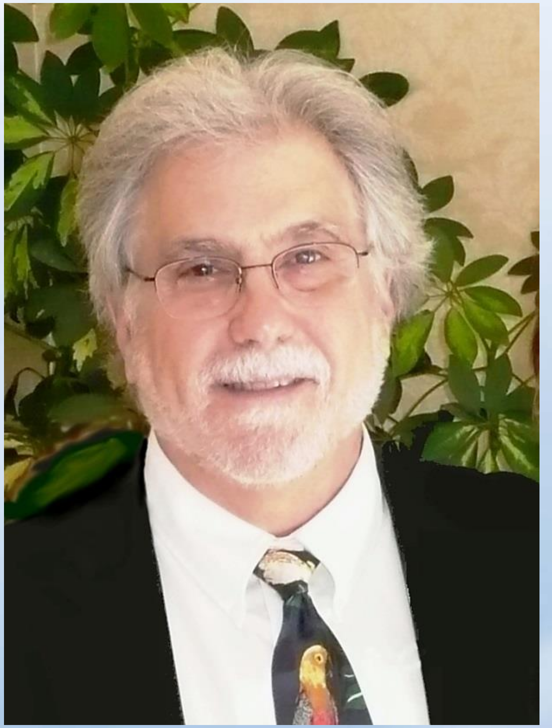
Steven L. Simon, Ph.D.
Head, Dosimetry Unit, DCEG

Principles of Radiation Physics and Dosimetry II



Radiation Epidemiology & Dosimetry Course

National Cancer Institute www.dceg.cancer.gov/RadEpiCourse

Part III.
DOSIMETRY: The Basics

Dosimetry is not a basic science, but is simply applied physics.

The primary goal of radiation dosimetry is a **quantitative estimation of the absorbed energy in tissue**, with an emphasis on the organ average dose.

To make estimates of radiation dose, one needs to understand the **processes** by which radiation **interacts** with tissue as it those **interactions** that result in the **transfer of energy** to the tissue.

What did we learn from the discussion on interactions of radiation with matter?

There are several different types of interactions, but all result in either releases of electrons or photons.

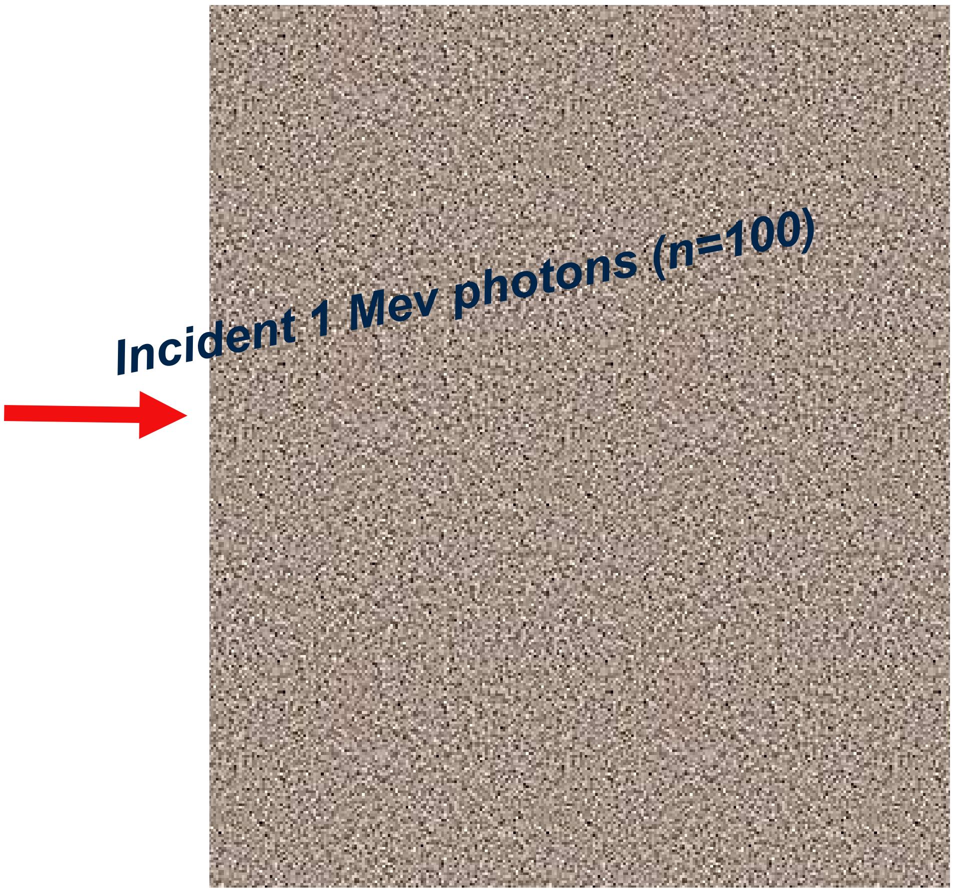
Because not all of the energy from an incident particle or photon is absorbed in a single interaction, **radiation exposure causes a cascade of events before all of the incident energy is absorbed**.

Example:

Suppose 1 Mev photons are incident on carbon (as a simulation of tissue). Let's see what happens inside the material from the exposure.

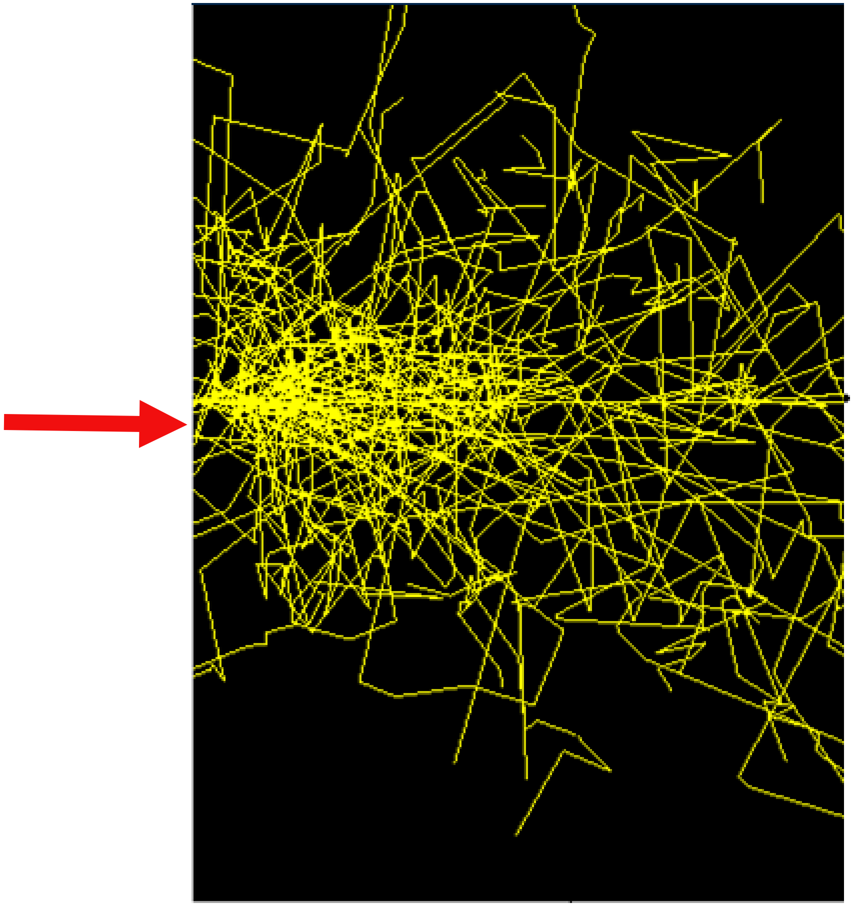
20 cm radius target, 30 cm deep

Photons and electrons calculated by SLAC EGS code.



20 cm radius target, 30 cm deep

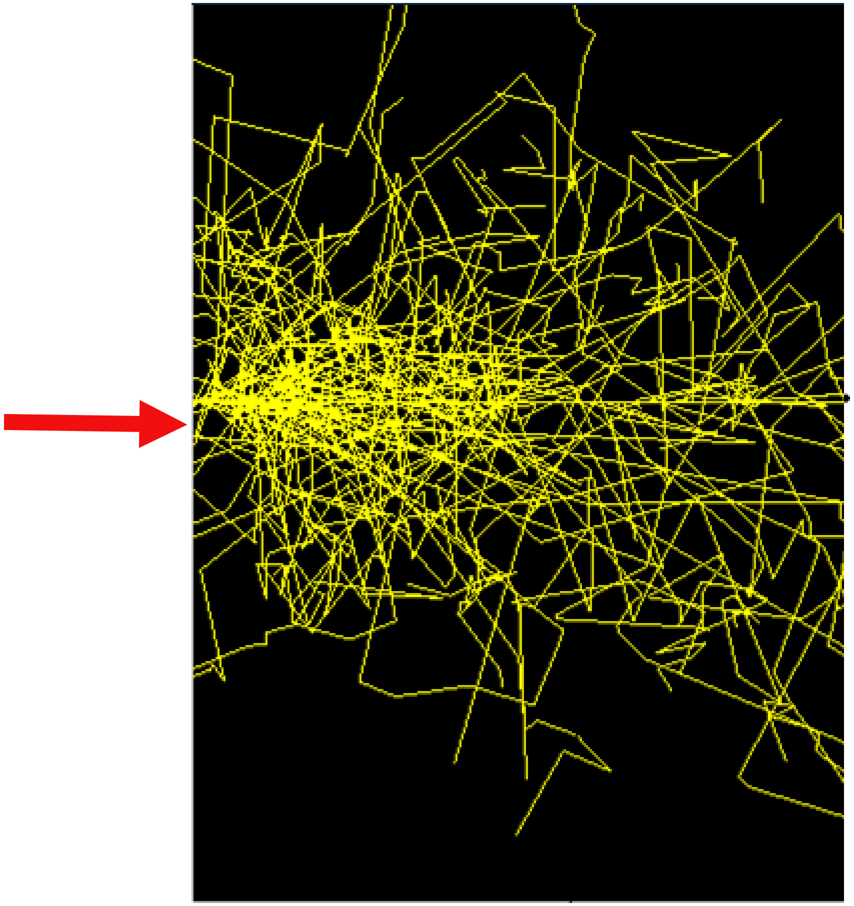
Photons and electrons calculated by SLAC EGS code.



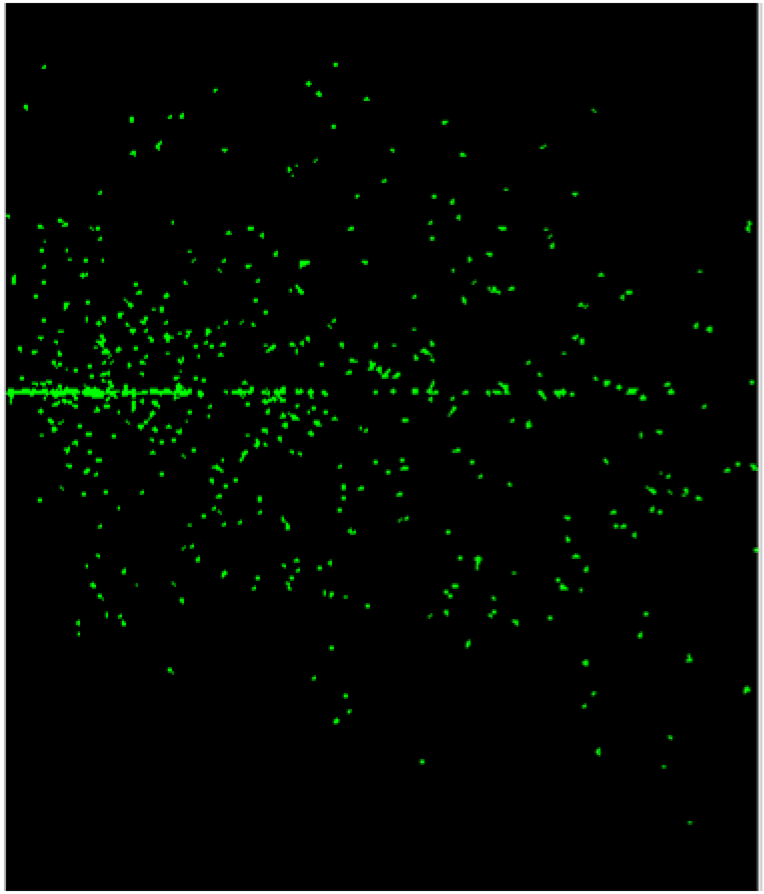
Scattered photons

20 cm radius target, 30 cm deep

Photons and electrons calculated by SLAC EGS code.

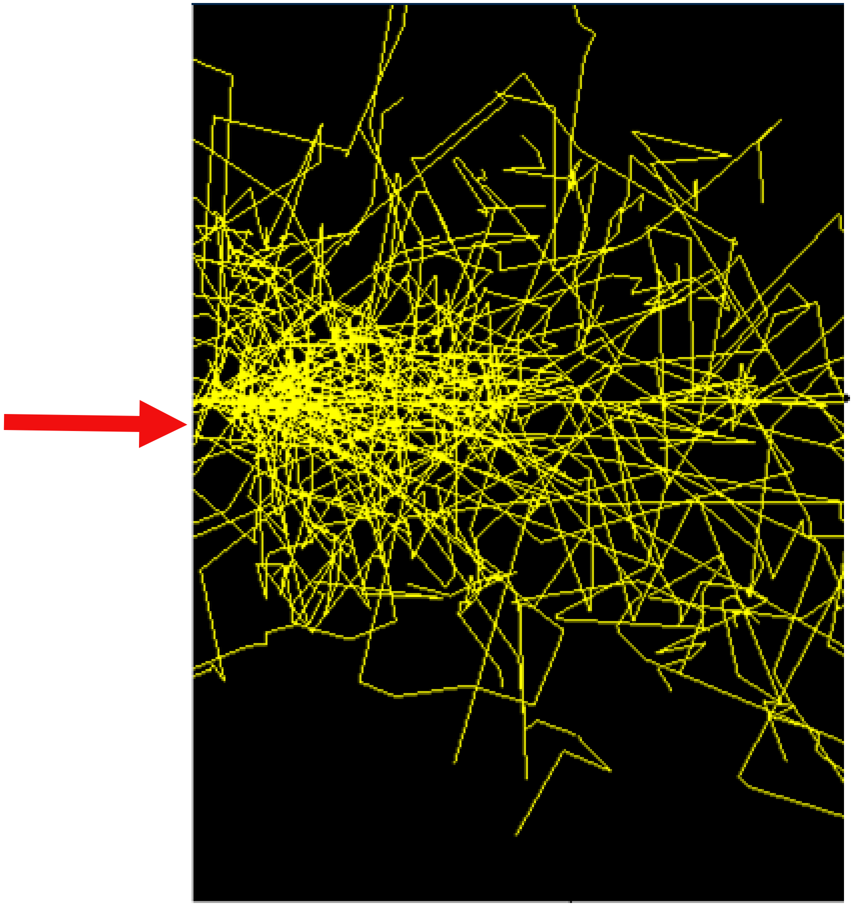


Scattered photons

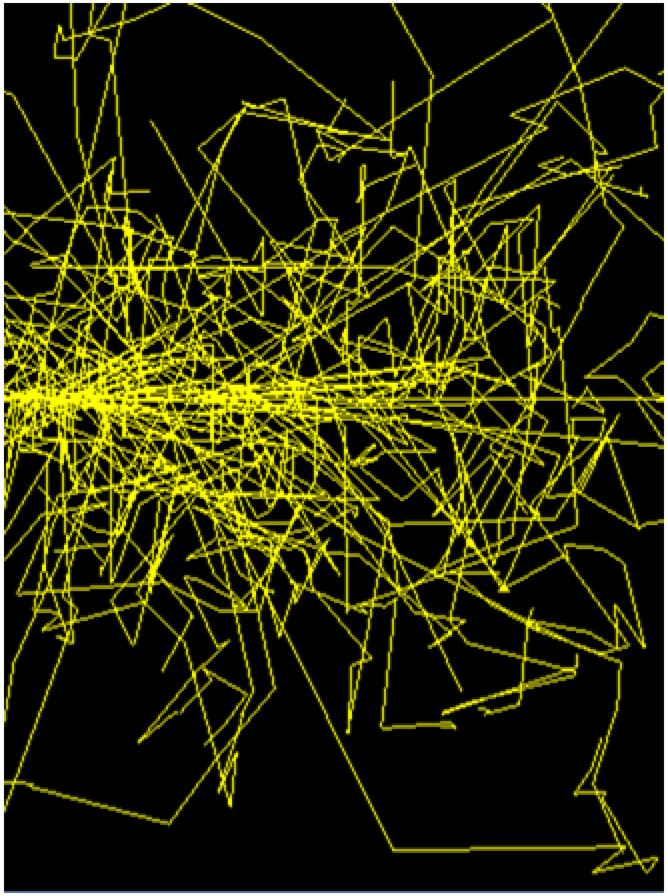


Electrons produced

Interactions are random on a micro-scale but result in a predictable average ionization



1st 100 photons



2nd 100 photons

Radiation Dose Quantities and Units

Three physical quantities are basic to radiation dosimetry of photons:

- exposure,
- kerma, and
- absorbed dose.

The conventional units (used in the U.S.) for these quantities were:

- **Roentgen (R) for exposure** (amount of ionizing x-ray exposure that would liberate 1 electrostatic unit of negative or positive charge per cm^3 of air)
- **rad for kerma and absorbed dose** (where 100 erg/g = 1 rad)

The International System of Units (SI) uses:

- **Coulomb per kilogram (C/kg) for exposure** (2.58 x 10-4 C/kg = 1 R) and
- **Joule per kilogram for kerma and absorbed dose** (1 Gy = 1 J/kg)

The special name for the joule per kilogram is the **Gray**.
`The SI system has no special name for units of exposure.

Exposure

(the technical definition in radiation dosimetry, not the dictionary meaning)

The 'exposure' X is defined as the absolute value of the total charge of one sign produced in air within a small volume of air as a result of ionization of the air.

Note that 'exposure' is a sometimes useful and is reported in many historical publications, but is now seldom used.

Units: Roentgen (conventional units) or C/kg (coulomb per kilogram of air, SI units).

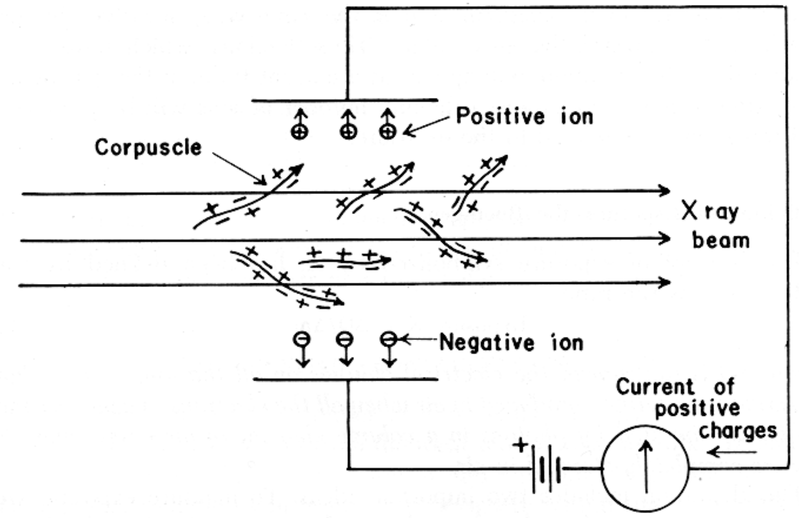


FIGURE VII-2. Diagram illustrating the ionization produced in air by an x-ray beam.

KERMA

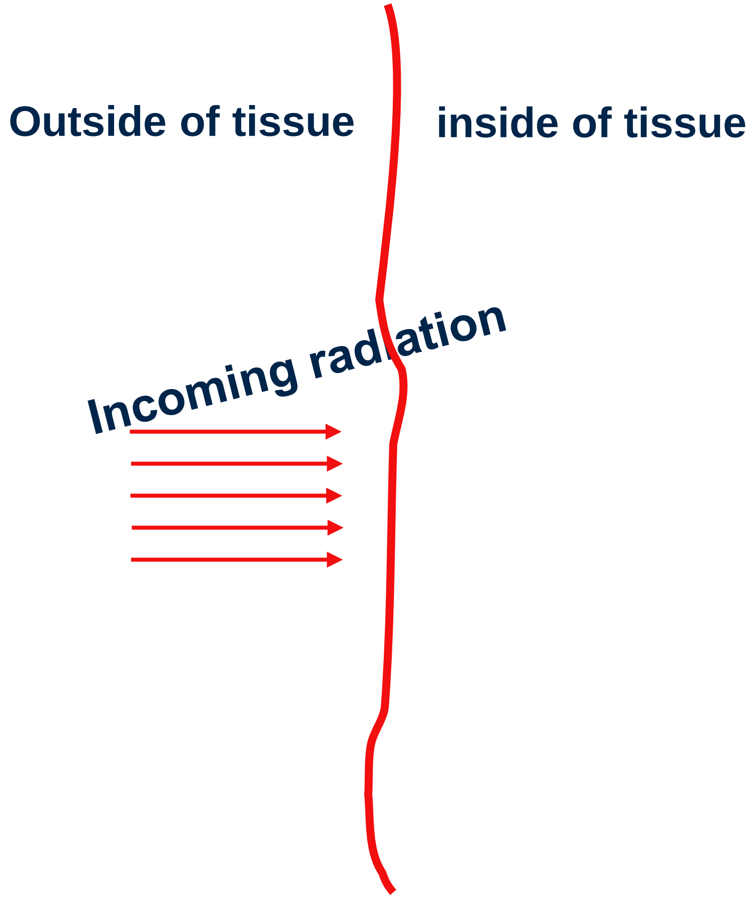
The '***kerma***' (***'kinetic energy released in medium'***) K is defined as:

$K = (dE_{tr}/dm)$

where dE_{tr} is the sum of the initial kinetic energies of the charged particles liberated by the photons (photons are often called 'indirectly ionizing particles, whereas, electrons are called 'directly ionizing' particles) in the volume element.

Units: joule/kg (SI with special name Gray), erg/gm (conventional with special name rad)

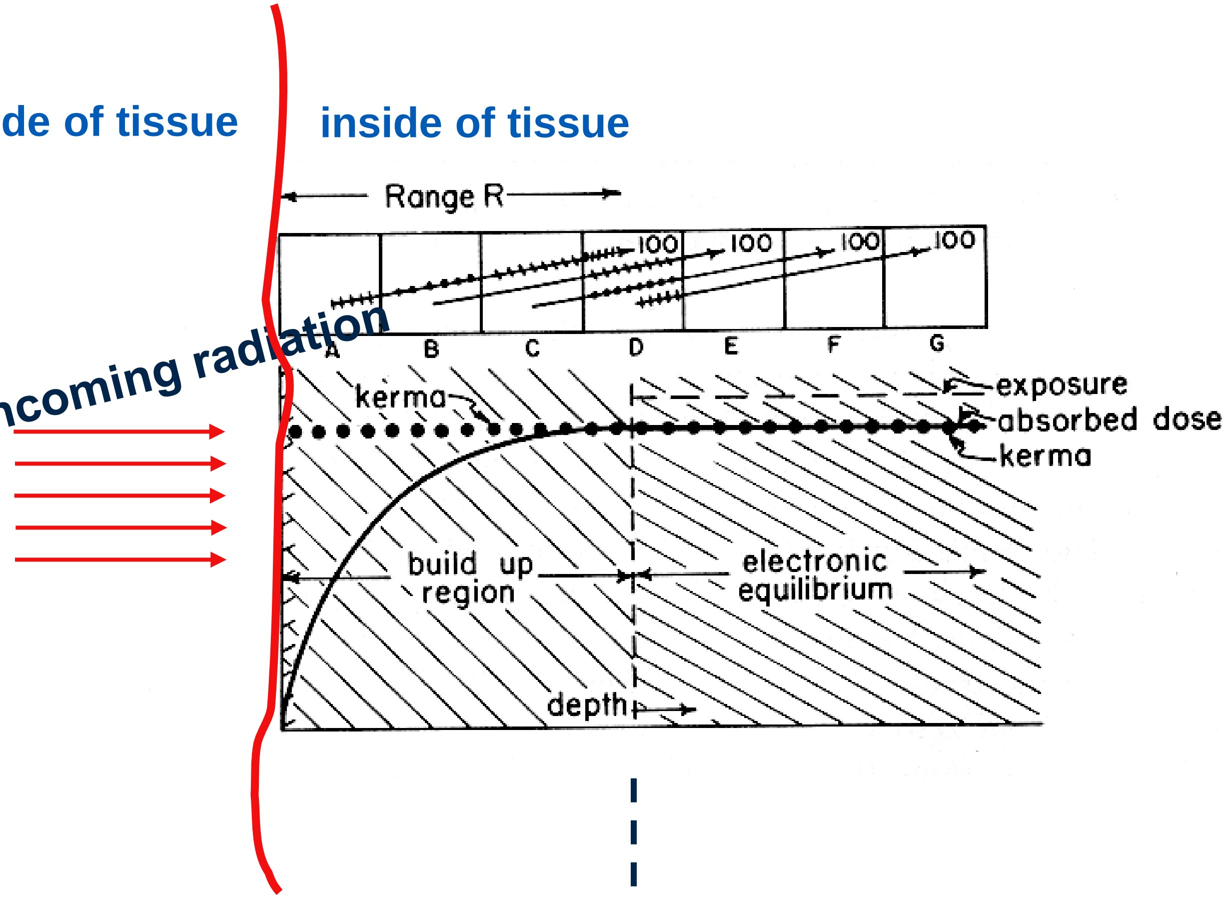
Kerma is closely related, but not exactly the same as absorbed dose


Outside of tissue
inside of tissue
Incoming radiation

Outside of tissue

inside of tissue

Incoming radiation



Kerma > dose in this region

Kerma = dose in this region (where number of secondary electrons entering equals those leaving)

Fundamental to understanding ‘absorbed dose’ is the concept of the ‘energy imparted’, ε, within a volume:

$$\varepsilon = R_{in} - R_{out} + \Sigma Q$$

where,

R_{in} is the incident energy on the volume, i.e., the sum of the energies (including ‘rest energies’) of the charged and uncharged ionizing particles that enter the volume,

R_{out} is the energy emerging from the volume, i.e., the sum of the energies (including ‘rest energies’) of the charged and uncharged ionizing particles that leave the volume,

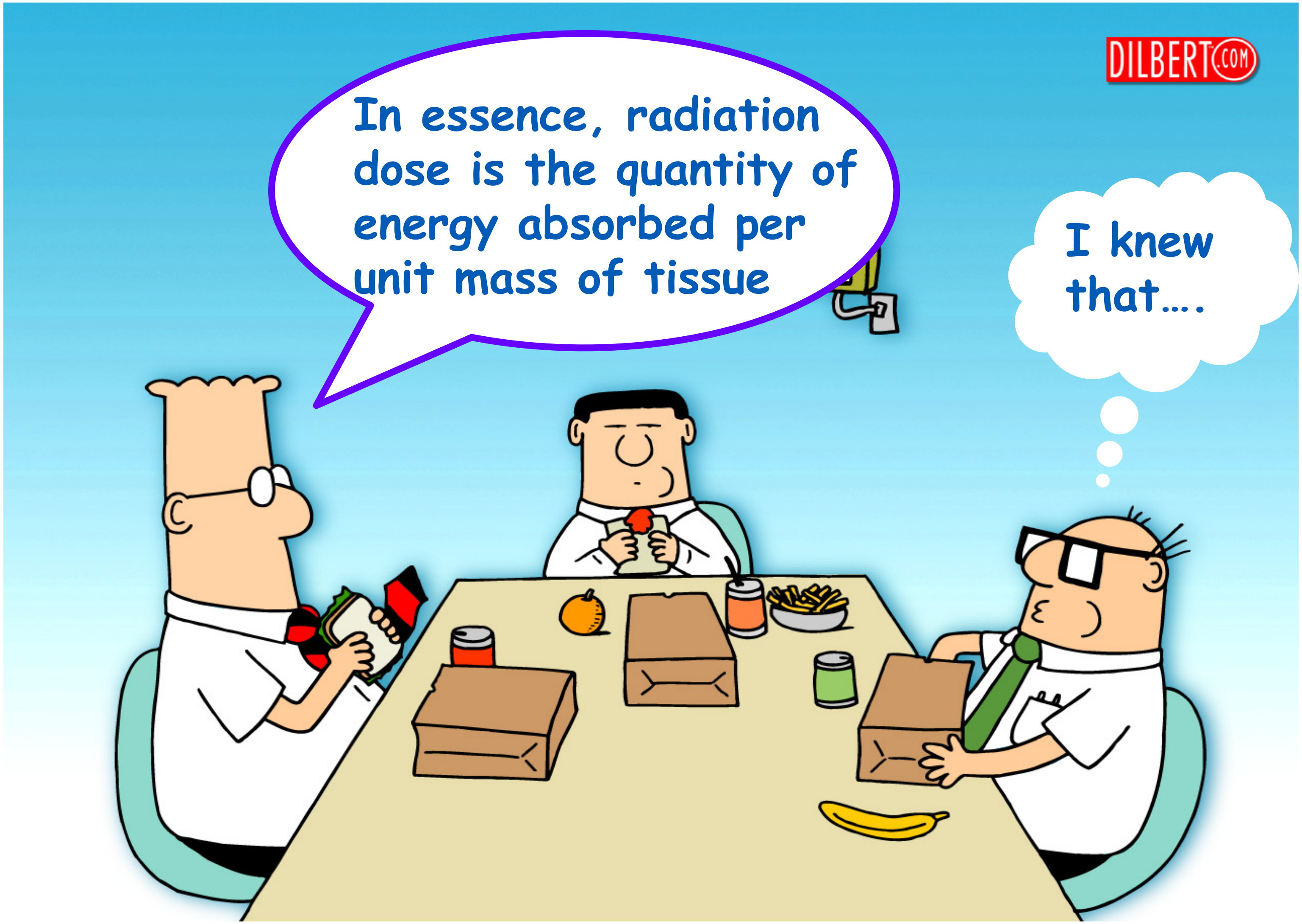
ΣQ is the sum of the all changes of the rest mass energy of the nuclei and particles in any interactions which occur in the volume.

The absorbed dose D is:

$$D = k_1 \frac{d\bar{\varepsilon}}{dm}$$

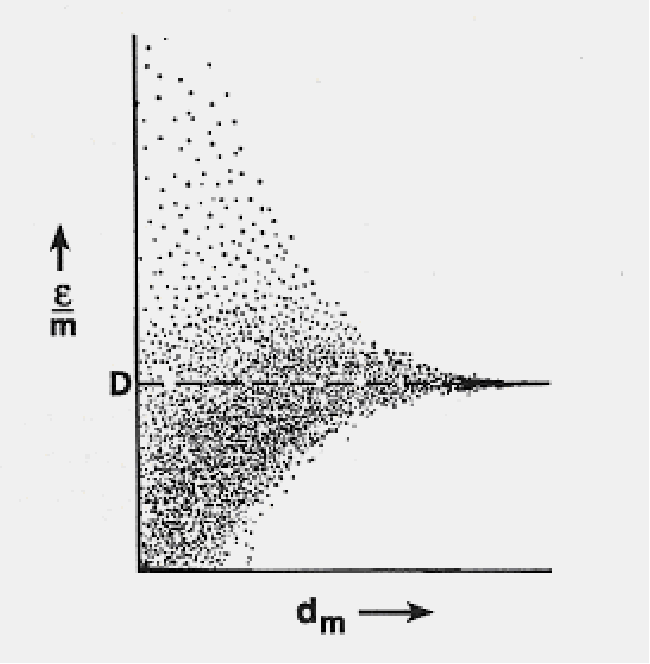
Note: The coefficient k_1 has the value of 1.0 for SI absorbed dose units (joule/kg with the special name of Gray [Gy]) and a value of 100 for conventional dose units (ergs/gram with the special name of rad).

The definition of dose! Yea!


DILBERT.COM
In essence, radiation dose is the quantity of energy absorbed per unit mass of tissue
I knew that….

For small volumes, there is statistical variation of the absorbed dose since the likelihood of interaction per unit distance is characterized by a probability.

The random variation of absorbed dose as a function of volume is shown here.



When averaged over the mass of an organ, the '<u>organ absorbed dose</u>' is probably the most useful measure of radiation dose for epidemiologic studies.

While the energy absorbed per unit mass defines **'absorbed dose'** on a macroscopic scale, it **may not properly define the spatial pattern of absorbed energy delivered on the microscopic level.**

Q: Does the deposition of energy on a micro-scale differ according to radiation type?

(Remember …the Coulomb interaction differs for particles of different charges)

Q: How might we specify how the energy is deposited on a micro-scale?

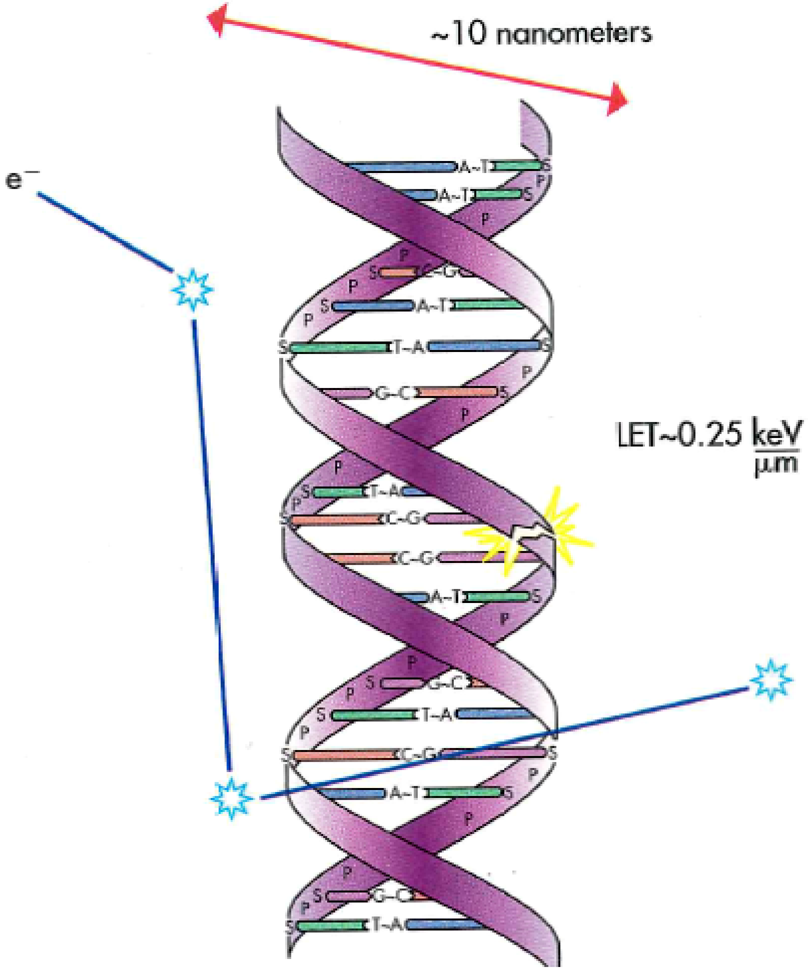
Radiobiology and, to some extent, dosimetry, considers the linear rate of transfer of energy to the irradiation medium (e.g., tissue).

The quantity, LET, i.e., "linear energy transfer", captures this concept.

<u>Note</u>: The rate of transfer of energy over the same path can differ for photons and charged particles and this has implications for the degree of local damage caused by the radiation.

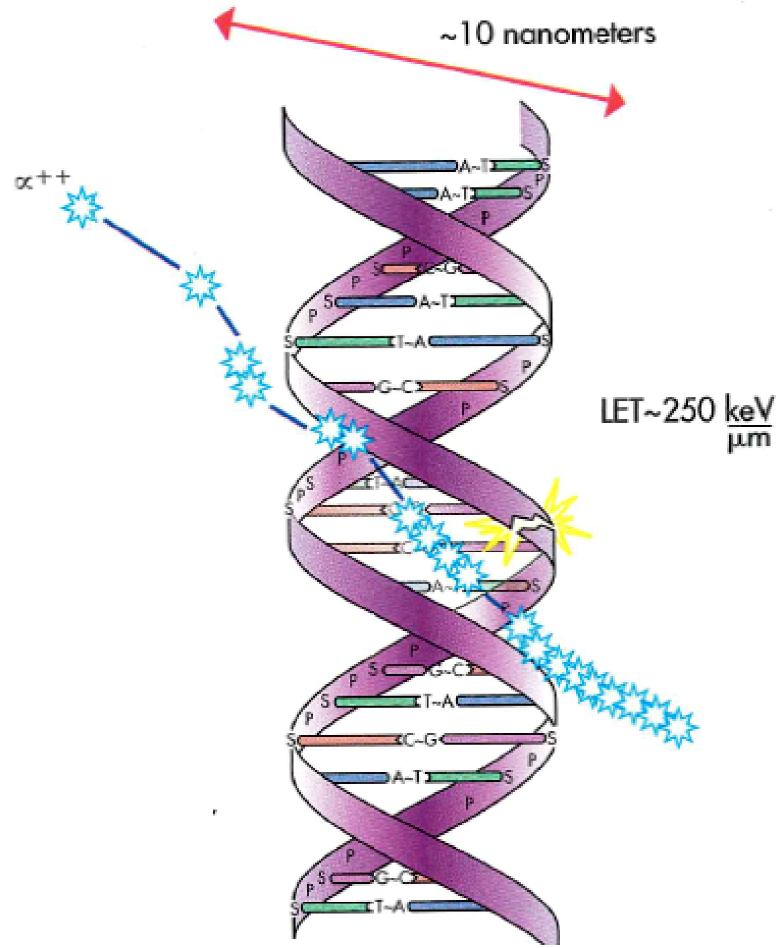
LET means linear energy transfer rate.

Example of "low" LET radiation damage for photons and electrons, ~0.25 keV energy lost per micron



Low likelihood of double strand DNA breakage

Example of "high" LET radiation damage for alpha particles, ~250 keV energy lost per micron



Higher likelihood of double strand breakage

Reminder: Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium.

An additional metric of dose, the **Equivalent dose (Sv),** accounts for the LET relative to photons by a multiplicative radiation weighting factor, W_R.

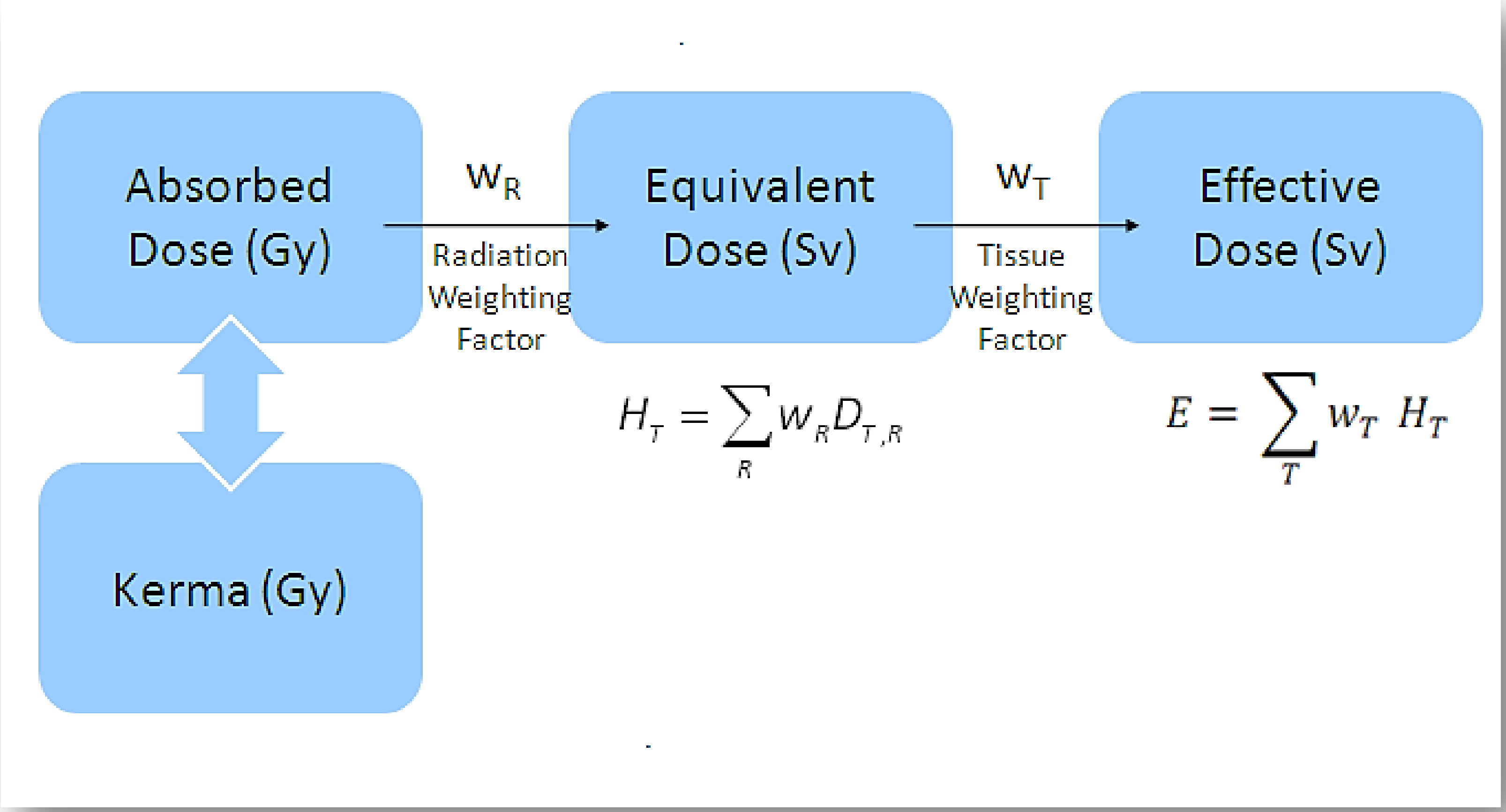
Equivalent dose may have use in radiation epidemiology though the occasions will be few.

An additional metric of dose, the **Effective Dose (also with units of Sv)** is a radiation protection quantity, normally without value in radiation epidemiology* since it approximately accounts for the radiation sensitivity of individual tissues (with a multiplicative factor W_T). Determination of tissue sensitivity is one of the primary objectives of radiation epidemiology to determine.

** may be used for approximate projection of total fatal cancers based on published risk coefficient (averaged over population).*

Absorbed dose (Gy) considers only the energy absorbed in the irradiation medium while **Equivalent Dose (Sv)** accounts for differences in LET. These metrics of dose are the most useful for epidemiology.

Effective Dose (Sv) accounts for approximate differences in tissue sensitivity for radiation protection (regulatory) purposes.



Equivalent Dose accounts for differences in LET and is sometimes of value in epidemiology.

Recommended radiation weighting factors.

Radiation type	**Radiation weighting factor, w_R**
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy

Effective Dose accounts for approximate differences in tissue sensitivity for radiation protection (regulatory) purposes and has little use in epidemiology.

NOTE: Weighting factors have changed over time and can lead to confusion about the meaning of published "doses."

ORGAN	ICRP 26	ICRP 60	ICRP 103
Bone marrow (red)	0.12	0.12	0.12
Colon	-	0.12	0.12
Lung	0.12	0.12	0.12
Stomach	-	0.12	0.12
Breast	0.15	0.05	0.12
Gonads	0.25	0.20	0.08
Bladder	-	0.05	0.04
Esophagus	-	0.05	0.04
Liver	-	0.05	0.04
Thyroid	0.03	0.05	0.04
Bone Surface	0.03	0.01	0.01

1977 **1991** **2007**

Let’s move now from theory to practice…

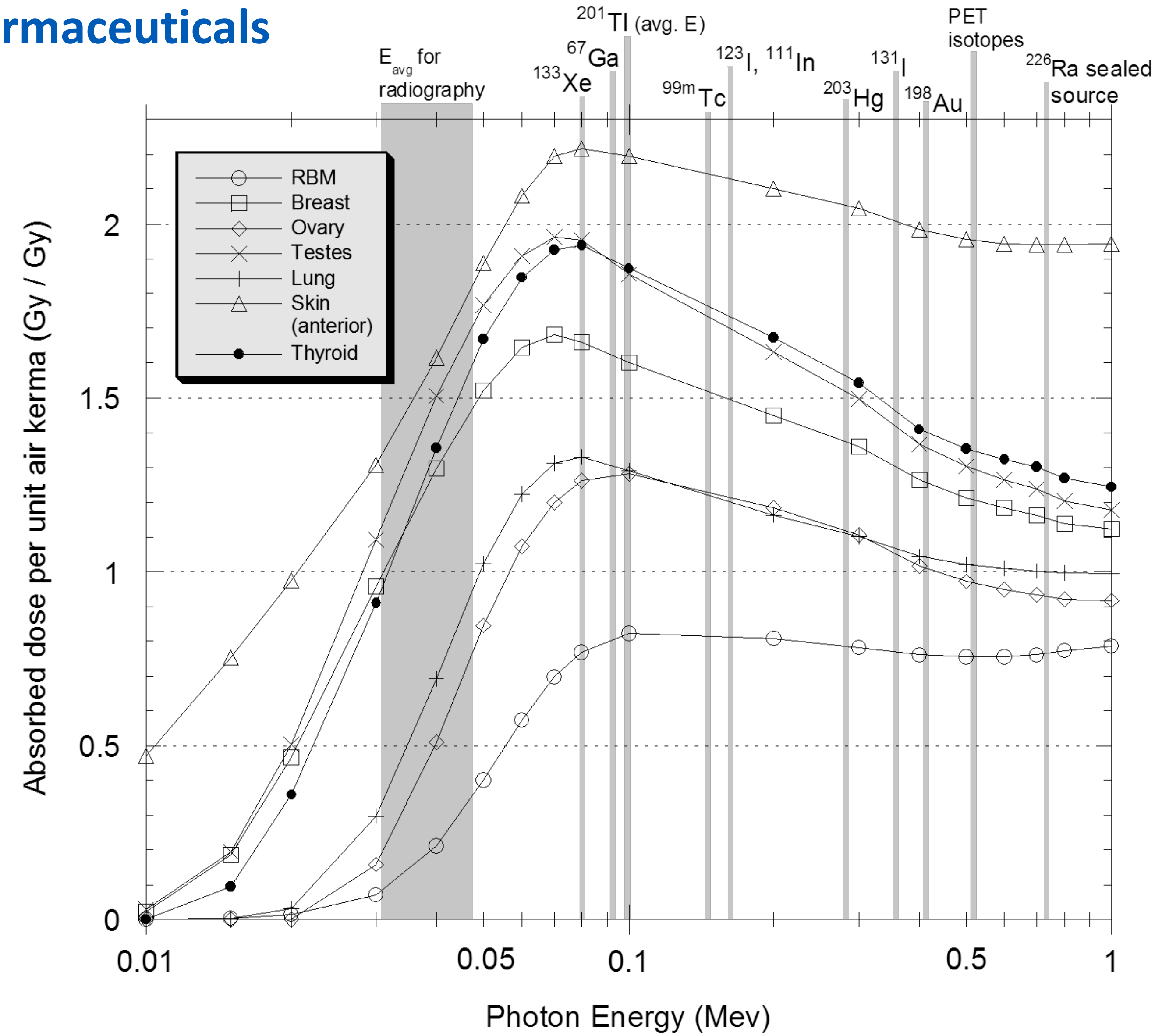
What aspects of radiation exposure are of direct relevance to radiation dosimetry <u>and</u> to radiation epidemiology?

1) **Specifics about the radiation**
   a) Type of radiation
   b) Energy of radiation

2) **Specifics about the exposure conditions**
   a) Internal or external exposure
   b) Geometry of exposure conditions
   c) Part of the body exposed
   d) Length of time of exposure
   e) Rate of exposure
   f) Total exposure

3) **Specifics about the person(s) exposed**
   a) Age, gender, body mass index, health status, etc.

Effect of increasing energy on organ dose per unit of air dose – example of anterior irradiation geometry for medical x-rays and some radiopharmaceuticals



INTERNAL RADIATION DOSE is a more complex subject because it also depends greatly on:

- Specific Radionuclide
- Type of radiation emitted
- Half-life
- Energy of radiation
- Chemical form of radionuclide
- Chemical and temporal behavior of nuclide in body (residence time in the body and accumulation in organs) , i.e., biokinetics
- Specifics about the exposed individual (age, health status), etc.

EXAMPLE: Iodine-131

The general equation to determine the dose following an accidental intake or following an oral medical administration of ^{131}I is:

$$D = \int_0^{\infty} \frac{A\ f_1\ f_2\ R(t)}{M_T(a)} \left[\sum_{i=1}^{n} Y_i\ E_i\ AF_i(T \leftarrow S, a) \right] dt$$

where,

A is the activity intake (or the administered activity of ^{131}I (Bq),

f_1 is the fraction of the iodine intake that is transferred to blood (generally assumed to be close to 100%)

f_2 is the fraction of the iodine intake that is absorbed by the thyroid (the rest is excreted primarily through urine),

R(t) is the fraction of the amount that enters the thyroid that is retained at any time, t,

Y_i is the fractional yield of radiation type i, per nuclear transformation,

E_i is the energy released per decay (~0.19 MeV β and ~0.36 MeV γ per nuclear transformation).

$AF_i(T \leftarrow S,a)$ is the fraction of the energy emitted in the source organ S that is absorbed, in the target organ T, and is a function of age, a,

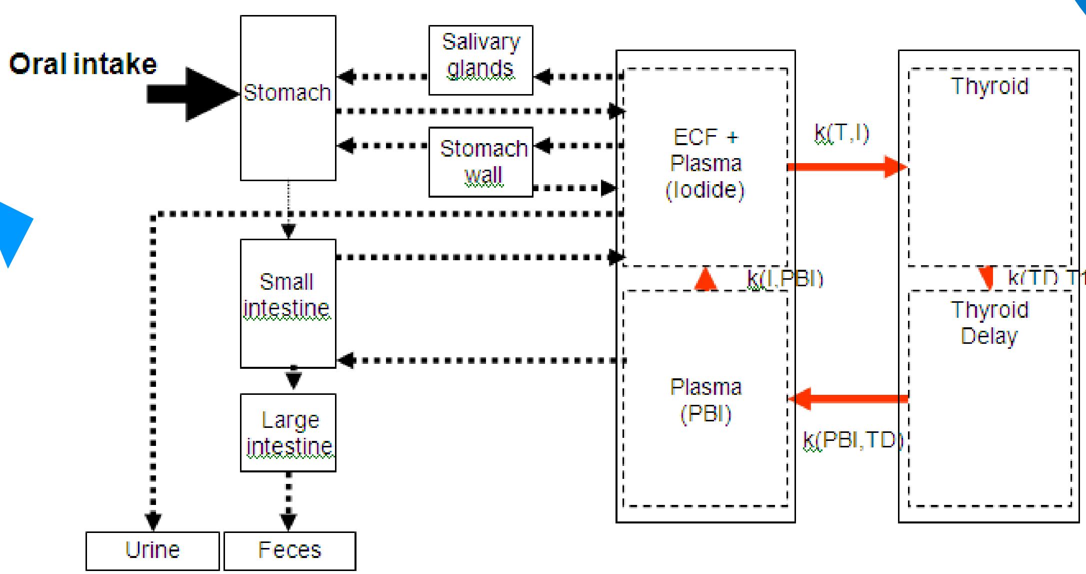
$M_{th}(a)$ is the mass of the thyroid in this case) and is a function of age, *a*

Simplified internal dosimetry equation incorporates all of previous factors.

$$D = \tilde{A}\, S$$

Dose = Time integral of decays in organ of interest x S factor

Equation is conveniently separated into components of biology (biokinetics, i.e., $\tilde{A}$) and physics (dosimetric factors, S)



Discussed in previous slides

Lets compare the magnitude of energy used in radiation physics and dosimetry with other things in life.

- Photons of visible light have energies of ~1.6 to 3 eV
- It takes about 34 eV to create ionize a single atom of air.
- X-rays have energies from about 1,000 eV to a few 100,000 eV.
- Iodine-131 has a prominent gamma ray emission of 364,000 eV
- Many radionuclides have gamma ray emissions with energy ~ 1,000,000 eV (1 MeV or 10^6 ev)
- 10^{12} eV is about the kinetic energy of a flying mosquito
- 6 x 10^{20} eV of energy is needed to power a 100 watt light bulb for one second
- One joule (J) = 6 x 10^{18} eV = 6 x 10^{12} MeV
- One Gray (radiation dose) is 1 joule of energy absorbed in 1 kg of material

COMPARISON (continued*)*

Assume that a fatal acute dose 70 kg adult is 10 Gy (= 10 J/kg) -> 700 J is transferred.

How much is 700 J in other terms?

•The energy of sunlight received on 1 square meter in bright daylight in 7/10 of a second.

•The metabolic energy derived from digestion of about 5 mg of carbohydrate, e.g., rice (typical serving is 200 g)

Other Comparisons:

•The chemical energy in a barrel of oil is equal to 8.5 million "doses" of 700 J each.

•The energy released by the Hiroshima atomic bomb is equal to about 8.8 $\times 10^{10}$ "doses" of 700 J each - fatal doses to the population of about 13 planet earths (with today's population of 6.8 billion people).

Of course, most energy was released as heat.

COMPARISON (continued)

So…what's the difference between transferring heat to a person and giving a radiation dose…they are both energy transfer??

The latter energy transfer is by i **on**

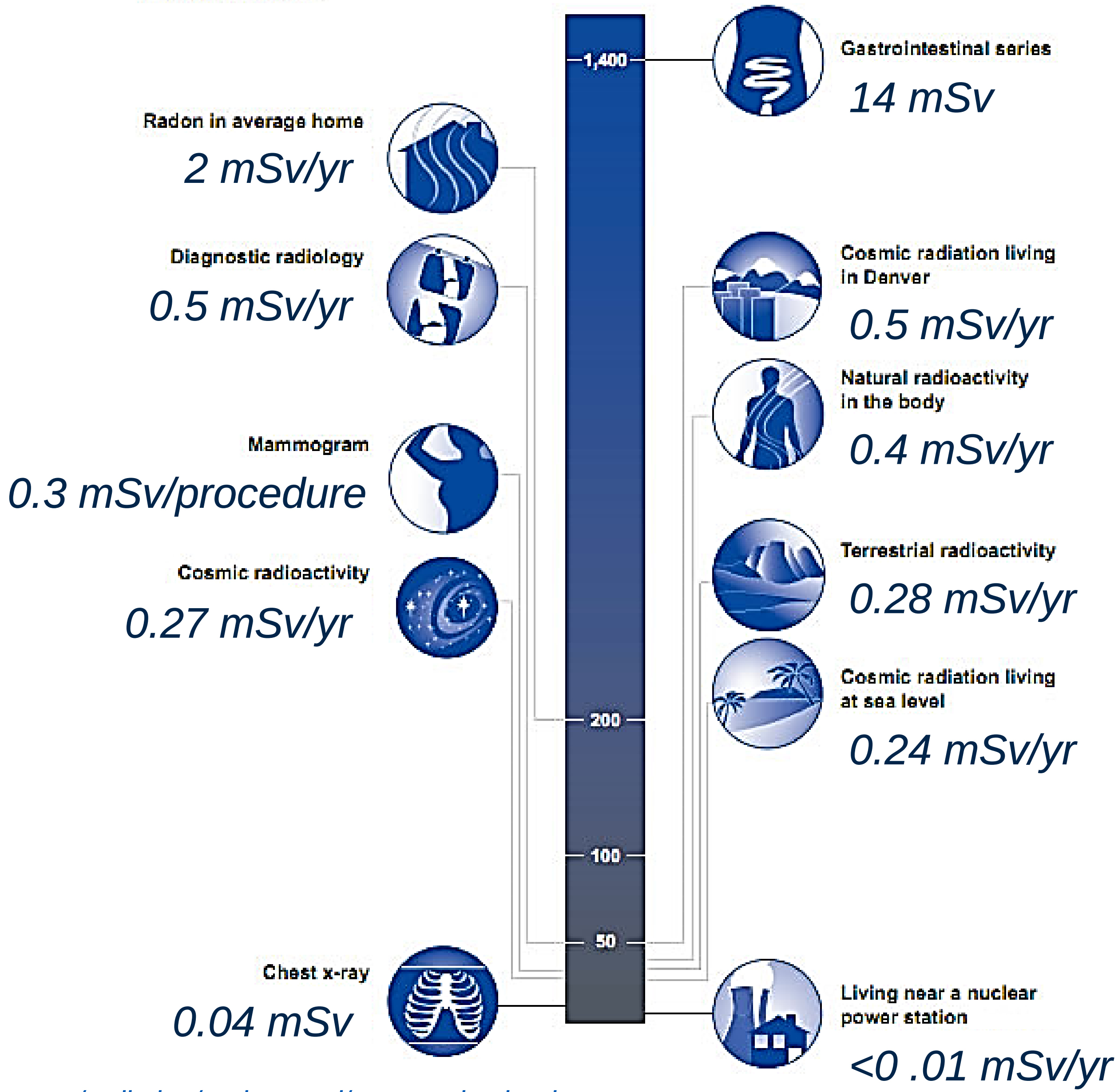
Part IV.
Sources of Radiation Exposure
(very short version !)

- Common sources of exposure
- Comparison of categories of radiation sources
- Environment (natural sources)
- Medical practice (diagnostic and therapeutic procedures)

<u>Not</u> discussed here due to lack of time are doses from:

- Occupations (industrial practices)
- Consumer products
- Accidental exposures and releases

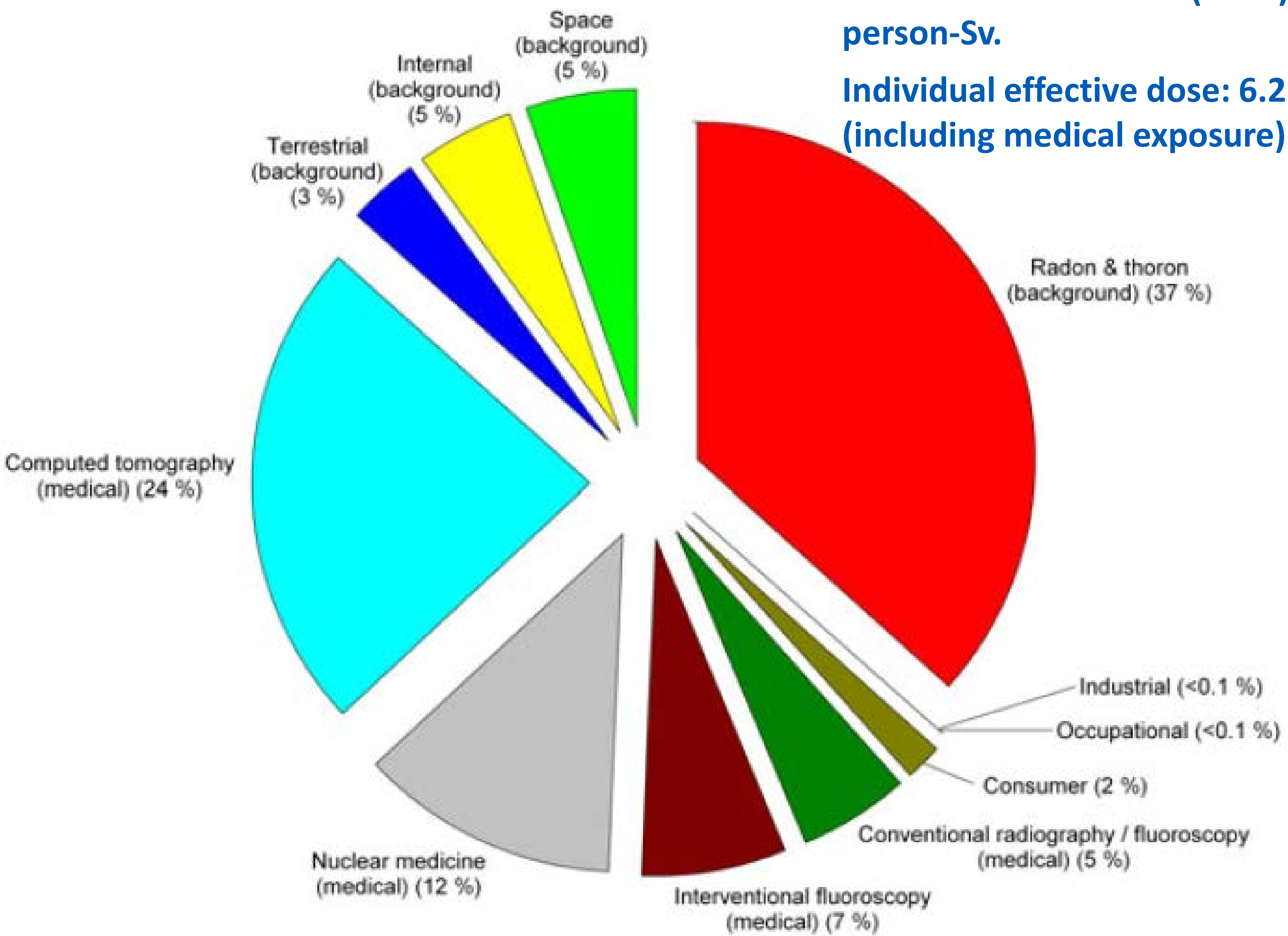
Comparison of Doses from Common Radiation Sources



http://www.epa.gov/radiation/understand/perspective.html

Collective dose in U.S. (2006): 1.9 M person-Sv.

Individual effective dose: 6.2 mSv (including medical exposure).



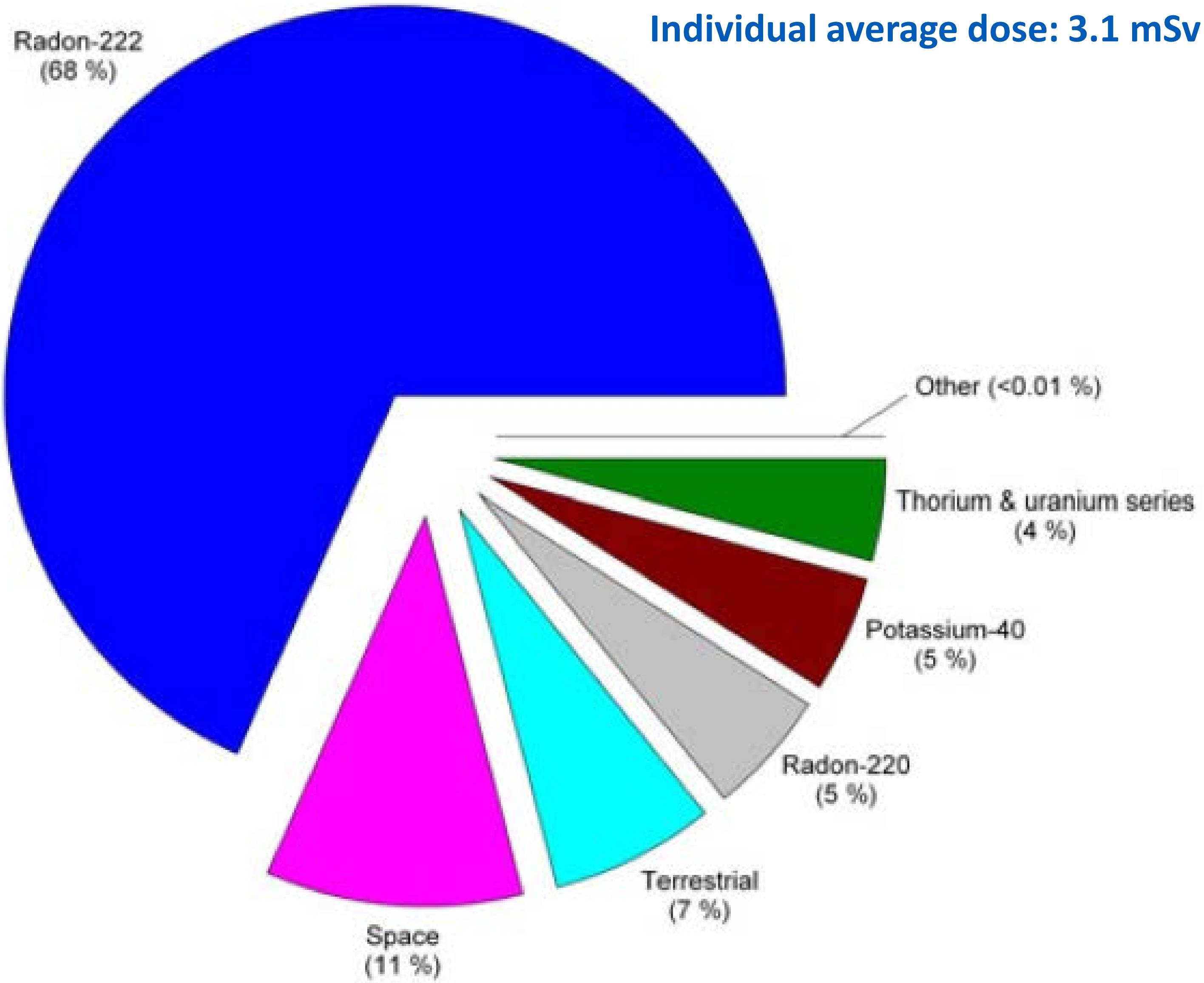
NCRP Report 160, 2009

Radiation Exposure in Medicine: Doses from procedures vary widely. The inevitable radiation exposure with medical procedures is usually considered as part of the cost to receive that benefit.

Most procedures give doses on the order of a few mSv.

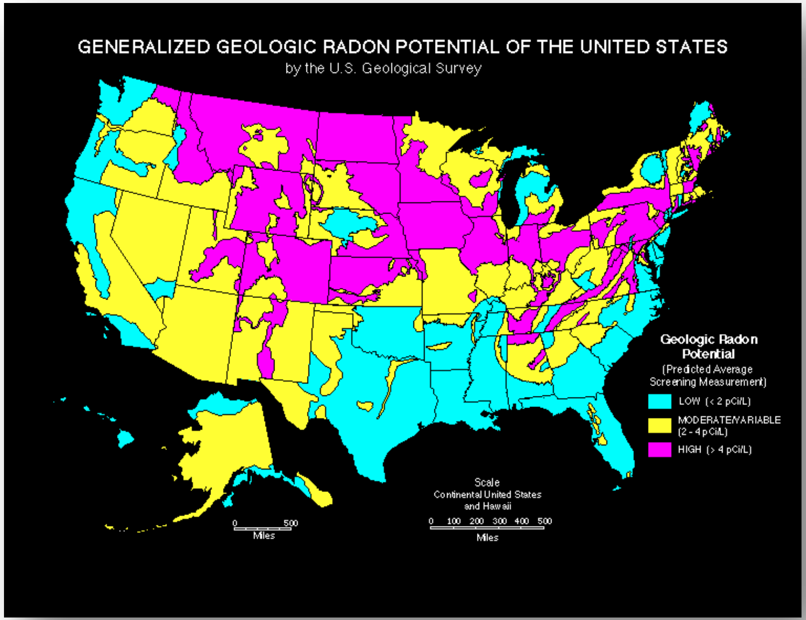
Complete Exams	Effective Dose mSv (mrem) [1]
Intravenous Pyelogram (kidneys, 6 films)	2.5 (250)
Barium Swallow (24 images, 106 sec. fluoroscopy)	1.5 (150)
Barium Enema (10 images, 137 sec. fluoroscopy)	7.0 (700)
CT Head	2.0 (200)
CT Chest	8.0 (800)
CT Abdomen	10.0 (1,000)
CT Pelvis	10.0 (1,000)
Angioplasty (heart study)	7.5 (750) - 57.0 (5,700) [3]
Coronary Angiogram	4.6 (460) - 15.8 (1,580) [3]

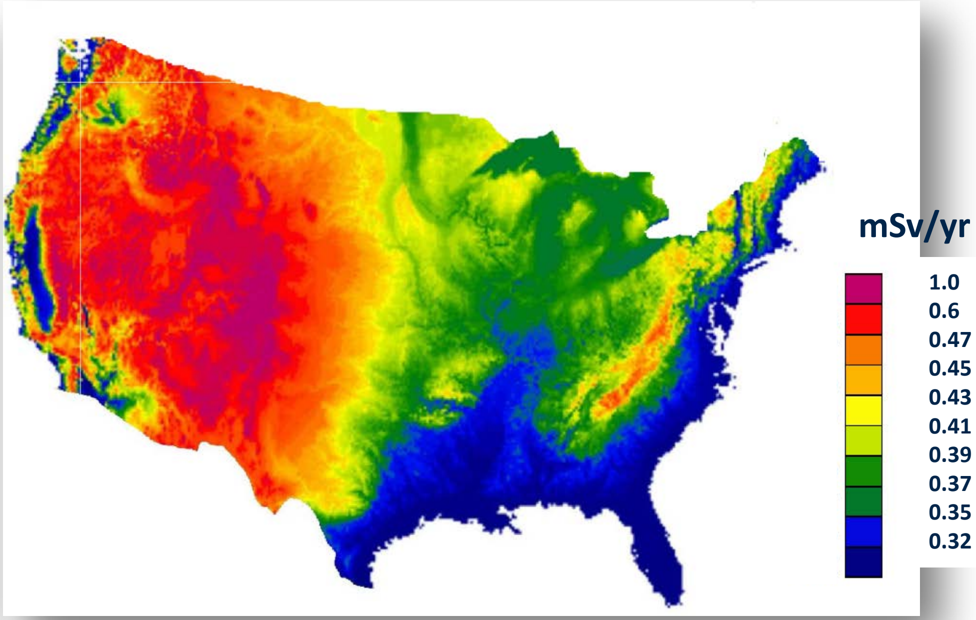
Background radiation exposure.
Individual average dose: 3.1 mSv

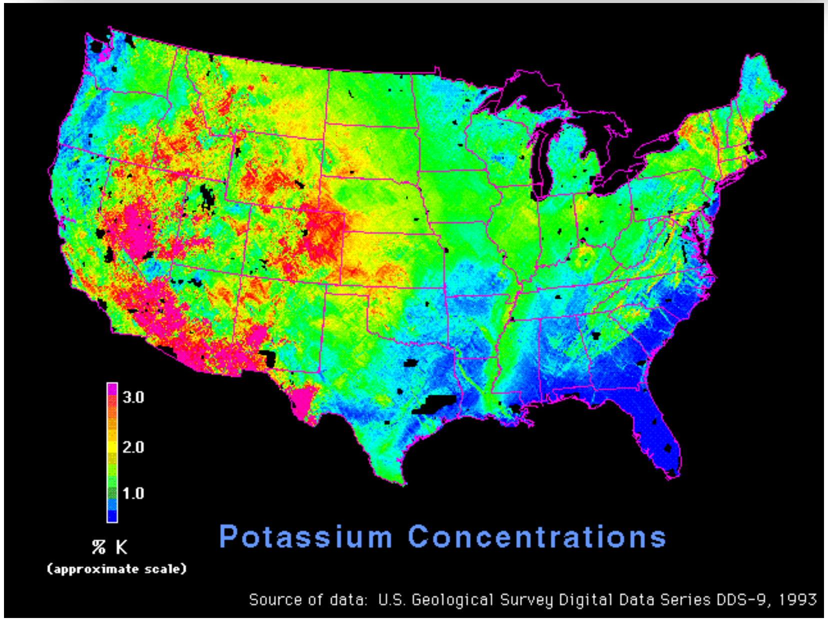


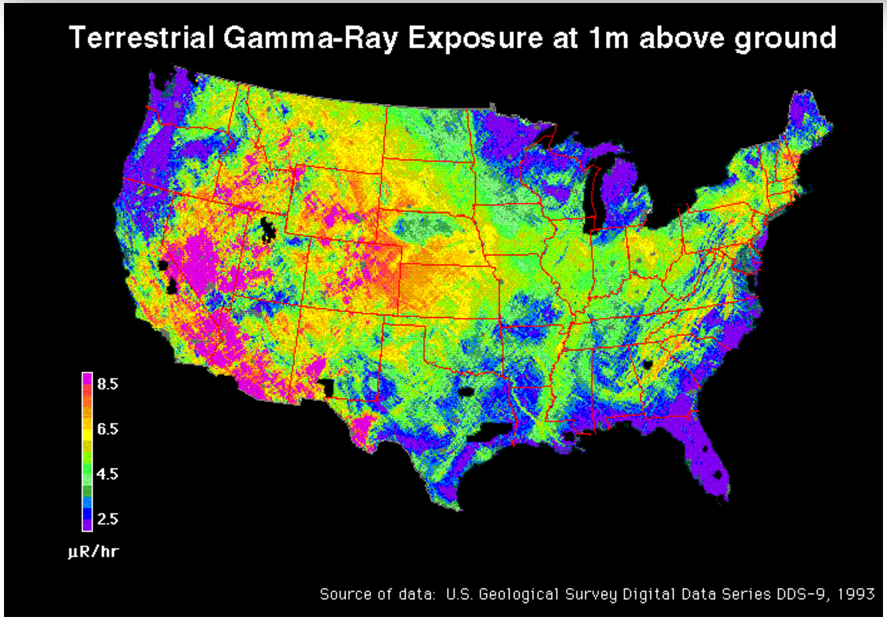
NCRP Report 160, 2009

Sources of Background Radiation Exposure



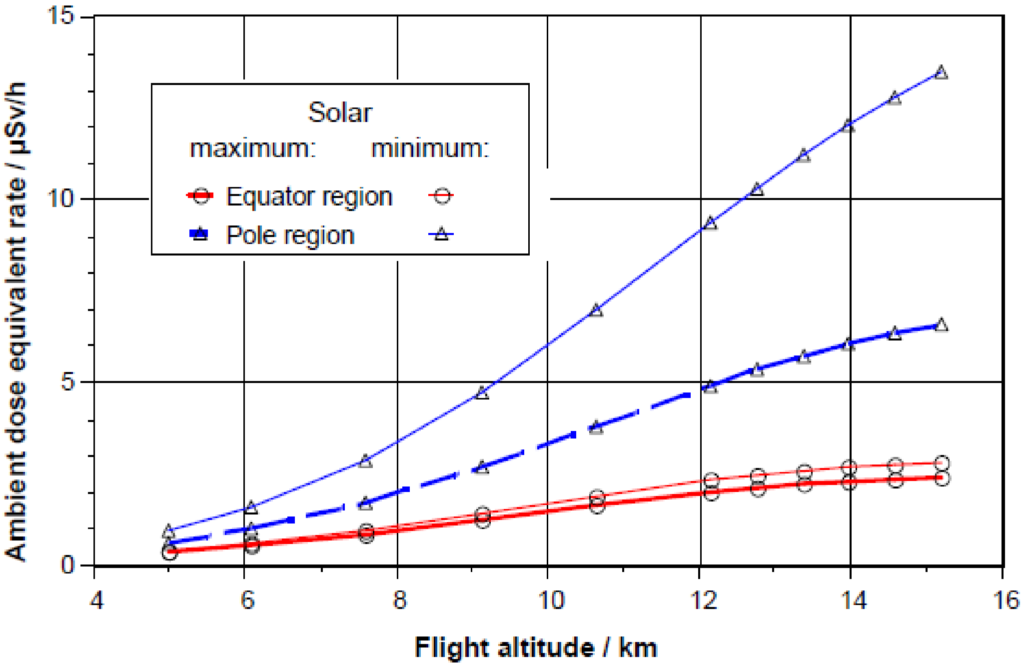


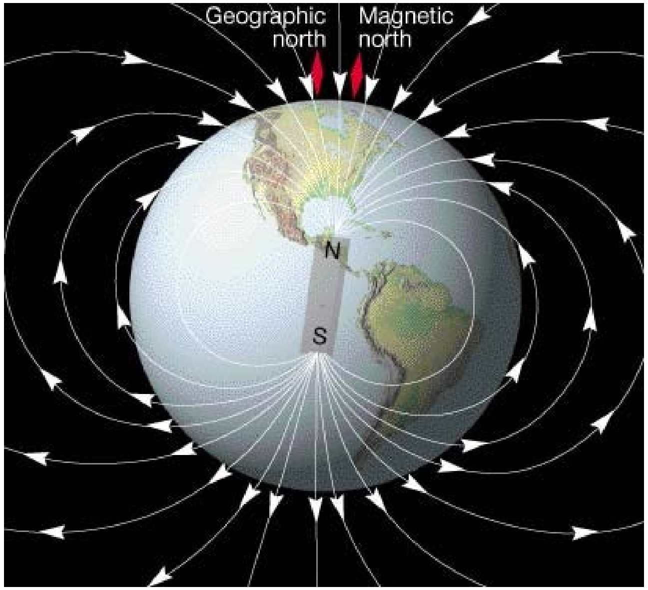




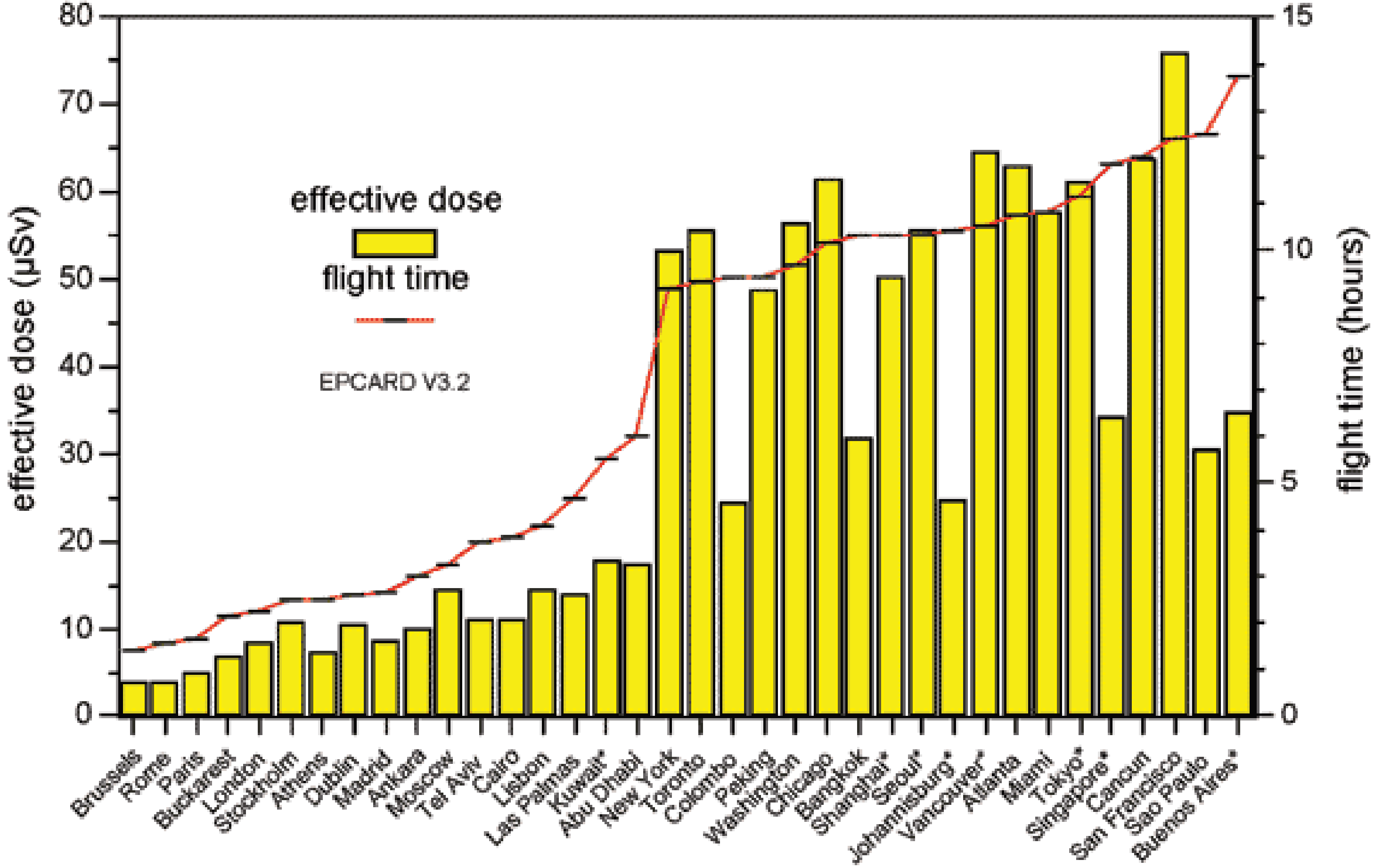
Source: USGS and Geological Survey of Canada

Cosmic ray dose is higher at greater altitudes and in polar regions for any given altitude.





Cosmic ray dose increases with elevation or altitude and with time spent at high altitudes, e.g., when flying internationally.



Data: GSF


THE END IS NEAR

PART V.
Dosimetry to Epidemiology

- Completing the Circle -

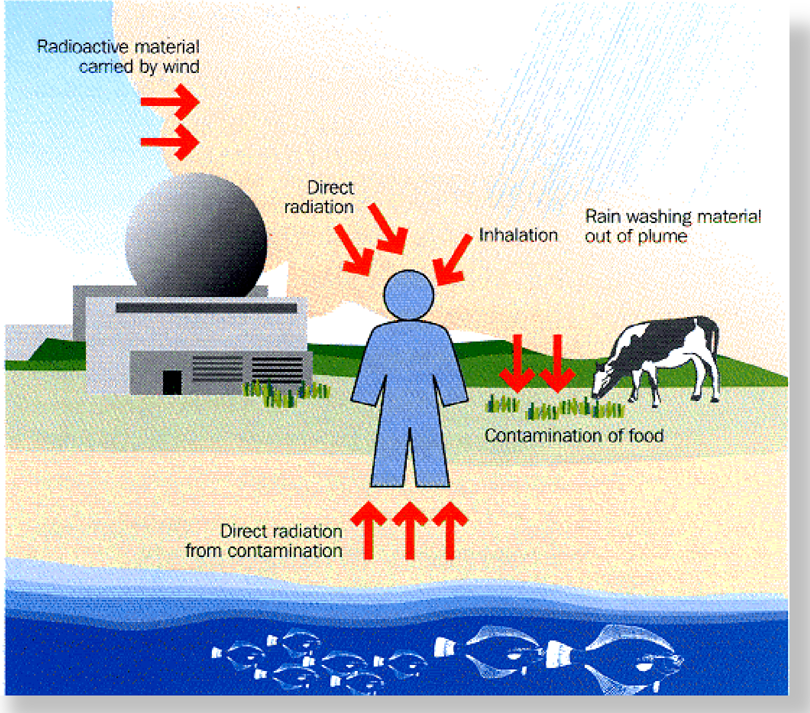
Up to this point, we've discussed dosimetry on a theoretical level, emphasizing the processes leading to the release and absorption of energy.

However, dosimetry, for the purposes of epidemiologic studies, depends primarily on applying the following principles.

<u>Applied Dosimetry</u> can be loosely subdivided into:

- "**Internal Dosimetry**" where the energy delivered to tissue from sources within the body, e.g., radionuclides, and
- "**External Dosimetry**" where the energy delivered to tissue originates from sources of radiation outside the body.

Though there are different techniques used in internal and external dosimetry, <u>the principles of physics remain the same.</u>



Almost all of the differences in medical, occupational, and environmental dosimetry can be attributed to:

- Differences in the sources of the radiation, and
- Whether the amount received by individuals was controlled, as in medical exposures,
- Whether exposure was received with moderate control but with some monitoring (typical of occupational exposures), or
- Exposure was received with no control and no monitoring on the individual level (typical of environmental exposures).

The major technical challenge of dosimetry for epidemiologic purposes is not in applying the physics of radiation interactions (something already well understood), but in determining **how the exposure was received** and **how much radiation** a person was exposed to.

Dosimetry for purposes of epidemiologic studies requires not only the concepts of physics, but also chemistry, anatomy, physiology, diet and nutrition, behavior and lifestyle, environmental science and ecology.

Dosimetry Physics + Exposure Assessment = Dose Assessment

To Reiterate: Because most dosimetry calculations conducted for epidemiologic studies are retrospective (i.e., doses were received in the past), most of the difficulties are associated with determining the **specifics of past exposure conditions** and not the application of the physical principles.

Relative Difficulty and Uncertainty in Reconstructing Radiation Doses

Relatively easy (exposure conditions are known):

- Medical x-ray procedures (therapeutic and diagnostic)
- Medical external beam radiation therapy

More difficult and uncertain

- Internal medical radioisotope procedures for past decades.
- Occupational dose for medical radiation workers

Still more difficult and uncertain:

- Occupational doses for industrial situations, particularly for poorly monitored working conditions
- Nuclear fallout related external doses

Substantially difficult and uncertain:

- Occupational doses for industrial situations, without radiation monitoring data
- Accident and nuclear fallout related internal doses
- Any situation without an adequate description of the source of radiation (energy and geometry) and the exposure conditions.

Closing Remarks for Epidemiologists

There are a variety of ‘types’ of doses used in past literature and in past and present radiation protection, including:

–shallow dose,
–deep dose,
–deep equivalent dose,
–absorbed dose,
–dose equivalent,
–equivalent dose,
–effective dose,
–effective dose equivalent,
–committed dose,
–committed effective dose,
–committed effective dose equivalent, etc.

Having worked in radiation epidemiology, my advice is…

- Be wary of the many dose-related terms and dose estimates available in historical literature, particularly if the explanation about the origin of the estimates is not provide or unclear.
- Understand that:
    - Some dose estimates serve purposes that are probably not of interest to you, such as for establishing compliance in radiation protection activities, etc.
    - Some dose estimates may have been calculated by methods, models, or with definitions that are no longer in use or accepted.
    - Doses may be averages over multiple organs or weighted by factors unknown to you or are irrelevant to you.
- Dose estimates other than **organ absorbed dose** will likely not be what is needed for your research purposes.
- **Stick with Gy (or rad)** in epidemiology, and possibly equivalent dose, though the applications for it will be few.

My advice (con't.) is…

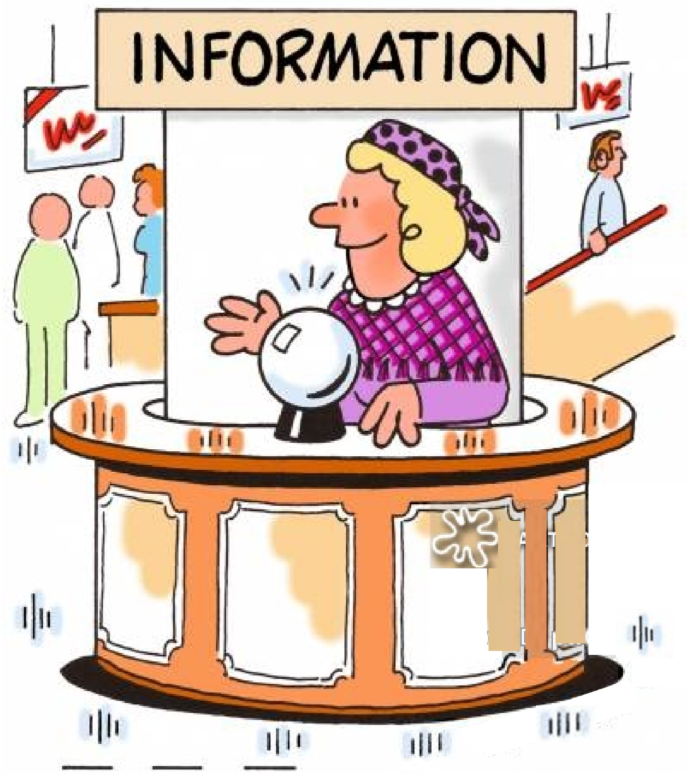
- When collaborating with other scientists who might not appreciate the requirements of epidemiology, seek clarification on exactly what *kind* of dose is being provided.

- Finally, ask for legitimate statements of uncertainty (or conversely, the precision) of dose estimates and never assume that doses are known with absolute (or even high) certainty.


THE END
IS NEAR.
I mean it this time...

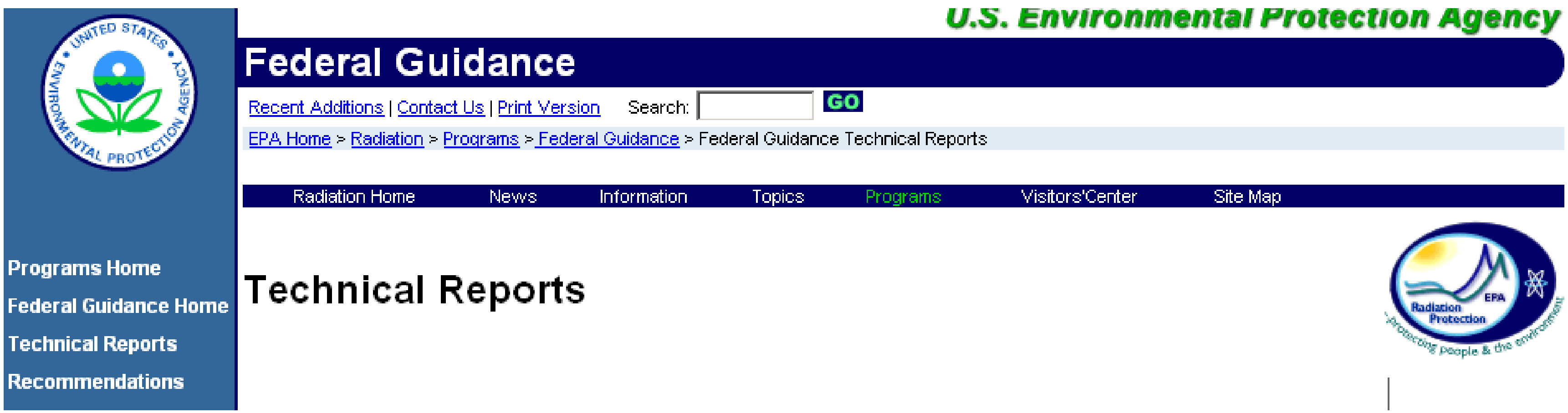
Part VI.

Where can you go for reliable information on dosimetry, dose estimation, dose limitation guidelines, etc. ?

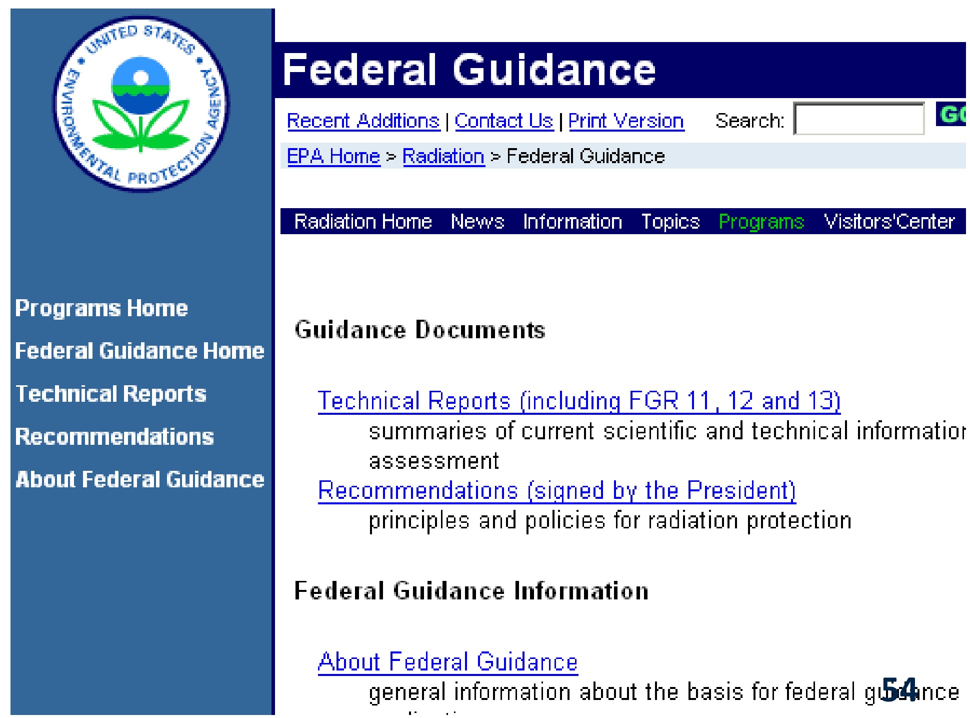


https://www.cartoonstock.com/

(1) EPA (e.g., Federal Guidance, Dose Coefficients, Limiting Values of Exposure)



http://www.epa.gov/radiation/federal/



(2) NCI website for links to useful organizations: http://dceg.cancer.gov/reb/tools/useful-links

Radiation Epidemiology Branch

Understanding the link between radiation exposure and cancer

Radiation Epidemiology > Tools & Resources > Useful Links

Tools & Resources

Useful Links

ICRP: International Commission on Radiological Protection

NIAID: Medical Countermeasures Against Radiological and Nuclear Threats

HPA: Health Protection Agency (UK)

IAEA: International Atomic Energy Agency

ICRU: International Commission on Radiation Units and Measurements

International Agency for Research on Cancer

International Commission on Non-Ionizing Radiation Protection

NRSB: Nuclear and Radiation Studies Board

NCRP: National Council on Radiation Protection and Measurements

RERF Publications: Radiation Effects Research Foundation

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

WHO, Ionizing Radiation Section: World Health Organization

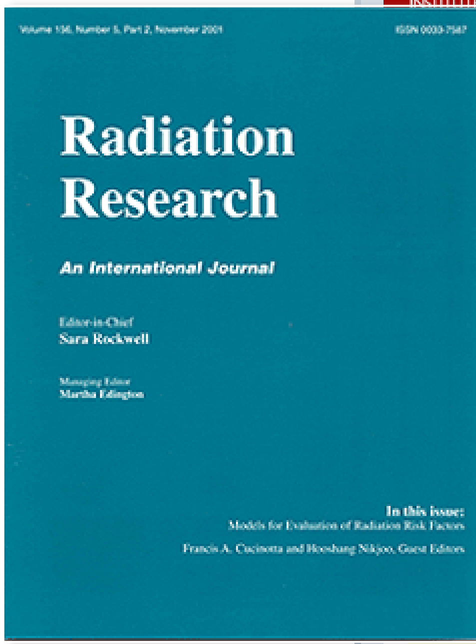
Radiation Research Society

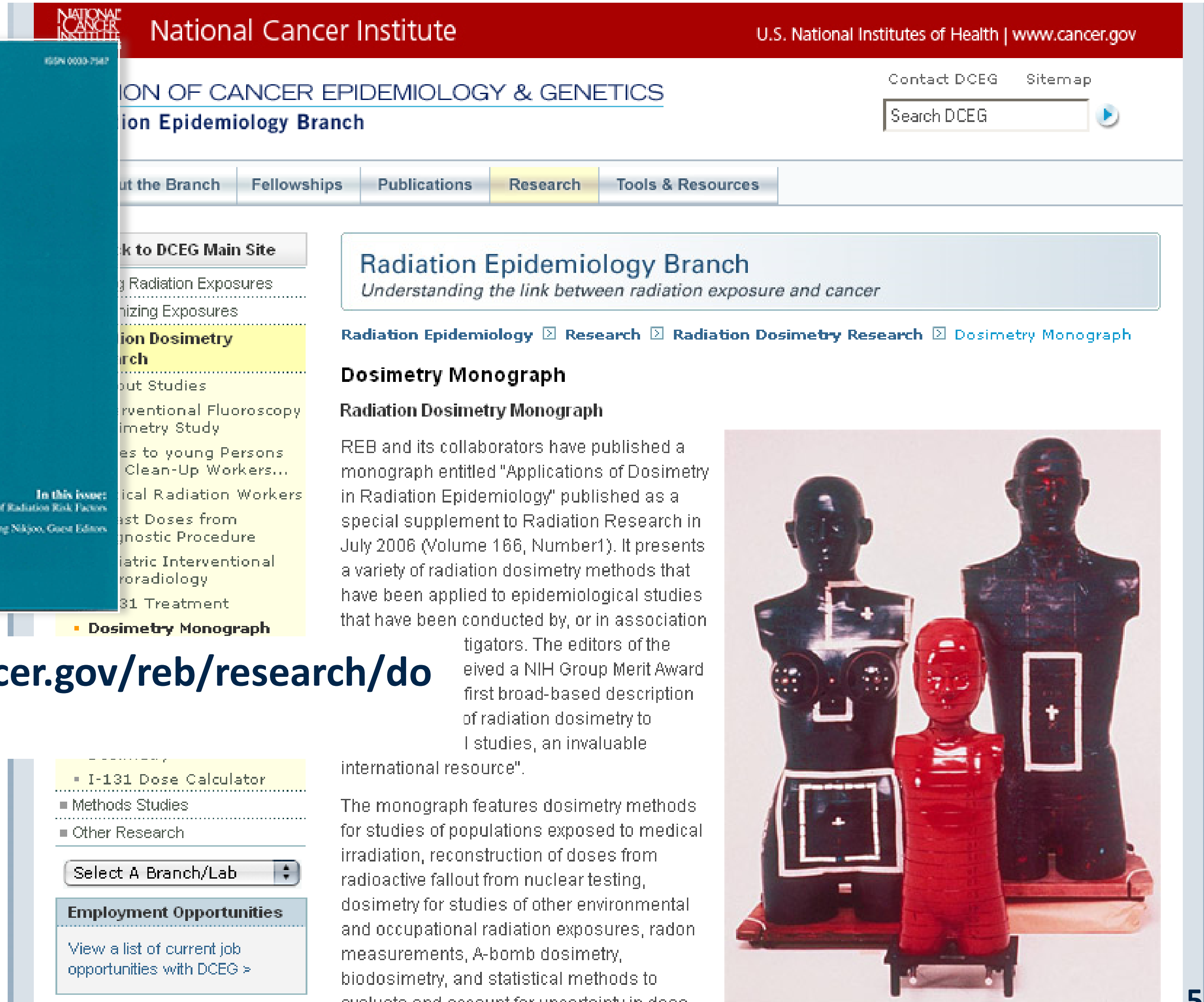
Health Physics Society

The Radiation Information Network

Late Health Effects of Ionizing Radiation Conference May 4-6 2009

(3) Applications of Dosimetry to Epidemiology – *Radiation Research* (July, 2006)

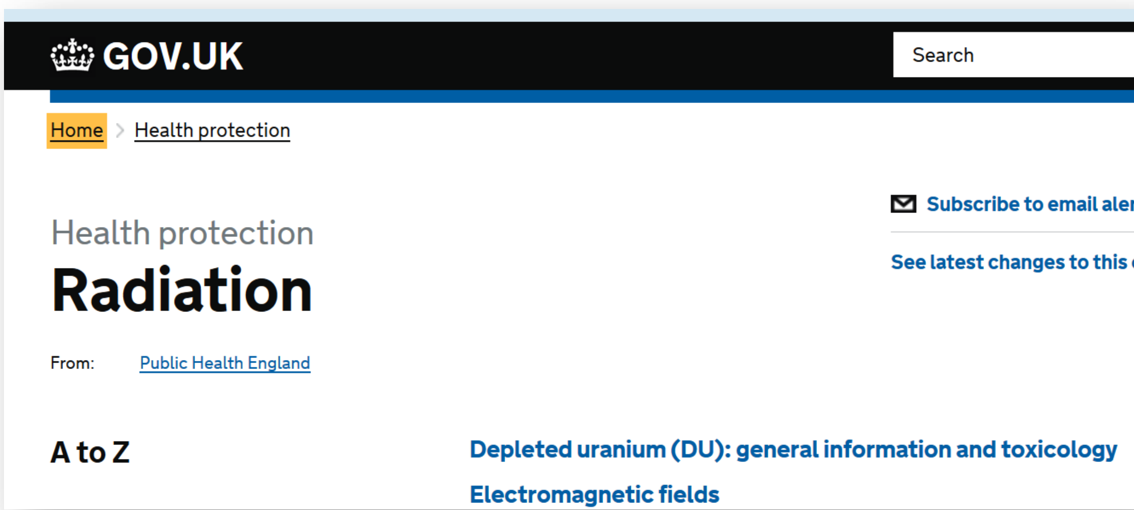




http://dceg.cancer.gov/reb/research/dosimetry/7

(4) International Atomic Energy Agency: https://www.iaea.org/

(5) UK Health Protection Agency: https://www.gov.uk/health-protection/radiation




That's all Folks!
REALLY !!

Questions and Answers

U.S. Department of Health and Human Services
National Institutes of Health | National Cancer Institute
www.dceg.cancer.gov/RadEpiCourse
1-800-4-CANCER
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