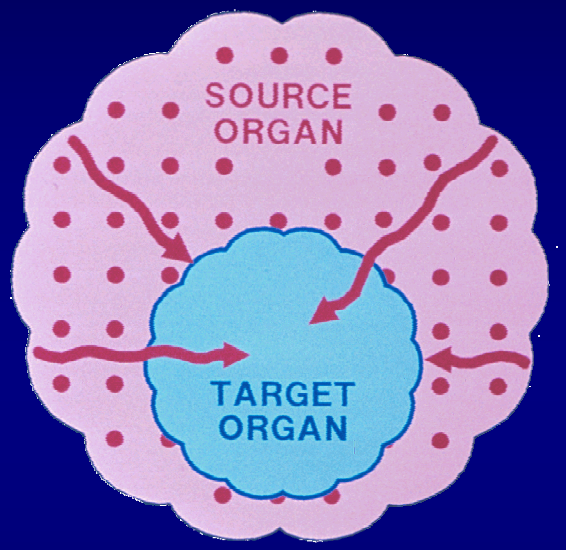
Source organ may be enclosed by target organ



Example

Dose to bladder wall from bladder contents

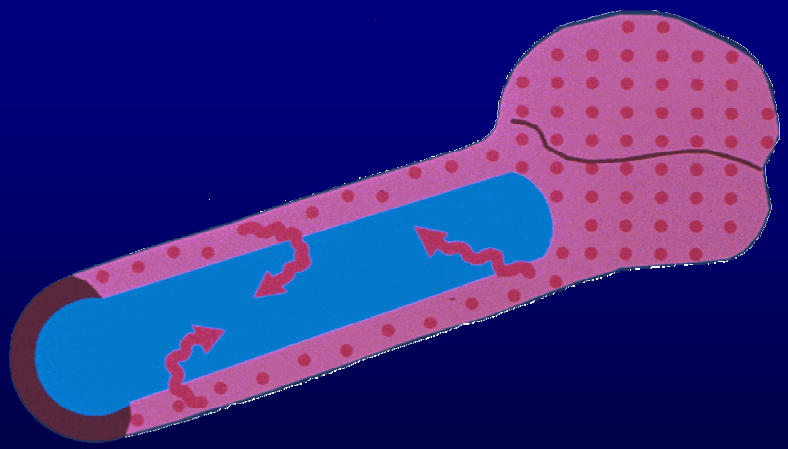
Target Inside Source



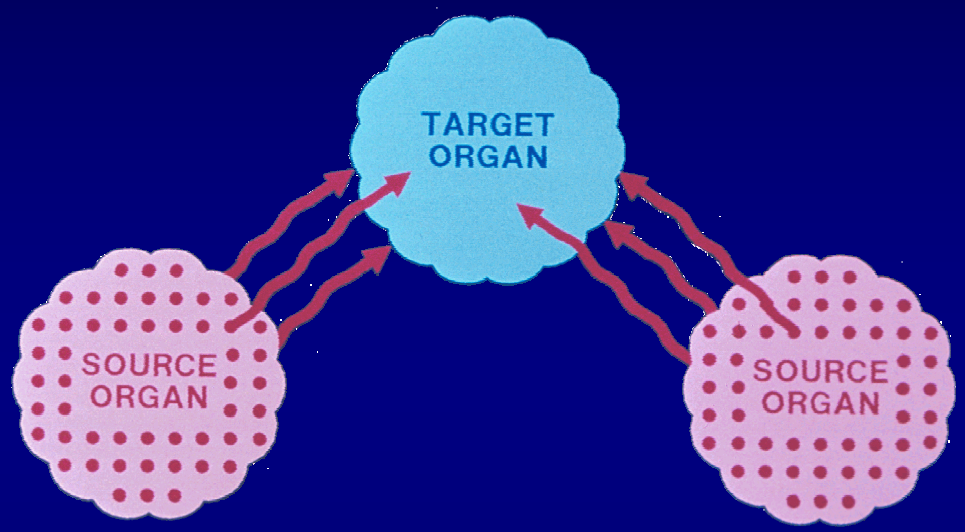
Target organ may be enclosed by source organ

Example

Dose to marrow from bone

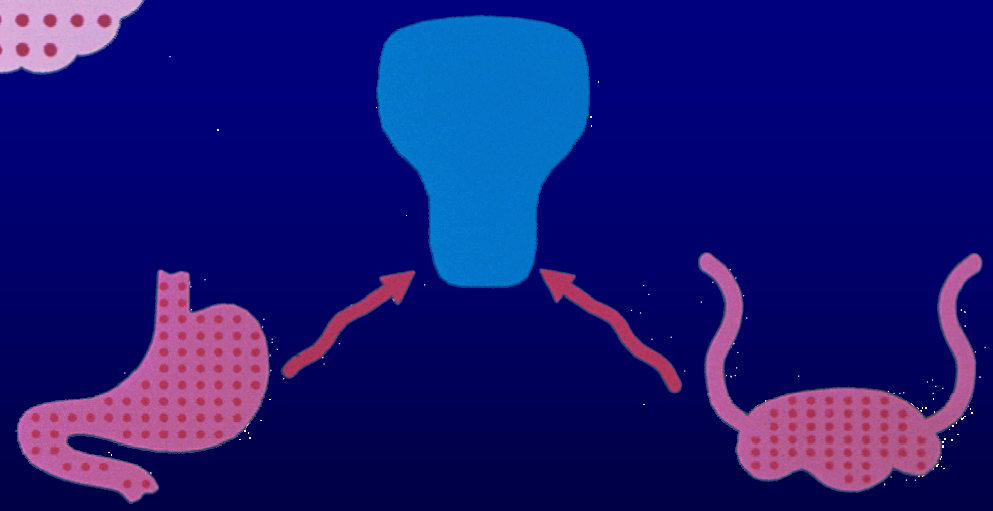


Multiple Source Organs



Example

Dose to uterus from stomach and bladder

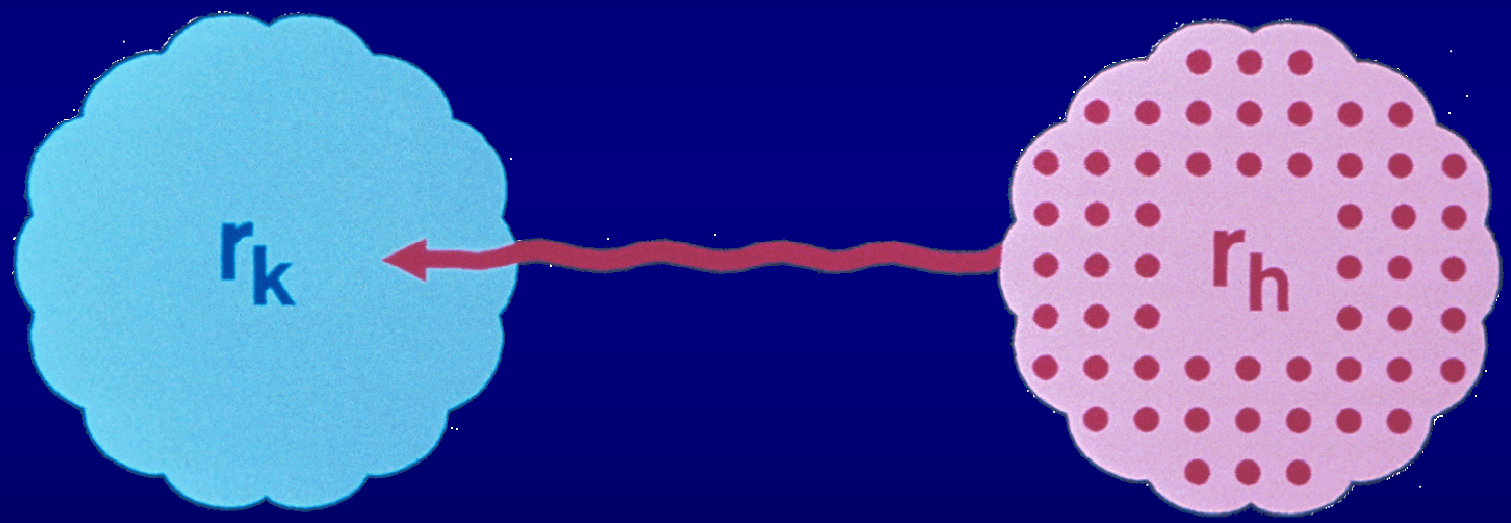


MIRD Dose Calculation Factors

- Amount of activity located in various organs of the body (A)
- Amount of time the activity remains in each tissue - residence time (T)
- Amount of energy emitted by the activity (Δ)
- Fraction of the energy emitted which is deposited in the organ for which the dose is to be calculated - specific absorbed fraction, ($\Phi(r_k \leftarrow r_h)$)
- Anatomical or physical conditions which may modify the distribution radically

MIRD Dose Equation

$$\overline{D}(r_k \longleftarrow r_h) = \tilde{A}_h \, S(r_k \longleftarrow r_h)$$



Target Organ

Source Organ

MIRD Dose Equation

$$\overline{D}(r_k \longleftarrow r_h) = \widetilde{A}_h \, S(r_k \longleftarrow r_h)$$

Component Definition:

The Mean Absorbed Dose Expressed in Rads to a Target Organ r_k from a Source Organ r_h wherein a Radionuclide is Uniformly Distributed

MIRD Dose Equation

$$\overline{D}(r_k \longleftarrow r_h) = \tilde{A}_h \, S(r_k \longleftarrow r_h)$$

Component Definition:

The Cumulated Activity in μCi-h in the Source Organ r_h

μCi-h = d/t * t = d
this is just total disintegrations

MIRD Dose Equation

$$\overline{D}(r_k \longleftarrow r_h) = \tilde{A}_h \, S(r_k \longleftarrow r_h)$$

Component Definition:

The Mean Absorbed Dose per Unit Cumulated Activity in rad/(μCi-h)

rad/μCi-h = rad/d
this is just the dose produced by each disintegration

MIRD Dose Equation

$$\overline{D}(r_k \leftarrow r_h) = \tilde{A}_h \, S(r_k \leftarrow r_h)$$

Component Definition:

The Mean Absorbed Dose Expressed in Rads to a Target Organ r_k from a Source Organ r_h Wherein a Radionuclide is Uniformly Distributed

Component Definition:

The Cumulated Activity in μCi-h in the Source Organ r_h

Component Definition:

The Mean Absorbed Dose per Unit Cumulated Activity in rad/(μCi-h)

$$\text{dose deposited} = \text{total disintegrations} * \frac{\text{dose deposited}}{\text{disintegration}}$$

MIRD Dose Equation

$$\overline{D}(r_k \longleftarrow r_h) = \widetilde{A}_h \, S(r_k \longleftarrow r_h)$$

$$S(r_k \longleftarrow r_h) = \sum_i \Delta_i \, \Phi_i \, (r_k \longleftarrow r_h)$$

(Dose Factor)

MIRD Dose Factor

$$S(r_k \longleftarrow r_h) = \sum_i \Delta_i \, \Phi_i \, (r_k \longleftarrow r_h)$$

Component Definition:

The Mean Absorbed Dose per Unit Cumulated Activity in rad/(μCi-h)

MIRD Dose Factor

$$S(r_k \longleftarrow r_h) = \sum_i \Delta_i \, \Phi_i \, (r_k \longleftarrow r_h)$$

Component Definition:

The Mean Energy Emitted per Unit Cumulated Activity (g-rad)/(μCi-h)

What is a g-rad/μCi-h ?

rad = energy/gram
energy = rad * gram = g-rad
μCi-h = d
Δ is just energy emitted/disintegration

MIRD Dose Factor

$$S(r_k \longleftarrow r_h) = \sum_i \Delta_i \, \Phi_i \, (r_k \longleftarrow r_h)$$

Component Definition:

The Specific Absorbed Fraction of Energy in Target Organ r_k for Particles i Emitted in Source Organ r_h in g^{-1}

g^{-1} = 1/gram = rad/energy

Φ = the fraction of the energy emitted which is absorbed per unit mass

$$\Phi = \frac{\dfrac{\text{energy deposited}}{\text{energy emitted}}}{\text{mass}} = \frac{\text{energy deposited}}{\text{energy emitted - mass}} = \frac{\text{absorbed dose}}{\text{energy emitted}}$$

MIRD Dose Factor

$$S(r_k \leftarrow r_h) = \sum_i \Delta_i \, \Phi_i \, (r_k \leftarrow r_h)$$

Component Definition:

The Mean Absorbed Dose per Unit Cumulated Activity in rad/(μCi-h)

Component Definition:

The Mean Energy Emitted per Unit Cumulated Activity (g-rad)/(μCi-h)

Component Definition:

The Specific Absorbed Fraction of Energy in Target Organ r_k for Particles i Emitted in Source Organ r_h in g^{-1}

$$\frac{\text{absorbed dose}}{\text{disintegration}} = \frac{\text{energy emitted}}{\text{disintegration}} * \frac{\text{absorbed dose}}{\text{energy emitted}}$$

Sample Problem

Calculate the Mean Dose to the Liver from a 10 μCi Intravenous Injection of ^{99m}Tc Labeled Compound that Localizes Uniformly and Completely in the Liver.

The Effective Half Life of this ^{99m}Tc Labeled Compound is 6.1 hours.

Solution to Sample Problem

Calculation of $\tilde{A}_{LI}$

The Cumulated Activity, $\tilde{A}_{LI}$, is the product of the Mean Lifetime of the Compound within the Organ and the Activity Residing in the Organ

$$\tilde{A}_{LI} = \overbrace{1.44 \times 6.1\ h}^{\text{Mean Lifetime}} \times \overbrace{10\ \mu Ci}^{\text{Activity}}$$

$$\tilde{A}_{LI} = 87.9\ \mu Ci\text{-}h$$

Look Familiar?
$A = T_m A_o$

MIRD Table

S, MEAN DOSE PER UNIT CUMULATED ACTIVITY, (RAD/μCI-H): TECHNETIUM-99M

Target organs	Source organs: Adrenals	Bladder contents	Intestinal tract: Stomach contents	SI contents	ULI contents	LLI contents	Kidneys	Liver	Lungs	Other tissue (muscle)
Adrenals	3.1E-03	1.5E-07	2.7E-06	1.0E-06	9.1E-07	3.6E-07	1.1E-05	4.5E-06	2.7E-06	1.4E-06
Bladder wall	1.3E-07	1.6E-04	2.7E-07	2.6E-06	2.2E-06	6.9E-06	2.8E-07	1.6E-07	3.6E-08	1.8E-06
Bone (total)	2.0E-06	9.2E-07	9.0E-07	1.3E-06	1.1E-06	1.6E-06	1.4E-06	1.1E-06	1.5E-06	9.8E-07
G.I. (stomach wall)	2.9E-06	2.7E-07	1.3E-04	3.7E-06	3.8E-06	1.8E-06	3.6E-06	1.9E-06	1.8E-06	1.3E-06
G.I. (SI)	8.3E-07	3.0E-06	2.7E-06	7.8E-05	1.7E-05	9.4E-06	2.9E-06	1.6E-06	1.9E-07	1.5E-06
G.I. (ULI wall)	9.3E-07	2.2E-06	3.5E-06	2.4E-05	1.3E-04	4.2E-06	2.9E-06	2.5E-06	2.2E-07	1.6E-06
G.I. (LLI wall)	2.2E-07	7.4E-06	1.2E-06	7.3E-06	3.2E-06	1.9E-04	7.2E-07	2.3E-07	7.1E-08	1.7E-06
Kidneys	1.1E-05	2.6E-07	3.5E-06	3.2E-06	2.8E-06	8.6E-07	1.9E-04	3.9E-06	8.4E-07	1.3E-06
Liver	4.9E-06	1.7E-07	2.0E-06	1.8E-06	2.6E-06	2.5E-07	3.9E-06	4.6E-05	2.5E-06	1.1E-06
Lungs	2.4E-06	2.4E-08	1.7E-06	2.2E-07	2.6E-07	7.9E-08	8.5E-07	2.5E-06	5.2E-05	1.3E-06
Marrow (red)	3.6E-06	2.2E-06	1.6E-06	4.3E-06	3.7E-06	5.1E-06	3.8E-06	1.6E-06	1.9E-06	2.0E-06
Other tissues (muscle)	1.4E-06	1.8E-06	1.4E-06	1.5E-06	1.5E-06	1.7E-06	1.3E-06	1.1E-06	1.3E-06	2.7E-06
Ovaries	6.1E-07	7.3E-06	5.0E-07	1.1E-05	1.2E-05	1.8E-05	1.1E-06	4.5E-07	9.4E-08	2.0E-06
Pancreas	9.0E-06	2.3E-07	1.8E-05	2.1E-06	2.3E-06	7.4E-07	6.6E-06	4.2E-06	2.6E-06	1.8E-06
Skin	5.1E-07	5.5E-07	4.4E-07	4.1E-07	4.1E-07	4.8E-07	5.3E-07	4.9E-07	5.3E-07	7.2E-07
Spleen	6.3E-06	6.6E-07	1.0E-05	1.5E-06	1.4E-06	8.0E-07	8.6E-06	9.2E-07	2.3E-06	1.4E-06
Testes	3.2E-08	4.7E-06	5.1E-08	3.1E-07	2.7E-07	1.8E-06	8.8E-08	6.2E-08	7.9E-09	1.1E-06
Thyroid	1.3E-07	2.1E-09	8.7E-08	1.5E-08	1.6E-08	5.4E-09	4.8E-08	1.5E-07	9.2E-07	1.3E-06
Uterus (nongravida)	1.1E-06	1.6E-05	7.7E-07	9.6E-06	5.4E-06	7.1E-06	9.4E-07	3.9E-07	8.2E-08	2.3E-06
Total body	2.2E-06	1.9E-06	1.9E-06	2.4E-06	2.2E-06	2.3E-06	2.2E-06	2.2E-06	2.0E-06	1.9E-06

(see page MIRD-30)

Solution to Sample Problem

$\bar{D}(LI \leftarrow LI) = \tilde{A}_{LI}\, S(LI \leftarrow LI)$

where $\tilde{A}_{LI} = 1.44 \times 6.1h \times 10\ \mu Ci$

$\tilde{A}_{LI} = 87.9\ \mu Ci\text{-}h$

$S(r_k \leftarrow r_h) = 4.6E\text{-}05\ rad/\mu Ci\text{-}h$

$D(LI \leftarrow LI) = 87.9\ \mu Ci\text{-}h \times 4.6E\text{-}05\ rad/\mu Ci\text{-}h = 0.00404\ rad$

$D(LI \leftarrow LI) = 4.04\ mrad$

Summary

$$D(t \leftarrow s) = \tilde{A} \times S$$

where:

$\tilde{A}$ = μCi-hr = initial activity x the mean life = disintegrations

$$S = \frac{\text{rad}}{\mu\text{Ci-hr}} = \frac{\text{rad}}{\text{disintegration}}$$ (given in MIRD tables)

Activity

The activity remaining is given by: $A = A_o e^{-\frac{0.693\,t}{T_e}}$

When $t = 0$, $A = A_o$ and when $t = \infty$, $A = 0$

The activity which has already decayed (i.e., disintegrated) is just the activity we started with minus that which remains:

$$A = A_o - A_o e^{-\frac{0.693\,t}{T_e}} = A_o \left(1 - e^{-\frac{0.693\,t}{T_e}}\right)$$

When $t = 0$, $A = 0$ and when $t = \infty$, $A = A_o$

Mean Life

$$\tilde{A} = 1.44 \times T_e \times A_o \qquad \text{for } t = \infty$$

or

$$\tilde{A}_t = 1.44 \times T_e \times A_o \left(1 - e^{-\frac{0.693\,t}{T_e}}\right)$$

If you want to determine the dose while the activity decays from A_o to some value $\tilde{A}_t$ at time t

where $1.44 \times T_e = T_m$

MIRD

Revised MIRD Tables

http://www.internaldosimetry.com/freedosestimates/adult/index.html

http://www.internaldosimetry.com/freedosestimates/pediatric/index.html

Dose Distribution

Tissue	Absorbed Dose (rad/mCi injected)		
	Normal liver	Early to intermediate diffuse parenchymal liver disease	Intermediate to advanced diffuse parenchymal liver disease
Liver	39	24	19
Ovaries	0.1	0.3	0.5
Red Marrow	2.7	4.5	8.9
Spleen	12	38	56
Testes	0.04	0.1	0.2
Total Body	1.4	1.4	1.4

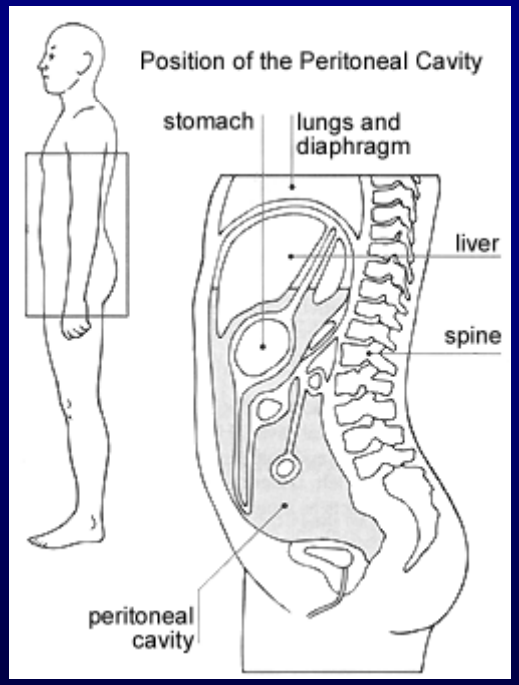
Radiopharmaceutical Package Insert

PHOSPHOCOL™ P 32

Table III. Radiation Doses

Surface/Organ		Pleural	Peritoneal	Prostate
% Retention Area/wt		90 4000 cm²	90 5000 cm²	100 16 g
Depth in tissue (cm)	Dose rate (rad/hr)*	Tissue dose (rads/20 mCi)		
0.004	10.2	23000	18000	910000
0.008	8.58	19000	15000	
0.012	7.61	17000	14000	
0.016	6.91	15000	12000	
0.020	6.36	14000	11000	
0.10	2.41	5400	4300	
0.20	0.94	2100	1700	

* For surface deposition of one μCi/cm²



Radiopharmaceutical Package Insert

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Depth in tissue (cm)	Dose rate (rad/hr)*	Tissue dose (rads/20 mCi)		
0.004	10.2	23000	18000	910000
0.008	8.58	19000	15000	
0.012	7.61	17000	14000	
0.016	6.91	15000	12000	
0.020	6.36	14000	11000	
0.10	2.41	5400	4300	
0.20	0.94	2100	1700	

* For surface deposition of one μCi/cm²

$$\frac{18{,}000\ \text{rad}}{\dfrac{20{,}000\ \mu\text{Ci} \times 0.9}{5{,}000\ \text{cm}^2}} = \frac{5{,}000\ \text{rad}}{\dfrac{\mu\text{Ci}}{\text{cm}^2}}$$

$$\frac{\left(\dfrac{5{,}000\ \text{rad}}{\dfrac{\mu\text{Ci}}{\text{cm}^2}}\right)}{\left(\dfrac{10.2\ \dfrac{\text{rad}}{\text{hr}}}{\dfrac{\mu\text{Ci}}{\text{cm}^2}}\right)} = 490\ \text{hr}$$

Radiopharmaceutical Package Insert

From the previous slide

$$\frac{\left(\dfrac{5{,}000\ \text{rad}}{\dfrac{\mu\text{Ci}}{\text{cm}^2}}\right)}{\left(\dfrac{10.2\ \dfrac{\text{rad}}{\text{hr}}}{\dfrac{\mu\text{Ci}}{\text{cm}^2}}\right)} = 490\ \text{hr}$$

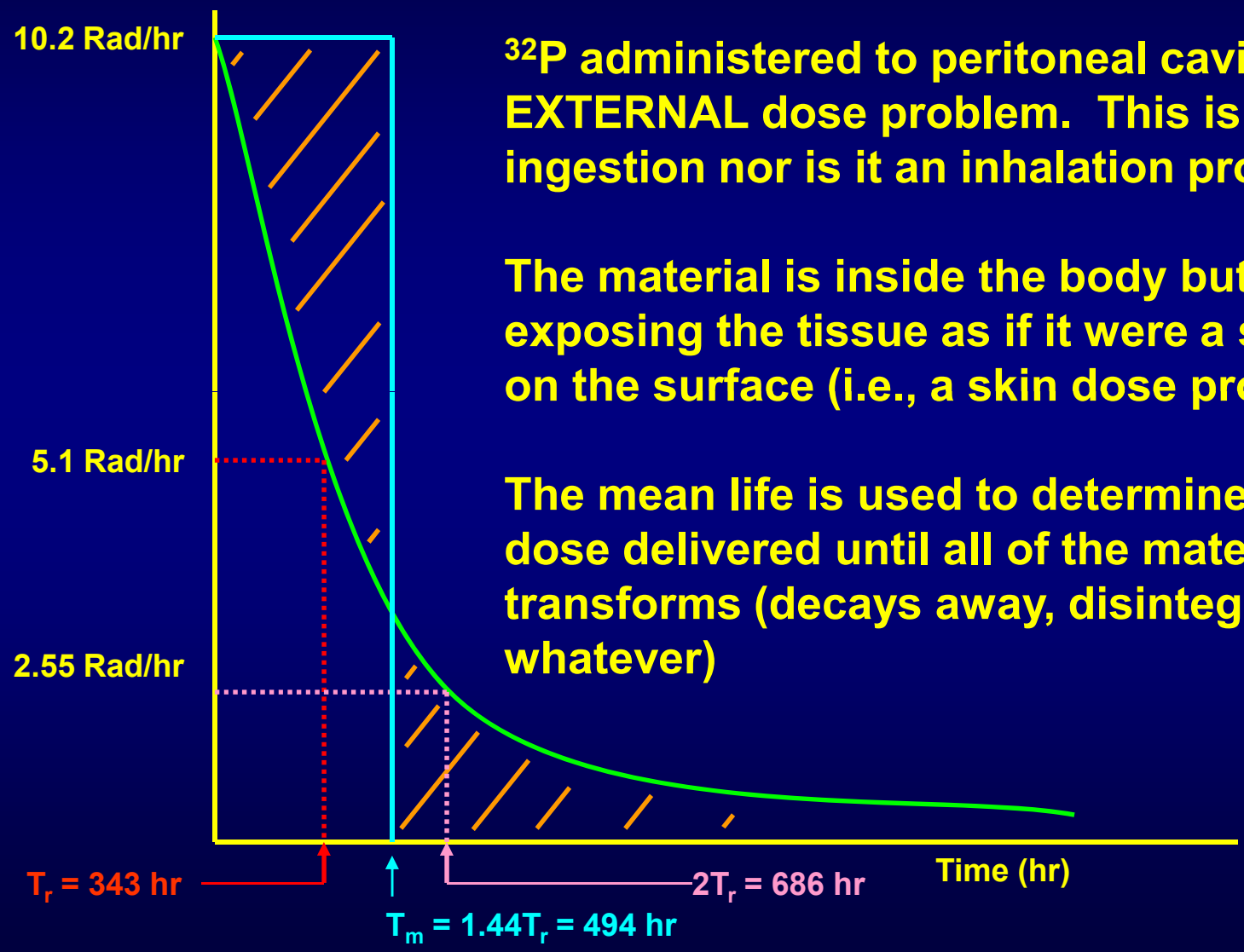
For ^{32}P: $T_r = 14.3\ d = 343\ hr$

No biological clearance so $T_b = \infty$

If $T_r = 343\ hr$ and $T_b = \infty$ then $T_e = 343\ hr$

$T_m = 1.44 \times 343\ hr = 494\ hr$

Mean Life



^{32}P administered to peritoneal cavity is an EXTERNAL dose problem. This is NOT an ingestion nor is it an inhalation problem.

The material is inside the body but it is exposing the tissue as if it were a source on the surface (i.e., a skin dose problem).

The mean life is used to determine the total dose delivered until all of the material transforms (decays away, disintegrates, whatever)

Nuclear Medicine Accident

Phoenix AZ (89)

Therapeutic dose was given instead of a diagnostic dose

YOUNG MOTHER'S STORY

"A Medical Error Could Cost Me My Life"

J. PETER MORTIMER

"It should have been a routine thyroid exam but, by mistake, I was given such a high dose of radiation that my thyroid was destroyed. I could get cancer. And I might have already contaminated my kids!"

BY DEBI LANE
TEMPE, ARIZONA

Last October, my biggest medical worry was a persistent, annoying tightening in my throat. When my doctor ordered a diagnostic thyroid scan, which would be performed at nearby Desert Samaritan Medical Center, I was relieved. He had explained that the thyroid gland is located near the windpipe, and that a simple test would reveal whether mine was "retro-sternal," meaning that it had dropped to an improper—and uncomfortable—position in my throat. I felt sure that if there was any problem, it could be remedied. Little did I know that, because of the test, I would soon fear for my life!

The morning I was scheduled to go to Desert Samaritan, November 1, was like most days in my house—hectic. My daughter Amy, then 16, left for school first; seven-year-old Cassie and eight-year-old Micah were bickering; four-year-old Kail was working his way through a bowl of cereal, and Clair, my husband, was reading the paper while I got backpacks and lunches ready. Soon everyone was headed out the door. I dropped Kail off at his grandparents' and drove to the hospital.

I expected the test to go smoothly. My doctor had already explained that the thyroid controls the way the body converts food into energy, and that it also absorbs iodine. In order to pinpoint the gland's location, I'd be given a tiny amount of radioactive iodine to swallow; then technicians would use a scanner—a radiation detector—to get a diagnostic image.

After I'd filled out the usual hospital forms, a technician led me through a large examining room containing the scanning equipment, and into a kitchenette. What I saw there made me a little worried. Lying on the counter were a lead cup, a straw, a syringe and rubber gloves. The technician put on the gloves, emptied the contents of the syringe into the cup and said, "Drink this." I nervously joked, "Is this going to make me glow for forty-thousand years?" The technician didn't smile. He sternly lifted the straw, as if to say, "Be quiet and drink." Like a good patient, I did.

Then the technician told me that the actual scan would be performed the next day. We set up an appointment, and I was dismissed. That afternoon, I picked up Kail, ran various errands, then picked up Cassie and Micah from after-school activities.

Clair had a late meeting that night, so we had dinner without him. After dinner, Kail started to choke on a piece of candy. Although he was soon fine, he was upset from the scare, so I let him sleep in our bed, where he snuggled close to me all night. These simple, everyday forms of caring for my family would come back to haunt me.

The next day, Clair and Kail came to the hospital with me. They waited in the hallway while I lay on a table in the examining room I'd passed through the day before, with the scanning camera centered over my neck. Suddenly, the two technicians started rushing back and forth, whispering to each other. Then one of them abruptly turned off the machine and said, "Have a seat outside."

I was terrified. As I waited, I saw two men rush into the examining room. Then the technician came back out and said the doctor needed to see me. I asked whether Clair could come, too. "No" was his abrupt answer. Then he led me into the kitchenette.

The two men I had just seen walked in and introduced themselves. One was the hospital's chief radiation safety officer, Martin Hilger, and the other was Dr. Richard Petersen, the radiologist. Dr. Petersen asked how he could contact my husband. When I said that Clair was right outside, he sent the technician back to get him—but not my son. Now I was sure they were going to tell us that I had a terrible, incurable disease. I felt sick to my stomach.

"Mrs. Lane," Dr. Petersen said, "there is really no easy way to say this . . . " I bent over and put my head between my legs and took a couple of breaths. "There's been a terrible mistake," the doctor continued: I had received the wrong amount of radiation. "Your thyroid has been destroyed," he said.

Through a fog, I heard Clair ask, "What exactly does this mean?"

"It will take about four weeks for her thyroid to die off," Dr. Petersen told Clair. "She'll have to take a synthetic hormone for the rest of her life." Then he added, unconvincingly, "It's an easy problem to manage." We soon learned we had far worse news to face. A woman named Karen Salmon, the hospital's chief nuclear medicine technologist, entered the room and explained that the amount *(continued)*

Problem

What is the whole body dose to a patient who is administered 30 millicuries of ^{99m}Tc?

Problem

Does MIRD account for the exposure of an organ when there is no radioactive material deposited in that organ?

Problem

Given an accumulated activity of ^{125}I and an identical accumulated activity of ^{131}I in an individual's thyroid, compare the dose to the testes from these two radionuclides. How would you explain any differences?

END OF MIRD

EMBRYO/FETAL DOSE

Objectives

After studying the material contained in this section and/or presented during a session, you should be able to:

- **calculate the embryo/fetal dose for an internal deposition using the simple approach**
- **calculate the embryo/fetal dose for an internal deposition using the realistic approach**

Source of E/F Dose

The dose to the embryo/fetus can originate from two sources:

- either a photon source outside the body of the pregnant woman which exposes both the woman and the E/F or
- radioactive material inhaled or ingested by the woman

We typically assume that for an external source, whatever exposure the woman receives is also received by the E/F. Although this may not be completely accurate it is conservative.

E/F Dose from Maternal Intakes

The E/F dose from an intake of radioactive material by the woman can also be divided into two sources:

- material located in the mother exposing the E/F remotely (must be photons to reach the E/F) and
- material which enters the bloodstream and transfers into the E/F across the placenta.

Regulatory Guide 8.36
"Radiation Dose to the Embryo/Fetus"

Appendix B - provides the fraction of INGESTED activity which ends up in the blood of the woman from the small intestine

Appendix A* - provides the dose to the uterus from activity located in the blood of the woman.

Appendix C* - provides the embryo/fetal dose derived from the activity in the blood of the woman as a function of gestation period

* see next slide

Regulatory Guide 8.36

* NOTE: some of the values in Appendix A and all the values in Appendix C were extracted from NUREG/CR-5631, Rev 1. The NUREG has since been revised (Rev 2). Rev 1 provided dose factors relative to the amount of radioactive material in the woman's blood while Rev 2 provides dose factors relative to the material in the woman's blood or the intake (depending on the specific Table).

Activity in Woman's Blood

Ingestion - the activity in the woman's blood is just the intake times the f_1 fraction from Reg Guide 8.36 Appendix B.

Inhalation - the activity in the woman's blood is the intake times the ICRP-30 lung model deposition fractions (next slide) times the f_1 fraction from Appendix B.

Injected - the activity in the woman's blood is the amount injected.

Inhalation

Class D: $A_D = I \times (0.48 + 0.15 \times f_1)$

Class W: $A_W = I \times (0.12 + 0.51 \times f_1)$

Class Y: $A_Y = I \times (0.05 + 0.58 \times f_1)$

A is the amount of the material originally inhaled (intake) that ends up in the blood (depends on the class of the material)

I is the intake

f_1 is the fraction absorbed from the GI tract to the blood (RG8.36 Appendix B)

see page MISC-62

Class D: $A_D = I \times (0.48 + 0.15 \times f_1)$

Compartments Clearing to Bodily Fluids	Fraction in Compartment (D x F)
a	0.3 x 0.5 = 0.15
c	0.08 x 0.95 = 0.076
e	0.25 x 0.8 = 0.2
h	0.25 x 0.2 = 0.05
Total	0.476
Compartments Clearing to GI	**Fraction in Compartment (D x F)**
b	0.3 x 0.5 = 0.15
d	0.08 x 0.05 = 0.004
Total	0.154

Class W: $A_W = I \times (0.12 + 0.51 \times f_1)$

Compartments Clearing to Bodily Fluids	Fraction in Compartment (D x F)
a c e&h	0.3 x 0.1 = 0.03 0.08 x 0.5 = 0.04 0.25 x 0.2 = 0.05
Total	0.12
Compartments Clearing to GI	**Fraction in Compartment (D x F)**
b d f&g	0.3 x 0.9 = 0.27 0.08 x 0.5 = 0.04 0.25 x 0.8 = 0.2
Total	0.51

Class Y: $A_Y = I \times (0.05 + 0.58 \times f_1)$

Compartments Clearing to Bodily Fluids	Fraction in Compartment (D x F)
a	0.3 x 0.01 = 0.003
c	0.08 x 0.01 = 0.0009
e	0.25 x 0.05 = 0.0125
h	0.25 x 0.15 x 0.9 = 0.03375
Total	0.05

Compartments Clearing to GI	Fraction in Compartment (D x F)
b	0.3 x 0.99 = 0.297
d	0.08 x 0.99 = 0.0792
f&g	0.25 x 0.8 = 0.2
Total	0.576

NUREG/CR-5631, Rev 2, Appendices

Appendix A - tables indicating the fraction of the activity injected into the woman's blood which is deposited in the embryo/fetus* (depends on time of gestation during which injection occurs)

*** Caution: read the Table headings carefully because some of the tables provide the fraction deposited in the fetal thyroid and still others provide the fraction deposited in the woman's body or the woman's liver or thyroid rather than the embryo/fetus after injection of the activity into her blood**

Sample Table from Appendix A

Table A21b. Fraction of activity deposited in the embryo/fetus* and fractions retained at start of subsequent 30-day periods after injection of 111In into the maternal transfer compartment (blood)

	Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
1	0	4.0E-11	5.9E-14	3.8E-17	2.5E-20	1.6E-23	1.0E-26	6.6E-30	4.3E-33	2.8E-36	----------
2	30		2.0E-06	3.2E-09	2.1E-12	1.3E-15	8.6E-19	5.5E-22	3.6E-25	2.3E-28	1.5E-31
3	60			6.4E-05	1.6E-07	1.0E-10	6.7E-14	4.3E-17	2.8E-20	1.8E-23	1.2E-26
4	90				6.0E-04	4.7E-06	3.1E-09	2.0E-12	1.3E-15	8.3E-19	5.3E-22
5	120					1.6E-03	1.0E-05	6.7E-09	4.4E-12	2.8E-15	1.8E-18
6	150						3.0E-03	1.8E-05	1.2E-08	7.5E-12	4.9E-15
7	180							5.1E-03	2.8E-05	1.8E-08	1.2E-11
8	210								7.9E-03	4.0E-05	2.6E-08
9	240									1.1E-02	4.9E-05
	270										1.2E-02
		1	2	3	4	5	6	7	8	9	

* some tables indicate fetal thyroid (A24d) or maternal body (A6a) or maternal liver (A9b) or maternal thyroid (A24b) instead of embryo/fetus

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Appendix B - tables indicating the radiation dose rates and doses delivered to the embryo/fetus (or fetal thyroid) for 1 μCi injected into the woman's blood (depends on time of gestation during which injection occurs)

Sample Table from Appendix B

Table B6. Radiation dose rates and doses to the embryo/fetus from 1 µCi of 55Fe injected into the maternal transfer compartment (blood)

	Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days)									Cumulated dose
		0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
1	0	1.6E-04	1.5E-04	2.7E-12	2.7E-12	1.6E-12	7.0E-13	6.8E-13	5.2E-13	3.7E-13	3.1E-04
2	30		1.8E-04	1.2E-07	1.2E-07	7.3E-08	3.1E-08	3.0E-08	2.3E-08	1.7E-08	1.8E-04
3	60			3.6E-06	3.6E-06	2.2E-06	9.4E-07	9.3E-07	7.0E-07	5.0E-07	1.2E-05
4	90				6.9E-05	4.4E-05	1.9E-05	1.8E-05	1.4E-05	1.0E-05	1.7E-04
5	120					1.6E-04	7.4E-05	7.2E-05	5.5E-05	3.9E-05	4.0E-04
6	150						1.6E-04	1.6E-04	1.2E-04	8.8E-05	5.3E-04
7	180							1.9E-04	1.5E-04	1.1E-04	4.6E-04
8	210								1.3E-04	9.4E-05	2.2E-04
9	240									1.3E-04	1.3E-04
		1	2	3	4	5	6	7	8	9	all 9

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Appendix C - same as Appendix B except that these tables are for radiopharmaceuticals commonly used in Nuclear Medicine rather than generic radionuclides

Sample Table from Appendix C

Table C3. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 60Co as vitamin B-12 injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days)									Cumulated dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	1.5E-02	1.4E-02	1.0E-02	9.7E-03	9.8E-03	9.8E-03	9.2E-03	8.7E-03	8.3E-03	9.5E-02
30		1.5E-02	1.1E-02	1.0E-02	1.0E-02	1.0E-02	9.7E-03	9.2E-03	8.7E-03	8.5E-02
60			1.2E-02	1.1E-02	1.1E-02	1.1E-02	1.0E-02	9.7E-03	9.2E-03	7.3E-02
90				1.2E-02	1.1E-02	1.1E-02	1.1E-02	1.0E-02	9.7E-03	6.5E-02
120					1.2E-02	1.2E-02	1.1E-02	1.1E-02	1.0E-02	5.7E-02
150						1.3E-02	1.2E-02	1.1E-02	1.1E-02	4.7E-02
180							1.3E-02	1.2E-02	1.1E-02	3.6E-02
210								1.3E-02	1.2E-02	2.5E-02
240									1.3E-02	1.3E-02

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Appendix D

- tables indicating the radiation doses delivered to the embryo/fetus as a result of chronic intake of radionuclides (Table D1 covers ingestion and Table D2 covers inhalation)

- also, tables indicating the radiation doses delivered to the embryo/fetus as a result of pre-existing radionuclides in the woman (i.e., radionuclides taken into her body before conception which are still there) (Table D3 covers ingestion and Table D4 covers inhalation)

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- also, tables indicating simple radiation dose factors for chronic intakes and pre-existing radionuclides (Table D5 covers ingestion and Table D6 covers inhalation)

- also, tables indicating comparisons between uterine doses and embryo/fetal doses from chronic intakes (Table D7 covers ingestion and Table D8 covers inhalation)

Sample Table from Appendix D

Table D1. Cumulated radiation doses to the embryo/fetus from chronic maternal ingestion of common chemical or physical forms of radiologically important radionuclides.

Nuclide	Compound	f_1	ALI (µCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (µCi)
H-3	Water	1E+00	8E+04	5E+00	1E-02	8E+02
C-14	Organic	1E+00	2E+03	7E-01	7E-02	1E+02
P-32	Phosphates	8E-01	6E+02	4E+00	1E-02	8E+00
Cr-51	All	1E-01	4E+04	1E+00	5E-02	2E+03
Fe-55	All	1E-01	9E+03	2E-01	2E-01	2E+03
Fe-59	All	1E-01	8E+02	2E+00	3E-02	2E+01
Co-58	Inorganic	5E-02	2E+03	3E-01	2E-01	3E+02
Co-60	Inorganic	5E-02	5E+02	3E-01	2E-01	8E+01
Zn-65	All	5E-01	4E+02	3E+00	2E-02	7E+00
Rb-86	All	1E+00	5E+02	5E+01	1E-03	5E-01
			a		b	a x b

Note: the activity values are approximate due to round-off errors

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Appendix E - tables indicating radiation doses delivered to the uterus as a result of acute intake of radionuclides (Table E1 covers ingestion and Table E2 covers inhalation)

Sample Table from Appendix E

Table E2. Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (µCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (µCi)
U-235	D	1E+00	9E-02	6E-01	6E-01
	W	8E-01	2E-02	2E+00	2E+00
	Y	4E-02	4E-04	1E+02	5E+00
U-236	D	1E+00	9E-02	6E-01	6E-01
	W	8E-01	2E-02	2E+00	2E+00
	Y	4E-02	4E-04	1E+02	5E+00
U-237	D	3E+03	4E-01	1E-01	3E+02
	W	2E+03	3E-01	2E-01	4E+02
	Y	2E+03	3E-01	2E-01	4E+02
U-238	D	1E+00	8E-02	6E-01	6E-01
	W	8E-01	2E-02	3E+00	2E+00
	Y	4E-02	4E-04	1E+02	6E+00

Simple Calculation Method

Dose = Intake x NUREG/CR-5631 Table D or E Dose Factors

(D for chronic and E for acute)

Sample from Table E1: Radiation doses to the uterus from ingestion

Nuclide	ALI (µCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (µCi)
Sr-85	3E+03	4E+00	1E-02	4E+01
Sr-85M	2E+05	3E+00	2E-02	3E+03
Sr-89	6E+02	5E-01	9E-02	6E+01
Sr-90	3E+01	2E-01	3E-01	9E+00

Dose to the uterus per µCi intake for Sr-90 would be:

(2E-01 rem/ALI)/(3E+01 µCi/ALI) = 0.0066 rem/µCi = 6.6 mrem/µCi

(50 mrem)/(9 µCi) = 5.5 mrem/µCi

Sample Simple Calculation Method

Assume intake by ingestion of 100 μCi ^{89}Sr at beginning of 3rd month of pregnancy. Calculate the total dose to the embryo/fetus for the pregnancy.

For the Simple Calculation Method, the time that the intake occurred during the pregnancy is irrelevant. The Tables in Appendices D and E do not specify any time during the pregnancy.

Sample Simple Calculation Method

From NUREG/CR-5631 Appendix E Table E1 (previous slide), the dose factor for ^{89}Sr is 0.5 rem per ALI which is 600 μCi. To determine the dose to the uterus from 100 μCi, take a simple ratio:

$$\frac{0.5 \text{ rem}}{600\ \mu\text{Ci}} = \frac{\text{dose}}{100\ \mu\text{Ci}};$$

$$\text{Dose} = \frac{100\ \mu\text{Ci}}{600\ \mu\text{Ci}} \times 0.5 \text{ rem} = 0.08 \text{ rem}$$

Realistic Calculation Method

The "realistic" method accounts for the time period during the pregnancy when the intake occurs.

Determine activity in blood (using the methods described earlier if the material is ingested, inhaled or injected)

Dose = Activity in Blood x NUREG/CR-5631 Tables B or C

Sample Realistic Calculation Method

Assume intake by inhalation of 100 μCi ^{55}Fe class D at beginning of 3rd month of pregnancy. Calculate the total dose to the embryo/fetus.

Equation for determining how much of the inhaled material gets to the blood is $A_D = I \times (0.48 + 0.15 \times f_1)$

(f_1 for Fe obtained from Reg Guide 8.36 Appendix B)

$A_D = 100\ \mu Ci \times (0.48 + 0.15 \times 0.1) = 100\ \mu Ci \times 0.495 = 50\ \mu Ci$

From NUREG/CR-5631 Appendix B Table B6, the dose factor for ^{55}Fe in the woman's blood at beginning of 3rd month is …….. (see next slide)

Sample Table from Appendix B

Table B6. Radiation dose rates and doses to the embryo/fetus from 1 µCi of 55Fe injected into the maternal transfer compartment (blood)

	Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days)									Cumulated dose
		0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
1	0	1.6E-04	1.5E-04	2.7E-12	2.7E-12	1.6E-12	7.0E-13	6.8E-13	5.2E-13	3.7E-13	3.1E-04
2	30		1.8E-04	1.2E-07	1.2E-07	7.3E-08	3.1E-08	3.0E-08	2.3E-08	1.7E-08	1.8E-04
3	60			3.6E-06	3.6E-06	2.2E-06	9.4E-07	9.3E-07	7.0E-07	5.0E-07	1.2E-05
4	90				6.9E-05	4.4E-05	1.9E-05	1.8E-05	1.4E-05	1.0E-05	1.7E-04
5	120					1.6E-04	7.4E-05	7.2E-05	5.5E-05	3.9E-05	4.0E-04
6	150						1.6E-04	1.6E-04	1.2E-04	8.8E-05	5.3E-04
7	180							1.9E-04	1.5E-04	1.1E-04	4.6E-04
8	210								1.3E-04	9.4E-05	2.2E-04
9	240									1.3E-04	1.3E-04
		1	2	3	4	5	6	7	8	9	all 9

Sample Realistic Calculation Method

From NUREG/CR-5631 Appendix B Table B6, the dose factor for ^{55}Fe in the woman's blood at beginning of 3rd month is 1.2E-5 rad/μCi in the blood

Remember that the activity transferred to the blood from the inhalation was:

A_D = 100 μCi x (0.48 + 0.15 x 0.1) = 100 μCi x 0.495 = 50 μCi

So, the total dose to the embryo/fetus is:

1.2E-5 rad/μCi x 50 μCi = 0.0006 rad = 0.6 mrad

Sample Realistic Calculation Method

What if we wanted to know the dose that the embryo/fetus received during the 7th month from the situation just described?

From the same table, the dose factor for the 7th month when ^{55}Fe is introduced into the woman's blood at the beginning of the 3rd month is …… (see next slide)

Sample Table from Appendix B

Table B6. Radiation dose rates and doses to the embryo/fetus from 1 µCi of 55Fe injected into the maternal transfer compartment (blood)

	Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days)									Cumulated dose
		0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
1	0	1.6E-04	1.5E-04	2.7E-12	2.7E-12	1.6E-12	7.0E-13	6.8E-13	5.2E-13	3.7E-13	3.1E-04
2	30		1.8E-04	1.2E-07	1.2E-07	7.3E-08	3.1E-08	3.0E-08	2.3E-08	1.7E-08	1.8E-04
3	60			3.6E-06	3.6E-06	2.2E-06	9.4E-07	9.3E-07	7.0E-07	5.0E-07	1.2E-05
4	90				6.9E-05	4.4E-05	1.9E-05	1.8E-05	1.4E-05	1.0E-05	1.7E-04
5	120					1.6E-04	7.4E-05	7.2E-05	5.5E-05	3.9E-05	4.0E-04
6	150						1.6E-04	1.6E-04	1.2E-04	8.8E-05	5.3E-04
7	180							1.9E-04	1.5E-04	1.1E-04	4.6E-04
8	210								1.3E-04	9.4E-05	2.2E-04
9	240									1.3E-04	1.3E-04
		1	2	3	4	5	6	7	8	9	all 9

Sample Realistic Calculation Method

From the table, the dose factor in the 7th month for ^{55}Fe introduced into the woman's blood at the beginning of the 3rd month is is 9.3E-7 rad/μCi

Since the activity transferred to the blood from the inhalation was 50 μCi

So, the dose that the embryo/fetus received only during the 7th month is:

9.3E-7 rad/μCi x 50 μCi = 0.0000465 rad = 0.05 mrad

Postnatal Dose

Table 4. Radiation doses (rem) from radionuclides, corresponding to Effective Dose or Effective Dose Equivalent[(a)]. These present radiation received during postnatal life from residual radioactivity at birth after injection of 1 μCi of radionuclides into the maternal transfer compartment at representative stages of pregnancy (this dose is not relevant for NRC)

Postnatal Dose

Gestational Days at Introduction	^{224}Ra	^{226}Ra	^{237}Np	^{238}Pu	^{239}Pu	^{241}Am
0	2.4E-27	6.4E-05	7.8E-11	2.2E-10	2.3E-10	1.3E-10
30	2.1E-24	1.9E-04	8.4E-04	3.0E-03	3.1E-03	1.2E-03
60	1.7E-21	5.2E-04	1.8E-02	8.6E-02	9.0E-02	2.0E-02
90	4.1E-18	4.6E-03	1.5E-01	8.9E-01	9.3E-01	1.8E-01
120	8.6E-15	3.2E-02	8.1E-01	4.1E+00	4.4E+00	8.8E-01
150	7.3E-12	9.0E-02	2.5E+00	1.0E+01	1.1E+01	2.2E+00
180	4.7E-09	1.9E-01	7.0E+00	2.3E+01	2.4E+01	4.9E+00
210	2.4E-06	3.5E-01	1.5E+01	4.4E+01	4.7E+01	9.6E+00
240	1.2E-03	6.1E-01	2.2E+01	7.1E+01	7.5E+01	1.4E+01
270	3.6E-01	7.2E-01	2.7E+01	8.3E+01	8.7E+01	1.7E+01

Note: only radionuclides that are expected to have relatively long residence time and produce large doses (alpha) are of concern postnatally

Embryo/Fetal Dose from Noble Gas

Table 5. Factors for radiation dose to the embryo/fetus resulting from a pregnant woman breathing representative radioactive noble gases at relevant times or period of gestation. Factors are given as dose (rad) resulting from breathing nominal atmospheres of 1.0 µCi/ml of ^{85}Kr, ^{133}Xe, or ^{222}Rn for various lengths of time up to 1 day. Approximate values for exposures of longer duration are calculated as multiples of the 1-day doses.

Embryo/Fetal Dose from Noble Gas

Gestational Days at Exposure	Exposure Times 5 min	10 min	15 min	30 min	1 hr	2 hr	6 hr	1 day
Krypton								
0	1.3E-02	2.7E-02	4.0E-02	8.0E-02	1.6E-01	3.2E-01	9.6E-01	3.8E+00
90	6.6E-03	1.3E-02	2.0E-02	4.0E-02	7.9E-02	1.6E-01	4.7E-01	1.9E+00
180	6.6E-03	1.3E-02	2.0E-02	4.0E-02	7.9E-02	1.6E-01	4.7E-01	1.9E+00
240	6.6E-03	1.3E-02	2.0E-02	4.0E-02	7.9E-02	1.6E-01	4.7E-01	1.9E+00
Xenon								
0	2.1E-02	4.4E-02	6.5E-02	1.3E-01	2.6E-01	5.2E-01	1.6E+00	6.2E+00
90	1.1E-02	2.2E-02	3.3E-02	6.7E-02	1.3E-01	2.7E-01	8.0E-01	3.2E+00
180	1.1E-02	2.1E-02	3.2E-02	6.4E-02	1.3E-01	2.6E-01	7.7E-01	3.1E+00
240	1.0E-02	2.1E-02	3.1E-02	6.3E-02	1.3E-01	2.5E-01	7.5E-01	3.0E+00
Radon								
0	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02
90	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02
180	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02
240	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02

Problem

A DPW ingests some ^{90}Sr. Bioassay indicates that the intake was 0.2 mCi and it occurred during the first month of pregnancy.

a. What is the estimated dose to the E/F? Use both the simplified and realistic methods. Explain any differences in the results using the two methods?

b. What would be the E/F dose if the intake had occurred in the ninth month of the pregnancy? Use both the simplified and realistic methods. Explain any differences between the doses from the intake in the first month and the doses from the intake in the ninth month.

Problem

If a woman elects not to declare her pregnancy, what would be the dose limit on the dose to her embryo/fetus?

END OF EMBRYO/FETAL DOSE

END OF CHAPTER 16