Internal Radiation Dosimetry

Overview

This tutorial will discuss many aspects of understanding radiation dosimetry. It will discuss the importance of the history of radiation exposures and why this led to ALARA and the current acceptable limits of this exposure for both personnel and patients. The tutorial will discuss the different calculations and formulas for how to evaluate these exposures. Also, it will focus on how different behaviors and diseases expose people to various risks, and the types of calculated risks received by different radiographic procedures.

Topics to be covered:

- Historical Background and Current Acceptable Limits
- MIRD (Medical Internal Radiation Dose Committee) Calculations
- Definitions of Terms in Radiation Dose Formulas
- Risk Factors in Behaviors/Disease and Radiographic Procedures

Historical Background and Current Acceptable Limits

Early Observations of Radiation Effects

- Marie Curie's Professor proudly carried in his coat pocket a vial containing the first sample of radium (an emitter of high energy alpha particles and gamma rays) ever produced; shortly thereafter, the first radiation burn was documented.
- To verify association between radiation and tissue damage, early researchers taped pieces of the new metal to their skin to observe results and confirmed that the radioactive material was indeed causing the burns.
- The now-familiar story of a multi-decade epidemiological study of radium-watch dial painters revealed that these workers, who tipped the brushes with their lips and during their careers ultimately swallowed large amounts of radium, had an incidence of bone cancer significantly greater than expected for the general population.

- An increase in thyroid cancer has likewise been observed in adults who, during the 1940's, underwent neck irradiation during childhood. A relationship has also been established between childhood radiation and parathyroid adenomas.

BACKGROUND

- Researchers have been unable to document a threshold level for causing radiation damage for long-term radiation effects. The assumption is made that the probability of radiation carcinogenesis and radiation-induced genetic abnormalities is never zero, regardless of how low the exposure dose
- The rates of carcinogenesis and radiation-induced abnormalities are too low to measure by most feasible techniques
- Time between exposure and manifestation of symptoms is inversely proportional to the absorbed dose
- At low exposure rates, biological repair corrects some of the damage Ionizing radiation includes charged particles, photons, and other products of natural and induced radiation. In the body, water is the most likely molecule most likely to be ionized by radiation. The water transfers its energy to another nearby molecule, inducing radiation damage in the second molecule. Depending upon dose rate, the tissue may or may not be able to repair itself.
- Effects recognized as being caused by ionizing radiation include acute burns, dermatitis and hair loss, and carcinogenesis, as well as genetic effects.

The ALARA Concept

- In the mid- 1970s, the ALARA concept was proposed and in 1995 became a mandatory part of one’s Policy and Procedure Manual. It was designed to heighten the awareness of Nuclear Medicine Technologists to the risk of ionizing radiation and to minimize their absorbed dose.
- It was based upon maintaining the radiation dose **As Low as Reasonably Achievable** and has contributed to a significant overall reduction in dose to radiation workers.

Maximum Permissible Dose for Radiation Workers

In accordance with current NRC Regulations, for Radiation workers, the **Maximum Permissible Doses** are listed below:

- **whole body**: 5 R in any given year = 50 mSv
- **internal organ**: 50 R in any given year = 500 mSv
- **lens of the eye**: 15 R in any given year = 150 mSv
- **extremities**: 50 R in any given year = 500 mSv (50 R is considered to be an acceptable level for the hands since there is essentially no bone marrow to be irradiated.)

Maximum Permissible Dose for Members of the General Public

- For members of the general public (our families and other non-radiation workers), the MPD is 0.1 R/yr – 1 mSv

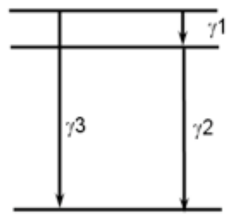
MIRD CALCULATIONS

"INPUT" AND "OUTPUT" DATA

- When evaluating individual radioisotopes to determine their ability to deliver radiation dose to the tissue, it is necessary to consider the decay scheme and both "input" and "output" data.
- The input data are those which may be determined directly from the decay scheme and the accompanying chart; output data include all possible contributions to the radiation dose. This includes, in addition to the primary radiations listed in the decay scheme, characteristic X-rays, internal conversion electrons, and Auger electrons.
- The decay scheme for Tc^{99m} and the table shown below were extracted from the MIRD Booklet (Medical Internal Radiation Dose Committee, a sub-committee of the Society of Nuclear Medicine).

Input data

Radiation	% abundance	Energy (MeV)
Gamma-1	98.6	0.0022
Gamma-2	98.6	0.1405
Gamma-3	1.4	0.1427



- The output data for Tc^{99m} are shown in the diagram below. While there are 20 contributors to the internal dose from Tc^{99m}, it should be noted that the majority of them confer a very small radiation dose because their % abundances are very small (<3% of all transitions)

Output data

Radiation	% abundance	Energy (MeV)
Gamma-1	0.00	0.0021
M-ICE, $\gamma 1$	98.6	0.0017
Gamma-2	86.3	0.1405
K-ICE, $\gamma 2$	8.63	0.1195
L-ICE, $\gamma 2$	1.09	0.1377
M-ICE, $\gamma 2$	0.36	0.1401
Gamma-3	0.03	0.1427
K-ICE, $\gamma 3$	0.96	0.1217
L-ICE, $\gamma 3$	0.30	0.1300
M-ICE, $\gamma 3$	0.10	0.14213
$K\alpha 1$ X-rays	4.30	0.0184
$K\alpha 2$ X-rays	2.16	0.0183
$K\beta 1$ X-rays	1.03	0.0206
$K\beta 2$ X-rays	0.18	0.0210
L X-rays	0.81	0.0024
KLL Auger electrons	1.49	0.0155
KLX Auger electrons	0.55	0.0178
KXY Auger electrons	0.07	0.0202
LMM Auger electrons	10.6	0.0019
MXY Auger electrons	123	0.0004

MIRD Standard Reference Man

- The MIRD Committee has developed a hypothetical "reference man", actually a bisexual construct that permits estimation of the factors required to calculate dose to one organ attributable to a source in another organ. A schematic drawing of this "reference man" is shown below

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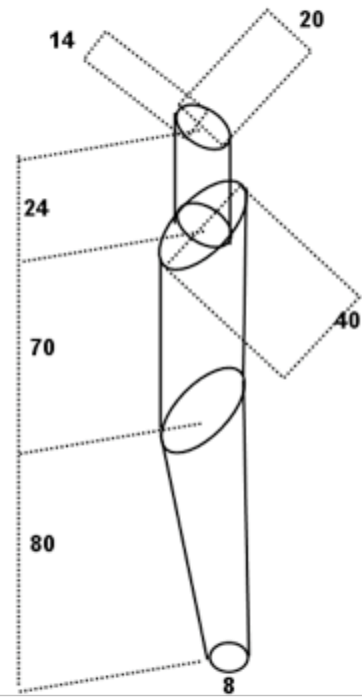

MIRD Standard Reference Man (dimensions in centimeters)

Radiation Dose Formulas: Definitions of Terms

C_O	Initial Concentration of Radioisotope in Tissue, μCi/g
t_{eff}	Effective Half Life (Days)
f_β , f_γ	Fraction of decays in which β, γ is emitted
E_β	Average β- energy, MeV
E_γ	γ-ray energy, MeV
φ	Fraction of Energy Absorbed

For beta particles, internal conversion and Auger electrons, which deposit essentially 100% of their energy into the body, the following formula has been derived:

$$D_{\beta} = k \cdot \bar{E}_{\beta} \cdot f_{\beta} \cdot C_o \cdot 1.443 \cdot T_{eff} \cdot \Phi$$

where Φ = fraction of energy absorbed = 1.00

when using appropriate conversion factors, this equation yields:

$$D_{\beta} = 73.8 \cdot \bar{E}_{\beta} \cdot f_{\beta} \cdot C_o \cdot 1.443 \cdot t_{eff} \text{ Rads}$$

For moderately energetic X- and gamma-rays, which deposit only part of their energy in the body, the following formula has been derived. In this case, φ typically falls in the range of about 0.1 – 0.7

$$D_{\gamma} = k \cdot E_{\gamma} \cdot f_{\gamma} \cdot C_o \cdot 1.443 \cdot t_{eff} \cdot \phi$$

where Φ typically has a value between 0.1 and 0.7

when using appropriate conversion factors, this equation yields:

$$D_{\gamma} = 73.8 \cdot E_{\gamma} \cdot f_{\gamma} \cdot C_o \cdot 1.443 \cdot t_{eff} \cdot \Phi \text{ Rads}$$

When the two equations are combined, the total dose equation, which represents contributions from both a beta particle and a gamma ray (non-penetrating and penetrating radiation, is:

$$\text{Total Dose} = 73.8\, C_0 \cdot t_{eff} \left[f_{\beta}\, \bar{E}_{\beta} + f_{\gamma} \cdot E_{\gamma} \cdot \phi\right] \text{ Rads}$$

Using a slightly different approach, we can derive a second equation that takes into account both penetrating (X, gamma) and non-penetrating radiations (alphas, betas, electrons). The equation shown below accounts for all these factors and indicates that the total dose is a summation of both penetrating and non-penetrating contributions.

Overall Dosimetry Equation

$$\bar{D}_T = \frac{\bar{A}_T}{m_T} \Sigma \Delta_{np} \phi_{np} + \Sigma \frac{\bar{A}_S}{m_T} \Sigma \Delta \phi_{(T \leftarrow S)}$$

In this equation, $T \leftarrow S$ means "Source to Target"

It is important to consider every radiation not only from the standpoint of self-irradiation of an organ, but also radiation transmitted to every other organ in the body. For example, we know that Tc^{99m} sulfur colloid localizes in the liver, spleen, and marrow. To calculate liver dose, we must be concerned with dose from the liver to the liver, from the spleen to the liver, and from the marrow to the liver.

SAMPLE CALCULATION:

Problem: calculate radiation dose to the liver from the intravenous injection of 8 mCi of Tc^{99m} sulfur colloid.

Assumptions: t_{phys}= 6 hr, t_{biol}= infinitely long, t_{eff}= 6 hr; Distribution: 90% in liver, 5% in spleen, 5% in bone marrow. While the contribution to liver dose from marrow is negligible, it has been included in the following equation for completeness.

Dosimetry Calculation

$$D_T = \frac{A_T}{m_T} \Sigma \Delta_{np} \phi_{np} + \Sigma \frac{A_S}{m_T} \Sigma \Delta \phi_{(L \leftarrow L)} + \Sigma \frac{A_S}{m_T} \Sigma \Delta \phi_{(L \leftarrow S)} + \Sigma \frac{A_S}{m_T} \Sigma \Delta \phi_{(L \leftarrow M)}$$

Natural Whole Body Background

- At sea level it averages ~ 300 mR annually
- In Denver and other cities 1 or more miles above sea level, the background dose is increased above that at sea level. At the height of 1 mile in the atmosphere, residents of Denver have a background dose twice that of people living at sea level. While it might sound logical that, because they are 1 mile closer to the sun, they have lost protection due to the inverse square law. That is not the case at all. The effect of 1 mile out of 93,000,000 miles is insignificant. The real reason is that the air over the heads of residents of Denver is much less dense than the air at sea level and therefore it cannot attenuate cosmic rays as well. In addition, there is more radioactivity in the soil in Denver than in most US cities located at sea level.
- There are several locations on earth where radium and uranium are plentiful in soil and the background may reach 7,000 mR/yr.

There are several sources of background radiation in humans

Minor Contributors to Background

- radiocontaminants in the food chain
- fallout from nuclear bomb testing
- emissions from Nuclear power plants
- flying in aircraft
- Household items, e.g., smoke detectors

Major Contributors to Background

- internal long-lived radioisotopes in our bodies, especially C-14 and K-40
- environmental exposure, especially Radon gas, which is by far the largest contributor to our background radiation dose.
- cosmic rays

Nuclear Medicine Procedures: Dosimetry (Estimated)

Reference: RSNA Website, November, 2016

Examination*	Effective Dose (mSv)	Administered Activity (MBq)†	Effective Dose (mSv/MBq)‡
Brain (^{99m}Tc-HMPAO–exametazime)	6.9	740	0.0093
Brain (^{99m}Tc-ECD–Neurolite)	5.7	740	0.0077
Brain (^{18}F-FDG)	14.1	740	0.019
Thyroid scan (sodium iodine 123)	1.9	25	0.075 (15% uptake)
Thyroid scan (^{99m}Tc-pertechnetate)	4.8	370	0.013
Parathyroid scan (^{99m}Tc-sestamibi)	6.7	740	0.009
Cardiac stress-rest test (thallium 201 chloride)	40.7	185	0.22
Cardiac rest-stress test (^{99m}Tc-sestamibi 1-day protocol)	9.4	1100	0.0085 (0.0079 stress, 0.0090 rest)
Cardiac rest-stress test (^{99m}Tc-sestamibi 2-day protocol)	12.8	1500	0.0085 (0.0079 stress, 0.0090 rest)
Cardiac rest-stress test (Tc-tetrofosmin)	11.4	1500	0.0076
Cardiac ventriculography (^{99m}Tc-labeled red blood cells)	7.8	1110	0.007
Cardiac (^{18}F-FDG)	14.1	740	0.019
Lung perfusion (^{99m}Tc-MAA)	2.0	185	0.011
Lung ventilation (xenon 133)	0.5	740	0.00074
Lung ventilation (^{99m}Tc-DTPA)	0.2	1300 (40 actually inhaled)	0.0049
Liver-spleen (^{99m}Tc–sulfur colloid)	2.1	222	0.0094
Biliary tract (^{99m}Tc-disofenin)	3.1	185	0.017
Gastrointestinal bleeding (^{99m}Tc-labeled red blood cells)	7.8	1110	0.007
Gastrointestinal emptying (^{99m}Tc-labeled solids)	0.4	14.8	0.024
Renal (^{99m}Tc-DTPA)	1.8	370	0.0049
Renal (^{99m}Tc-MAG3)	2.6	370	0.007
Renal (^{99m}Tc-DMSA)	3.3	370	0.0088
Renal (^{99m}Tc-glucoheptonate)	2.0	370	0.0054
Bone (^{99m}Tc-MDP)	6.3	1110	0.0057
Gallium 67 citrate	15	150	0.100
Pentreotide (^{111}In)	12	222	0.054
White blood cells (^{99m}Tc)	8.1	740	0.011
White blood cells (^{111}In)	6.7	18.5	0.360
Tumor (^{18}F-FDG)	14.1	740	0.019

Radiographic Procedures: Dosimetry (Estimated)

Reference: American Nuclear society website, November 2016

X-Ray - Chest	10 mrem
X-Ray - Mammography	40 mrem
X-Ray - Skull	10 mrem
X-Ray - Cervical Spine	20 mrem
X-Ray - Lumbar Spine	600 mrem
X-Ray - Upper GI	600 mrem
X-Ray - Abdomen kidney/bladder	70 mrem
X-Ray - Barium Enema	800 mrem
X-Ray - Pelvis	60 mrem
X-Ray - Hip	70 mrem
X-Ray - Dental Bitewing/Image	0.5 mrem
X-Ray - Extremity hand and foot	0.1 mrem
CT Scans - Head	200 mrem
CT Scans - Chest	700 mrem
CT Scans - Abdomen	800 mrem
CT Scans - Pelvis	600 mrem
CT Scans - Extremity	10 mrem
CT Scans - Angiography heart	1,200 mrem
CT Scans - Angiography head	1,000 mrem
CT Scans - Spine	600 mrem
CT Scans - Whole Body	1,275 mrem
CT Scans - Cardiac	300 mrem

Risks which increase the chance of death by 4 in 10,000 = The Fatal Cancer Risk from 1 REM

RISKY BEHAVIOR/SITUATION	CAUSE OF DEATH
Smoking 28 packs of cigarettes	Cancer, heart disease
Drinking 200 liters of wine	Cirrhosis of the liver
Spending 400 hours in a coal mine	Black lung disease
Spending 1200 hours in a coal mine	Accident
Living 2 years in New York or Boston	Air pollution
Traveling 40 hours by canoe	Accident
Traveling 70 hours by bicycle	Accident
Traveling 20,000 miles by car	Accident
Flying 400,000 miles by jet	Accident
Flying 600,000 miles by jet	Cancer from cosmic radiation
Living 7 years in Denver	Cancer from cosmic radiation
Living 17 years in a stone/brick Bldg.	Cancer from natural radiation
500 chest x-rays	Cancer from radiation
20 screening mammography studies	Cancer from radiation
Living 33 years with a cigarette smoker	Cancer and Heart Disease
1600 tablespoons of peanut butter	Liver cancer from aflatoxin B
Drinking Miami water for 400 years	Cancer from chloroform
Eating 40,000 charcoal broiled steaks	Cancer from benzopyrene
Living 500 years at the boundary of nuclear power plant in the open	Cancer from Radiation

Consultants In Nuclear Medicine
Nucmedconsultants@comcast.net
Stephen Karesh, PhD
Phone: 773-802-7617
Fax: 773-304-2545
2910 W. Estes Ave. Chicago, IL 60645-2394