Part A. Dose magnitudes

1. Definitions

2. Effects of the ionization radiation

3. Natural background

4. Medical application

5. Rules for workers & zones

1. Definitions

Ionizing radiation

→ directly ionizing: charged particles (electrons, protons, …)
→ indirectly ionizing: photons, neutrons

of the order of 10 eV required to ionise an atom

electromagnetic radiation:

$$E = \frac{hc}{\lambda} \Rightarrow \lambda \approx 100\,\text{nm}$$

(hard ultraviolet)

	Ionization potential (eV)
carbon	11.260
oxygen	13.618
potassium	4.341
iron	7.870
lead	7.416

1. Definitions

Quantities and units used to quantify **stochastic effects:**

Exposure

↓

Absorbed Dose

Energy absorbed per mass unity (Joule/kg; Gray - Gy).

↓

Radiation type weighting factor

Equivalent Dose

(Joule/kg; Sievert - Sv).

↓

Tissue type weighting factor

Effective Dose

(Joule/kg; Sievert - Sv).

1 Sv = 100 rem.

1 mSv = 0.1 rem.

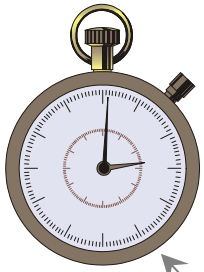
1. Definitions

$$\frac{dN}{dt} = -\lambda N(t)$$

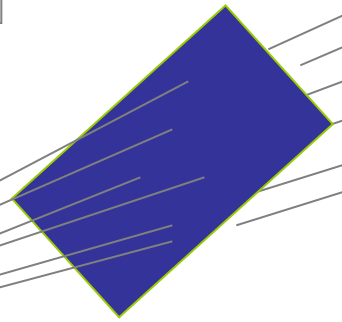
$$N(t) = N(0)e^{-\lambda t}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

Becquerel (Bq):
1 Bq = 1 s^{-1}
(Curie (Ci):
1 Ci = 3.7 10^{10} Bq)

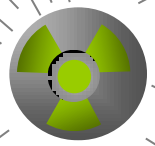


Activity

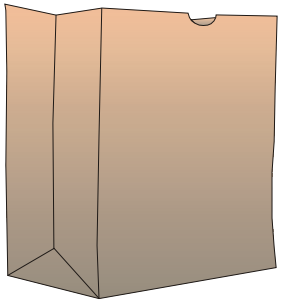


Fluence F

particles per cm^2
~ 1/$distance^2$



Absorbed dose D



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

$$\dot{D} = \frac{dD}{dt}$$

gray (Gy): 1 Gy = 1 $J.kg^{-1}$
(rad: 1 rad = 0.01 Gy)

Biological effects:

Effective dose E (Sv)

Ambient dose equivalent H*(d)

1. Definitions

Ionising Radiation Dose (Equivalent Dose):
is a measure of the radiation dose absorbed by a tissue depending on the different types of ionizing radiation.

1 mSv = 0,001 Sv (Sievert)

Energy absorbed per kilogram: 1 Sv = 1 Joule / 1 kg (1 Joule = 0,25 calories)

Assuming that the hours per year for a worker is **2000 hours**:

0,001 Sv / 2000 h = 0,0000005 Sv/h = 0,5 µSv/h

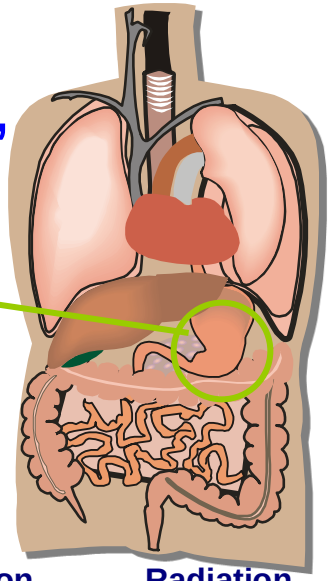
1. Definitions

ICRP Publication 60 (1991):

Organ dose D_T

$$D_T = \frac{1}{m_T} \int_{m_T} D dm$$

Individual organ, e.g. stomach



Tissue or organ equivalent dose $H_{T,R}$

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

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

Unit of equivalent dose: $J.kg^{-1}$
Special name: Sievert (Sv)
Old unit: rem (1 Sv = 100 rem)

Type and energy range of radiation	Radiation weighting factor w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons	
< 10 keV	10
10 - 100 keV	5
> 100 keV to 2 MeV	10
>2 - 20 MeV	20
> 20 MeV	10
	5
Protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

1. Definitions

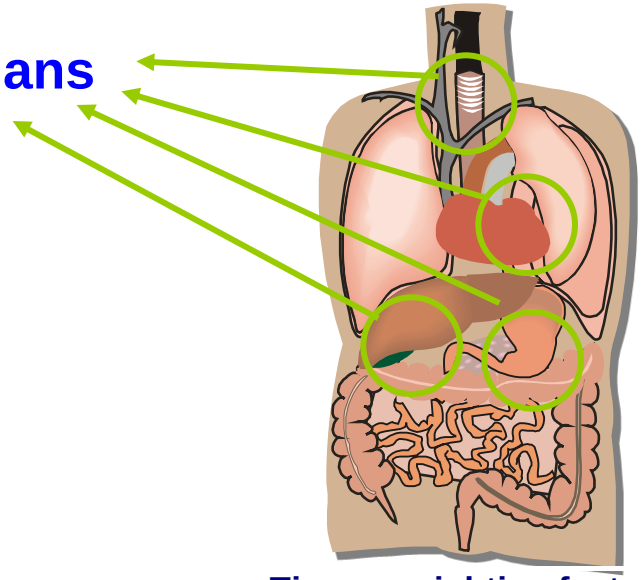
ICRP Publication 60 (1991):

Effective dose E

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

Unit of effective dose: Sv

Σ different organs



Tissue or organ	Tissue weighting factor w_T
Gonads	0.20
Bone marrow (red)	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

Dose limits on:

- ***Effective dose E***
- ***Tissue or organ equivalent dose H_T***

ICRP Publication 103 (2007)

Tissue weighting factor w_T

	ICRP 60	ICRP 103
Gonads	0.20	0.08
Bone marrow (red)	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Oesophagus	0.05	0.04
Thyroid	0.05	0.04
Skin	0.01	0.01
Bone surface	0.01	0.01
Brain	-	0.01
Salivary gland	-	0.01
Remainder	0.05	0.12
Total	1	1

Radiation weighting factor w_R

$$2.5 + 18.2\, e^{-[\ln E_n]^2/6}, \quad E_n < 1\,\text{MeV}$$

$$5.0 + 17.0\, e^{-[\ln 2E_n]^2/6}, \quad 1\,\text{MeV} \le E_n \le 50\,\text{MeV}$$

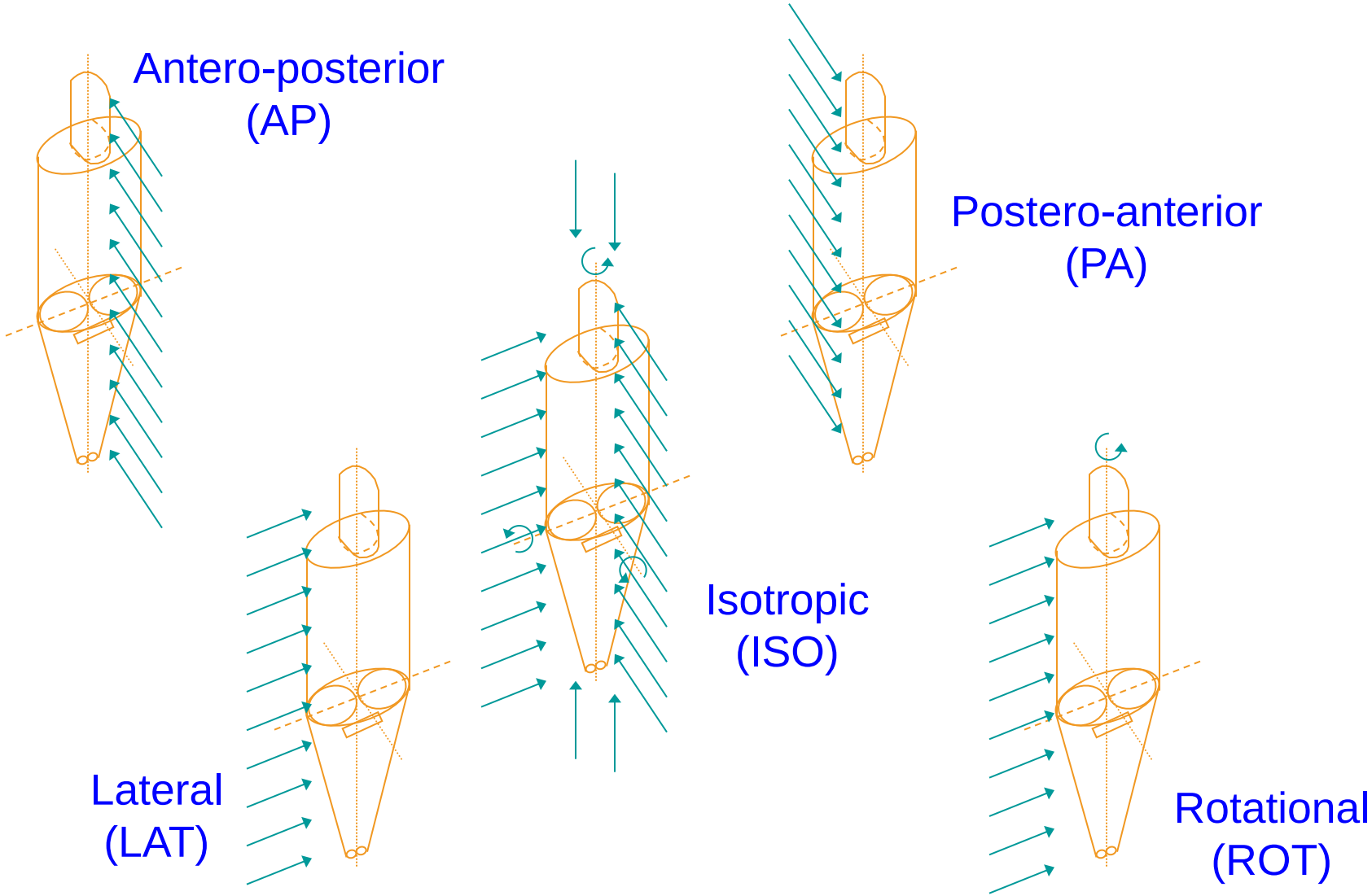
$$2.5 + 3.25\, e^{-[\ln 0.04E_n]^2/6}, \quad E_n > 50\,\text{MeV}$$

neutrons

protons: 2

1. Definitions

ICRP Publication 60 (1991): Irradiation geometries



1. Definitions

ICRU Report 51 (1993):

Protection quantities (ICRP) → operational quantities

Dose equivalent

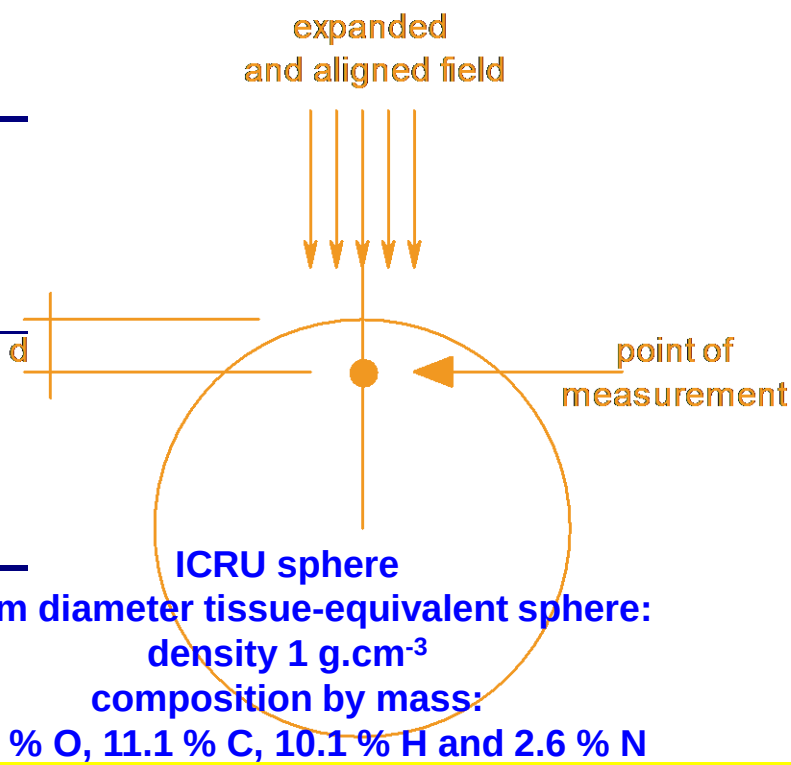
$$H = Q \cdot D$$

Unit of dose equivalent: Sv

Unrestricted linear energy transfer L (keV·μm^{-1})	Quality factor Q
L < 10	1
10 ≤ L ≤ 100	0.32 L - 2.2
L > 100	300 / L$^{1/2}$

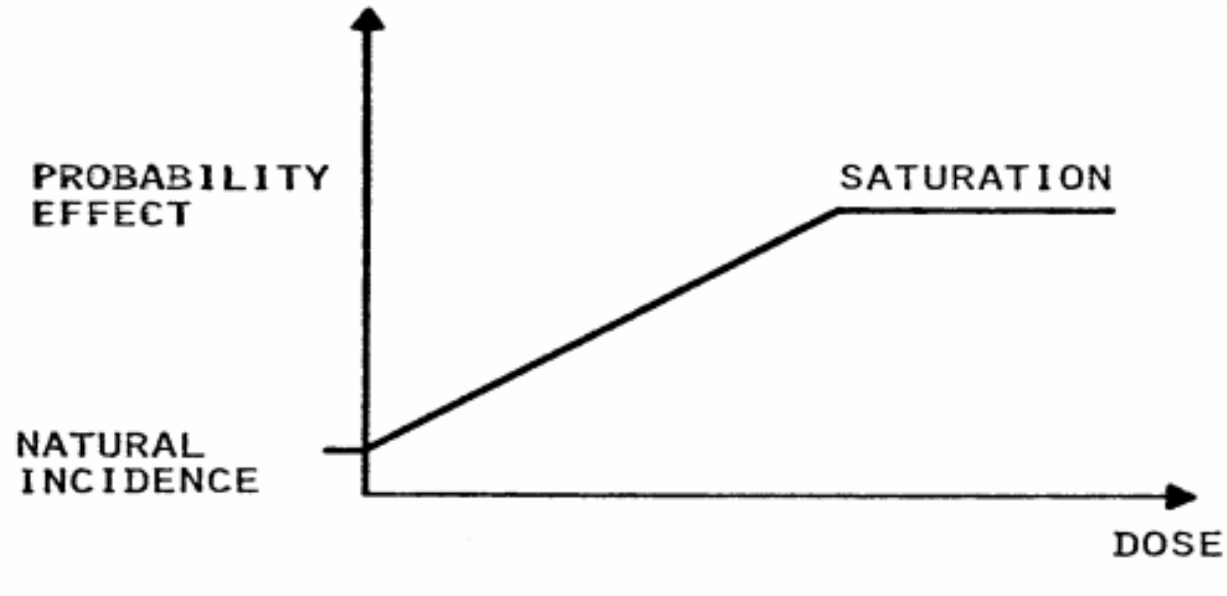
Ambient dose equivalent H*(d)

→ H*(10) ***(d = 10 mm)***



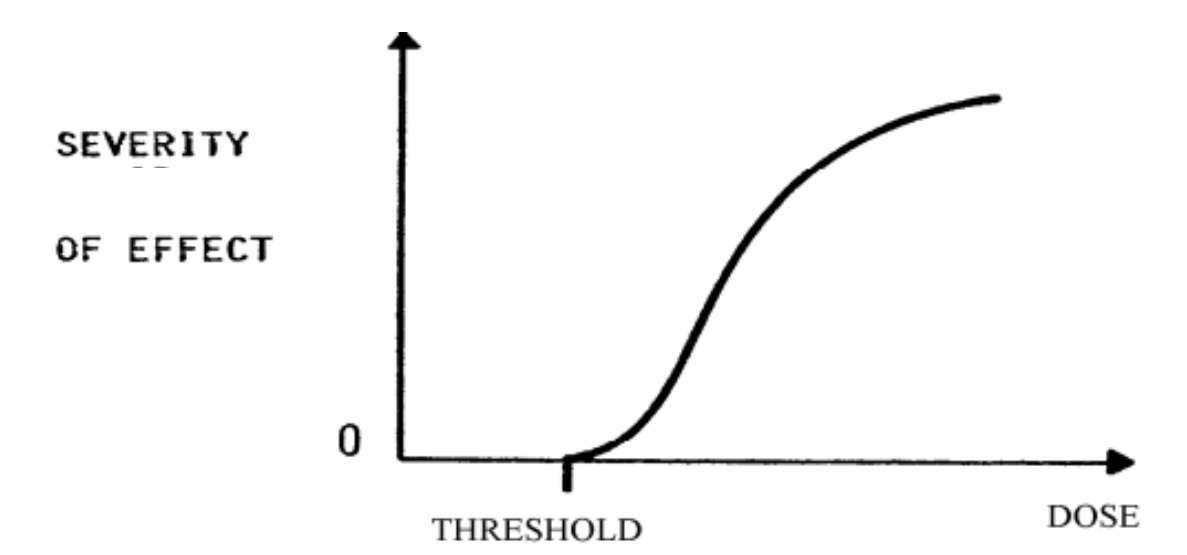
DETRIMENTAL EFFECTS OF IR

Dose Response Curve for a ***Stochastic Effect*** with no Threshold Dose Below which the Effect Dose not Occur.



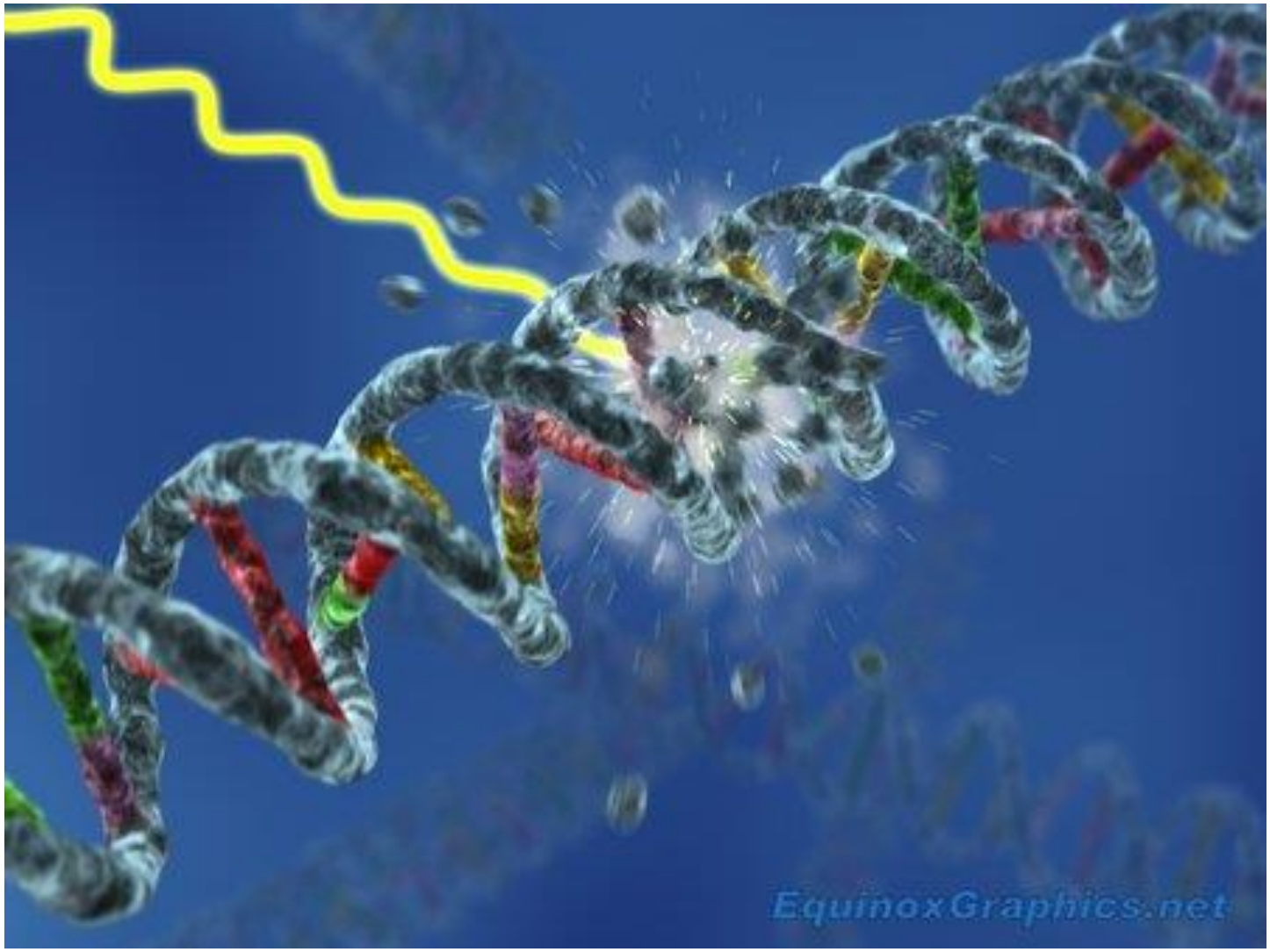
DETRIMENTAL EFFECTS OF IR

Dose Response Curve for a ***Deterministic*** Effect Exhibiting a Threshold Dose Below which the Effect Dose not Occur.



2. Effects of the ionization radiation

DNA AS A TARGET



2. Effects of the ionization radiation

Radiation

⇩

Electrical Effect (Ionization)

⇩

Physical & Chemical Changes

⇩

Damage to DNA

⇩ ⇩

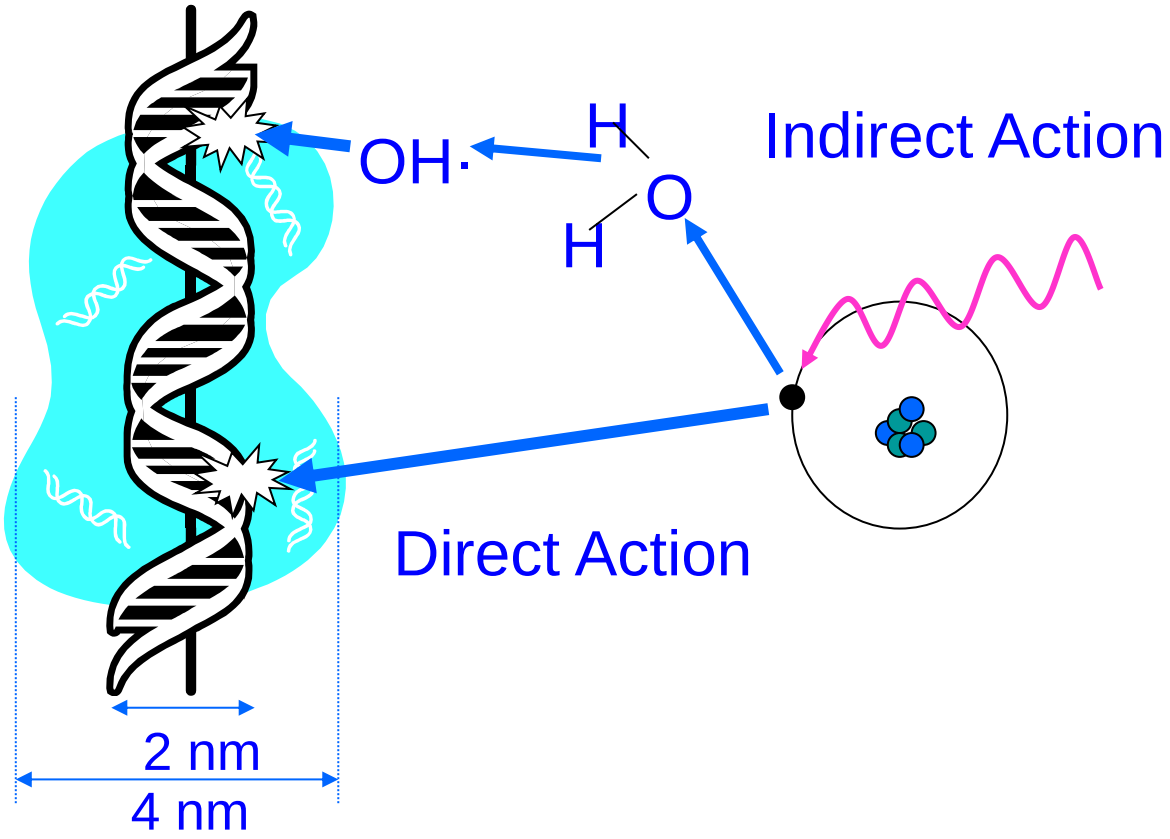
Cell Death | **Cell Transformation**

⇩ ⇩ ⇩

Early Effect | **Cancer** | **Hereditary Defects**

RADIATION INTERACTION WITH MATTER

The radiation-induced DNA damage can occur through a direct action or an indirect action.



For X- and Gamma-rays: 35% of the damage is direct and 65% indirect.

2. Effects of the ionization radiation

OXIGEN EFFECT

$H^* + O_2 \rightarrow HO_2^*$

Less oxidant but with a largest half life.

$HO_2^* + H^* \rightarrow H_2O_2$

$HO_2^* + HO_2^* \rightarrow H_2O_2 + O_2$

$e^-_{aq} + O_2 \rightarrow O_2^-$

$O_2^- + H_2O \rightarrow HO_2^* + OH^-$

Radiotherapy generates radicals in cellular DNA and adjacent molecules that lead to cell death. Oxygen is important because it intercepts the short-lived free radicals and enhances DNA damage.

2. Effects of the ionization radiation

WHOLE BODY RESPONSE: ADULT

	Dose (Gy)	Prodromic	Latency	Desease manifestation	Death
Bone marrow syndrome	1-5	Few hours	Some days - 3 weeks	Infections, haemorrhage, anaemia	30-60 days (>3Gy)
Gastrointestinal syndrome	5-15	Few hours	2-5 days	Dehydration, Malsnutrition, Infections	10-20 days
Central Nervous system syndrome	> 15	Minutes	Few hours	Convulsions, Ataxia, Coma	1-5 days

Lethal dose - LD50/30:

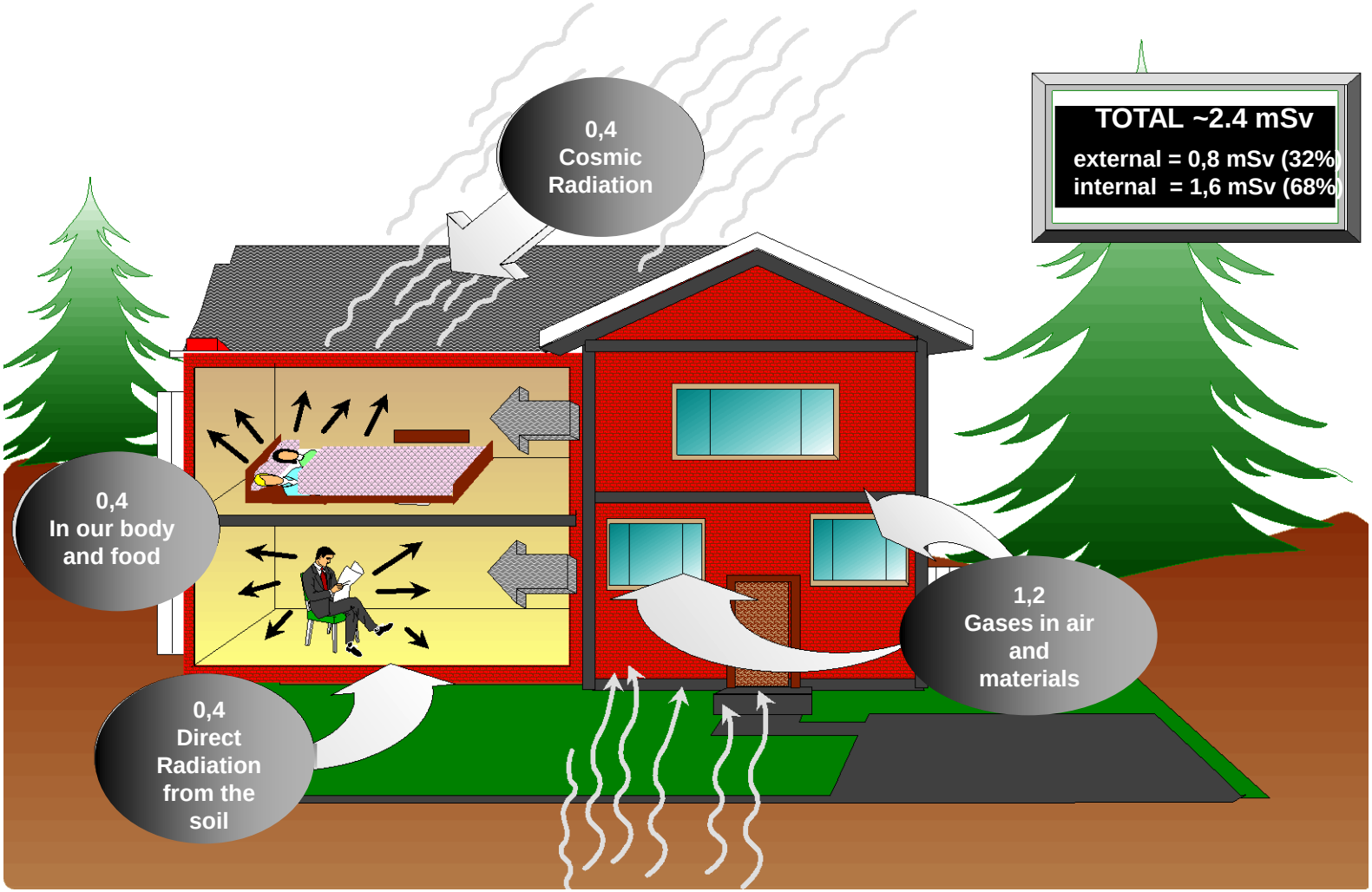
Dose which would cause death to 50% of the population in 30 days.

For humans after whole body irradiation LD50/30 is about 2.5 – 4.5 Gy.

2. Effects of the ionization radiation

Effect	Population	Exposure period	Probability/Sv
Hereditary effects	Whole population	Lifetime	1 % (all generations)
Fatal cancer	Whole population	Lifetime	5 %
	Working population	Age 18-65	4 %
Health detriment	Whole population	Lifetime	7.3 %
	Working population	Age 18-65	5.6 %

3. Natural background

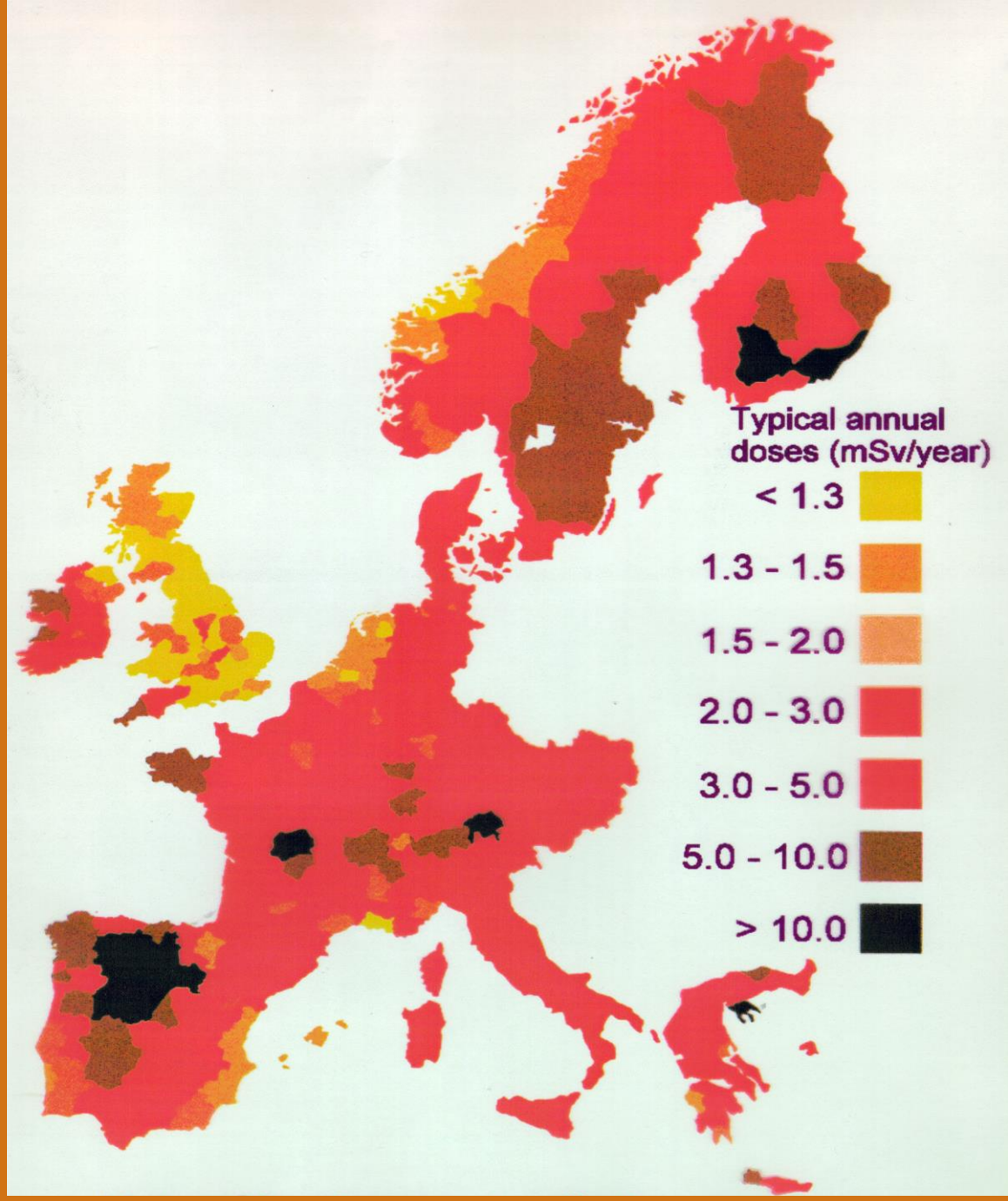


3. Natural background

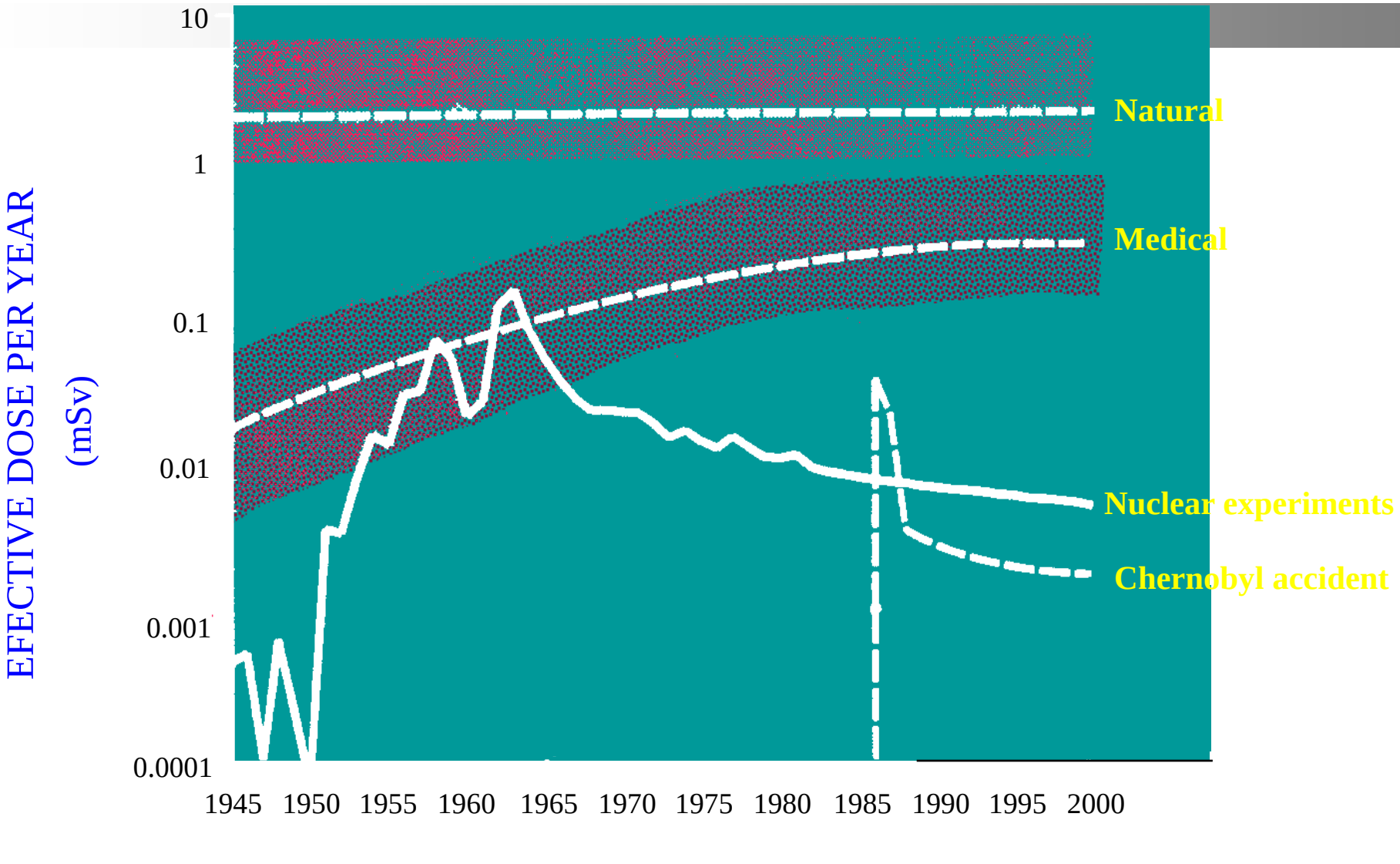
WORLDWIDE AVERAGE DOSES

Source	*Effective dose (mSv per year)*	*Typical range (mSv per year)*
External exposure		
• Cosmic rays	0.4	0.3-1.0
• Terrestrial gamma rays	0.5	0.3-0.6
Internal exposure		
• Inhalation	1.2	0.2-10
• Ingestion	0.3	0.2-0.8
Total	2.4	1–10

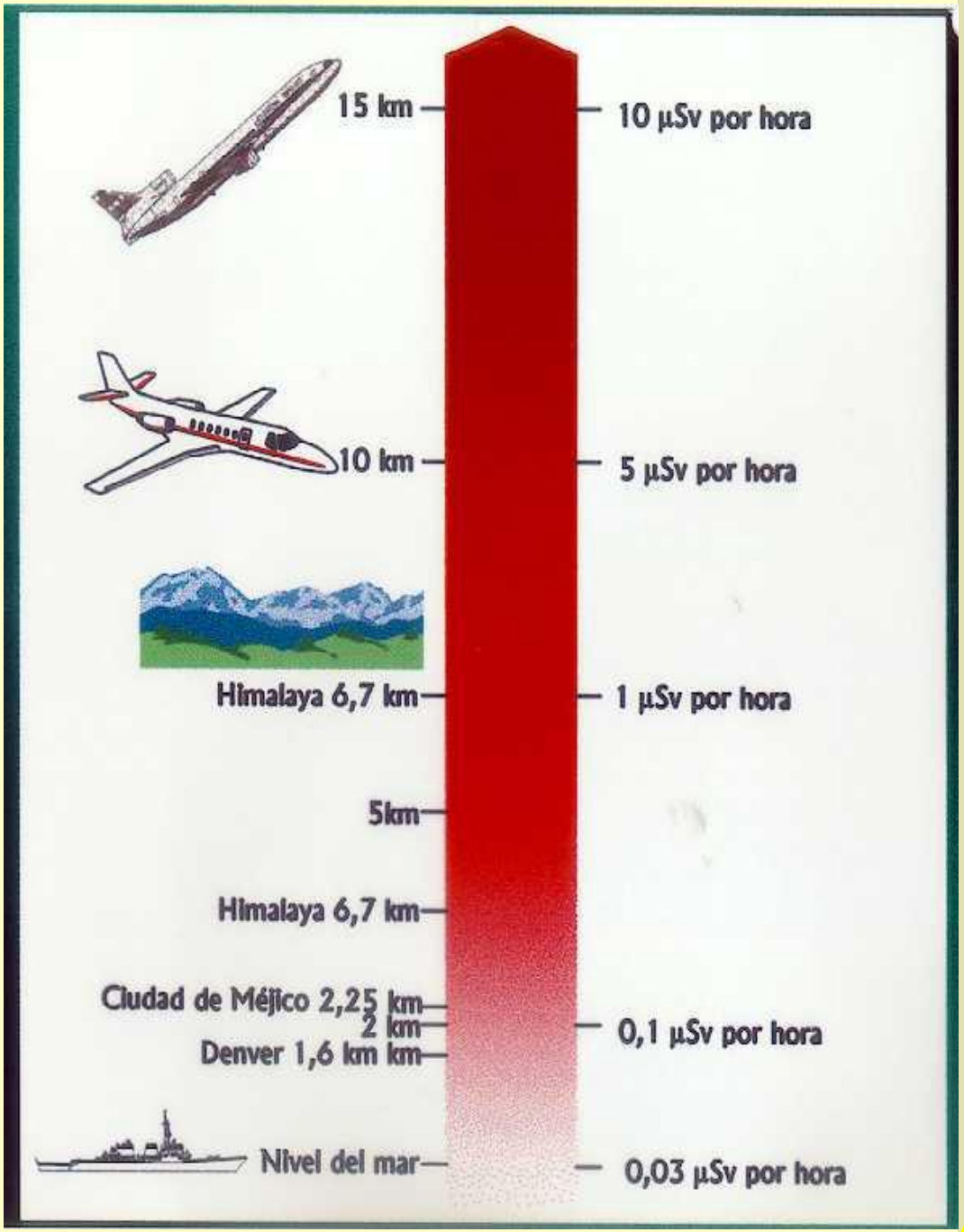
Natural background radiation exposure in Europe



3. Natural background

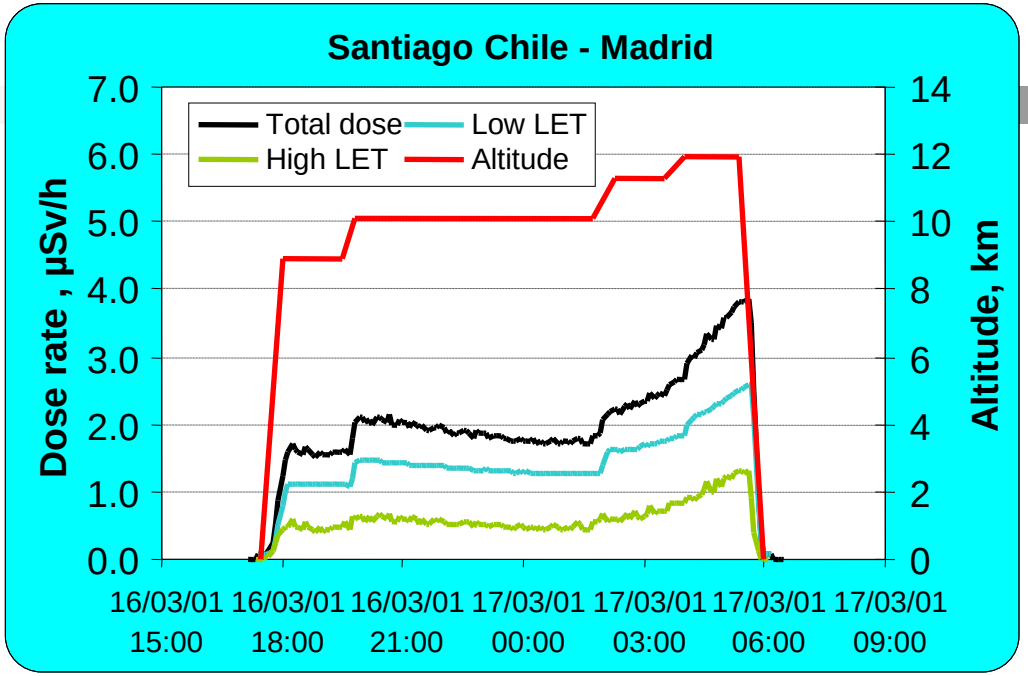


3. Natural background



Cosmic Radiation

3. Natural background



Flight duration:	12.52 h
Time at high altitude:	11.33 h
Average altitude:	10.3 km

	Average dose - rate ($\mu Sv\ h^{-1}$)	*Annual dose (600 hours) ($mSv\ a^{-1}$)*
Experimental:	2.03	1.22
CARI 6:	2.25	1.35
EPCARD:	1.94	1.17

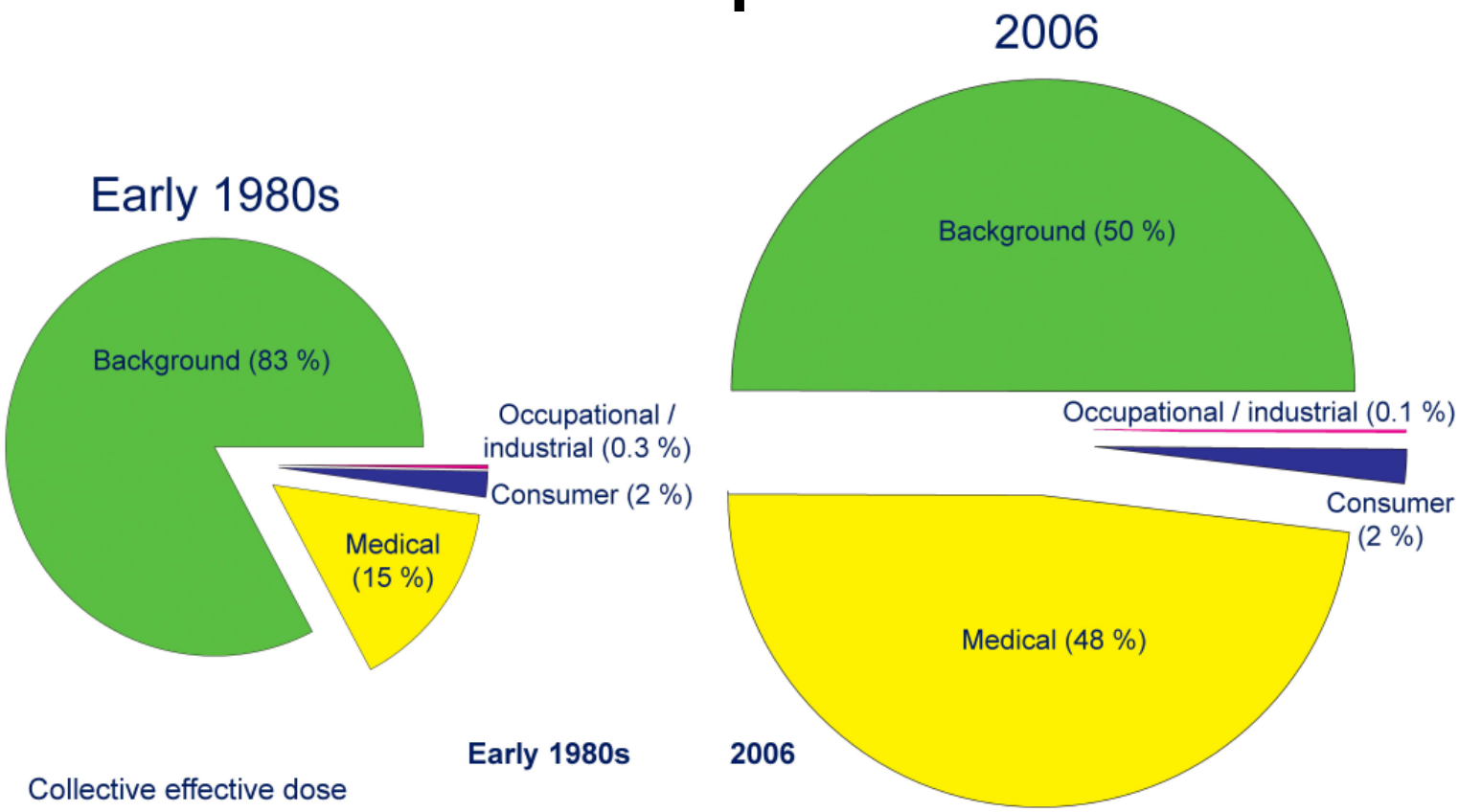
3. Natural background

AVERAGE DOSES TO WORKERS

Radiation source	*Number of workers*	*Average dose (mSv per year)*
Enhanced natural sources		
• **Mining (excluding coal)**	**760,000**	**2.7**
• **Coal mining**	**3,900,000**	**0.7**
• **Air travel (crew)**	**250,000**	**3**
• **Mineral processing**	**300,000**	**1.0**
• **Above ground workplaces (radon)**	**1,250,000**	**4.8**
Total	**6.500,000**	**1.7**

4. Medical application

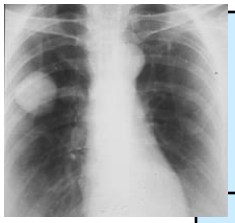
Radiation exposure to US



	Early 1980s	2006
Collective effective dose (person-Sv)	835,000	1,870,000
Effective dose per individual in the U.S. population (mSv)	3.6	6.2

Medical dose per capita (mSv) .54 3.0 has increased 560%

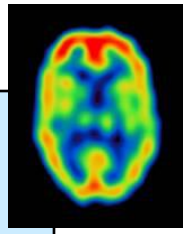
4. Medical application



RADIATION RISKS IN X-RAY EXAMINATIONS

Examination	Skin dose (mGy)	Effective dose (mGy)	Risk (%)
Urography	30	8	0.04
Lumbar spine	40	5	0.025
Abdomen	10	2.5	0.013
Chest	2	0.25	0.0013
Extremities	3	0.025	0.00013

RADIATION RISKS IN NUCLEAR MEDICINE



Examination	Radiopharmaceutical	Effective dose (mSv)	Risk (%)
Myocardium	Tl-201 chloride	23	0.12
Bone	Tc-99m MDP	3.6	0.018
Thyroid	Tc-99m pertechnetate	1.1	0.006
Lungs	Tc-99m MAA	0.9	0.005
Kidney clearance	Cr-51 EDTA	0.01	0.00005

4. Medical application

Radiation doses to patients from various types of medical imaging procedures

- With X-rays

Type of procedure	Average adult effective dose **(mSv)**	Estimated dose equivalent **(n. of chest X-rays)**	Approx. Equiv. Period of natural background radiation
Dental X-ray	**0.005 – 0.01**	**0.25 -0.5**	**< 1.5 day**
Chest X-ray	**0.02**	**1**	**3 days**
Mammography	**0.4**	**20**	**60 days**
CT	**2 - 16**	**100 - 800**	**300 days – 7.4 years**
Interventional fluoroscopy	**5 - 70**	**250 - 3500**	**2.3 years – 32.2 years**

Initiative to reduce unnecessary radiation exposure from medical imaging, FDA. 2010

DOSE LIMITS - PERSONAL

➢ WORKERS :

1. For Exposed Workers - A: maximum dose 50 mSv per official year (100 mSv for 5 years)
2. For Exposed Workers - B: maximum dose 6 mSv per official year
3. For None Exposed Workers: 1 mSv per official year
4. For women during pregnancy (*): 1 mSv
5. For general public: 1 mSv per official year

5. Rules for workers & zones

Aplication	Dose Limit Workers	Dose Limit Public
Effective Dose	20 mSv/year averaged for 5 years periods[1]	1 mSv/year[2]
Equivalent Dose (/year):		
Cristaline	150 mSv	15 mSv
Skin [3]	500 mSv	50 mSv
Hands and foot	500 mSv	------

1 The effective dose will be below 50 mSv any year.

2 Under exceptional situations a higher effective dose could be accepted, if the average in 5 years Is not above 1mSv/year.

3 These dose limits (equivalent dose) prevent deterministic effects after local exposures.

1 mSv/year is the annual limit for public

due to artificial radiations

Exposed Worker

Annual dose (2000 h/year):

< 1 mSv/year

Dose per day:

< 12 µSv

Dose rate @ public areas:

< 0.5 µSv/h

The smoker case

Annual dose (1.5 pack/day):

13 mSv/year

Dose per cigarrette:

~ 1.2 µSv/cigarette

Dose rate (5min/cigarette):

~ 14.4 µSv/h

AREA DOSE LIMITS

- **ZONE CLASIFICATION:**

1. **Controlled Zone**: dose higher than 6 mSv (per official year)

   i. Limit Access Zone: dose higher than 100 mSv (for 5 years)

   ii. Ruled Access Zone: high dose rate (short period)

   iii. Prohibited Access Zone: high dose (single exposition)

2. **Watched Zone**: dose lower than 6 mSv (per official year)

Always ANNUAL DOSE is ABOVE the background LEVEL

DOSE LIMITS - SIGNALS

WATCHED ZONE > 0,5 μSv/h up to 3 μSv/h

CONTROLLED ZONE > 3 μSv/h up to 25 μSv/h

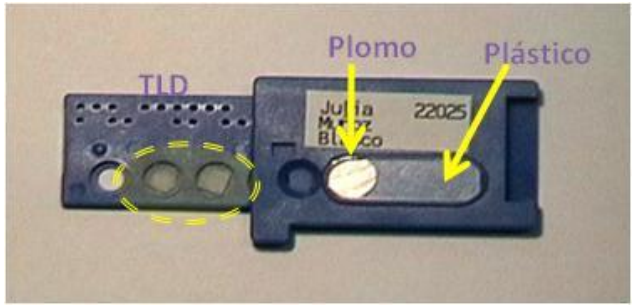
LIMIT ACCESS ZONE > 25 μSv/h up to 1 mSv/h

RULED ACCESS ZONE > 1 mSv/h up to 100 mSv/h

PROHIBITED ACCESS ZONE > 100 mSv/h

Passive personnel dosimeters

- Thermoluminiscense
- Based on detectors TLD-100 (LiF: Mg, Ti):
  - Equivalent dose
  - Range of usage: 10µGy-10Gy.
- The filter system allow to distinguish the energy radiation



Whole body dosimeter

5. Rules for workers & zones

Different passive dosimeters configurations