# Radiation Dose and Hazard Assessment

**Fall, 2022**

**Kyoung-Jae Chung**

***Department of Nuclear Engineering***

**Seoul National University**

# Introduction

- Radiation dosimetry is the branch of science that attempts to quantitatively relate specific measurements made in a radiation field to physical, chemical, and/or biological changes that the radiation would produce in a target.
- Dosimetry is essential for quantifying the incidence of various biological changes as a function of the amount of radiation received (dose–effect relationships), for comparing different experiments, for monitoring the radiation exposure of individuals, and for surveillance of the environment.
- Understanding the activity in Becquerels is the first step to finding out about any possible biological effects, but does not tell us a great deal by itself. This is because, apart from the absolute amount of energy absorbed in the body, the biological effects are related to:
  - The size of the exposed area or body: for the same absolute amount of radiation, a larger body will feel less effect, so the measures of radiation exposure must be inherently about the exposure per kilogram of tissue.
  - The radiation type: some types of radiation are intrinsically more damaging than others.
  - The distribution of the dose: some tissues of the body are more sensitive to radiation than others.

# Exposure

- Exposure is defined for gamma and X rays in terms of the amount of ionization they produce in air.
- Definition (ICRU, 1962): the quotient $\Delta Q/\Delta m$, where $\Delta Q$ is the sum of all charges of one sign produced in air when all the electrons liberated by photons in a mass $\Delta m$ of air are completely stopped in air.
- The unit roentgen (R) is defined as

$$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C\,kg^{-1}}$$

*Example*

Show that 1 esu cm$^{-3}$ in air at STP is equivalent to the definition (12.1) of 1 R of exposure.

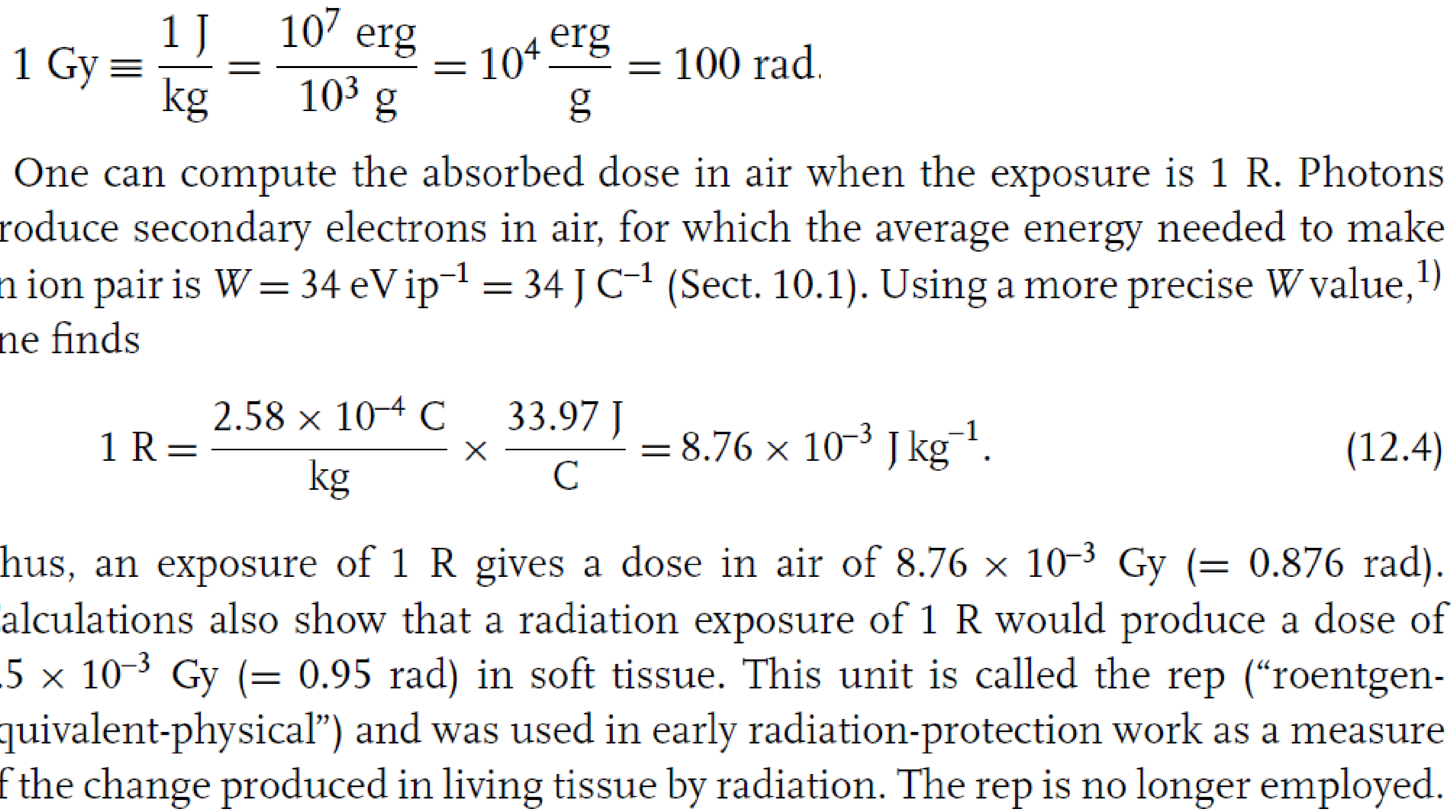
*Solution*

Since the density of air at STP is 0.001293 g cm$^{-3}$ and 1 esu = $3.34 \times 10^{-10}$ C (Appendix B), we have

$$\frac{1\ \mathrm{esu}}{\mathrm{cm^3}} = \frac{3.34 \times 10^{-10}\ \mathrm{C}}{0.001293\ \mathrm{g} \times 10^{-3}\ \mathrm{kg\,g^{-1}}} = 2.58 \times 10^{-4}\ \mathrm{C\,kg^{-1}}. \tag{12.2}$$

# Absorbed dose

- Radiation damage depends on the absorption of energy from the radiation and is approximately proportional to the mean concentration of absorbed energy in irradiated tissue. For this reason, the basic unit of radiation dose is expressed in terms of absorbed energy per unit mass of tissue.
- The unit of absorbed dose, J kg$^{-1}$, is called the gray (Gy).



$$1\ \mathrm{Gy} \equiv \frac{1\ \mathrm{J}}{\mathrm{kg}} = \frac{10^7\ \mathrm{erg}}{10^3\ \mathrm{g}} = 10^4\,\frac{\mathrm{erg}}{\mathrm{g}} = 100\ \mathrm{rad}.$$

One can compute the absorbed dose in air when the exposure is 1 R. Photons produce secondary electrons in air, for which the average energy needed to make an ion pair is $W = 34\ \mathrm{eV\ ip^{-1}} = 34\ \mathrm{J\ C^{-1}}$ (Sect. 10.1). Using a more precise $W$ value,$^{1)}$ one finds

$$1\ \mathrm{R} = \frac{2.58 \times 10^{-4}\ \mathrm{C}}{\mathrm{kg}} \times \frac{33.97\ \mathrm{J}}{\mathrm{C}} = 8.76 \times 10^{-3}\ \mathrm{J\ kg^{-1}}. \tag{12.4}$$

Thus, an exposure of 1 R gives a dose in air of $8.76 \times 10^{-3}$ Gy (= 0.876 rad). Calculations also show that a radiation exposure of 1 R would produce a dose of $9.5 \times 10^{-3}$ Gy (= 0.95 rad) in soft tissue. This unit is called the rep ("roentgen-equivalent-physical") and was used in early radiation-protection work as a measure of the change produced in living tissue by radiation. The rep is no longer employed.

# Dose equivalent (outdated)

- It has long been recognized that the absorbed dose needed to achieve a given level of biological damage (e.g., 50% cell killing) is often different for different kinds of radiation.
- The dose equivalent $H$ is defined as the product of the absorbed dose $D$ and a dimensionless quality factor $Q$, which depends on LET:

$$H = QD$$

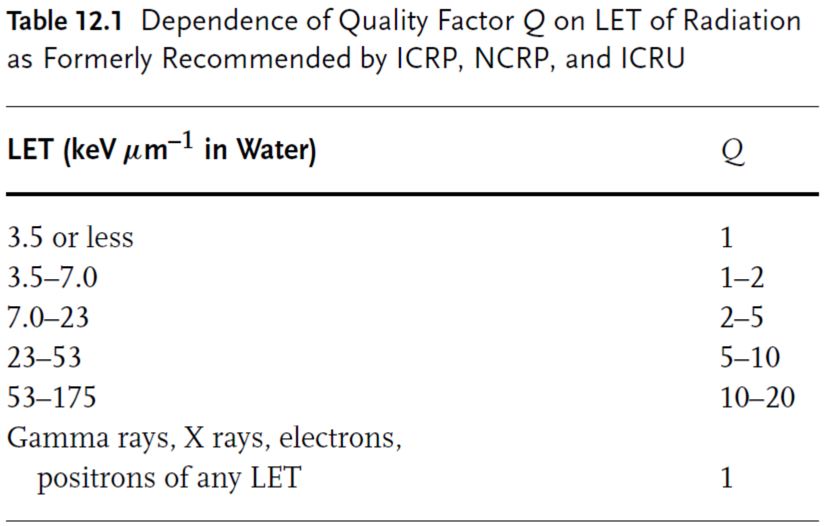


**Table 12.1** Dependence of Quality Factor $Q$ on LET of Radiation as Formerly Recommended by ICRP, NCRP, and ICRU

| LET (keV $\mu$m$^{-1}$ in Water) | $Q$ |
|---|---|
| 3.5 or less | 1 |
| 3.5–7.0 | 1–2 |
| 7.0–23 | 2–5 |
| 23–53 | 5–10 |
| 53–175 | 10–20 |
| Gamma rays, X rays, electrons, positrons of any LET | 1 |

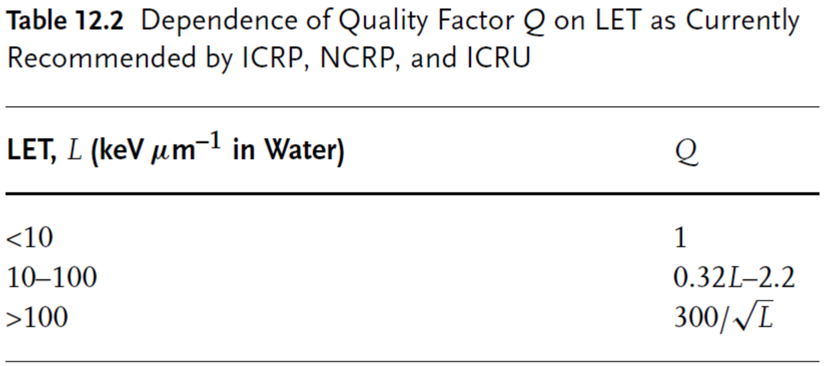


**Table 12.2** Dependence of Quality Factor $Q$ on LET as Currently Recommended by ICRP, NCRP, and ICRU

| LET, $L$ (keV $\mu$m$^{-1}$ in Water) | $Q$ |
|---|---|
| <10 | 1 |
| 10–100 | $0.32L$–2.2 |
| >100 | $300/\sqrt{L}$ |

- By the early 1990s, the ICRP and NCRP replaced the use of LET-dependent quality factors by radiation weighting factors, $w$, specified for radiation of a given type and energy. The quantity, $H = wD$, is then called the equivalent dose.

# Equivalent dose

- It is often said that absorbed dose cannot be used to characterize the biological effects of radiation. In fact, absorbed dose cannot be used to characterize damage to any material. All it represents is how much energy has been absorbed by the medium and not what damage it has caused. In this respect, absorbed dose treats all types of radiation equally.
- Since dosimetry is primarily concerned with the safety of personnel, another quantity called the equivalent dose has been defined to characterize the damaging effects of radiation on tissues.
- Unit: sievert (Sv), 1 Sv = 100 rem

$$H_{T,R} = w_R D_{T,R}$$

$$H_T = \sum_R w_R D_{T,R}$$

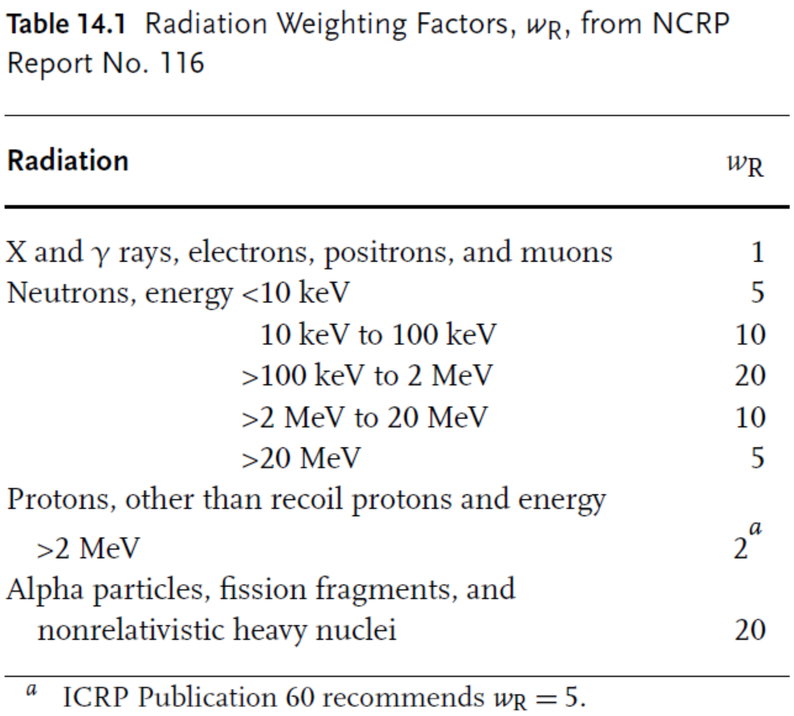


**Table 14.1** Radiation Weighting Factors, $w_R$, from NCRP Report No. 116

| **Radiation** | $w_R$ |
|---|---|
| X and γ rays, electrons, positrons, and muons | 1 |
| Neutrons, energy <10 keV | 5 |
| 10 keV to 100 keV | 10 |
| >100 keV to 2 MeV | 20 |
| >2 MeV to 20 MeV | 10 |
| >20 MeV | 5 |
| Protons, other than recoil protons and energy >2 MeV | 2[a] |
| Alpha particles, fission fragments, and nonrelativistic heavy nuclei | 20 |

[a] ICRP Publication 60 recommends $w_R = 5$.

# Radiation weighting factor (ICRP Publication 103)

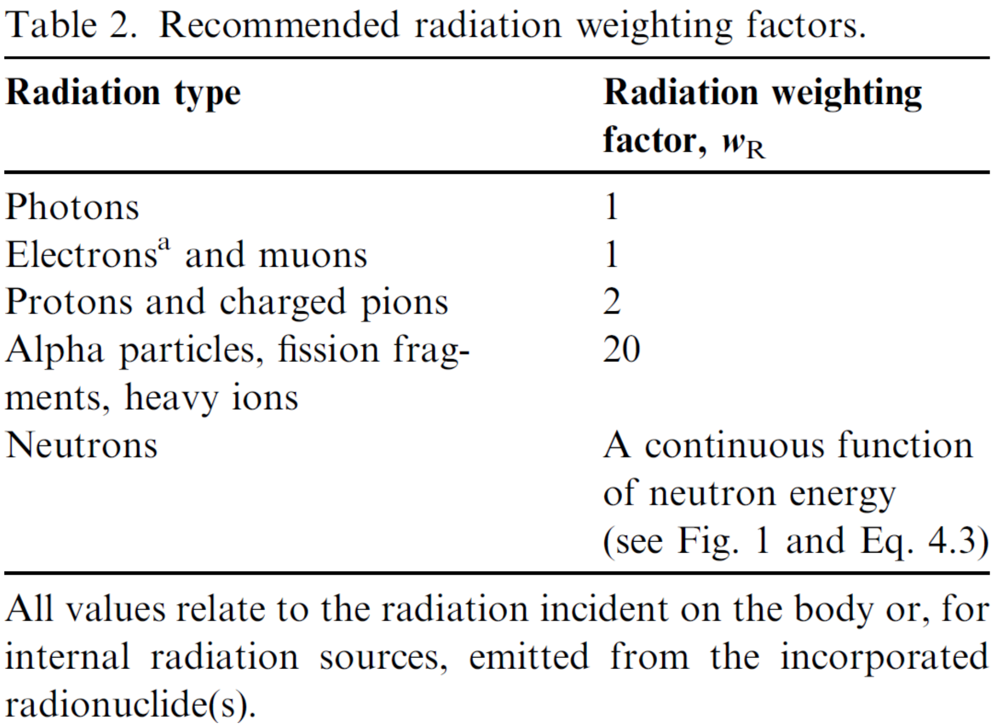


Table 2. Recommended radiation weighting factors.

| **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 (see Fig. 1 and Eq. 4.3) |

All values relate to the radiation incident on the body or, for internal radiation sources, emitted from the incorporated radionuclide(s).

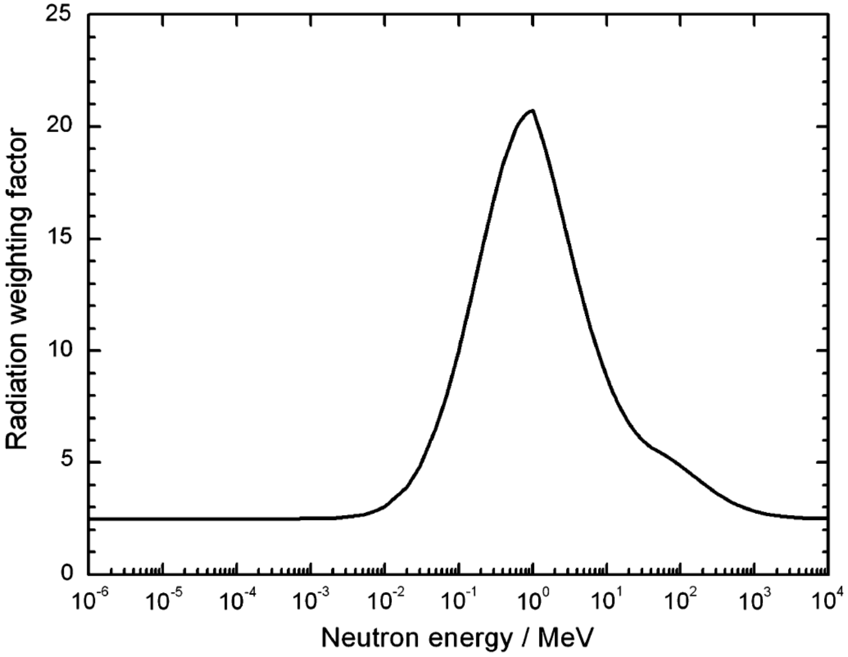
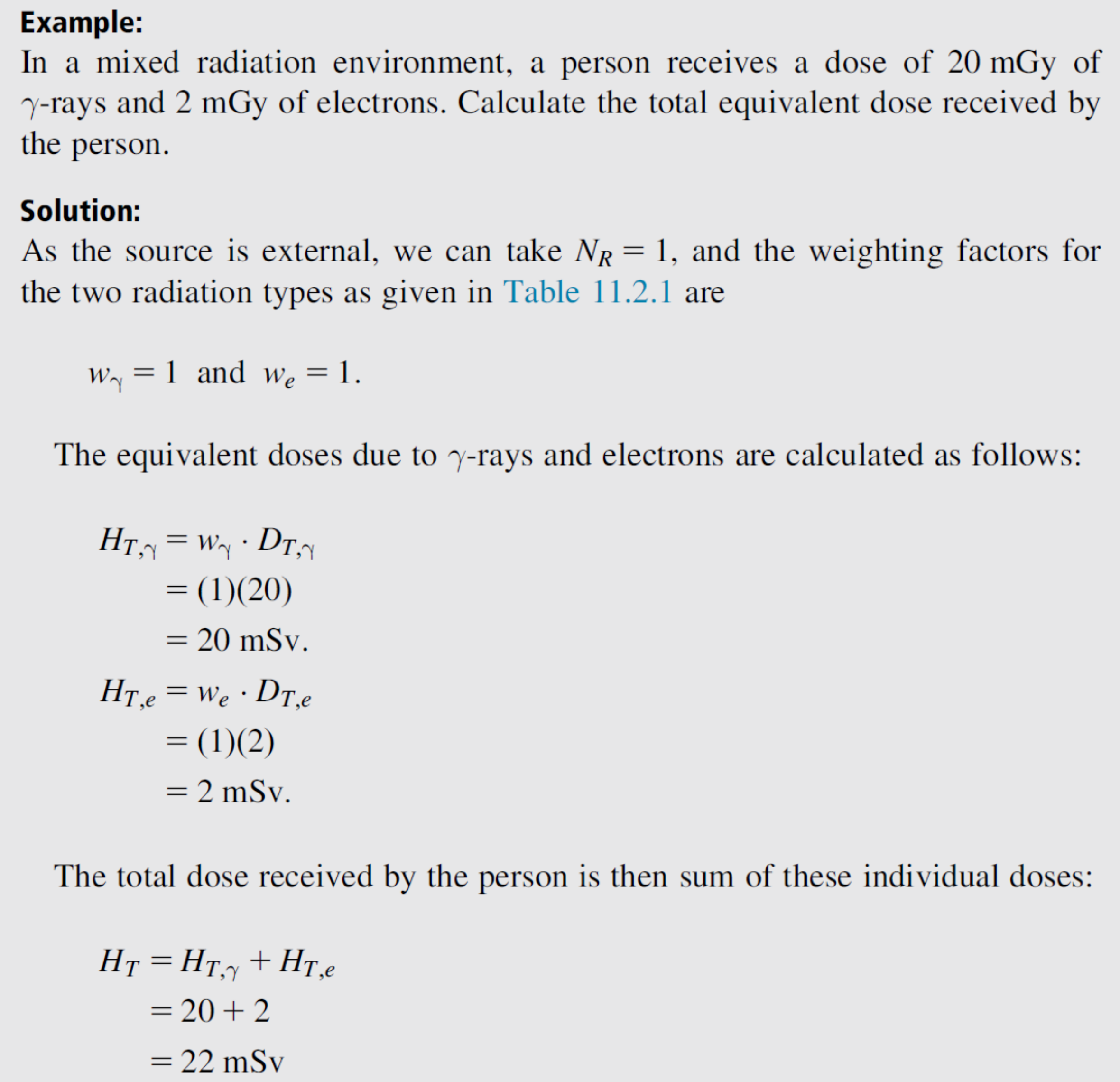


Fig. 1. Radiation weighting factor, $w_R$, for neutrons versus neutron energy.

$$w_R = \begin{cases} 2.5 + 18.2e^{-[\ln(E_n)]^2/6}, & E_n < 1\ \text{MeV} \\ 5.0 + 17.0e^{-[\ln(2E_n)]^2/6}, & 1\ \text{MeV} \leqslant E_n \leqslant 50\ \text{MeV} \\ 2.5 + 3.25e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50\ \text{MeV} \end{cases} \qquad (4.3)$$

# Equivalent dose



**Example:**

In a mixed radiation environment, a person receives a dose of 20 mGy of $\gamma$-rays and 2 mGy of electrons. Calculate the total equivalent dose received by the person.

**Solution:**

As the source is external, we can take $N_R = 1$, and the weighting factors for the two radiation types as given in Table 11.2.1 are

$$w_\gamma = 1 \text{ and } w_e = 1.$$

The equivalent doses due to $\gamma$-rays and electrons are calculated as follows:

$$\begin{aligned} H_{T,\gamma} &= w_\gamma \cdot D_{T,\gamma} \\ &= (1)(20) \\ &= 20 \text{ mSv}. \\ H_{T,e} &= w_e \cdot D_{T,e} \\ &= (1)(2) \\ &= 2 \text{ mSv}. \end{aligned}$$

The total dose received by the person is then sum of these individual doses:

$$\begin{aligned} H_T &= H_{T,\gamma} + H_{T,e} \\ &= 20 + 2 \\ &= 22 \text{ mSv} \end{aligned}$$

# Effective dose

- The equivalent dose can be used for one tissue type only, as it does not address the sensitivity of different tissue types to the same type of radiation. The question is, how can we determine the whole-body equivalent dose to estimate the level of risk in a certain radiation environment? Or, how can we estimate the whole-body dose if the dose received by a particular organ is known? This is done by using the quantity called effective dose as defined by the relation

$$E = \sum_T w_T H_T$$

- For uniform whole-body irradiation

$$E = \sum_T w_T H_T = H_T \sum_T w_T = H_T$$

ICRP Publication 103

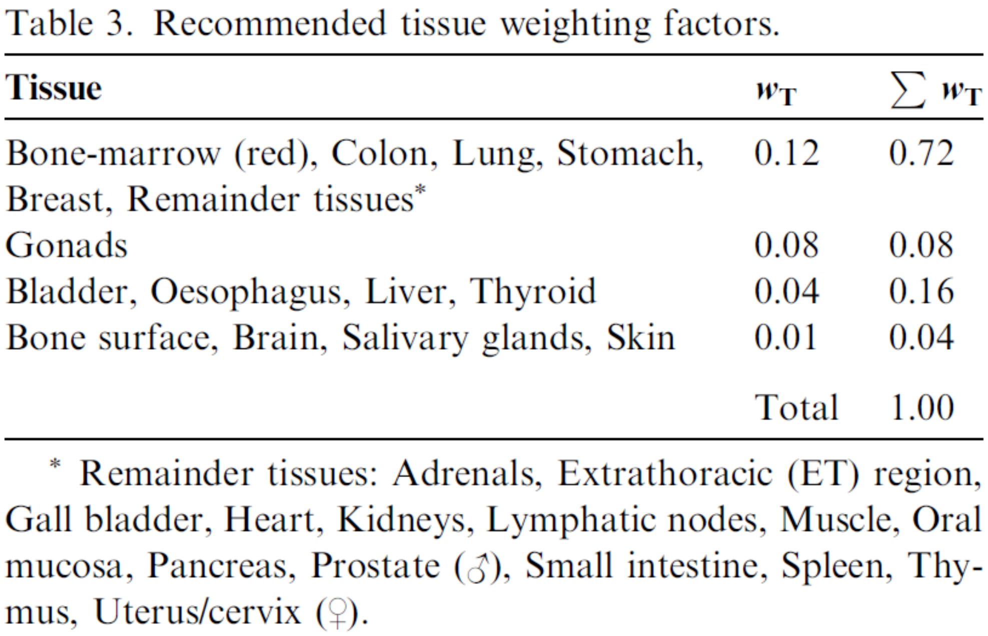
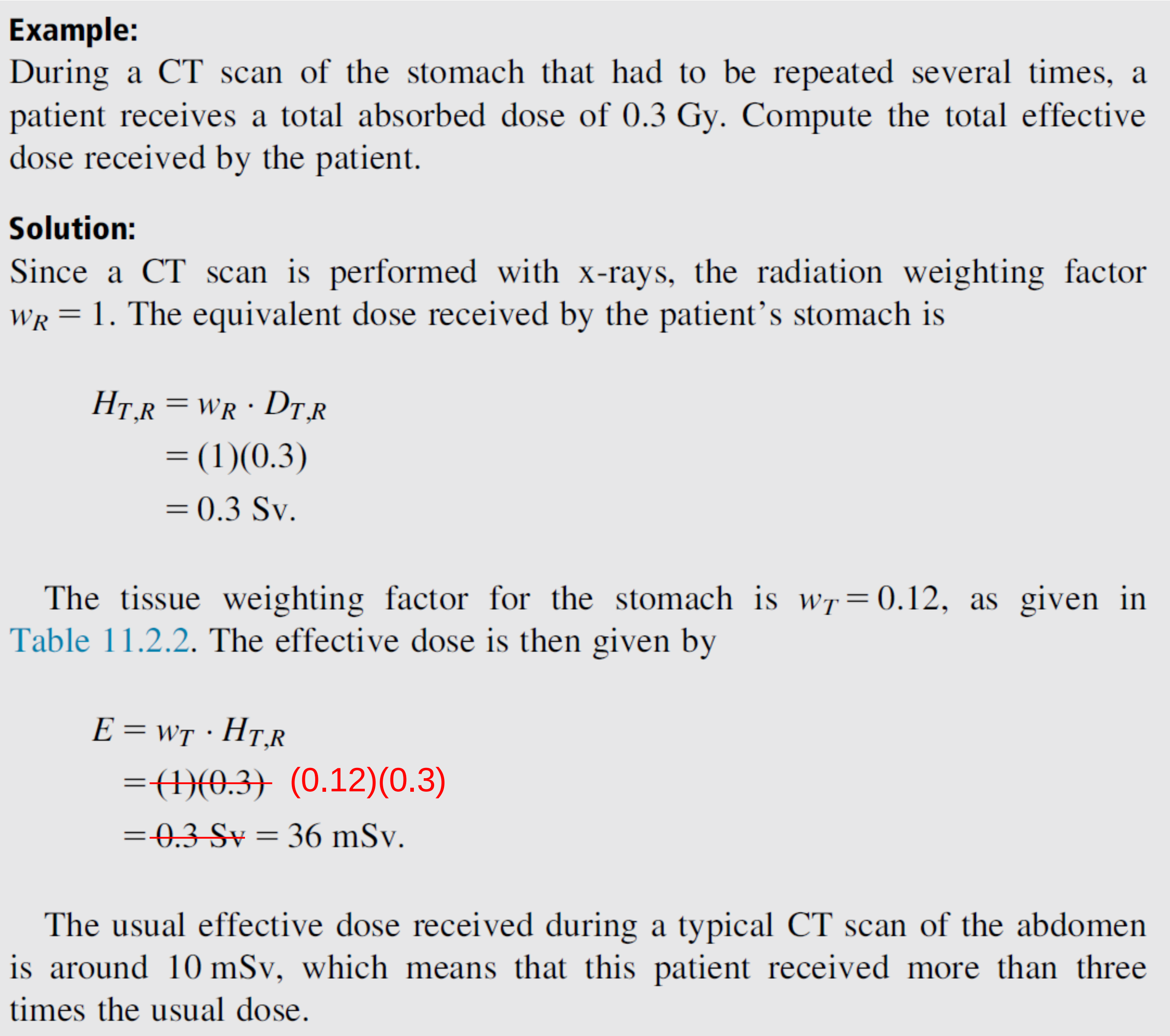


Table 3. Recommended tissue weighting factors.

| Tissue | $w_T$ | $\sum w_T$ |
|---|---|---|
| Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues* | 0.12 | 0.72 |
| Gonads | 0.08 | 0.08 |
| Bladder, Oesophagus, Liver, Thyroid | 0.04 | 0.16 |
| Bone surface, Brain, Salivary glands, Skin | 0.01 | 0.04 |
| | Total | 1.00 |

* Remainder tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

# Effective dose



**Example:**
During a CT scan of the stomach that had to be repeated several times, a patient receives a total absorbed dose of 0.3 Gy. Compute the total effective dose received by the patient.

**Solution:**
Since a CT scan is performed with x-rays, the radiation weighting factor $w_R = 1$. The equivalent dose received by the patient's stomach is

$$\begin{aligned} H_{T,R} &= w_R \cdot D_{T,R} \\ &= (1)(0.3) \\ &= 0.3\ \text{Sv}. \end{aligned}$$

The tissue weighting factor for the stomach is $w_T = 0.12$, as given in Table 11.2.2. The effective dose is then given by

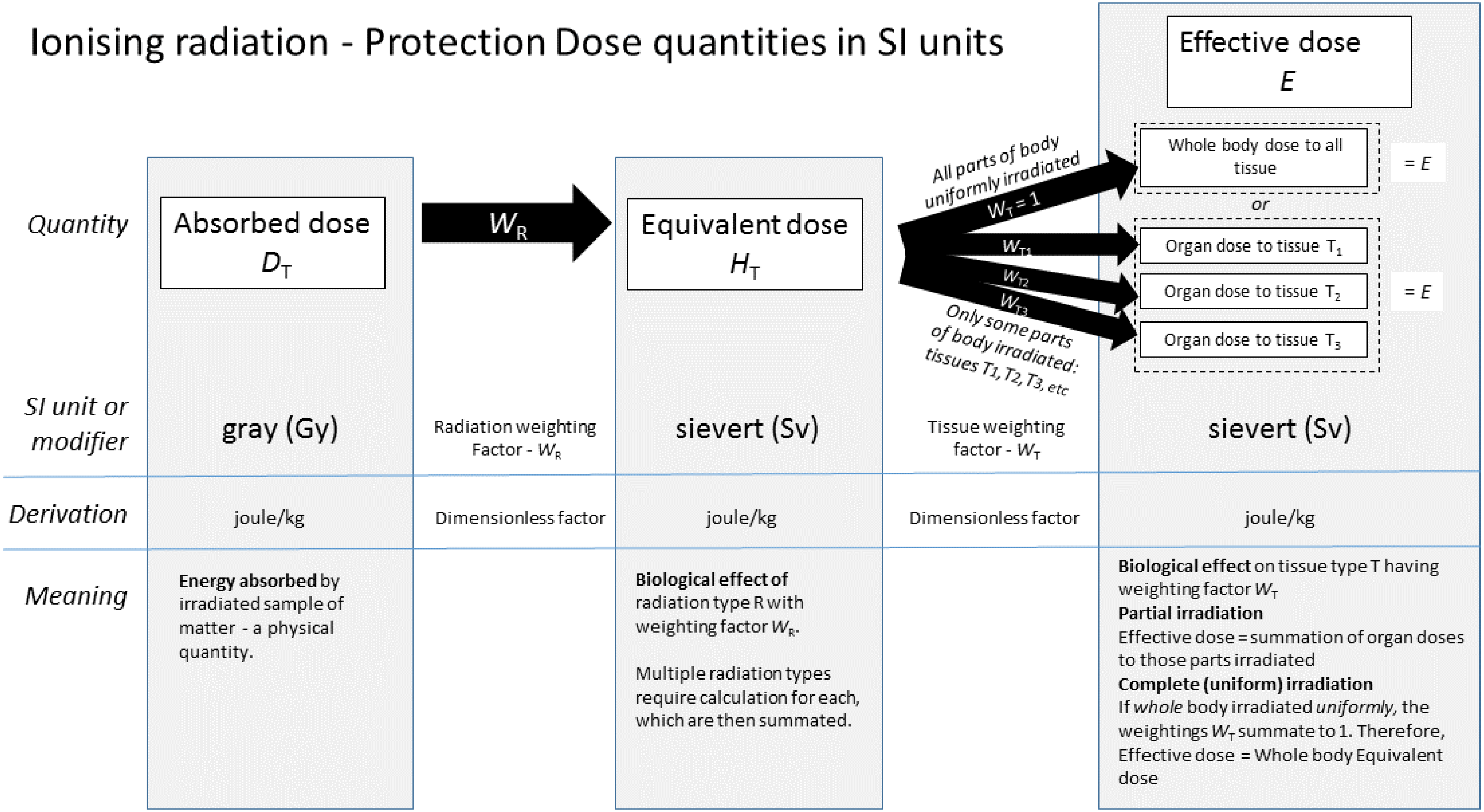
$$E = w_T \cdot H_{T,R}$$

$=$ ~~$(1)(0.3)$~~ (0.12)(0.3)

$=$ ~~$0.3$ Sv~~ $= 36$ mSv.

The usual effective dose received during a typical CT scan of the abdomen is around 10 mSv, which means that this patient received more than three times the usual dose.

# Relationships of protection dose quantities in SI units

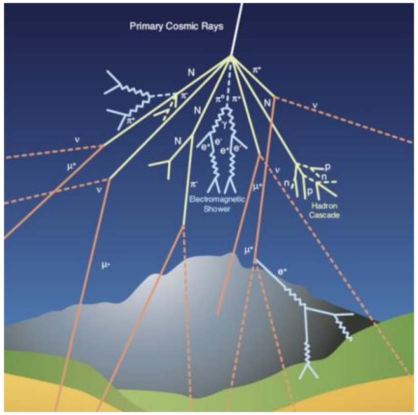


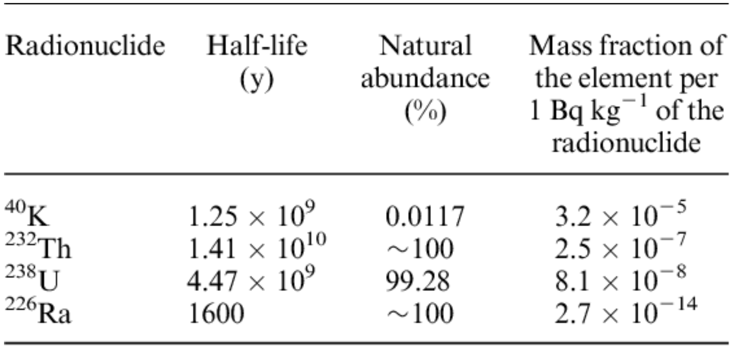
Ionising radiation - Protection Dose quantities in SI units

| | | | | | |
|---|---|---|---|---|---|
| *Quantity* | Absorbed dose $D_T$ | $W_R$ | Equivalent dose $H_T$ | All parts of body uniformly irradiated $W_T = 1$<br>$W_{T1}$<br>$W_{T2}$<br>$W_{T3}$<br>*Only some parts of body irradiated: tissues T1, T2, T3, etc* | Effective dose $E$<br>Whole body dose to all tissue = $E$<br>*or*<br>Organ dose to tissue $T_1$<br>Organ dose to tissue $T_2$<br>Organ dose to tissue $T_3$<br>= $E$ |
| *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 $W_R$.<br>Multiple radiation types require calculation for each, which are then summated. | | **Biological effect** on tissue type T having weighting factor $W_T$<br>**Partial irradiation**<br>Effective dose = summation of organ doses to those parts irradiated<br>**Complete (uniform) irradiation**<br>If *whole* body irradiated *uniformly*, the weightings $W_T$ summate to 1. Therefore, Effective dose = Whole body Equivalent dose |

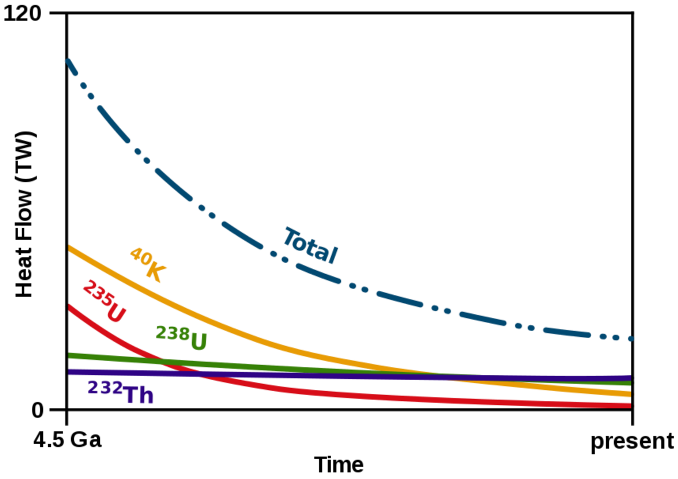
# Exposures from the natural environment

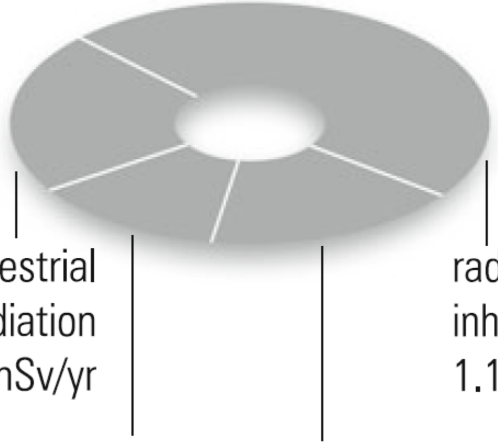
- Cosmic rays
- Terrestrial radiation (from the Earth's crust)
- Incorporation (eating, drinking, and breathing)





| Radionuclide | Half-life (y) | Natural abundance (%) | Mass fraction of the element per 1 Bq kg$^{-1}$ of the radionuclide |
|---|---|---|---|
| $^{40}$K | $1.25 \times 10^9$ | 0.0117 | $3.2 \times 10^{-5}$ |
| $^{232}$Th | $1.41 \times 10^{10}$ | ~100 | $2.5 \times 10^{-7}$ |
| $^{238}$U | $4.47 \times 10^9$ | 99.28 | $8.1 \times 10^{-8}$ |
| $^{226}$Ra | 1600 | ~100 | $2.7 \times 10^{-14}$ |





terrestrial radiation 0.5 mSv/yr

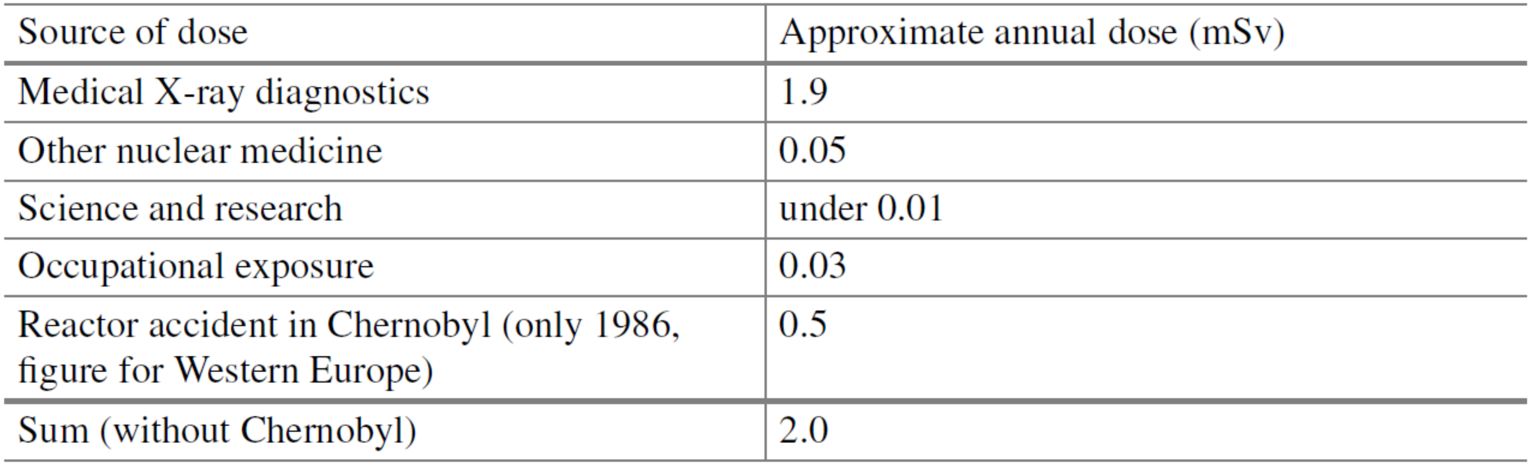
cosmic radiation 0.3 mSv/yr

ingestion 0.4 mSv/yr

radon inhalation 1.1 mSv/yr

Global average ~ 2.3 mSv/yr

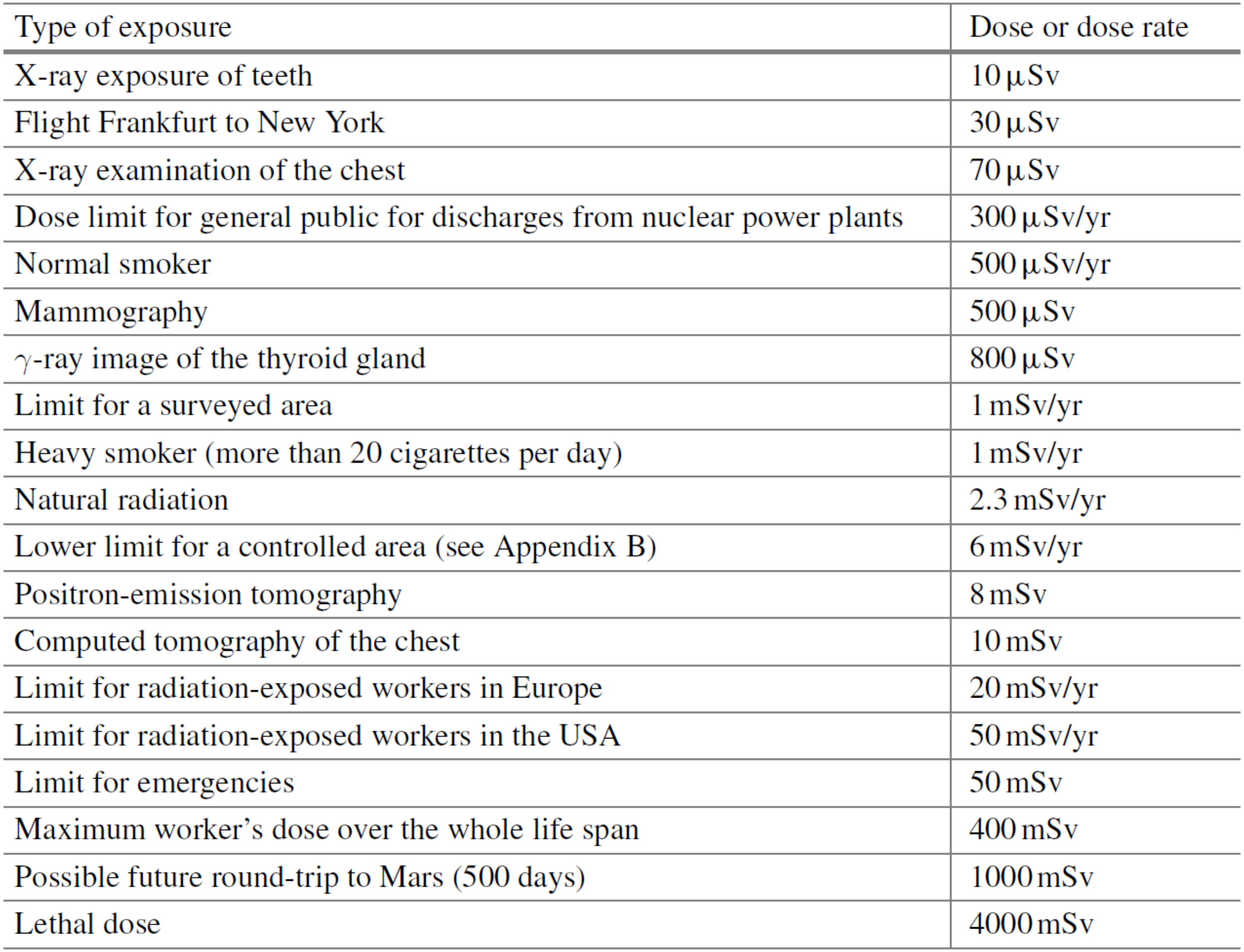
# Exposures from man-made sources (excluding smoking)



| Source of dose | Approximate annual dose (mSv) |
|---|---|
| Medical X-ray diagnostics | 1.9 |
| Other nuclear medicine | 0.05 |
| Science and research | under 0.01 |
| Occupational exposure | 0.03 |
| Reactor accident in Chernobyl (only 1986, figure for Western Europe) | 0.5 |
| Sum (without Chernobyl) | 2.0 |

- The world average of the whole-body exposure can be estimated to be about 4.3 mSv/yr: about 2.3 mSv/yr from the natural environment and about 2.0 mSv/yr from technical installations (mainly medicine).

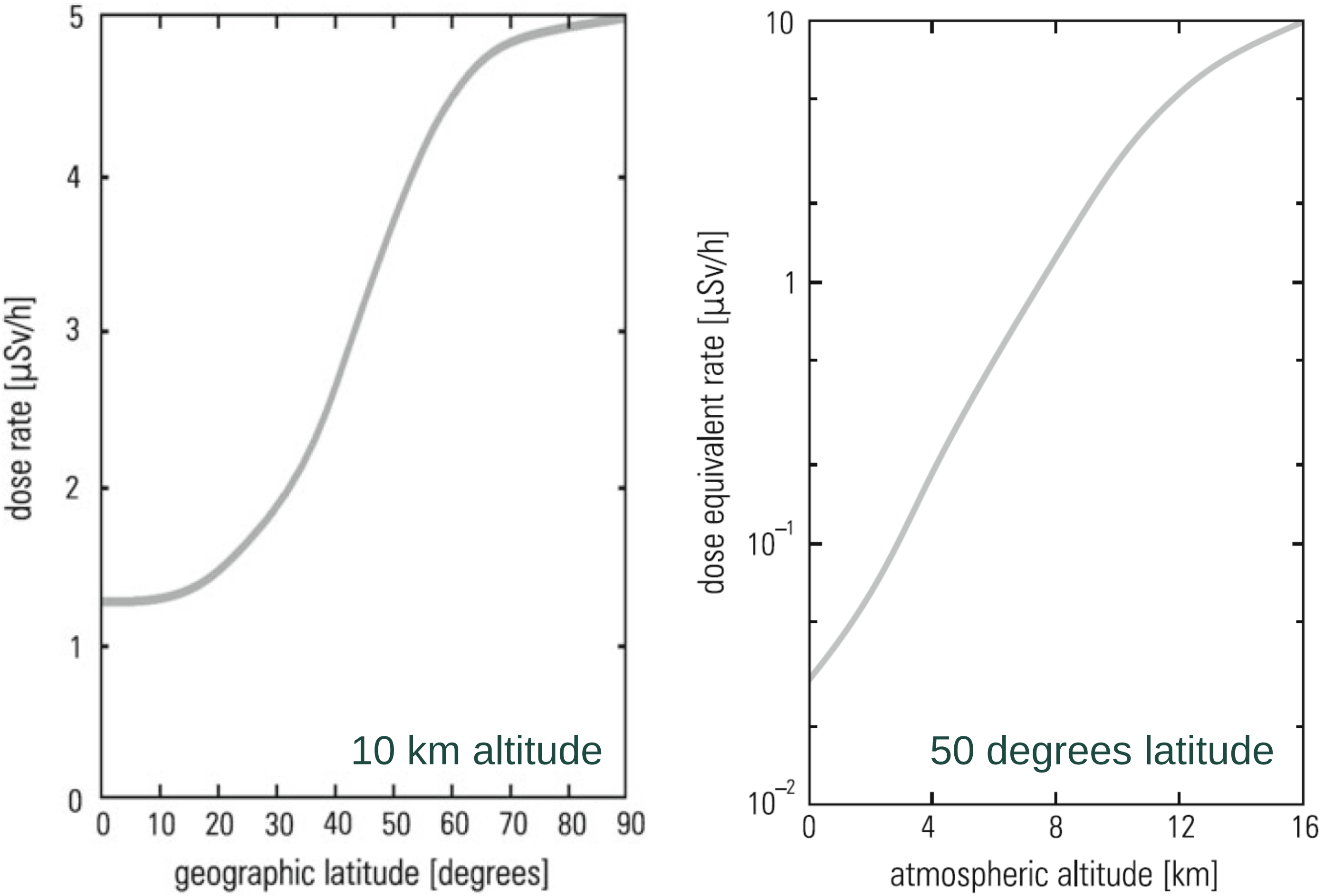
# Typical dose rates or doses for some exposures (whole-body doses)



| Type of exposure | Dose or dose rate |
|---|---|
| X-ray exposure of teeth | 10 μSv |
| Flight Frankfurt to New York | 30 μSv |
| X-ray examination of the chest | 70 μSv |
| Dose limit for general public for discharges from nuclear power plants | 300 μSv/yr |
| Normal smoker | 500 μSv/yr |
| Mammography | 500 μSv |
| $\gamma$-ray image of the thyroid gland | 800 μSv |
| Limit for a surveyed area | 1 mSv/yr |
| Heavy smoker (more than 20 cigarettes per day) | 1 mSv/yr |
| Natural radiation | 2.3 mSv/yr |
| Lower limit for a controlled area (see Appendix B) | 6 mSv/yr |
| Positron-emission tomography | 8 mSv |
| Computed tomography of the chest | 10 mSv |
| Limit for radiation-exposed workers in Europe | 20 mSv/yr |
| Limit for radiation-exposed workers in the USA | 50 mSv/yr |
| Limit for emergencies | 50 mSv |
| Maximum worker's dose over the whole life span | 400 mSv |
| Possible future round-trip to Mars (500 days) | 1000 mSv |
| Lethal dose | 4000 mSv |

# Exposures from air travel

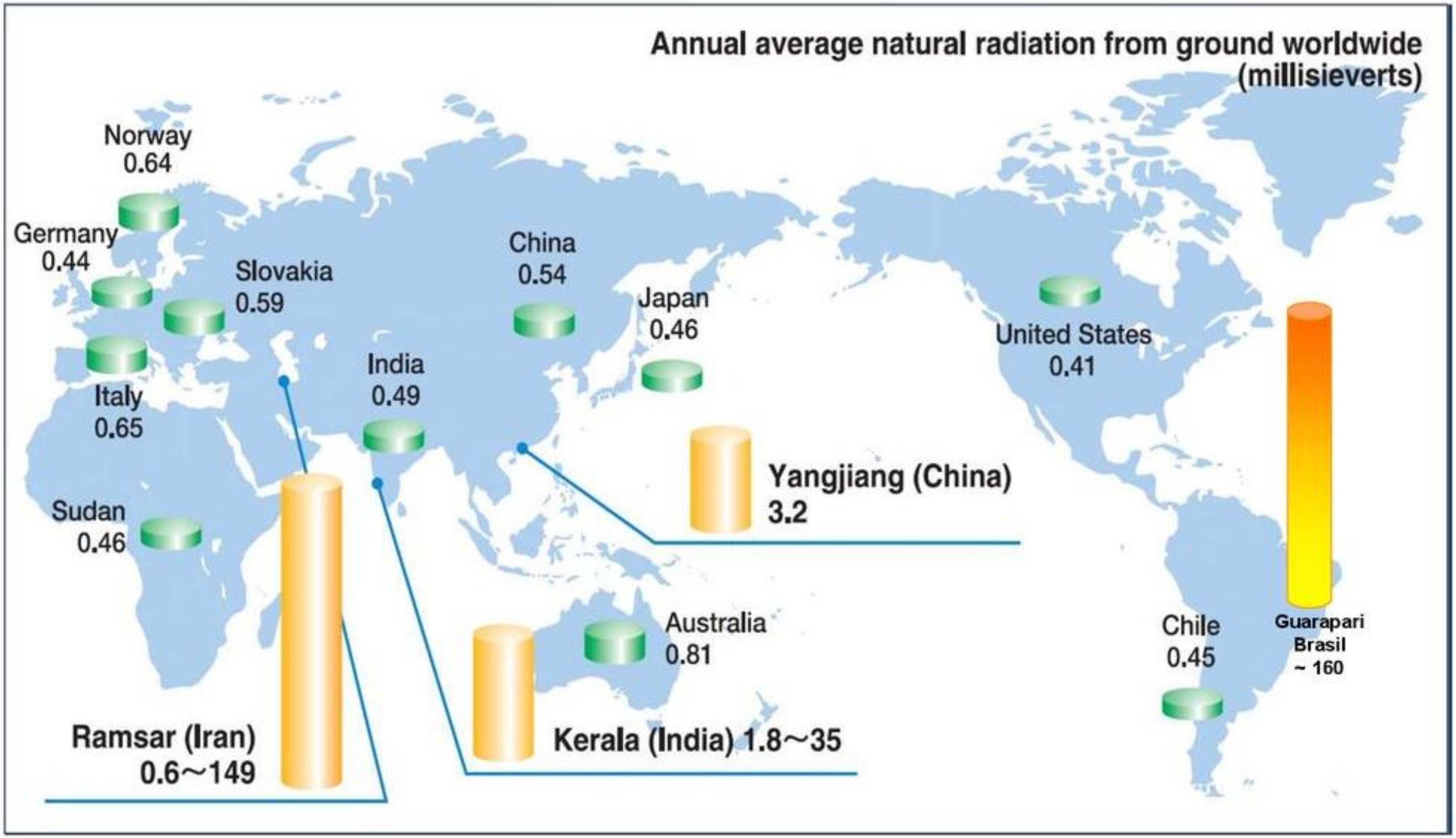
- Personnel flying at altitudes of 10~12 km are exposed to an annual dose of 2.5 mSv (for 500 flight hours per year).



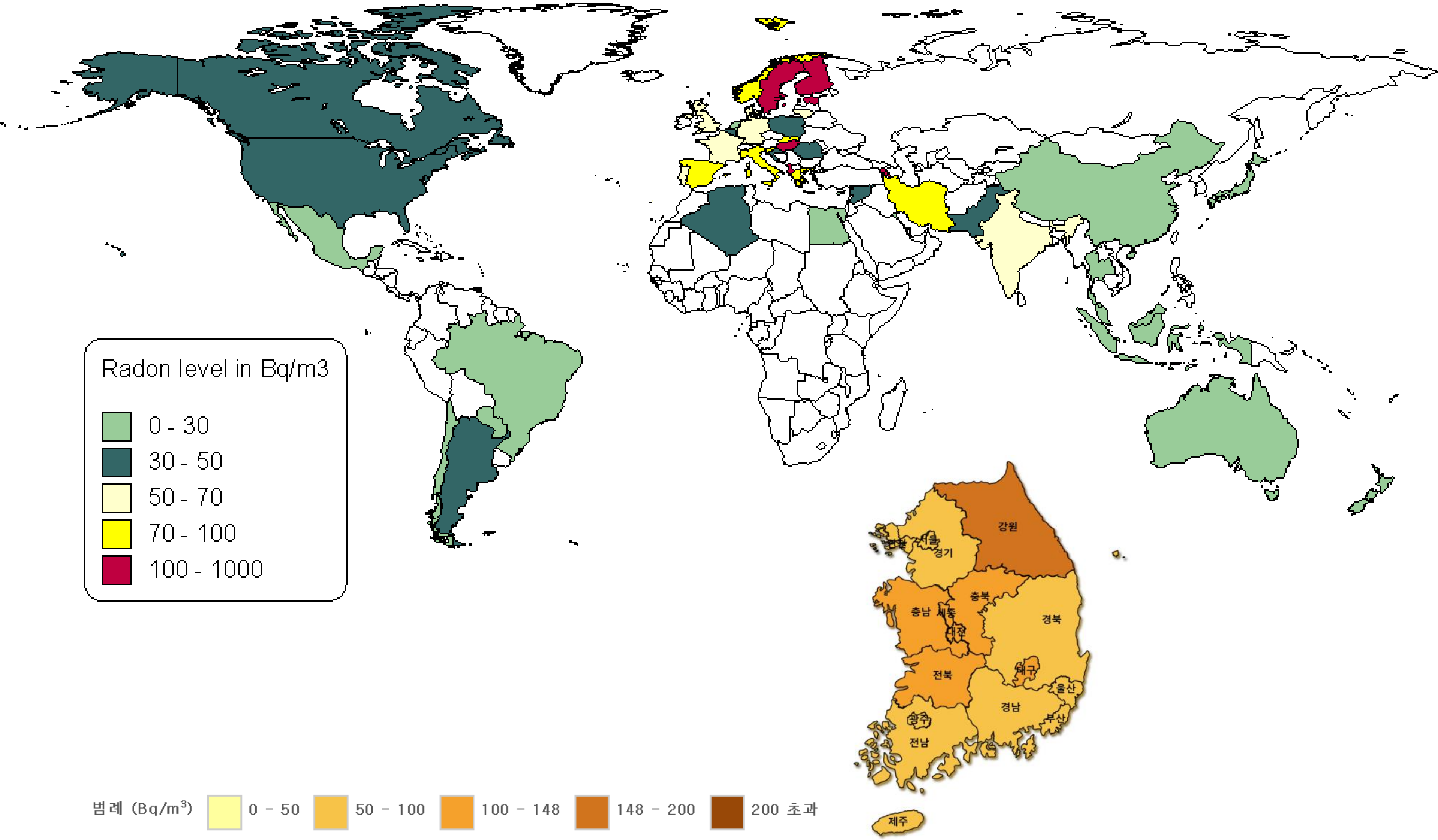
# Exposures from smoking

- It is well known that smoking has adverse effects on health, but it is less widely known that radioactive exposures play a significant part in the negative effects.
- Radioactive isotopes, particularly radioactive lead-210 ($^{210}Pb$) enter the tobacco plant via its roots from the soil, and also radon ($^{222}Rn$) will enter the tobacco leaves from the air. This eventually leads to significant exposures of the lungs.
- The isotopes $^{210}Pb$ and $^{222}Rn$ decay after a number of radioactive transmutations into the radioisotope polonium ($^{210}Po$) ending eventually in stable lead ($^{206}Pb$).
- Smokers are victims of the fact that tar is sticky: these radioisotopes tend to stick to the airborne droplets of tar in the smoke.

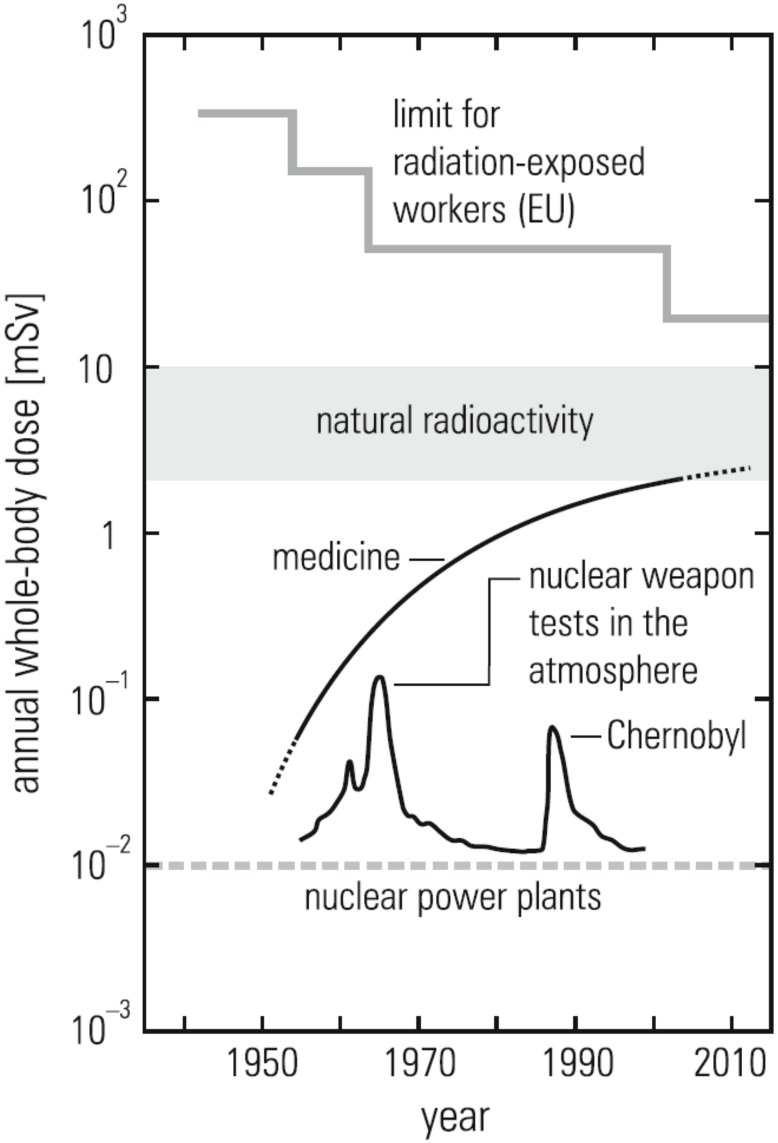
# Background radiation in the world



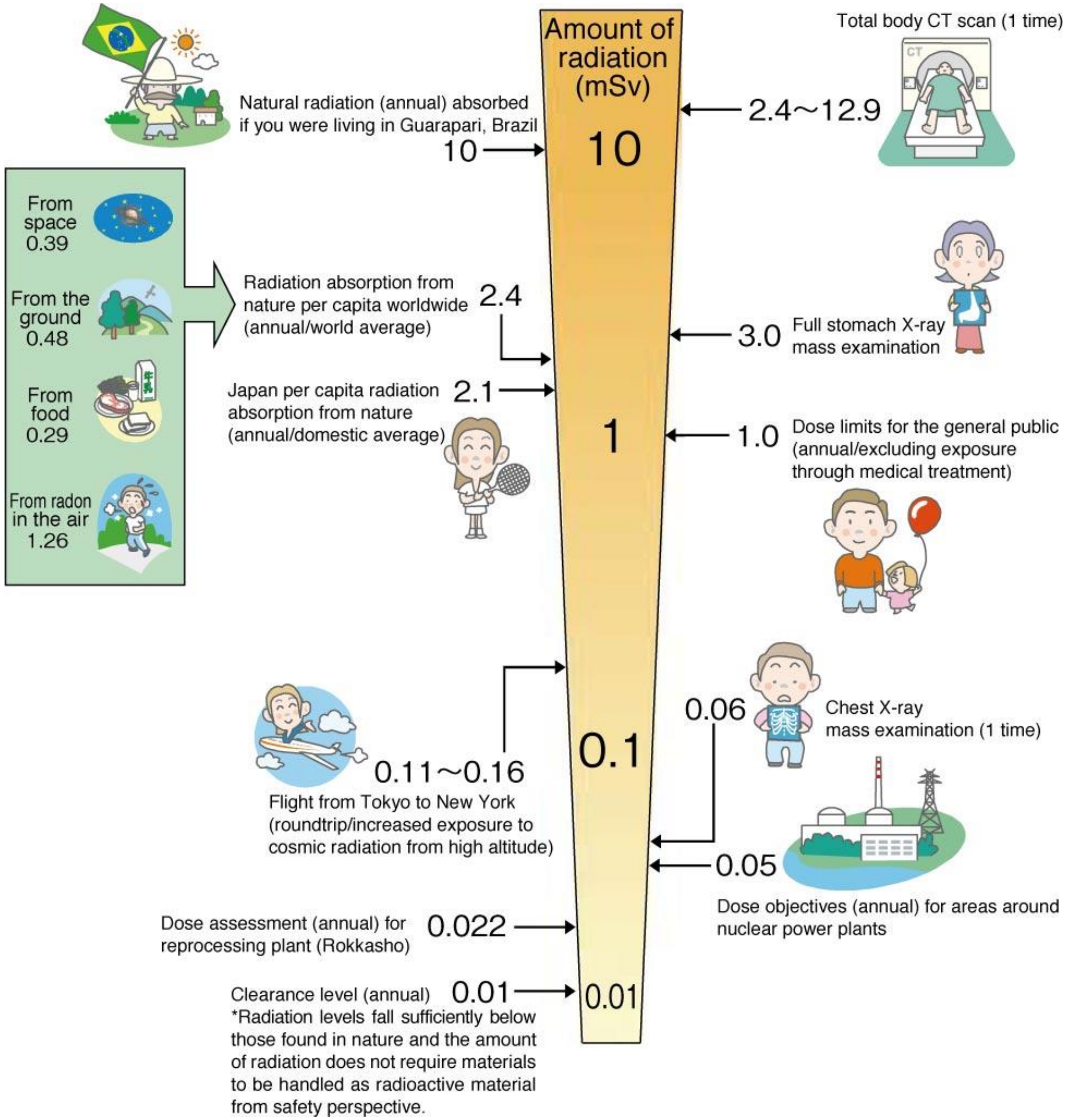
# World radon map



# Annual dose (Western Europe)



# Radiation in daily life



Amount of radiation (mSv)

10

1

0.1

0.01

Natural radiation (annual) absorbed if you were living in Guarapari, Brazil 10

From space 0.39

From the ground 0.48

From food 0.29

From radon in the air 1.26

Radiation absorption from nature per capita worldwide (annual/world average) 2.4

Japan per capita radiation absorption from nature (annual/domestic average) 2.1

0.11~0.16 Flight from Tokyo to New York (roundtrip/increased exposure to cosmic radiation from high altitude)

Dose assessment (annual) for reprocessing plant (Rokkasho) 0.022

Clearance level (annual) 0.01
*Radiation levels fall sufficiently below those found in nature and the amount of radiation does not require materials to be handled as radioactive material from safety perspective.

Total body CT scan (1 time) 2.4~12.9

3.0 Full stomach X-ray mass examination

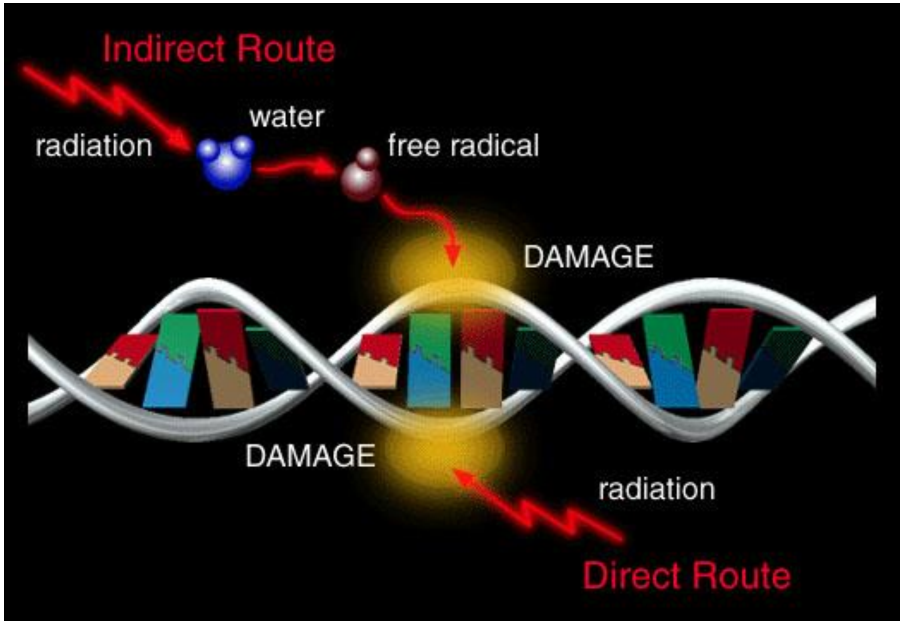
1.0 Dose limits for the general public (annual/excluding exposure through medical treatment)

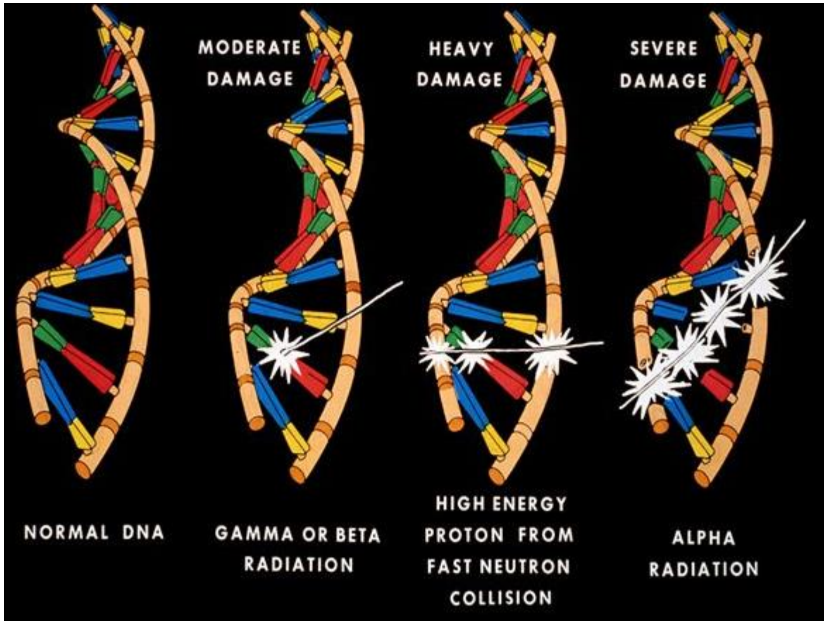
0.06 Chest X-ray mass examination (1 time)

0.05 Dose objectives (annual) for areas around nuclear power plants

# Radiation damage

- Any radiation exposure can potentially have negative effects on health. This can be considered as the basic principle of radiation protection.
- The biological effect of ionizing radiation is a consequence of the energy transfer, by ionization and excitation, to cells in the body.
- Factors of radiation effects on individual cells: (1) the dose rate, (2) the collisional stopping power (LET, linear energy transfer), and others such as the state of the cell's life cycle, the exposure time, age, general health, and nutritional status.





# Time frame for radiation effects

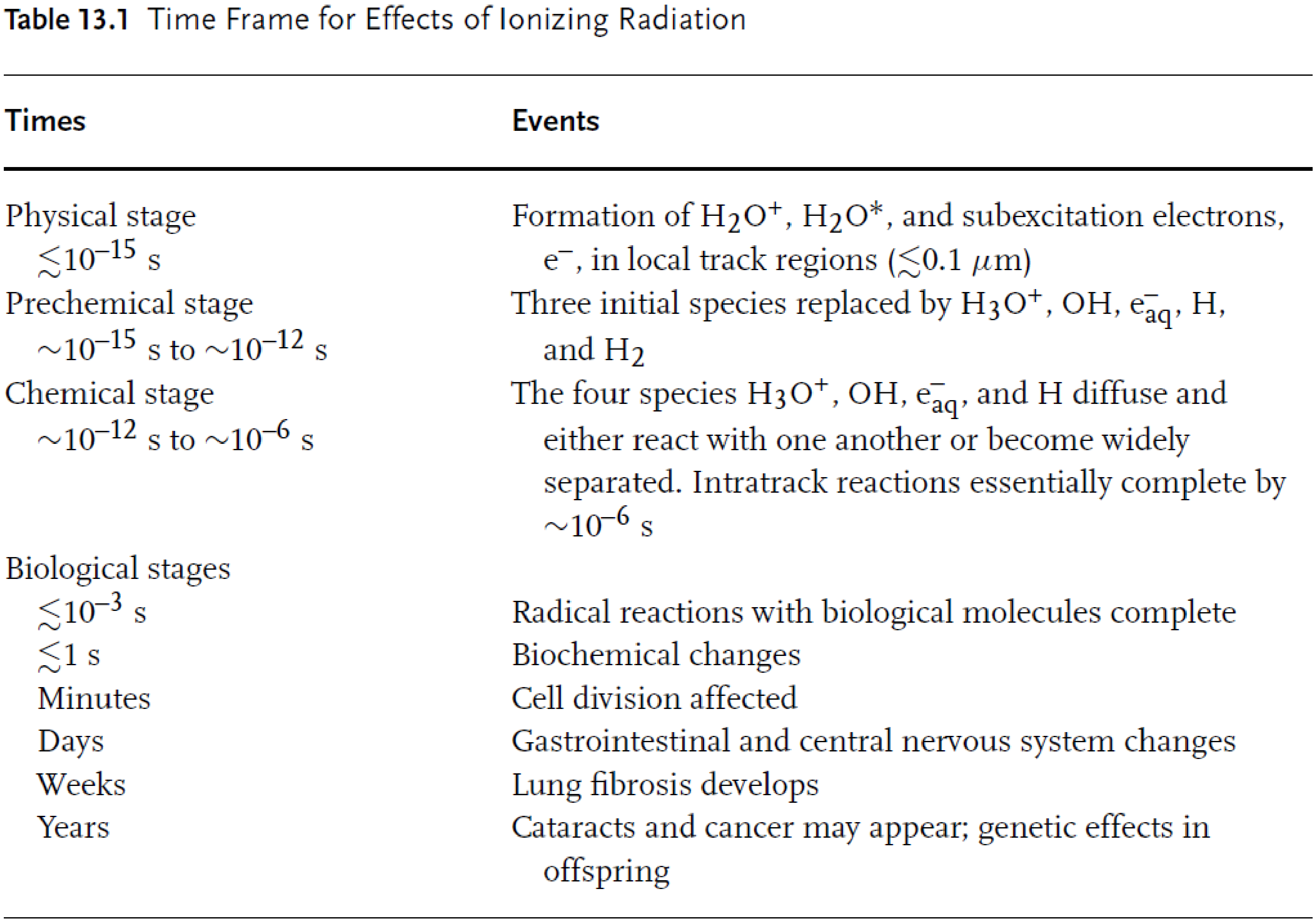


**Table 13.1** Time Frame for Effects of Ionizing Radiation

| **Times** | **Events** |
|---|---|
| Physical stage<br>$\lesssim 10^{-15}$ s | Formation of $H_2O^+$, $H_2O^*$, and subexcitation electrons, $e^-$, in local track regions ($\lesssim 0.1\ \mu m$) |
| Prechemical stage<br>$\sim 10^{-15}$ s to $\sim 10^{-12}$ s | Three initial species replaced by $H_3O^+$, OH, $e^-_{aq}$, H, and $H_2$ |
| Chemical stage<br>$\sim 10^{-12}$ s to $\sim 10^{-6}$ s | The four species $H_3O^+$, OH, $e^-_{aq}$, and H diffuse and either react with one another or become widely separated. Intratrack reactions essentially complete by $\sim 10^{-6}$ s |
| Biological stages | |
| $\lesssim 10^{-3}$ s | Radical reactions with biological molecules complete |
| $\lesssim 1$ s | Biochemical changes |
| Minutes | Cell division affected |
| Days | Gastrointestinal and central nervous system changes |
| Weeks | Lung fibrosis develops |
| Years | Cataracts and cancer may appear; genetic effects in offspring |

# Examples of charged-particle tracks in water

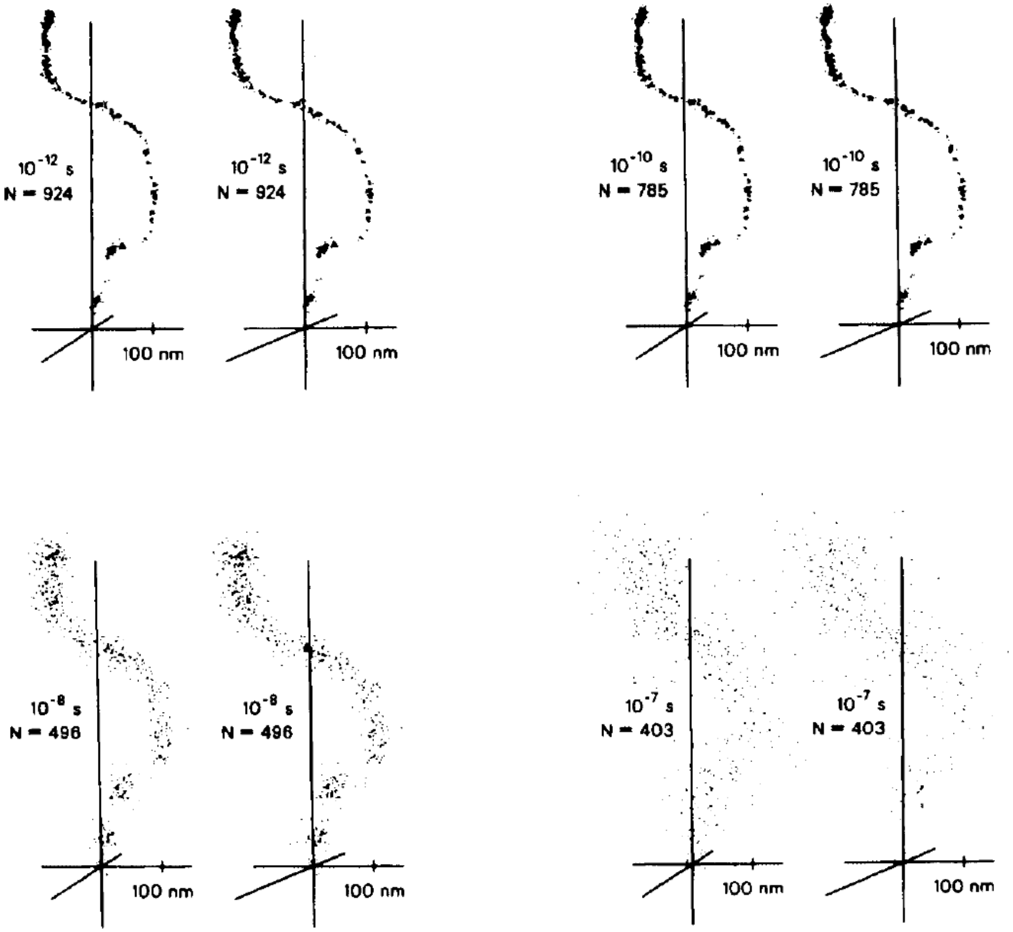


**Fig. 13.1** Chemical development of a 4-keV electron track in liquid water, calculated by Monte Carlo simulation. Each dot in these stereo views gives the location of one of the active radiolytic species, OH, $H_3O^+$, $e^-_{aq}$, or H, at the times shown. Note structure of track with spurs, or clusters of species, at early times. After $10^{-7}$ s, remaining species continue to diffuse further apart, with relatively few additional chemical reactions. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

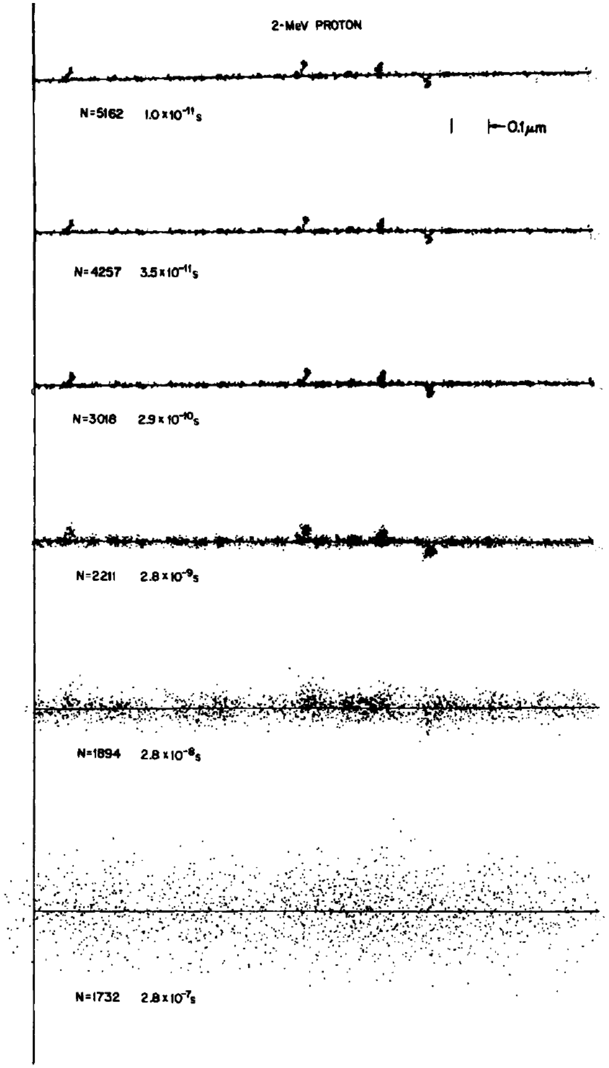
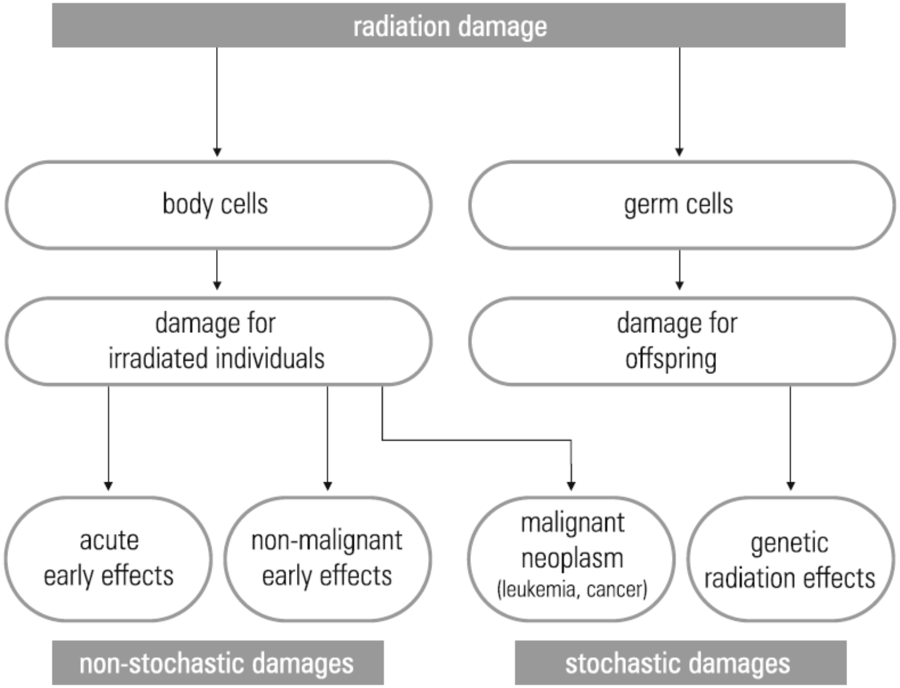


**Fig. 13.2** Development of a 1-$\mu$m segment of the track of a 2-MeV proton, traveling from left to right, in liquid water. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

# Acute radiation syndrome



radiation damage

body cells

germ cells

damage for irradiated individuals

damage for offspring

acute early effects

non-malignant early effects

malignant neoplasm (leukemia, cancer)

genetic radiation effects

non-stochastic damages

stochastic damages

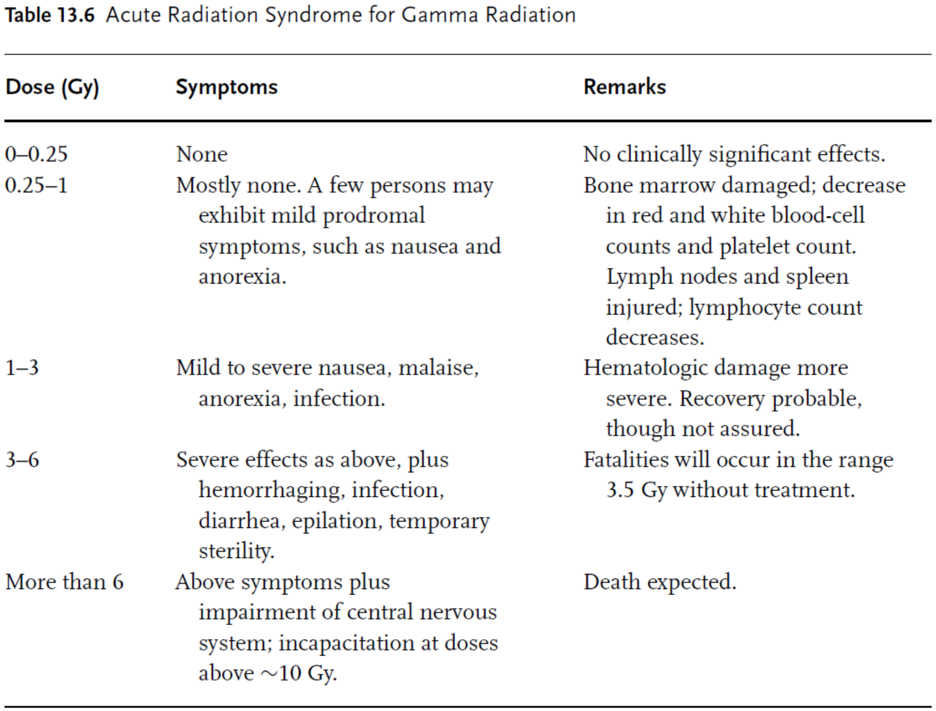


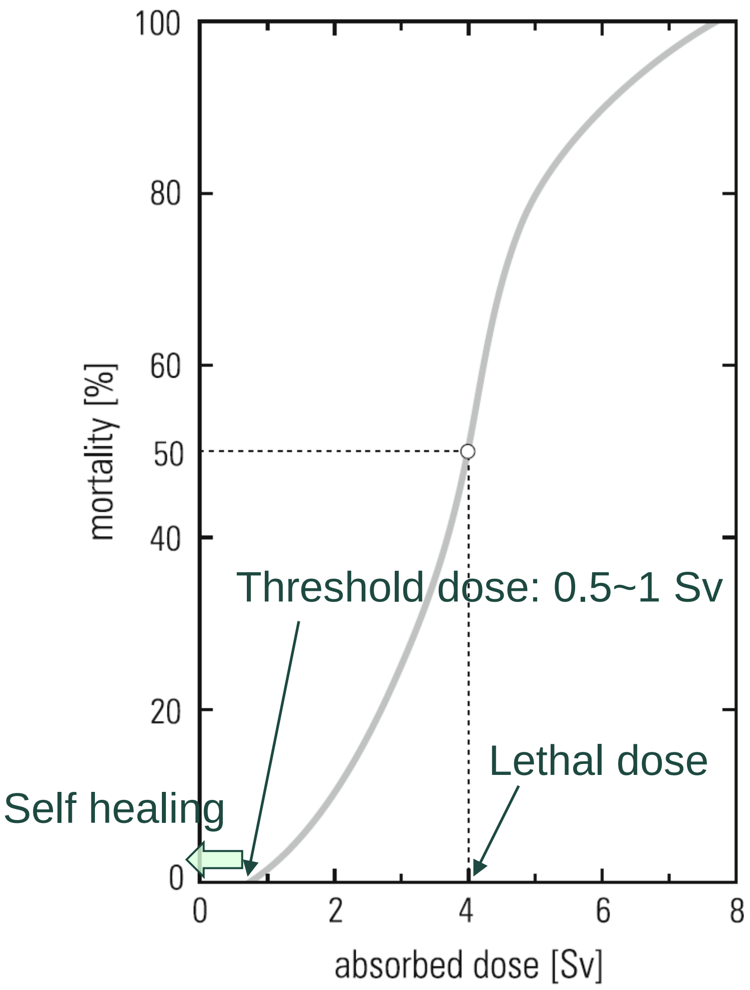
**Table 13.6** Acute Radiation Syndrome for Gamma Radiation

| Dose (Gy) | Symptoms | Remarks |
|---|---|---|
| 0–0.25 | None | No clinically significant effects. |
| 0.25–1 | Mostly none. A few persons may exhibit mild prodromal symptoms, such as nausea and anorexia. | Bone marrow damaged; decrease in red and white blood-cell counts and platelet count. Lymph nodes and spleen injured; lymphocyte count decreases. |
| 1–3 | Mild to severe nausea, malaise, anorexia, infection. | Hematologic damage more severe. Recovery probable, though not assured. |
| 3–6 | Severe effects as above, plus hemorrhaging, infection, diarrhea, epilation, temporary sterility. | Fatalities will occur in the range 3.5 Gy without treatment. |
| More than 6 | Above symptoms plus impairment of central nervous system; incapacitation at doses above ~10 Gy. | Death expected. |

- An acute, whole-body, gamma-ray dose of about 4 Gy without treatment would probably be fatal to about 50% of the persons exposed. This dose is known as the LD50—that is, the dose that is lethal to 50% of a population. More specifically, it is also sometimes called the LD50/30, indicating that the fatalities occur within 30 days.

# Effects of radiation on human death and cancer incidence

Early effect: mortality after 30 days for different whole-body doses for humans

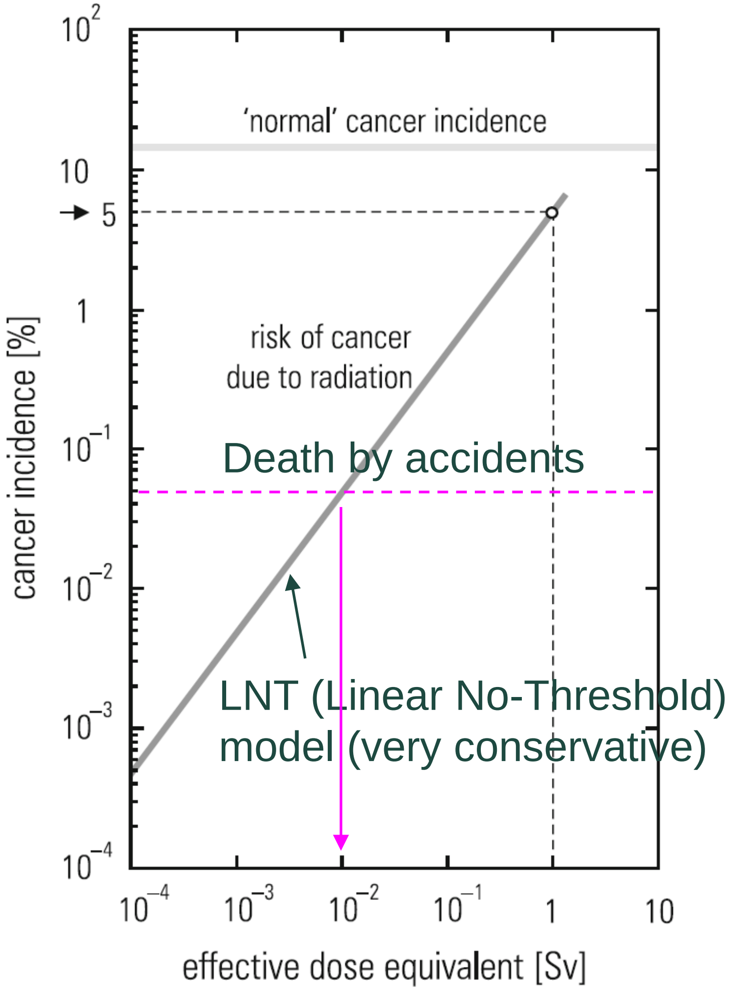


Threshold dose: 0.5~1 Sv

Lethal dose

Self healing

Delayed (or “late”) effect: probability of cancer incidence vs absorbed dose

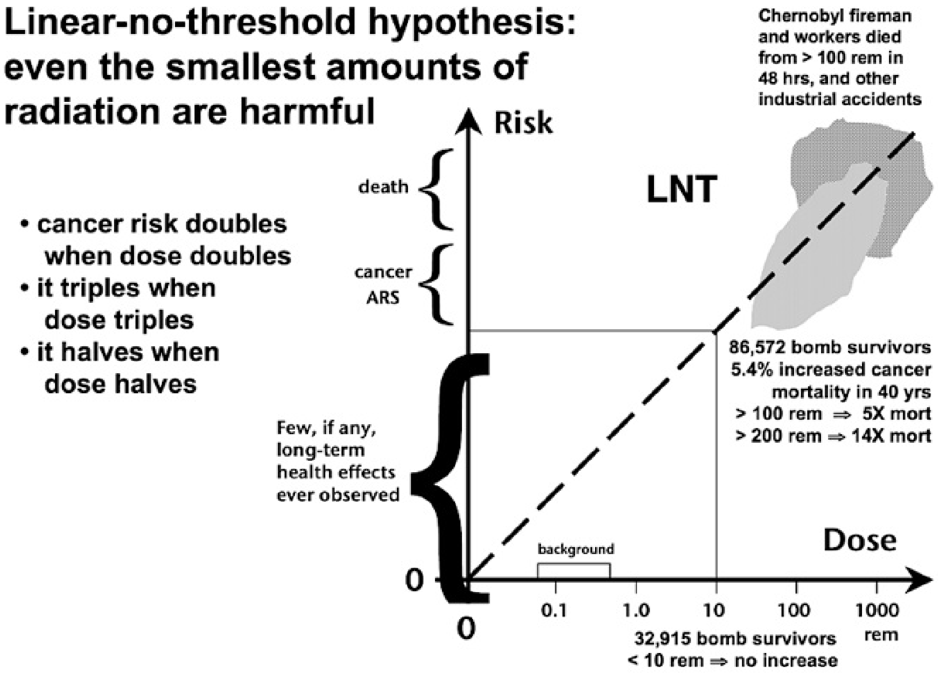


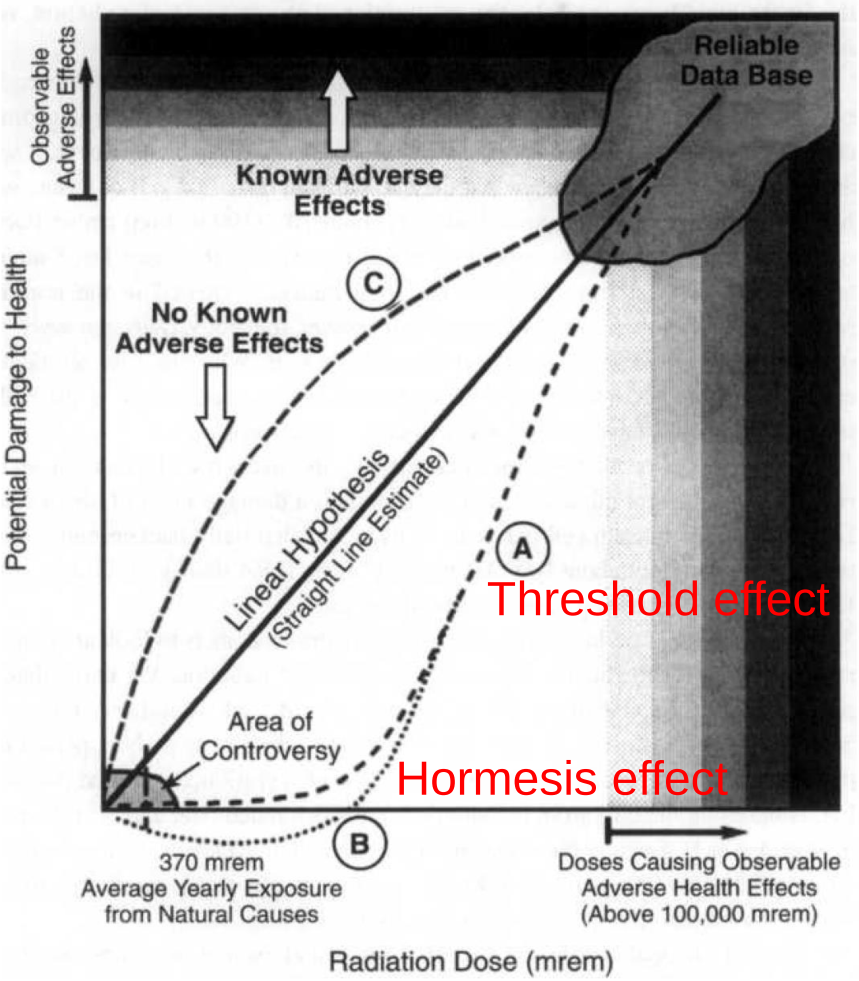
Death by accidents

LNT (Linear No-Threshold) model (very conservative)

# Models for determining the human health effects of radiation dose

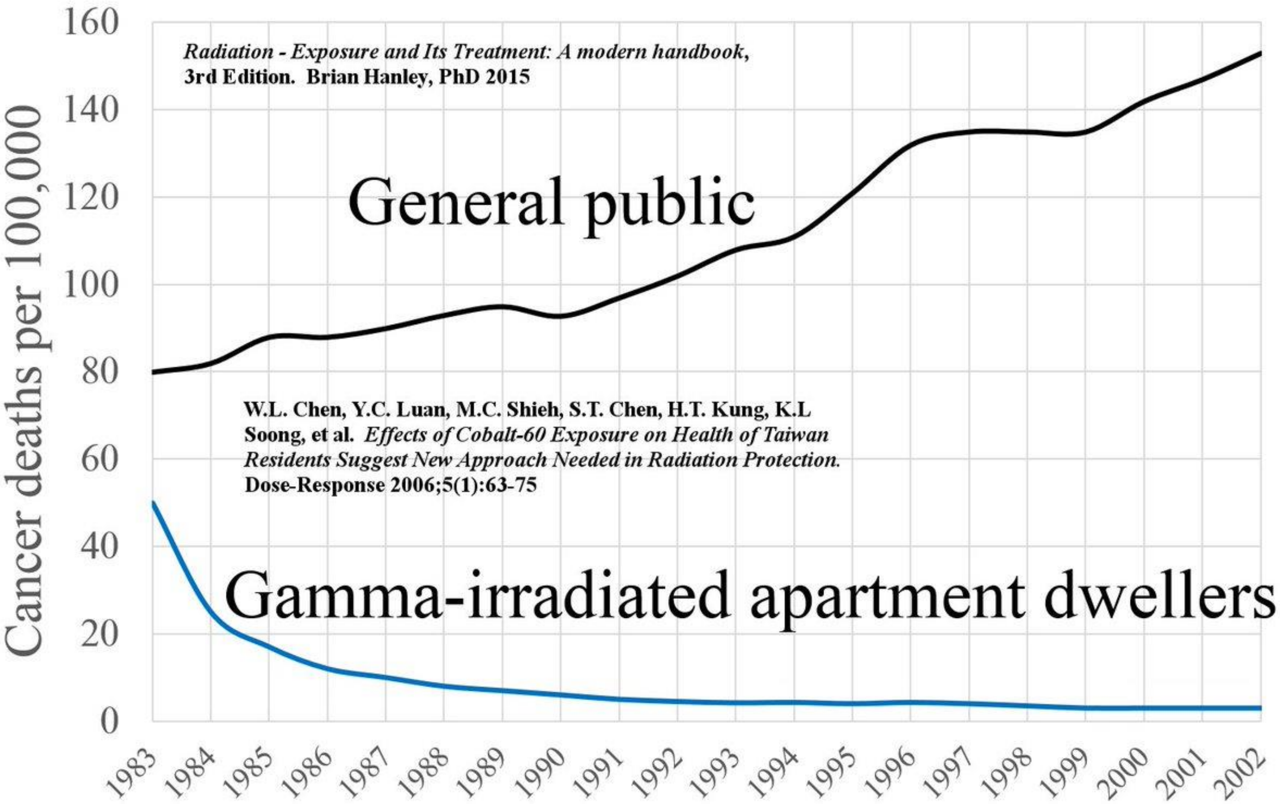
- Clear evidence for the radiation dose greater than 100 mSv.
- There are still debates for the effect of radiation dose under 100 mSv.





# Evidence of hormesis

- In Taiwan in the early 1980s, radioactive cobalt-60 (half-life 5.3 years) was accidentally included in some steel building materials, and these materials were then used to build 1,700 apartments. Over the course of two decades, some 10, 000 people occupied these apartments, receiving doses between a few mSv per year and a few tens of mSv per year (average total dose ~ 0.4 Sv).



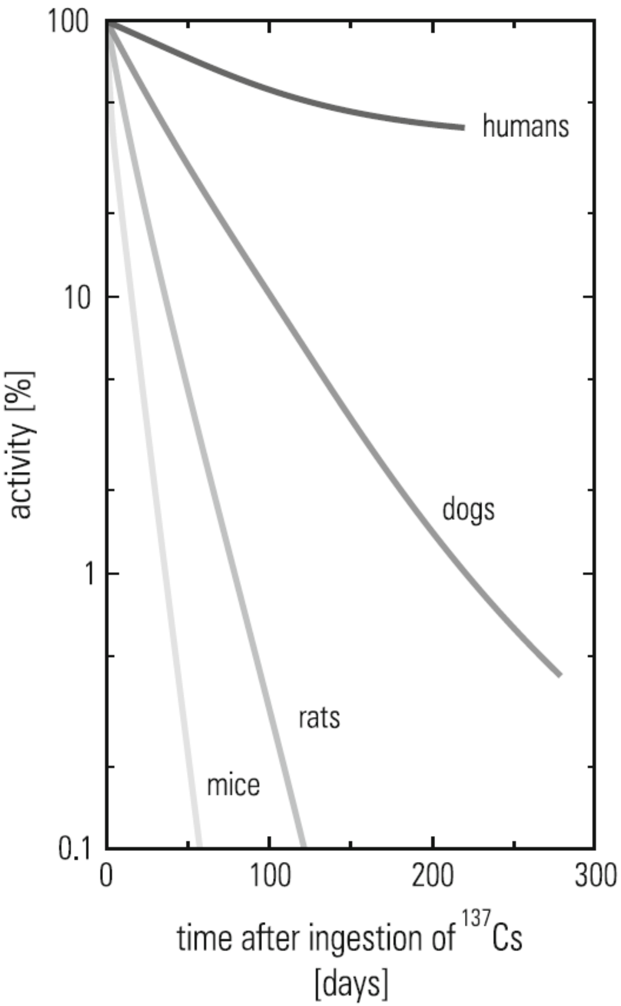
*Radiation - Exposure and Its Treatment: A modern handbook*, 3rd Edition. Brian Hanley, PhD 2015

W.L. Chen, Y.C. Luan, M.C. Shieh, S.T. Chen, H.T. Kung, K.L Soong, et al. *Effects of Cobalt-60 Exposure on Health of Taiwan Residents Suggest New Approach Needed in Radiation Protection.* Dose-Response 2006;5(1):63-75

# Biological half-life

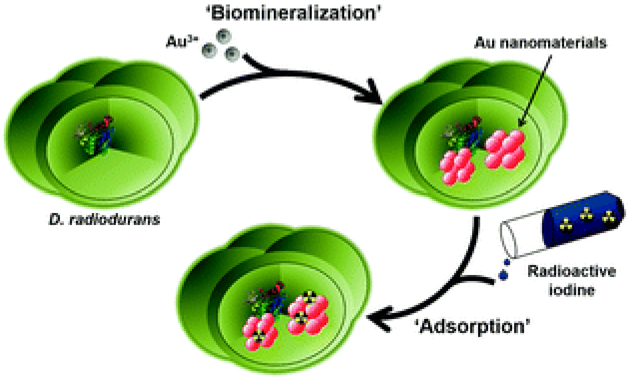
- The human body will have some ability to excrete incorporated material, and this ability will vary according to the substance involved.

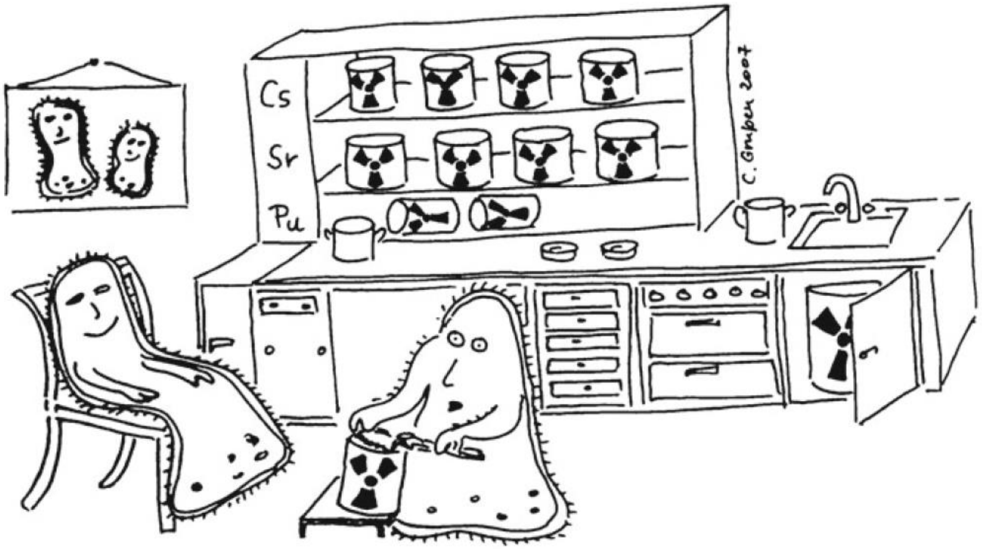
Physical half-life of $^{137}Cs$ ~ 30 yrs



# Radiation resistance

- The lethal dose, remembering that doses are inherently per-kilogram measures, for all mammals is about the same (humans: 4 Sv, dogs: 4 Sv, monkeys: 5 Sv, rabbits: 8 Sv, marmots: 10 Sv).
- In contrast to that, spiders (with a lethal dose of 1,000 Sv) and viruses (2,000 Sv) are much more resistant against ionizing radiation.
- The bacteria deinococcus radiodurans and deinococcus radiophilus can survive enormous doses (30,000 Sv) because of their extraordinary ability to repair radiation damage. They have even been found in the hot reactor cores of nuclear power plants.





*"So, Deino, shall we have some delicious caesium-137 for dessert?"*

# Principles of radiation protection (ICRP Publication 103)

- Principle of Justification: Any decision that alters the radiation exposure situation should do more good than harm.
  - This means that, by introducing a new radiation source, by reducing existing exposure, or by reducing the risk of potential exposure, one should achieve sufficient individual or societal benefit to offset the detriment it causes.
- Principle of Optimization of Protection: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.
  - This means that the level of protection should be the best under the prevailing circumstances, maximizing the margin of benefit over harm. In order to avoid severely inequitable outcomes of this optimization procedure, there should be restrictions on the doses or risks to individuals from a particular source (dose or risk constraints and reference levels).
- Principle of Application of Dose Limits: The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission.

# Exposure limit

- The principal recommendations from NCRP Report No. 116 and ICRP Publication 60 are summarized in Table 14.4.

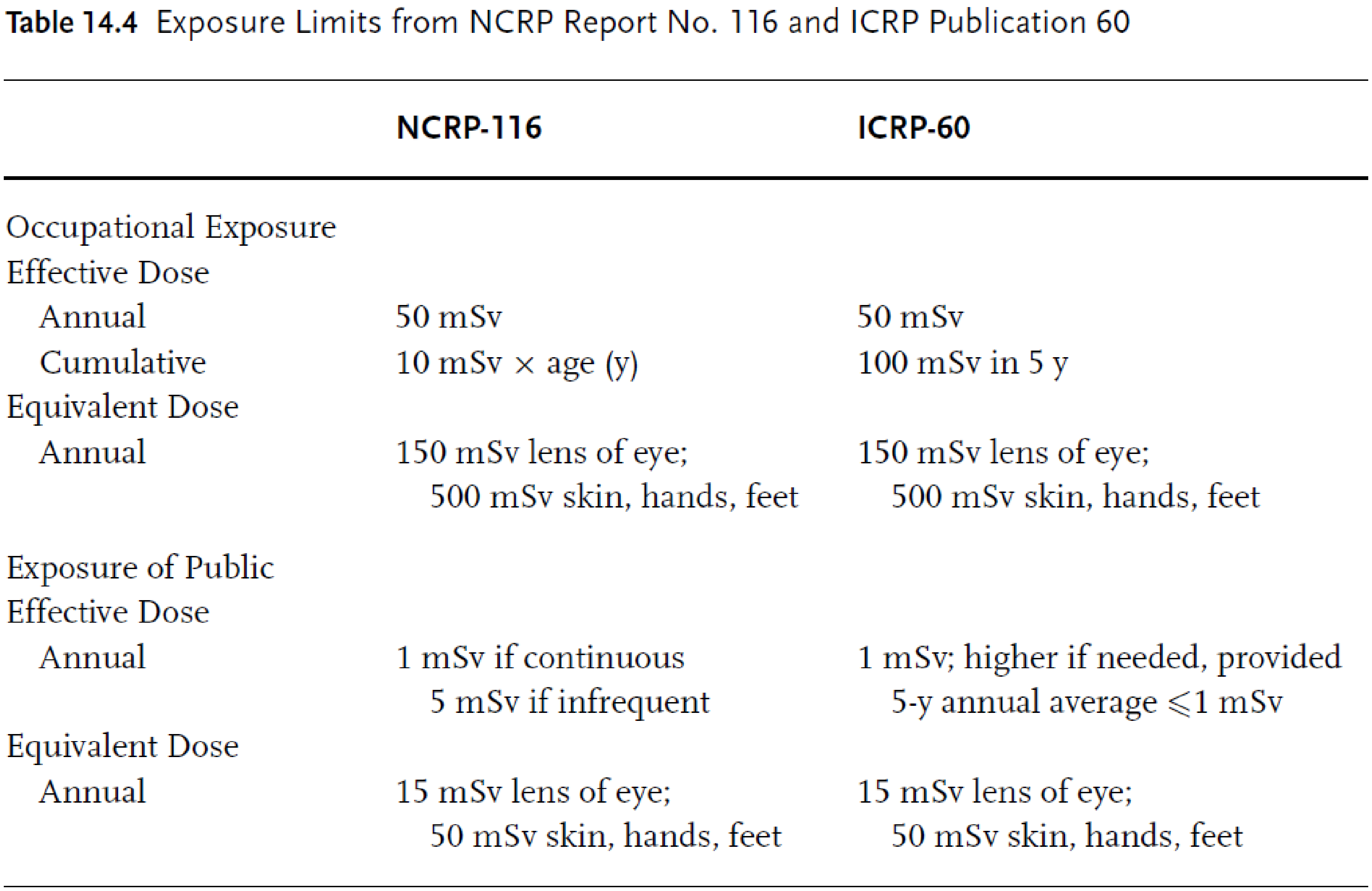
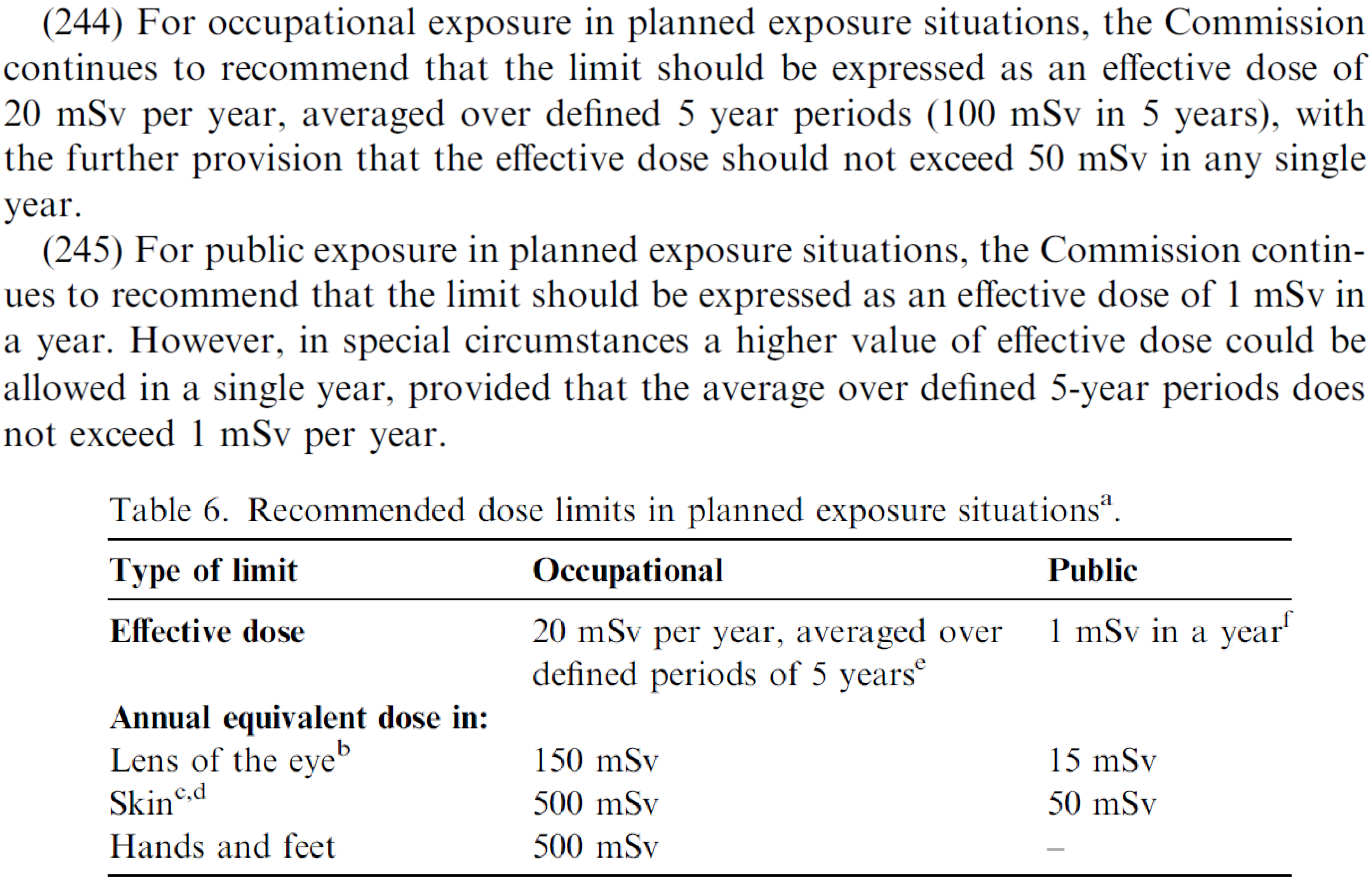


**Table 14.4** Exposure Limits from NCRP Report No. 116 and ICRP Publication 60

| | NCRP-116 | ICRP-60 |
|---|---|---|
| Occupational Exposure | | |
| Effective Dose | | |
| Annual | 50 mSv | 50 mSv |
| Cumulative | 10 mSv × age (y) | 100 mSv in 5 y |
| Equivalent Dose | | |
| Annual | 150 mSv lens of eye;<br>500 mSv skin, hands, feet | 150 mSv lens of eye;<br>500 mSv skin, hands, feet |
| Exposure of Public | | |
| Effective Dose | | |
| Annual | 1 mSv if continuous<br>5 mSv if infrequent | 1 mSv; higher if needed, provided<br>5-y annual average $\leqslant 1$ mSv |
| Equivalent Dose | | |
| Annual | 15 mSv lens of eye;<br>50 mSv skin, hands, feet | 15 mSv lens of eye;<br>50 mSv skin, hands, feet |

# Exposure limit (ICRP Publication 103)



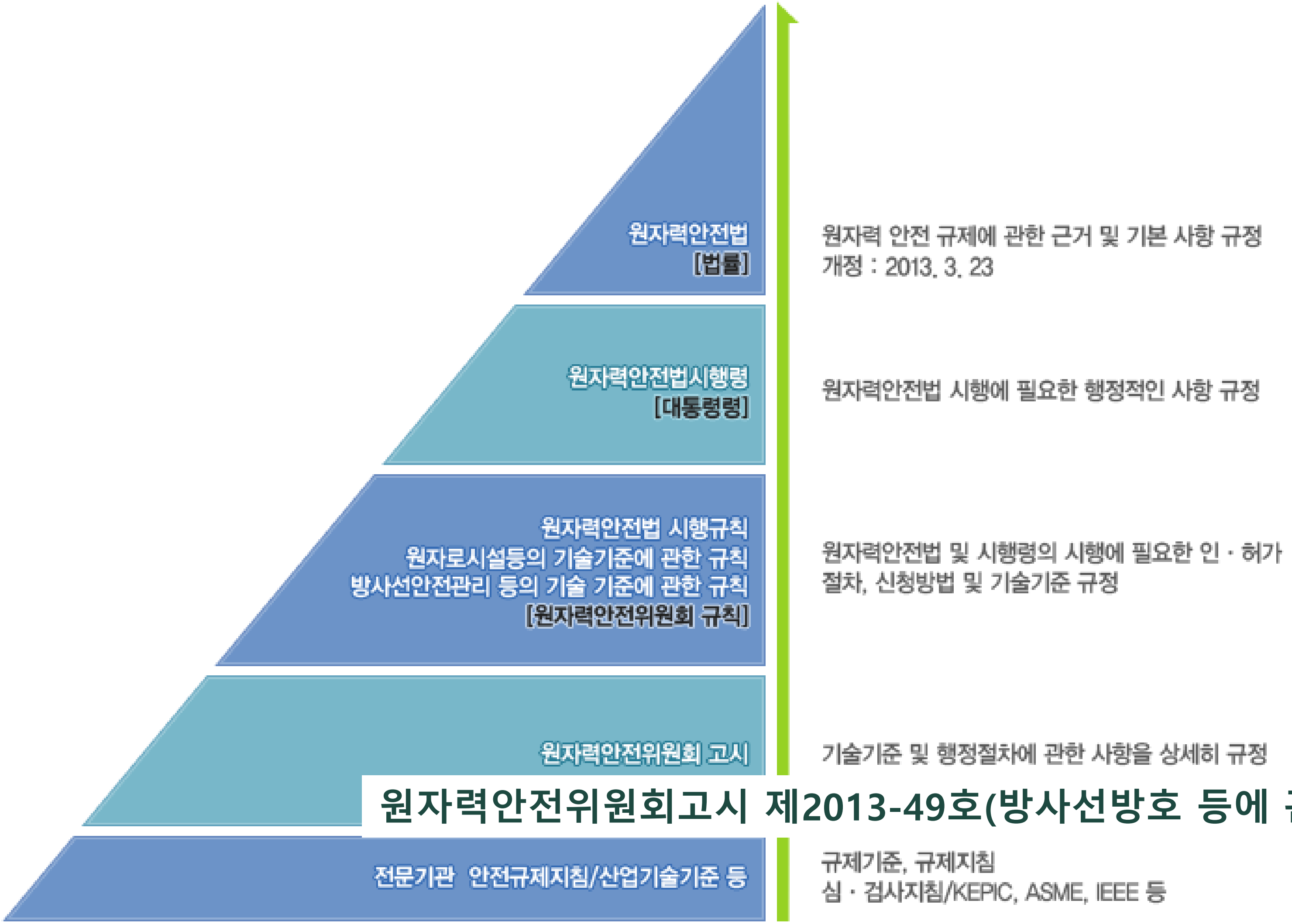
(244) For occupational exposure in planned exposure situations, the Commission continues to recommend that the limit should be expressed as an effective dose of 20 mSv per year, averaged over defined 5 year periods (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year.

(245) For public exposure in planned exposure situations, the Commission continues to recommend that the limit should be expressed as an effective dose of 1 mSv in a year. However, in special circumstances a higher value of effective dose could be allowed in a single year, provided that the average over defined 5-year periods does not exceed 1 mSv per year.

Table 6. Recommended dose limits in planned exposure situations[a].

| **Type of limit** | **Occupational** | **Public** |
|---|---|---|
| **Effective dose** | 20 mSv per year, averaged over defined periods of 5 years[e] | 1 mSv in a year[f] |
| **Annual equivalent dose in:** | | |
| Lens of the eye[b] | 150 mSv | 15 mSv |
| Skin[c,d] | 500 mSv | 50 mSv |
| Hands and feet | 500 mSv | – |

# 우리나라의 방사선 안전 규제: 원자력안전위원회



원자력안전법
[법률]

원자력 안전 규제에 관한 근거 및 기본 사항 규정
개정 : 2013. 3. 23

원자력안전법시행령
[대통령령]

원자력안전법 시행에 필요한 행정적인 사항 규정

원자력안전법 시행규칙
원자로시설등의 기술기준에 관한 규칙
방사선안전관리 등의 기술 기준에 관한 규칙
[원자력안전위원회 규칙]

원자력안전법 및 시행령의 시행에 필요한 인ㆍ허가 절차, 신청방법 및 기술기준 규정

원자력안전위원회 고시

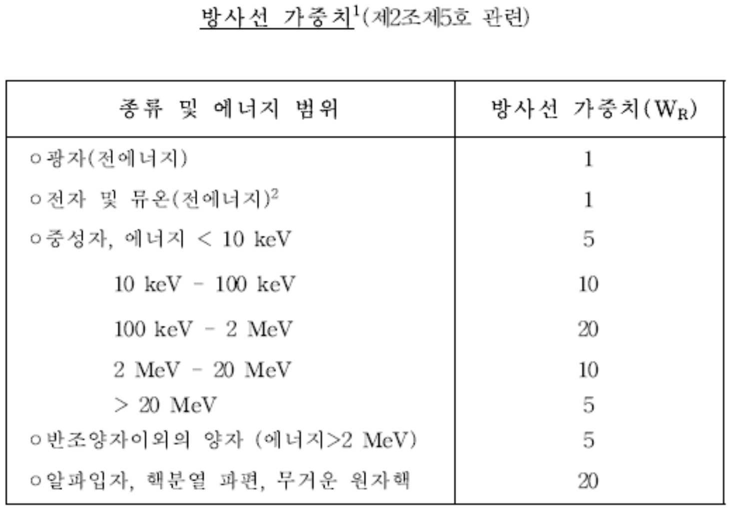
기술기준 및 행정절차에 관한 사항을 상세히 규정

**원자력안전위원회고시 제2013-49호(방사선방호 등에 관한 기준)**

전문기관 안전규제지침/산업기술기준 등

규제기준, 규제지침
심ㆍ검사지침/KEPIC, ASME, IEEE 등

# 원자력안전위원회 고시 제2013-49호

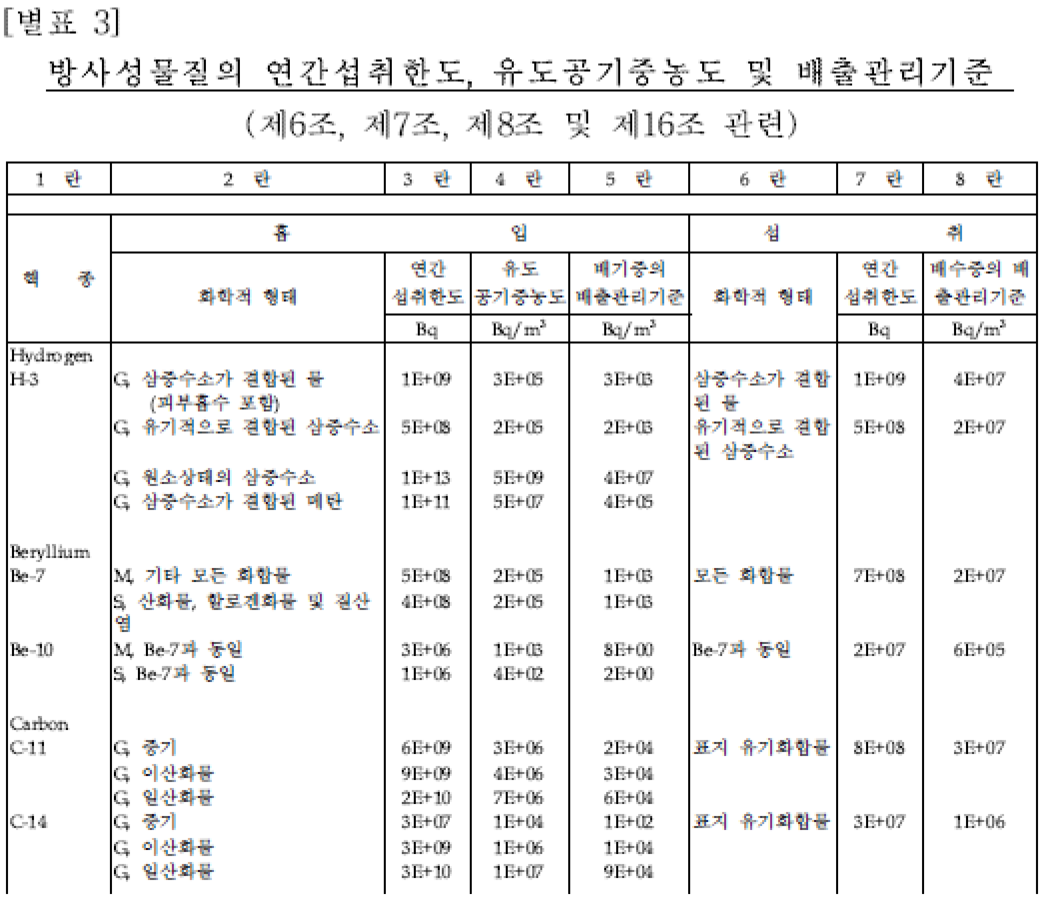


방사선 가중치[1](제2조제5호 관련)

| 종류 및 에너지 범위 | 방사선 가중치($W_R$) |
|---|---|
| ㅇ광자(전에너지) | 1 |
| ㅇ전자 및 뮤온(전에너지)[2] | 1 |
| ㅇ중성자, 에너지 < 10 keV | 5 |
| 10 keV – 100 keV | 10 |
| 100 keV – 2 MeV | 20 |
| 2 MeV – 20 MeV | 10 |
| > 20 MeV | 5 |
| ㅇ반조양자이외의 양자 (에너지>2 MeV) | 5 |
| ㅇ알파입자, 핵분열 파편, 무거운 원자핵 | 20 |

조직 가중치[1](제2조제6호 관련)

| 조직 또는 장기 | 조직가중치($W_T$) | 조직 또는 장기 | 조직가중치($W_T$) |
|---|---|---|---|
| 생식선 | 0.20 | 간 | 0.05 |
| 골수(적색) | 0.12 | 식 도 | 0.05 |
| 대 장 | 0.12 | 갑상선 | 0.05 |
| 폐 | 0.12 | 피 부 | 0.01 |
| 위 | 0.12 | 뼈표면 | 0.01 |
| 방 광 | 0.05 | 기타 조직 | 0.05[2,3] |
| 유 방 | 0.05 | | |



[별표 3]

방사성물질의 연간섭취한도, 유도공기중농도 및 배출관리기준

(제6조, 제7조, 제8조 및 제16조 관련)

| 1 란 | 2 란 | 3 란 | 4 란 | 5 란 | 6 란 | 7 란 | 8 란 |
|---|---|---|---|---|---|---|---|
| 핵 종 | 흡입 | | | | 섭취 | | |
| | 화학적 형태 | 연간 섭취한도 | 유도 공기중농도 | 배기중의 배출관리기준 | 화학적 형태 | 연간 섭취한도 | 배수중의 배출관리기준 |
| | | Bq | $Bq/m^3$ | $Bq/m^3$ | | Bq | $Bq/m^3$ |
| Hydrogen | | | | | | | |
| H-3 | G, 삼중수소가 결합된 물 (피부흡수 포함) | 1E+09 | 3E+05 | 3E+03 | 삼중수소가 결합된 물 | 1E+09 | 4E+07 |
| | G, 유기적으로 결합된 삼중수소 | 5E+08 | 2E+05 | 2E+03 | 유기적으로 결합된 삼중수소 | 5E+08 | 2E+07 |
| | G, 원소상태의 삼중수소 | 1E+13 | 5E+09 | 4E+07 | | | |
| | G, 삼중수소가 결합된 메탄 | 1E+11 | 5E+07 | 4E+05 | | | |
| Beryllium | | | | | | | |
| Be-7 | M, 기타 모든 화합물 | 5E+08 | 2E+05 | 1E+03 | 모든 화합물 | 7E+08 | 2E+07 |
| | S, 산화물, 할로겐화물 및 질산염 | 4E+08 | 2E+05 | 1E+03 | | | |
| Be-10 | M, Be-7과 동일 | 3E+06 | 1E+03 | 8E+00 | Be-7과 동일 | 2E+07 | 6E+05 |
| | S, Be-7과 동일 | 1E+06 | 4E+02 | 2E+00 | | | |
| Carbon | | | | | | | |
| C-11 | G, 증기 | 6E+09 | 3E+06 | 2E+04 | 표지 유기화합물 | 8E+08 | 3E+07 |
| | G, 이산화물 | 9E+09 | 4E+06 | 3E+04 | | | |
| | G, 일산화물 | 2E+10 | 7E+06 | 6E+04 | | | |
| C-14 | G, 증기 | 3E+07 | 1E+04 | 1E+02 | 표지 유기화합물 | 3E+07 | 1E+06 |
| | G, 이산화물 | 3E+09 | 1E+06 | 1E+04 | | | |
| | G, 일산화물 | 3E+10 | 1E+07 | 9E+04 | | | |

# Homework

- J. Turner, Atoms, Radiation, and Radiation Protection, Wiley (2007), chapter 14

  Problems: 13, 14