Radioactivity

Lecture 7

Dosimetry and Exposure Limits

Radiation Exposure - Radiology

The radiation impact on biological and genetic materials requires some protective measures!

Units for scaling the decay

Classical Unit: 1 Curie [Ci]

$$1\left[Ci\right]=\frac{dN}{dt}=3.7\cdot 10^{10}\left[\frac{decays}{s}\right]$$

Modern Unit: 1 Becquerel [Bq]

$$1\left[Bq\right]=\frac{dN}{dt}=1\left[\frac{decay}{s}\right]$$

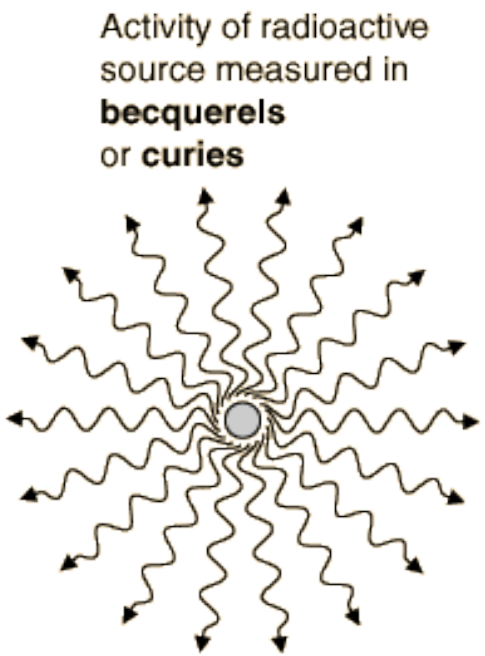
The so-called dosimetry units (rad, rem) determine the amount of damage radioactive radiation can do to the human body. They depend on the kind and nature of the incident radiation

(X-rays, γ-rays, α-particles, β-particle, or neutrons).

It also depends on the energy loss of the particular radiation and the associated ionisation effects in the human body material.

Refresher example

You have a radioactive sample that emits one alpha particle per second. What is the activity of the sample in Bq and in Ci?



$$\frac{dN}{dt} = 1\left[\frac{decay}{s}\right] = 1\left[Bq\right]$$

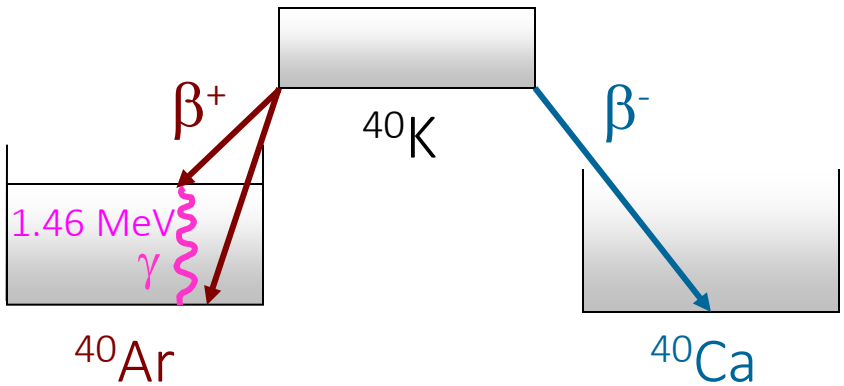
$$1\left[Ci\right] = \frac{dN}{dt} = 3.7 \cdot 10^{10}\left[\frac{decays}{s}\right] = 3.7 \cdot 10^{10}\left[Bq\right]$$

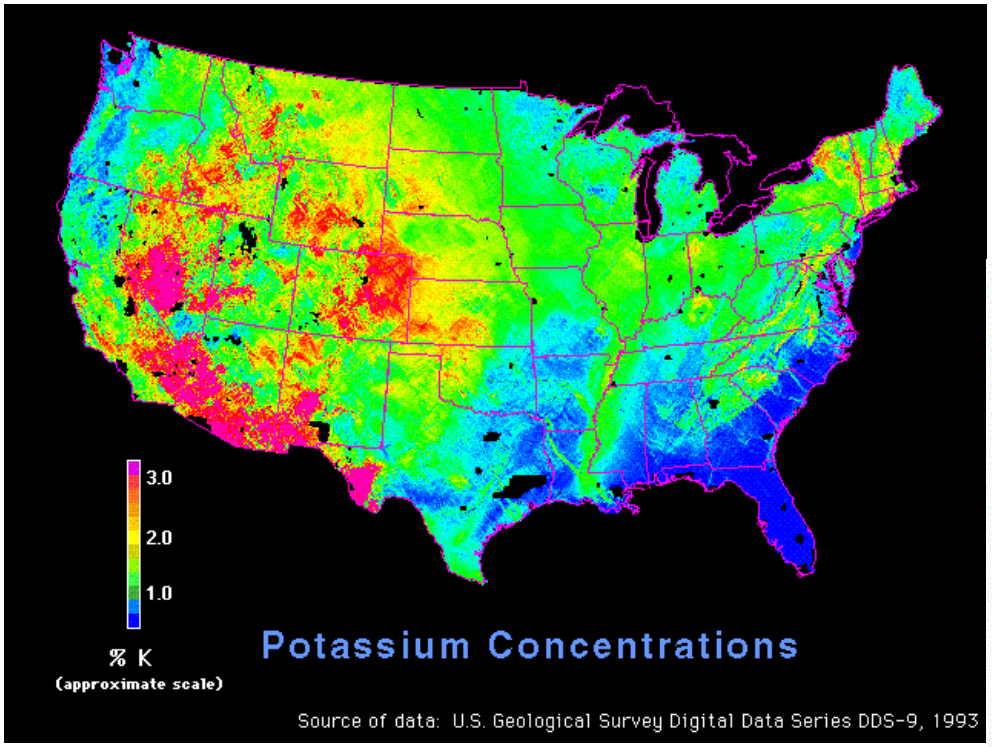
$$1\left[Bq\right] = \frac{1}{3.7 \cdot 10^{10}}\left[Ci\right] = 2.7 \cdot 10^{-11}\left[Ci\right]$$

The nature of the radiation doesn't make any difference on the activity!

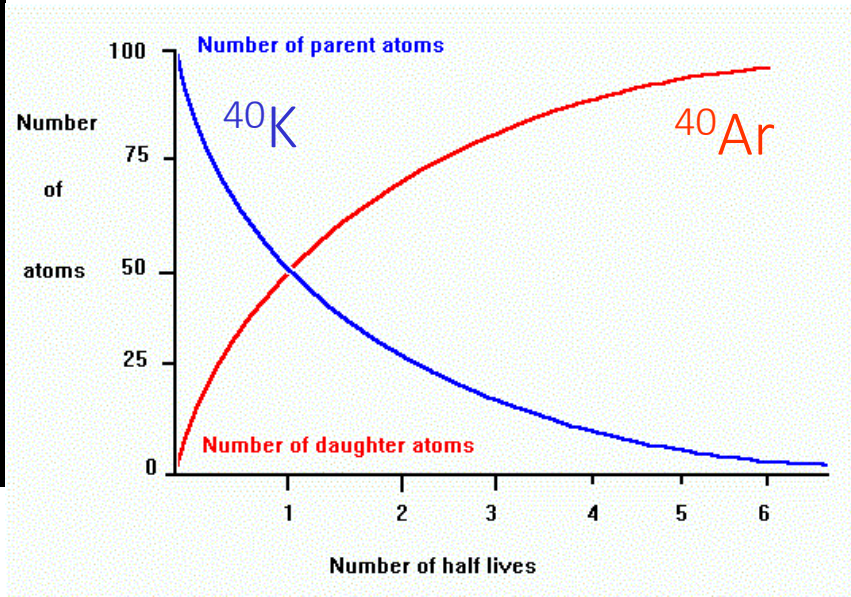
Long lived ^{40}K radioactivity

^{40}K has a half-life of $T_{1/2}=1.28\cdot10^{9}$ years its natural abundance is 0.021 % of the elemental potassium abundance.



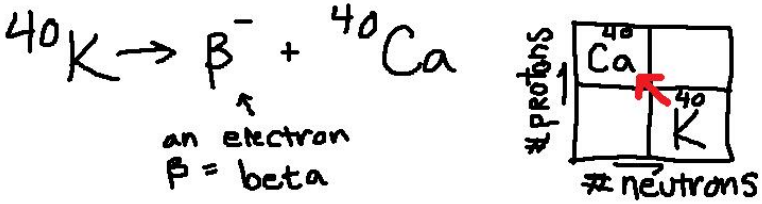


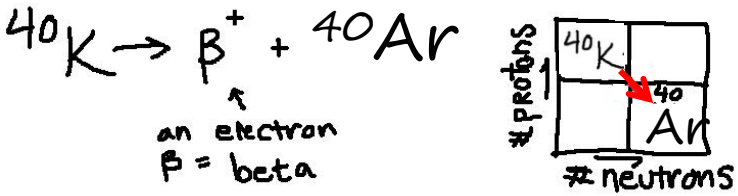
Potassium-Argon dating method



^{40}K in Human Body

The human body contains ~ $7 \cdot 10^{20}$ radioactive ^{40}K particles, $T_{1/2}$=1.25 10^9y.
What is the activity in Becquerel and Curie?





$$A(t) = \lambda \cdot N(t)$$

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.69}{1.25 \cdot 10^9 [y]} = \frac{0.69}{1.25 \cdot 10^9 \cdot 3.14 \cdot 10^7 [s]} = 1.53 \cdot 10^{-17} [s^{-1}]$$

$$A = 1.53 \cdot 10^{-17} [s^{-1}] \cdot 7 \cdot 10^{20} = 10700 [s^{-1}] = 10700 [Bq]$$

$$A = 10700 [Bq] = \frac{1.07 \cdot 10^4}{3.7 \cdot 10^{10}} [Ci] = 2.9 \cdot 10^{-7} [Ci] = 0.3 [\mu Ci]$$

Radiological Units

Dose: $$D = \frac{E}{m}$$

Amount of energy *E* deposited by radiation into body part of mass *m*.

Unit Rad or Gray

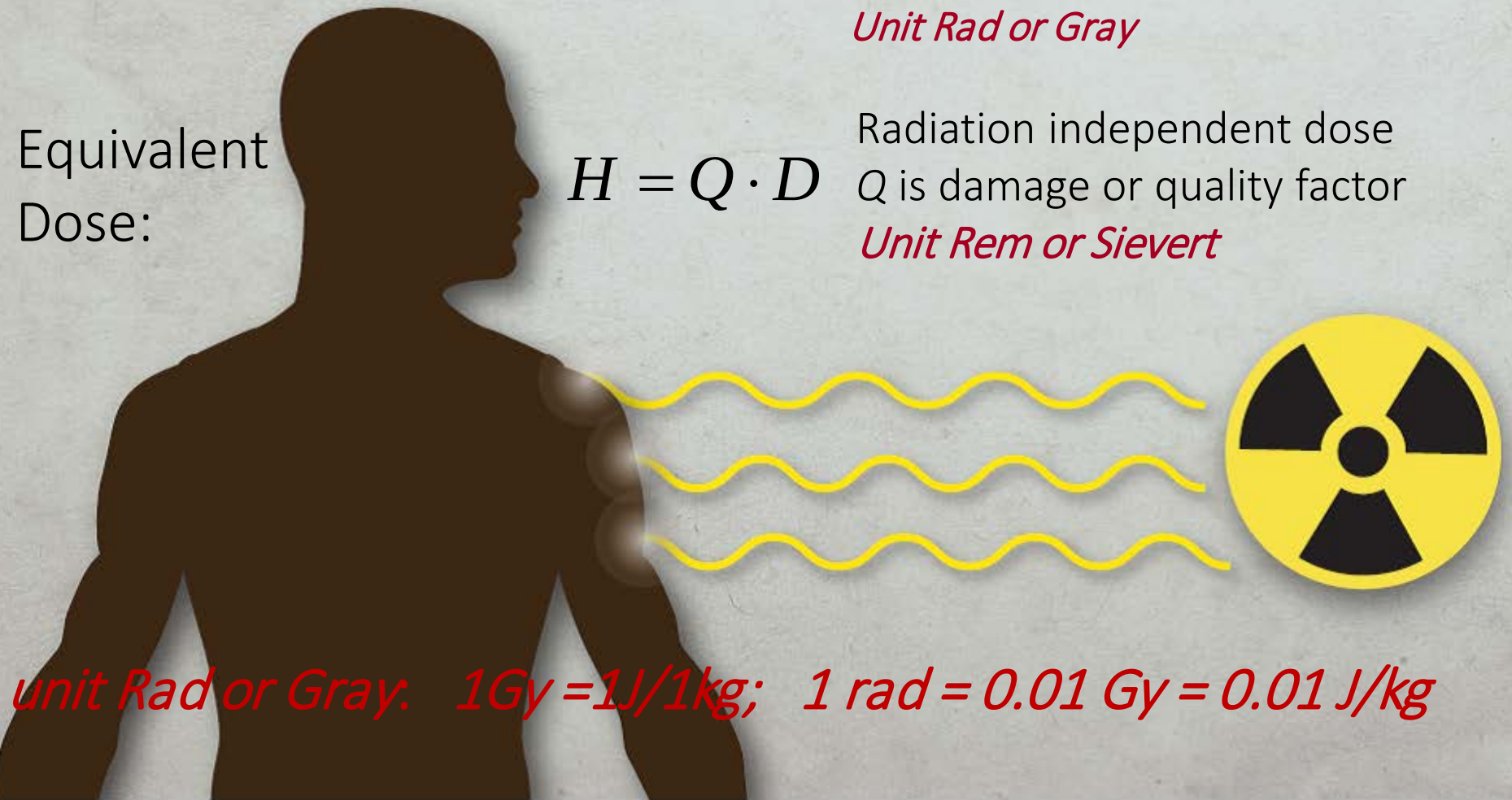
Equivalent Dose:

$$H = Q \cdot D$$

Radiation independent dose

Q is damage or quality factor

Unit Rem or Sievert

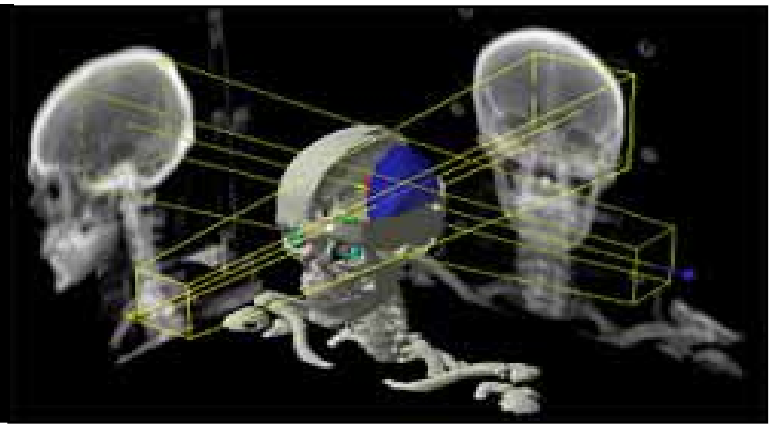


unit Rad or Gray: 1Gy =1J/1kg; 1 rad = 0.01 Gy = 0.01 J/kg

Biological Impact Measures

Each kind of radiation has a different impact on body material through the kind of physical interaction during the stopping of the radiation and the amount of energy transferred to biological system. Each kind of radiation has a specific weighting factor Q to determine the equivalent dose:

Photons:	Q=1
Neutrons: E<10keV	Q=5
Neutrons: E>10keV	Q=15
Protons:	Q=5
Alphas :	Q=20

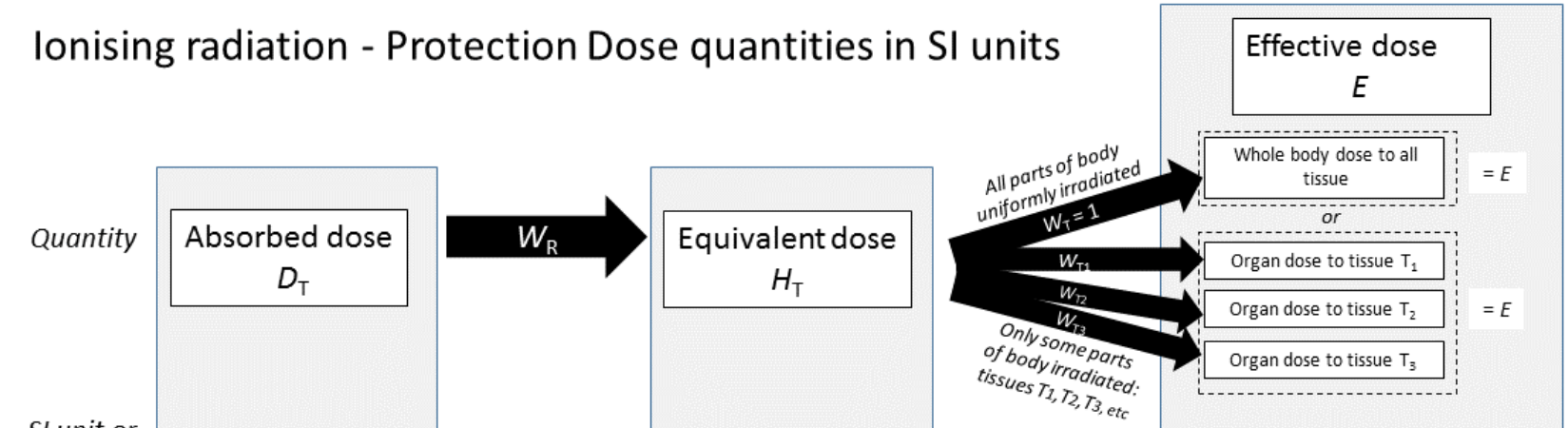


In radiology, in particular for medical applications, this is refined by the introduction of body-part specific weighting factors for the different kind of radiation particles or waves!

Equivalent Dose to Effective Dose

$$H = Q \cdot D \qquad E = \sum W_T \cdot D$$

Ionising radiation - Protection Dose quantities in SI units

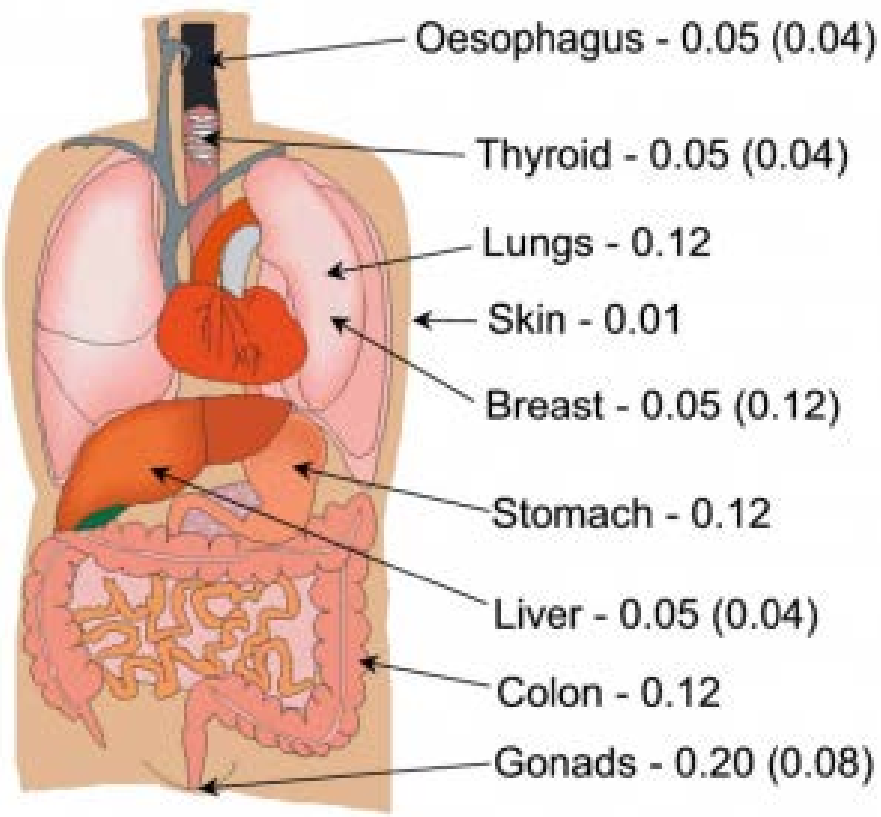


Quantity	Absorbed dose D_T	W_R	Equivalent dose H_T	All parts of body uniformly irradiated: $W_T = 1$; Only some parts of body irradiated: tissues T1, T2, T3, etc: W_{T1}, W_{T2}, W_{T3}	Effective dose E: Whole body dose to all tissue = E or Organ dose to tissue T_1, Organ dose to tissue T_2, Organ dose to tissue T_3 = E
SI unit or modifier	gray (Gy)	Radiation weighting Factor - W_R	sievert (Sv)	Tissue weighting factor - W_T	sievert (Sv)
Derivation	joule/kg	Dimensionless factor	joule/kg	Dimensionless factor	joule/kg
Meaning	**Energy absorbed** by irradiated sample of matter - a physical quantity.		**Biological effect of** radiation type R with weighting factor W_R. Multiple radiation types require calculation for each, which are then summated.		**Biological effect** on tissue type T having weighting factor W_T **Partial irradiation** Effective dose = summation of organ doses to those parts irradiated **Complete (uniform) irradiation** If *whole* body irradiated *uniformly*, the weightings W_T summate to 1. Therefore, Effective dose = Whole body Equivalent dose

Weighting Factors

Tissue Weighting Factors (ICRP 60)

Organ or Tissue	**W_T**
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05 [2,3]



Dose units in Radiology

The Sievert (Gray) is a measure of biological effect.

1 Gray (Gy) = 1 Joule/kg (Energy/mass)

1 Sievert (Sv) = 1 Gray x Q, where Q is a "quality factor" based on the type of particle.

Q for electrons, positrons, and x-rays = 1 Q = 3 to 10 for neutrons, protons dependent upon the energy transferred by these heavier particles.

Q = 20 for alpha particles and fission fragments.

Converting older units:

1 rad = 1 centigray = 10 milligrays (1 rad = 0.01 Gy = 10 mGy)

1 Gy = 100 rad

1 rem = 1 centisievert = 10 millisieverts (1 rem = 0.01 Sv = 10 mSv)

1 Sv = 100 rem

Nominal background radiation absorbed dose of 100 mrad/year = 1 mGy/yr.

Nominal background radiation dose biological equivalent of 100 mrem/year = 1mSv/yr.

Occupational whole body limit is 5 rem/yr = 50 mSv/yr.

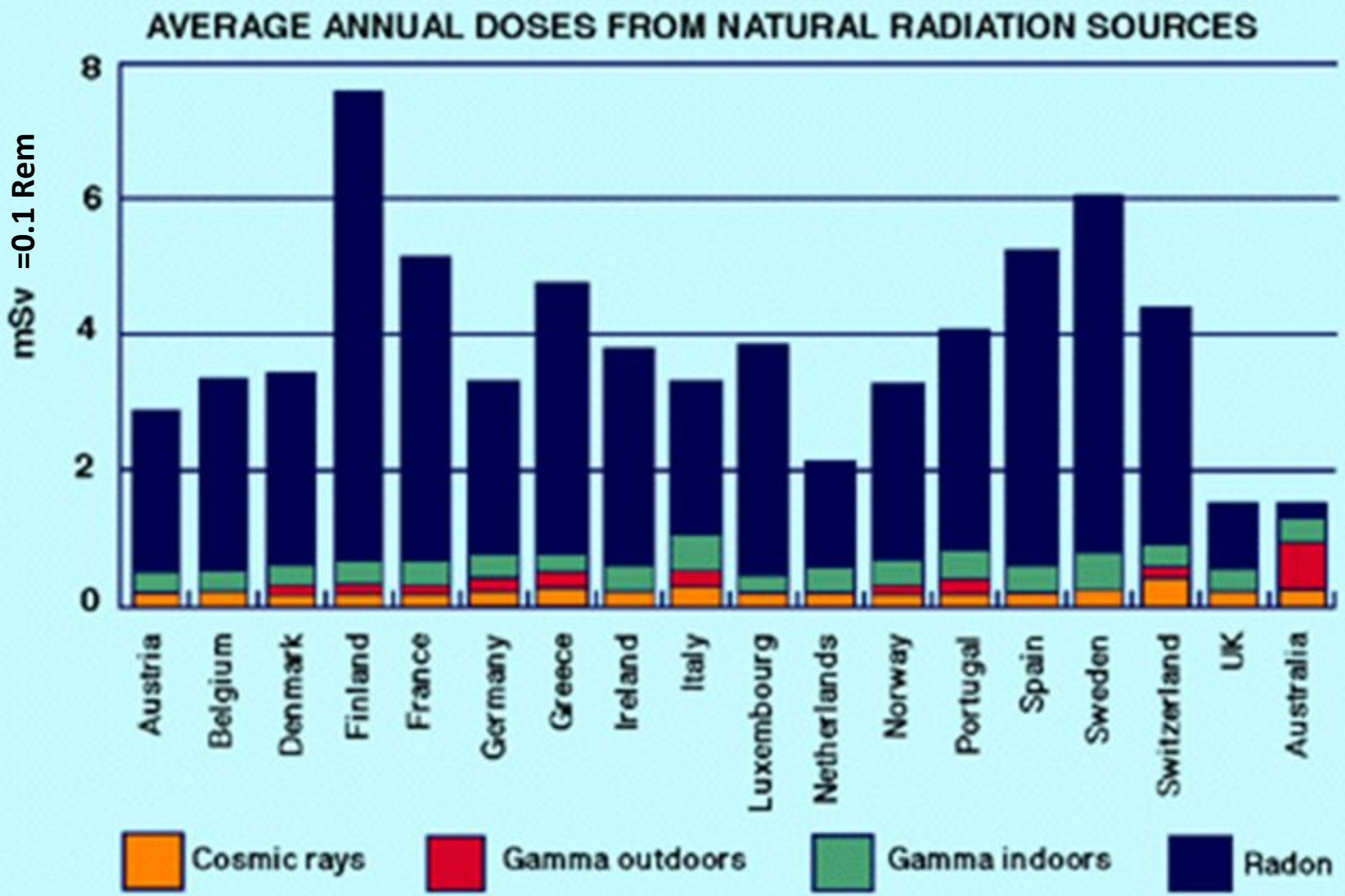
2.5 mrem/hr or 25 uSv/hr is maximum average working level in industry.

Exposure rate from Naturally Occurring Radioactive Material; an empirically derived conversion factor for Ra-226 decay series: 1.82 microR/ hour = 1 picoCurie/gram.

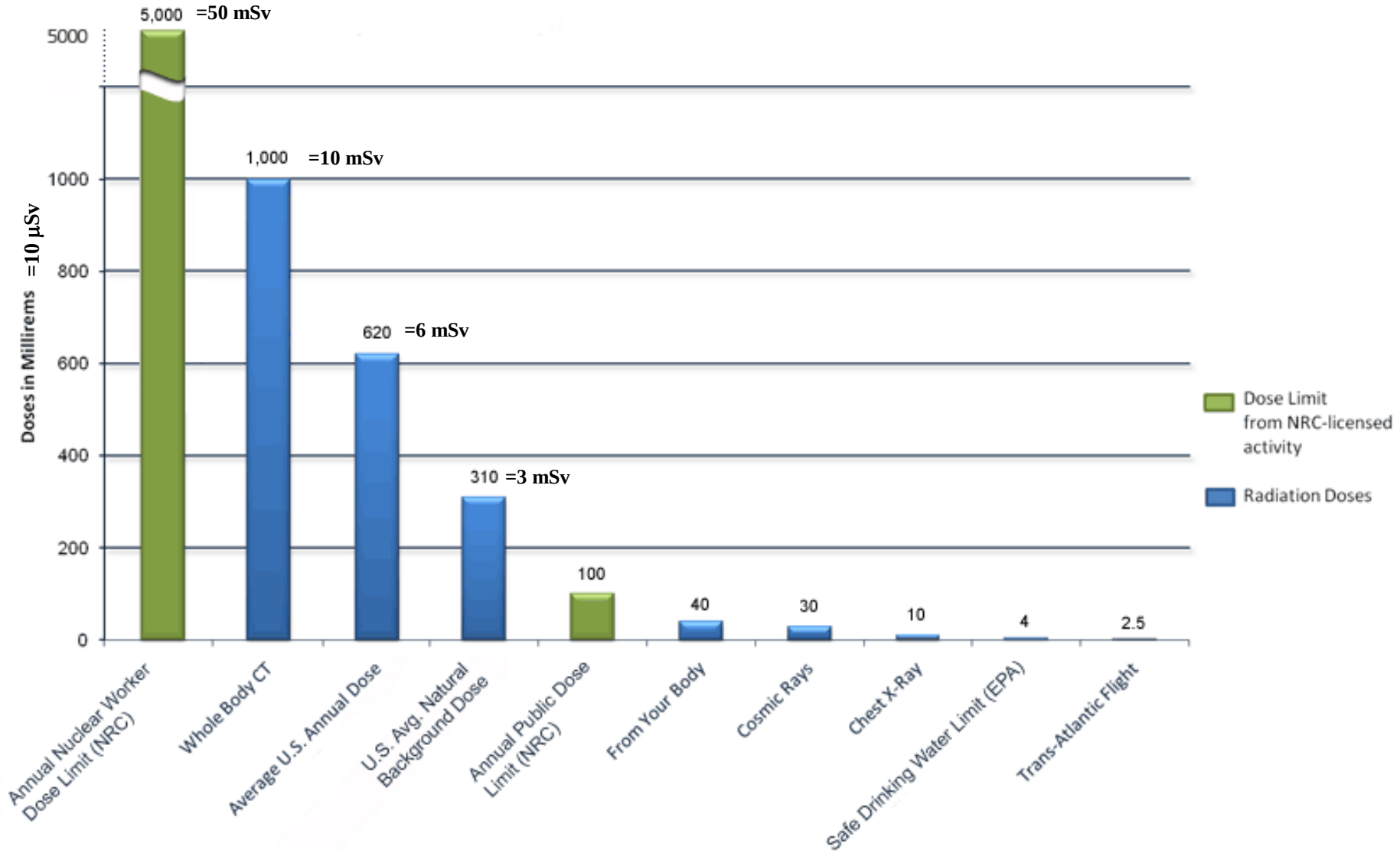
Annual Average Total Effective Dose Equivalent to the U.S. Population

Natural Background, Radon	200 mrems	2 mSv
Cosmic and Terrestrial source	56	0.6
Medical and Dental X-Rays	54(+~100)	0.55
Internal Source, ^{40}K	40	0.4
Tobacco Smoking	280	2.8
Other Consumer Products	10	0.1
Total, All Population	640	6.4
Total, Non-Smokers	360	3.6

International Dose Distribution



Radiation doses and regulatory limits
(in mRem= 0.001Rem=0.00001 Sv 0.01mSv=10μSv)



Comparing the Risks:

Radiation, Smoking, and Driving

Procedure	Dose	Chance of Death	Equivalent to	
			Number of Cigarettes Smoked	Number of Highway Miles Driven
	Bone Marrow	*From Leukemia*		
^{131}I treatments for thyrotoxicosis	15 rems	3×10^{-4}	2200.0	5357.0
Chest radiograph	10 mrems	2×10^{-7}	1.5	3.6
Skull examination	78 mrems	1.6×10^{-6}	11.4	28.0
Barium enema	875 mrems	17.5×10^{-6}	128.0	313.0

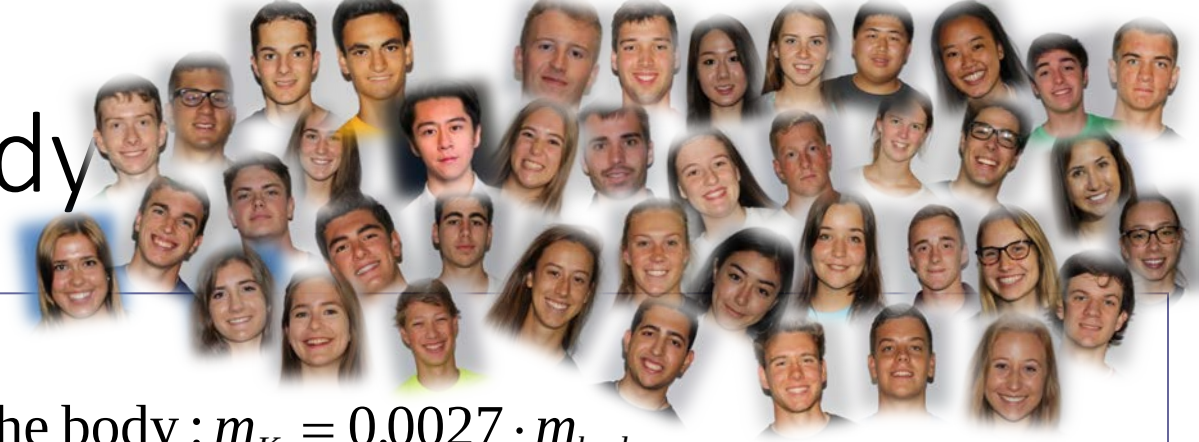
A full set of dental X-rays using a high energy X-ray machine and E-speed film has a relative cancer risk equivalent to that of smoking ~2-3 cigarettes.

Internal γ Glowing from ^{40}K

On average, 0.27% of the mass of the human body is potassium K of which 0.021% is radioactive ^{40}K with a half-life of $T_{1/2}=1.25\cdot10^{9}$ [y]. Each decay releases an average of E_{avg}= 0.5 MeV β- and γ-radiation, which is mostly absorbed by the body but a small fraction escapes the body.

Calculate, how many radioactive ^{40}K atoms are in your body system!

^{40}K in your body



* mass of the body : m_{body}
* mass of potassium K in the body : $m_K = 0.0027 \cdot m_{body}$
* mass of radioactive ^{40}K in the body : $m_{^{40}K} = 0.00021 \cdot m_K = 5.67 \cdot 10^{-7} \cdot m_{body}$

$$40g \text{ of } {}^{40}K \equiv 6.023 \cdot 10^{23} \; atoms$$

$$m_{^{40}K} = 5.67 \cdot 10^{-7} \cdot m_{body} [g] \equiv \frac{6.023 \cdot 10^{23} \cdot 5.67 \cdot 10^{-7} \cdot m_{body}}{40} [particles] = N_{^{40}K}$$

$$\frac{N_{^{40}K}}{m_{body}} = 8.54 \cdot 10^{15} \; [particles / g]$$

to calculate $N_{^{40}K}$, you need the body mass m_{body} in gramm.

for 80 kg body : $N_{^{40}K} = 6.83 \cdot 10^{20} \; [particles]$

Calculate the absorbed body dose over an average human lifetime of t = 70 y for this source of internal exposure.

* $$Dose: \quad D = \frac{E_{absorbed}}{m_{body}} = t \cdot A(^{40}K) \cdot \frac{E_{avg}}{m_{body}}$$

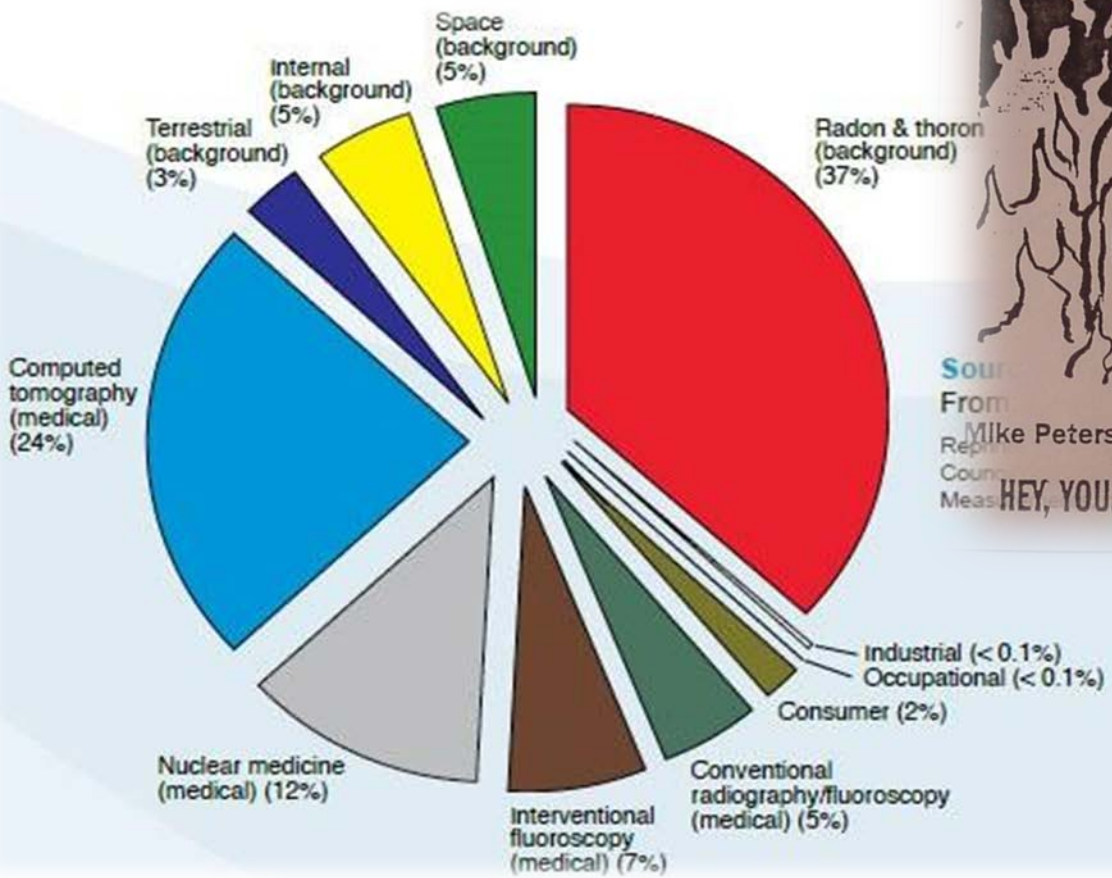
* $$Activity: \quad A(^{40}K) = \lambda \cdot N_{^{40}K} = \ln 2 / T_{1/2} \cdot N_{^{40}K}$$

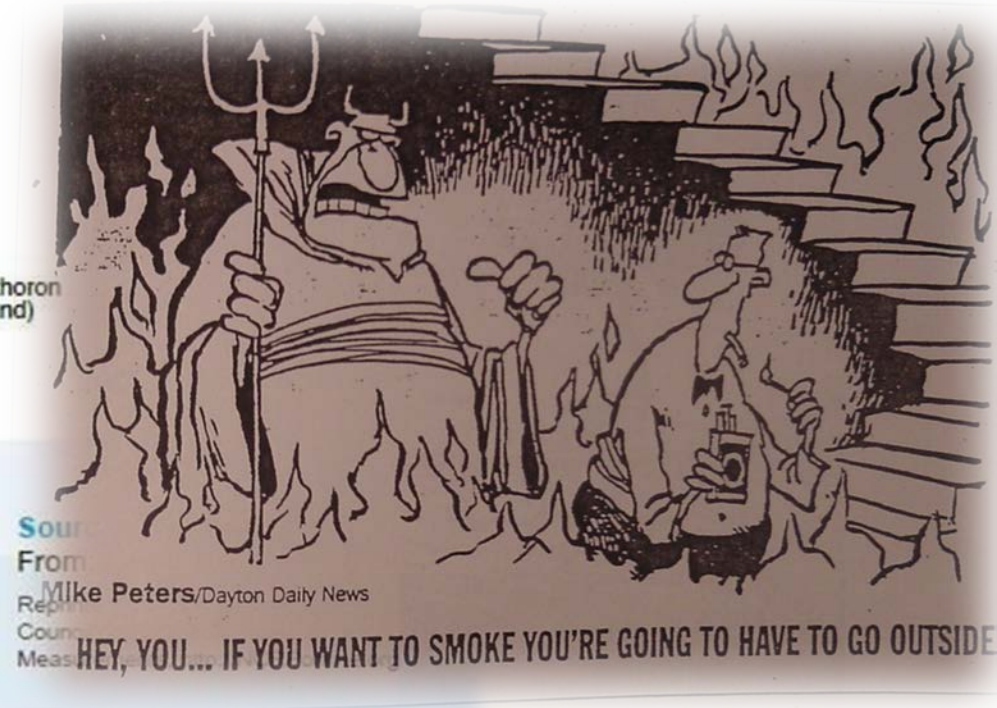
$$D = 70\,[y] \cdot \frac{\ln 2}{1.25 \cdot 10^{9}\ [\mathrm{y}]} \cdot (8.54 \cdot 10^{15}\,[g^{-1}] \cdot m_{body}) \cdot \frac{0.5\ [MeV]}{m_{body}}$$

$$D = 1.66 \cdot 10^{11} [MeV / kg] = 2.63 \cdot 10^{-2} [J / kg] = 2.63 \cdot 10^{-2} [Gy]$$

$$with: \quad 1[eV] = 1.602 \cdot 10^{-19} [J]$$

Exposure to other natural or man-made radioactivity





Tobacco contains α-emitter ^{210}Po with $T_{1/2}$=138.4 days. Through absorption in bronchial system smoking adds 280 mrem/year to the annual dose of US population.

https://www.nrc.gov/about-nrc/radiation/around-us/calculator.html

Medical radioactivity

$$\frac{D}{h}=\frac{3000\mu R}{3600s}=\frac{3000\cdot 10^{-6}\cdot 10^{-2}Gy}{3600s}=8.33\cdot 10^{-9}\frac{Gy}{s}=\frac{0.511MeV}{60kg}\cdot A=\frac{0.511\cdot 1.602\cdot 10^{-13}J}{60kg}A=1.36\cdot 10^{-15}Gy\cdot A$$

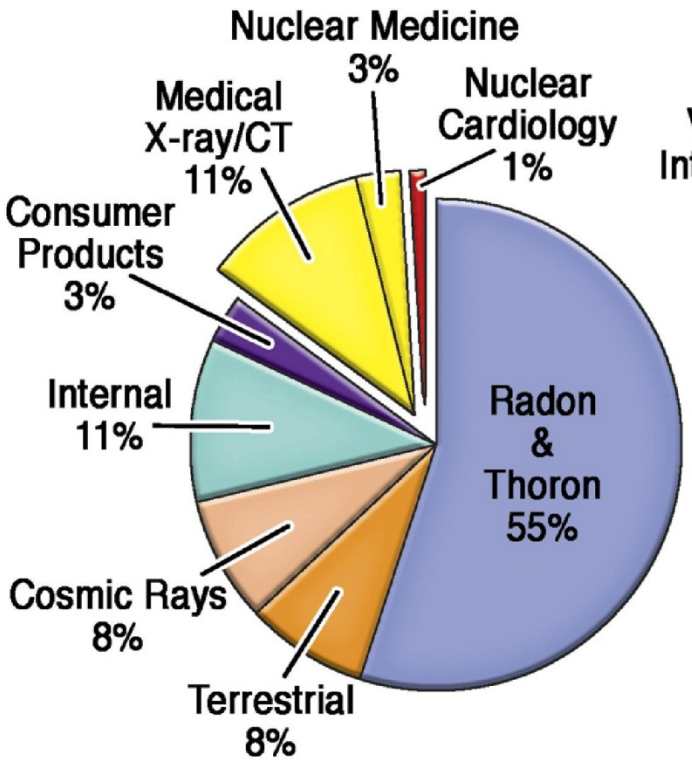
$$A=\frac{8.33\cdot 10^{-9}\frac{Gy}{s}\cdot}{1.36\cdot 10^{-15}Gy}=6.11\cdot 10^{6}Bq=6.11MBq$$

$$N\left(^{18}F\right)=\frac{A}{\lambda\left(^{18}F\right)}=\frac{A}{\ln 2}\cdot T_{1/2}\left(^{18}F\right)=\frac{6.11\cdot 10^{6}}{\ln 2}\cdot 109.7\cdot 60s=5.8\cdot 10^{10}\ \ ^{18}F$$

$$M\left(^{18}F\right)=N\left(^{18}F\right)\cdot\frac{18g}{6.022\cdot 10^{23}}=1.7\cdot 10^{-12}g=1.7pg$$

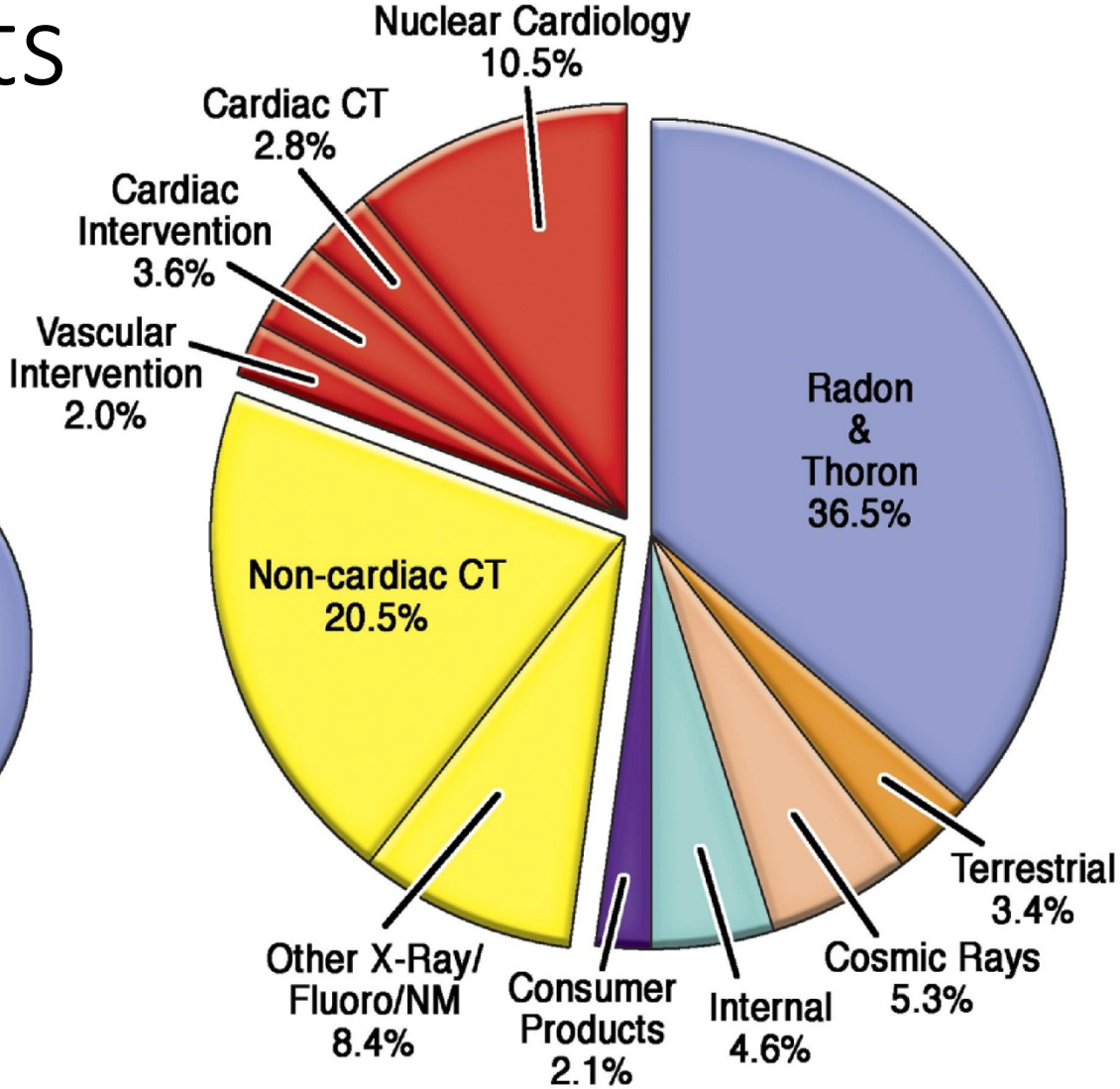
Certainly much more … taken about 4 hours after infusion and distributed via blood flow over entire body.

Developments



1980-1982

Medical Radiation: 0.53 mSv per capita per year
Non-medical Radiation: 3.1 mSv per capita per year
Cardiovascular Radiation Collective Effective Dose: 6,700 person-Sv
Medical Radiation Collective Effective Dose: 123,000 person-Sv



2006

Medical Radiation: 3.0 mSv per capita per year
Non-medical Radiation: 3.2 mSv per capita per year
Cardiovascular Radiation Collective Effective Dose: 356,000 person-Sv
Medical Radiation Collective Effective Dose: 899,000 person-Sv